Dear reviewers and editor:

We would like to thank you for taking the time to review our manuscript and suggest such valuable information in order to improve its quality. Even minor suggestions helped in the progress of the text's value.

A set of minor changes and typos has been corrected throughout the document. Following this introduction, you may find a detailed answer to Reviewer #1's and Reviewer #2's comments. Changes due to Reviewer #1's comments are indicated in purple in the new version, while changes due to Reviewer #2's comments are indicated in green. Changes due to comments from both reviewers are marked in red.

Reviewer #1:

Summary of the Paper

The paper titled "Disentangling the Drivers of Soil CO2 Ventilation in a Mediterranean Dryland using In Situ and Remote Sensing Techniques" by Jesús Abril-Gago et al. investigates the main atmospheric drivers controlling soil CO2 and radon (Rn) dynamics in a Mediterranean shrubland in southern Spain. The study identifies 10 periods where dilution and enriching ventilation periods can be seen.

We appreciate Reviewer #1 efforts to review the manuscript. Now we will proceed answering every comment and suggestion.

General comments

The authors provide a comprehensive view of the ventilation phenomena. The methodology is detailed and involves sensible statistical analysis. The identification of surface atmospheric pressure as a key driver is a significant contribution to understanding soil-atmosphere interactions in drylands.

The paper does not discuss the flux contribution of the phenomena to the overall surface flux. Doing so, would strengthen the discussion and connect to the authors introduction: "CO2 fluxes obtained with the EC technique have been traditionally associated with biological processes […] while abiotic geochemical and mechanical processes […] were traditionally neglected".

The paper is well-structured with clear sections on methodology, results, and discussion. The use of figures and tables support the findings effectively. The writing is clear and the arguments are well-presented.

The authors appreciate Reviewer #1's comments. We also appreciate the issue raised regarding the quantification and contribution of the CO_2 fluxes due to the ventilation mechanism. For this reason, we have addressed it and included a discussion of this topic in Section 4.4 of the manuscript. The reply and details of such topic are given in the reply to the next comment, since it focuses on this specific topic.

Technical comments

As the paper does not discuss the flux quantification for the phenomena, it is hard to grasp how important is it and if the enriching and diluting ventilations compensate each other over the time. This point should be further discussed.

We especially appreciate Reviewer #1 for this comment, since it evidences that an interesting discussion was missing from the manuscript.

We have now calculated the CO_2 fluxes for the different periods considered: enriching ventilation, diluting ventilation, precipitation pulses, and background (the rest of the dataset). The corresponding average (± standard deviation) CO_2 fluxes for these periods are present in the table below.

	Enriching	Diluting	Precipitation	Background
F^{CO2} (μmol m^{-2} s^{-1})	0.05 ± 0.11	0.30 ± 0.13	0.62 ± 0.32	0.11 ± 0.10
% of cases	4.1%	3.5%	19.3%	73.1%

Thus, significant CO_2 emissions are confirmed to happen during precipitation and after, as considered in the manuscript. Additionally, significant CO_2 emissions were recorded during the diluting ventilation, suggesting that the large CO_2 concentrations stored in the soil are ejected into the atmosphere and recorded by the eddy covariance tower. On the other hand, during the enriching ventilation, very low CO_2 fluxes were recorded, suggesting that underground accumulation of CO_2 may be happening. However, the CO_2 emitted during the diluting phase overpasses the CO_2 captured during the enriching phase. Finally, the average background CO_2 emission (non-ventilation, non-precipitation) suggests that the ecosystem is a natural source of CO_2, at least during the period considered in this study.

This discussion has been added to Section 4.4 as:

> […] boundary layer. Consistently, CO_2 fluxes remain relatively low during this phase (0.05 ± 0.11 μmol m^{-2} s^{-1}), approximately half of those observed under non-ventilation conditions, supporting the interpretation that CO_2 is being temporarily stored within the soil.
>
> […] CO_2 and Rn into the soil pores, compressing air within the soil and displacing CO_2-rich soil air to the atmosphere producing a significant CO_2 flux (0.30 ± 0.13 μmol m^{-2} s^{-1}) up to three times that observed under non-ventilation conditions.

The authors have identified surface atmospheric pressure as a key driver for the ventilation phenomena. It would add to the paper to have an annex figure which identifies periods which shifts in surface atmospheric pressure and maybe other conditions (strong turbulence) are in place but ventilation is not possible (high water content). It would be a counter example for figure 1.

The authors appreciate this suggestion by Reviewer #1. We believe this could be an interesting phenomenon to observe, since it could confirm the low soil humidity condition as necessary for soil ventilation. However, due to the relatively limited dataset, we could not observe such a case. The only period not fulfilling the soil humidity condition coincided with a period of almost constant atmospheric pressure and low friction velocity. Nevertheless, the authors will consider this suggestion and take it into account on upcoming campaigns, aiming to sample during a more humid period (e.g. spring). Additionally, this hypothesis could be explored at other stations, equipped with similar instrumentation within international observation networks such as ICOS and ACTRIS.

Overall Assessment

Overall, the paper is clear and brings contributions to the field of soil-atmosphere interactions in drylands. The methodology is well-explained, and the findings are supported by the observations. The flux quantification not a goal for the study is a minor limitations that should be mentioned in the discussion and could be addressed in future research.

We appreciate Reviewer #1 comments and dedication to review the manuscript. We hope that the changes introduced please Reviewer #1 concern, especially regarding the lack of discussion about the quantification of the fluxes caused by the phenomena investigated.

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Reviewer #2:

> ***In this study, the authors investigate how atmospheric processes drive CO_2 exchange between the soil and the atmosphere in a semiarid region. They analyze 10 soil ventilation events, which are characterized by an increase in soil CO_2 and Rn concentrations and a simultaneous decrease in atmospheric pressure, followed by a decline in the soil concentrations and an increase in atmospheric pressure. The authors conduct a detailed statistical analysis to identify and evaluate the potential atmospheric drivers underlying these events.***
>
> ***The manuscript is well-structured and clearly written, with figures and results presented in a comprehensive way.***

We appreciate Reviewer #2's efforts in reviewing the manuscript. We will now address each comment and suggestion in detail, with the hope that the issues can be clarified and resolved, ultimately improving the quality of the manuscript.

> ***My main suggestion for improvement lies in amplifying the broader significance of the study. I think that the impact and relevance of this case study could be enhanced if the authors describe how frequent/typical such soil ventilation events are and how important the related CO_2 exchange with the atmosphere is compared to other (e.g. biological) CO_2 fluxes. Furthermore, the authors could discuss in more detail how their results can be used to improve the carbon cycle models and what is still missing/open for future research. This could be done in the introduction and in the final discussion.***

The authors thank Reviewer #2 for their time dedicated to the improvement of this study. We hope that the changes included noticeably amplify the significance of the study, especially the inclusion of the discussion about how important CO_2 fluxes are during ventilation events compared to fluxes during other periods.

Since the limited database available for this study does not cover a whole year, a statistical analysis regarding the frequency of occurrence of the ventilation events could not be as reliable as desired. Nevertheless, for the considered dataset, the occurrence of 1.7 events per month, while 7.6 % of the 30-min intervals were classified as ventilation period. This has been added to line 230 as:

In the end, a total of 10 events were identified, encompassing 661 intervals of 30-min resolution, entailing 7.6% of the available database.

Regarding the assessment of the importance of how important the CO_2 exchanges during ventilation events are compared to other (e.g. biological) fluxes, it has been performed and included in the manuscript. CO_2 fluxes we calculated based on the turbulent exchanges captured by the eddy tower, and different periods were considered: enriching ventilation, diluting ventilation, precipitation pulses, and background (the rest of the dataset). The average (± standard deviation) CO_2 fluxes for these periods are present on the table below.

	Enriching	Diluting	Precipitation	Background
F^{CO2} (μmol m^{-2} s^{-1})	0.05 ± 0.11	0.30 ± 0.13	0.62 ± 0.32	0.11 ± 0.10
% of cases	4.1%	3.5%	19.3%	73.1%

The ecosystem seems to act as a net source of CO_2 during every period. However, the emission during the non-ventilation non-precipitation period seems to be reduced during the enriching ventilation, suggesting that part of the emission is stored underground. Additionally, during the diluting ventilation phase, CO_2 increase significantly, suggesting that the stored CO_2 is being emitted to the atmosphere. Nevertheless, the largest emissions are observed to be caused by precipitation and reactivation of the biological processes.

This discussion has been added to Section 4.4 as:

[…] boundary layer. Consistently, CO_2 fluxes remain relatively low during this phase (0.05 ± 0.11 μmol m^{-2} s^{-1}), approximately half of those observed under non-ventilation conditions, supporting the interpretation that CO_2 is being temporarily stored within the soil.

[…] CO_2 and Rn into the soil pores, compressing air within the soil and displacing CO_2-rich soil air to the atmosphere producing a significant CO_2 flux (0.30 ± 0.13 μmol m^{-2} s^{-1}) up to three times that observed under non-ventilation conditions.

Lastly, the main contribution of this study to carbon cycle models is the advance in the characterization of certain ecosystems and the different carbon processes involved in the global carbon cycle (Faimon et al., 2020; Moya et al., 2022). This contribution is now clearer with the estimations of the CO_2 fluxes during the different phenomena, as presented before. This discussion has been included in the Conclusions as:

Turbulent fluxes show that the ecosystem is a net source of CO_2. During enriching ventilation, CO_2 emissions drop to about half the background non-ventilation fluxes, suggesting temporary underground storage of CO_2. In contrast, diluting ventilation emissions increase by three times the background non-ventilation fluxes, suggesting the release to the atmosphere of stored CO_2. These results emphasize the role of the soil ventilation as a transient mechanism, modulating CO_2 emissions in semiarid ecosystems.

[…] soil–atmosphere interactions. Accounting for the impact of soil ventilation processes can therefore improve the representation of these exchanges in carbon cycle models, particularly in ecosystems where underground storage and release of

CO_2 occur under specific atmospheric conditions, reducing uncertainties in climate change projections.

Below are more specific, line-by-line comments.

L. 45: Please provide a reference for this statement. You could also provide more details here to strengthen the motivation for your study.

We appreciate Reviewer #2 for raising this issue. We have consequently added a set of references to strengthen the motivation:

Sanchez-Cañete, E. P., Serrano-Ortiz, P., Kowalski, A. S., Oyonarte, C., and Domingo, F.: Subterranean CO_2 ventilation and its role in the net ecosystem carbon balance of a karstic shrubland, Geophys. Res. Lett., 38, L09802, https://doi.org/10.1029/2011GL047077, 2011.

López-Ballesteros, A., Serrano-Ortiz, P., Kowalski, A. S., Sánchez-Canete, E. P., Scott, R. L., and Domingo, F.: Subterranean ventilation of allochthonous CO_2 governs net CO_2 exchange in a semiarid Mediterranean grassland, Agric. For. Meteorol., 234, 115-126, https://doi.org/10.1016/j.agrformet.2016.12.021, 2017.

L. 171: Are there time periods with very low MLH << 500m (e.g., during nights), which may not be detected due to the reduced overlap of the laser beam with the receiver field of view? If so, how have you treated such periods in the statistical analysis of the ventilation events?

The authors understand the concerns introduced by Reviewer #2. However, there are several aspects that need to be considered.

On the one hand, low mixing layer heights (MLH < 500 m), especially during nocturnal stable conditions, may indeed be affected by the reduced overlap between the laser beam and the receiver field of view in ceilometer measurements. However, STRATfinder applies an overlap correction, allowing MLH and ABLH detection down to approximately 210–255 m (Kotthaus et al., 2020), which significantly mitigates this limitation.

Regarding the statistical analysis, no additional filtering of low-MLH periods was applied. The statistical evaluation is primarily based on Spearman rank correlation coefficients, which depend on monotonic relationships rather than on exact magnitudes. Therefore, potential biases in absolute MLH values under very stable conditions are not expected to significantly affect the results.

This discussion has been added to line 172 as:

… to the free troposphere (Kotthaus et al., 2023). To mitigate the impact of incomplete overlap at low altitudes, the RCS data were corrected using the overlap function provided by the manufacturer, providing reliable ABLH and MLH retrievals down to approximately 210–255 m (Kotthaus et al., 2020). Further methodological…

L. 172: Please explain briefly the difference between ABLH and MLH.

We appreciate this issue raised by Reviewer #2, and the following sentence has been introduced in line 169:

> … algorithm (Kotthaus et al., 2020) to retrieve the Mixing Layer Height (MLH), the convective mixing layer that develops during daytime due to surface heating, and the Atmospheric Boundary Layer Height (ABLH), which represents the top of the atmospheric boundary layer including the mixing layer and residual layers of previous days, marking the transition to the free troposphere (Kotthaus et al., 2023). To mitigate the …

L. 178: To guide the reader, it would be helpful to explain here for which purpose the additional borehole setup has been installed.

The authors thank Reviewer #2 for this comment, since it will clarify the reason for the datasets considered in the study.

The borehole setup was installed at the station six months prior to the SCARCE campaign, taking part in a regional network of similar boreholes and wells. In this specific analysis, it was considered due to the specific features of the setup. With instruments installed in a borehole they sample the atmospheric air flowing inside it, with no effects of the porosity that affect the sensors installed in the underground profile. This could have evidenced effects of the porosity in the CO_2 and Rn concentrations, like attenuation or temporal shifts in the variations. Nevertheless, this aspect of the phenomenon is being investigated in a different study.

An explanation on the purpose of such setup has been consequently included in line 183 as:

> … the borehole interior. The additional borehole setup provides an alternative perspective on subsurface gas dynamics, as the instruments sample air circulating within the borehole, which is less affected by soil porosity than sensors installed directly within the soil profile. Three GMP252 …

L. 206-208: If the ventilation events are selected based on the requirement that the CO_2 and Rn concentration increase has to coincide with an atmospheric pressure decrease, it appears quite obvious that the atmospheric pressure and the soil concentration is correlated. Is the conclusion in Fig. 2 that P^{air} and CO_2 are correlated then not trivial? Please clarify.

The authors understand the concern raised by Reviewer #2. The strong relationship between atmospheric pressure variations and soil gas concentrations is already well documented in the literature, especially at the study site. In our study, atmospheric pressure was therefore exclusively used as a physical consistency criterion for event identification, ensuring that the detected episodes correspond to genuine ventilation events. Once the events were identified, the statistical analysis focused on investigating the role of other meteorological variables.

Regarding the interpretation of Fig. 2, the observed correlation between P^{air} and CO_2 was therefore expected, as stated in line 210, and was included in the discussion of Fig. 2 for completeness and to be compared with the degree of correlation with the rest meteorological variables. More importantly, Figs. 2 and 3 clearly illustrate that atmospheric pressure is not the only driver of soil gas variability, and that it does not explain the full range of observed concentration changes during ventilation events.

This discussion has been included in the manuscript in line 212 as:

> … pressure increase. Atmospheric pressure was used here exclusively as a physical criterion for event detection, while the subsequent analysis focused on the role of boundary layer dynamics in modulating the events through different meteorological variables. The inter-event periods…

Additionally, to make it clear that this strong correlation is not a main conclusion from Fig. 2, line 331 was rearranged as:

> … Cañete et al., 2011, 2013, 2016). As preconditioned, P^{air} showed a strong negative correlation in both periods (-0.94 ± 0.04); however, the importance of P^{air} as a potential driver is already known (e.g., Sánchez-Cañete et al., 2013; Moya et al., 2019)…

> ***L. 212-215: Please motivate why the additional high-turbulence conditions need to be fulfilled. Is this a strong criterium, i.e., does this high-turbulence condition lead to much less events?***

We thank Reviewer #2 for raising this point. The requirement of high-turbulence conditions was introduced based on previous studies investigating ventilation events. In addition, applying a turbulence threshold is a standard procedure in eddy covariance studies to ensure the reliability of flux measurements (e.g., CO_2 fluxes in this study).

Regarding the reviewer's question, this condition did not lead to the exclusion of any potential ventilation events in the available dataset. Therefore, it did not reduce the number of detected events but was included to ensure the physical consistency and reliability of the analyzed periods.

We have consequently added the following comment to line 219:

> … (O'Connor et al., 2010). The high-turbulence conditions were met easily during daytime, with daily average u_* exceeding 0.2 m s^{-1} for every potential event, and maximum…

> ***L. 246-248: How did you define the exact start and end points of the ventilation events? Does this have an impact on the (time-shifted) correlations?***

We appreciate this issue raised by Reviewer #2, since it is a methodological point which can be improved in the manuscript.

The start and end of each ventilation event were identified based on the characteristic temporal evolution of the CO_2 and Rn concentrations. Specifically, the beginning of an event was defined as the onset of a minimum 8 h long and rapid increase of 90 Bq m^{-3} h^{-1} in the tracer series Rn^{50cm} or Rn^{bh}, or 80 ppm h^{-1} in the CO_2^{150cm} series (being CO_2^{150cm} the CO_2 series with the most variability), and comprising a decrease in atmospheric pressure and increase in the turbulence variables. On the other hand, end corresponded to the completion of the subsequent minimum 8 h long and similarly rapid decrease in concentrations during the diluting phase, comprising an increase in the atmospheric pressure and decrease in the turbulence variables.

Regarding the time-shifted correlations, the shifts were applied to the driver time series within the identified event periods, lasting several hours. Additionally, the 8 h minimum length of the event was tested, with minimum lengths ranging from 6 to 12 h. However, this criterium change did not lead to significant changes in the statistical analysis. Thus, shifts in 30 minutes in the location of the beginning and ending of the event will not significantly impact the correlations, which included every single 30-min interval within every event. Since each event lasts more than one day and contains many 30-min observations (> 48), small uncertainties in the exact start or end of the events are not expected to significantly affect the resulting correlations.

Considering this point raised by Reviewer #2, the information in Section 3.2 has been rearranged aiming to improve the reader's understanding and a new discussion has been included in line 222 as:

> The beginning of each event was defined as the onset of a sustained (minimum 8 h) and rapid increase in tracer concentrations, exceeding 90 Bq m^{-3} h^{-1} for Rn (Rn^{50cm} or Rn^{bh}) or 80 ppm h^{-1} for CO_2 (CO_2^{150cm}), the latter being the most variable CO_2 series and most sensitive to the concentration changes. The end of the event corresponded to the completion of a similarly sustained and rapid decrease in concentrations during the diluting phase. Sensitivity tests using minimum event durations between 6 and 12 h showed no significant impact on the statistical results. Therefore, given the use of 30-min averaged data and events lasting longer than one day, small uncertainties in the exact start and end times are not expected to significantly affect the correlation analyses. The inter-event periods…

L. 271-272: From Fig. 1 it seems that the CO_2 concentration begins to decrease in the lowest soil layer as the dilution event starts. However, one might expect that if atmospheric air infiltrates the soil, the CO_2concentration in the upper soil layer would decrease before that in the deeper layers. Is it due to upward transport of CO_2 from deeper soil layers? Can you comment on this?

We thank Reviewer #2 for bringing up this interesting discussion.

We agree with the hypothesis suggested by Reviewer #2. When the diluting ventilation starts, CO_2 within the soil is expelled to the atmosphere, and significantly larger CO_2 concentrations have to pass by the 50 and 15 cm sensors in order to exit, which might cause CO_2 concentrations to increase. This can explain also why the maxima in the 150, 50 and 15 cm CO_2 series were observed consecutively in that order. The color of the CO_2^{bh} was modified in Fig. 1 so that its different behavior with respect to the other CO_2 series is now clearer.

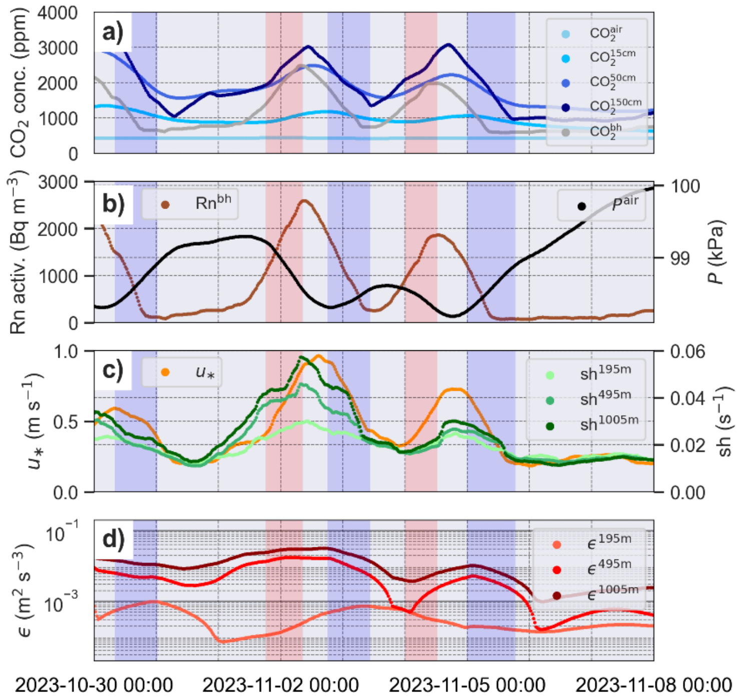

Figure 1. Rolling-averaged temporal series of (a) CO_2 concentration in the atmosphere (air), at different vadose-zone depths (15, 50 and 150 cm) and in the borehole (bh); (b) Rn concentration in the borehole (left axis) and atmospheric pressure (right axis); (c) surface friction velocity (left axis) and wind shear (right axis) at the selected atmospheric intervals; and (d) ϵ at the selected atmospheric height ranges. Blue and red shading indicate diluting and enriching ventilation periods, respectively.

L. 278: Maybe change "Rn-free" into "Rn-depleted".

We appreciate this suggestion raised by Reviewer #2. However, we consider that Rn-depleted suggest that the atmosphere was once Rn-rich and then was depleted. Instead, we have rewritten the sentence in line 293 as:

… confirming that atmospheric air with low Rn concentrations was easily entering…

L. 301-303: Soil water content is expected to influence Rn emanation (see e.g. Zhuo et al., 2006, https://doi.org/10.1080/18811248.2006.9711127). Since Rn is used as a tracer for soil ventilation, its source strength must be stable or well-characterized. Please discuss whether soil moisture variability could introduce bias into the interpretation of Rn as a pure ventilation tracer or if the effect is negligible.

We thank Reviewer #2 for highlighting this important point and for referring us to the study by Zhuo et al. (2006). Soil moisture is indeed known to influence Rn emanation under certain conditions. However, in the present study soil moisture variability is not expected to significantly bias the interpretation of Rn as a tracer of soil ventilation.

First, the methodology excludes periods with precipitation and the following day, which corresponds to the main periods of soil moisture variability at the study site. Observations from the soil moisture sensors show that noticeable variations occur only at 15 cm depth and typically persist for a short period after rainfall. In contrast, soil water content at 50 and 150 cm depth remains relatively stable during the analyzed periods, even after precipitation pulses. Therefore, the variability in soil moisture during the selected ventilation events is limited.

Second, the statistical analysis indicates that soil water content shows a moderate correlation with Rn during the enriching phase (ρ_S around 0.74) but a weak correlation during the diluting phase (ρ_S around −0.26). Furthermore, the partial correlation analysis does not indicate a significant independent effect of soil moisture on Rn concentrations when other variables are controlled. This suggests that the observed Rn variability during the selected events is primarily associated with ventilation processes rather than changes due to soil moisture variations, probably because they are not significant at the period considered or at the location of study.

The manuscript now includes the discussion about this phenomenon in lines 72 and 208, respectively:

> … crust (Moed et al., 1988). However, the amount of Rn released into the pore air (emanation) can be influenced by soil moisture content (Zhuo et al. 2006). Thus, in poorly…

> … periods during and up to one day after precipitation were not considered in this study, thereby reducing potential biases associated with soil moisture variability and its effect on Rn emanation (Zhuo et al., 2006). Additionally,…

Fig. 2: Please clarify whether the correlation coefficient r_s was calculated individually for each of the 10 ventilation events and then averaged, or whether a single r_s was derived from the pooled data across all events.

We appreciate Reviewer #2 help to improve the understanding of the study.

The ρ_S was directly calculated with the pooled data across all events. This is, they are calculated with the 661 intervals of 30-min resolution, as indicated in line 230. This has been specified in line 320, right before the discussion of Figure 2 as:

> … atmospheric variables, calculated with the selected 661 intervals of 30-min resolution. All ρ_S greater…

L. 311-312: Are you referring to the correlation between CO_2^{air} and the soil concentration of Rn or the soil concentration of CO_2 (or both)?

We thank Reviewer #2 for this suggestion. The authors meant to refer to both CO_2 and Rn. It is now clear in line 326 as:

> In contrast, CO_2^{air} showed a lower but still significant correlation with soil CO_2 and Rn concentrations…

L. 395-399: How much larger is the maximized (shifted) correlation compared to the un-shifted correlation, e.g., in respect of the uncertainty/variability in the derived correlation coefficients?

We appreciate Reviewer #2 for raising this calculation that was not performed.

ρ_S increases ranging from 0.6% to 3.9% could be observed after undergoing the corresponding shifts. We understand that this is a modest but yet significant increase in the correlation coefficients. The corresponding values have been included in the discussion between lines 410 and 419 as:

> … the shifted correlations revealed that P^{air} maximized its ρ_S (increasing slightly by 2.2%) during enriching ventilation intervals […]. The opposite pattern was observed for u_*, with ρ_S maximizing (increasing slightly by 2.1%) when shifted 30 min earlier for […]
>
> […] while ϵ^{495m} maximized ρ_S (increasing significantly by 3.9%) when the series was shifted 30 min later […]. During enriching ventilation periods, ϵ^{495m}, ϵ^{1005m}, sh^{495m} and sh^{1005m} showed maximum ρ_S (increasing by 1.2%, 0.6%, 1.9% and 1.6%, respectively) when shifted 30, 30, 60 and 30 min later, respectively, […]