

Reply to Reviewer #1

We thank the reviewer for their careful reading of the manuscript and for their constructive comments and suggestions. Their comments have helped us improve both the clarity and the scientific quality of the manuscript. Below we provide a point-by-point response to every comment. Reviewer comments are shown in bold while our responses are given in normal font.

General comments:

1) The article mainly considers global horizontal irradiance for the classification. Given that it focuses on BSRN data, this choice should at least be better motivated, or better yet, the effect of using both direct and global/direct irradiance quantified (I do expect that adding direct irradiance would make the algorithm much more sensitive to small clouds in front of the sun / short shadow events). I believe the current approach could easily be applied to the direct/diffuse irradiance components.

Thank you for this very relevant remark. The choice of input variables required by MuscaDet was the result of careful consideration during its development, as explained below.

We agree that the use of direct normal irradiance (DNI), or of the direct/diffuse irradiance components more generally, could provide additional information for cloud detection. In particular, DNI is expected to be more sensitive than GHI to small clouds crossing the solar disk and to short-duration attenuation events. Therefore, incorporating DNI could potentially improve the sensitivity of the method to such events, especially when their impact on GHI remains relatively limited.

However, although the current implementation of MuscaDet requires at least two components, we deliberately sought to minimize the constraints associated with the additional component during its development. The objective was to avoid restricting the future applicability of the method to stations measuring global, direct and diffuse irradiances, and to leave open the possibility of extending it to stations measuring only global irradiance. In such future implementations, the tests $B_N > 10 \text{ W m}^{-2}$ and $K < 0.9$ could potentially be replaced by other sources of information, for example a satellite-derived cloud mask.

The following paragraph has been added to the Conclusions (lines 585–590) to clarify the rationale behind this methodological choice and its implications for future developments of MuscaDet:

“Beyond the refinement of the detection criterion itself, an interesting future development of MuscaDet would be to extend its applicability to stations equipped with a single pyranometer measuring only E . Although the current implementation requires two

components, particular attention was paid during its development to limiting its dependence on the additional component, with the aim of preserving the possibility of such an extension. The criterion based on direct irradiance is mainly used to discard overcast conditions characterized by low variability in E . This function could potentially be fulfilled by other sources of information, such as a satellite-derived cloud mask.”

2) Related to the previous comment, the distinction between „cloudless skies“ and „clear sun“ situations as introduced by Bright et al., 2020, should be mentioned and discussed. Which of these scenarios are the main focus of the present work?

Thank you for this comment. Indeed, the objective of MuscaDet is to detect cloudless skies rather than clear-sun conditions, which is consistent with the objective of confidently identifying cloud-free instants, an important requirement for the evaluation of clear-sky models. This distinction also motivates the use of a multiscale approach, with maximum temporal scales of 120 min, as the objective is to identify cloud-free periods rather than only short-lived clear-sun conditions. The following paragraph has been added to the Introduction (lines 41–44) to clarify this aspect.

“Bright et al. (2020) proposed a distinction between “cloudless skies” and “clear sun”. The former refers to a sky free of clouds over the entire sky dome, such that clouds affect neither direct nor diffuse irradiance, whereas the latter refers to the absence of clouds between the Sun and the station, such that direct irradiance is not affected by clouds, while diffuse irradiance may still be affected. In this work, we focus on the detection of cloudless skies.”

3) Also applicable to many other prior studies, I have always been puzzled by the fact that clear-sky detection algorithms / their thresholds are mostly formulated in terms of absolute values of solar irradiance (instead of e.g. atmospheric transmittance). In particular, this leaves variability due to changes in sun-earth distance over the year unaccounted for. For closer sun / higher levels of extraterrestrial solar irradiance (e.g. in northern winter), variability thresholds will be stricter than for larger sun-earth distances (e.g. in Northern hemispheric summer). Technically, it seems easy enough to at least scale irradiances to mean earth-sun distance prior to classification.

The method proposed by Lefèvre et al. (2013) uses the modified clearness index as the main variable for the detection of cloud-free situations. This normalization explicitly accounts for, among other effects, the seasonal variation in Earth–Sun distance.

In MuscaDet, the detection does not rely on a normalization of the measured irradiance. Instead, it is based on the fitting of sequences of E to the MLB model, in which the extraterrestrial irradiance E_0 explicitly accounts for the variation in Earth–Sun distance. Consequently, the effect highlighted by the reviewer is explicitly accounted for in MuscaDet, despite the absence of an explicit normalization of the measured irradiance.

We agree that defining detection criteria in a form that is independent of the absolute irradiance level is an important aspect of robust and reliable cloud-free detection, particularly when considering variations in time of day, season, and location. A direct formulation based on absolute irradiance values could indeed lead to different detection sensitivity under different conditions. We are confident that our approach, based on fitting the MLB function and inspired by the method of Long and Ackerman, effectively addresses this issue.

4) Use of the correlation / Eq.4: at first sight, this indeed seems like a new and promising innovation, and I do agree with the statement that (L592): „The normalized nature of ρ and R^2 makes them particularly attractive ...“. Note however that a fundamental challenge for using correlation is mentioned and implicitly addressed in the current formulation based on Eq.4 / Appendix: the slow change of solar zenith angle around solar noon / for some polar observation. This implies that the MLB-function has little value for predicting changes in irradiance. For me, this raises an important question: is it really the linear correlation coefficient as a goodness-of-fit criterium which serves as main source of information for the classification? Focusing on this quote: „It can be observed that Eq. (4) reduces to the standard Pearson correlation coefficient when $Var(E_{meas}) \gg \sigma_{tol}^2$ “. While this sentence is indeed true, it remains unclear whether this limit is actually relevant in the present application. Some thoughts on this:

*** A correlation of $\rho=0.999$ suggests an extremely good fit (RMSE of fit residual is 4.4%, or $\sqrt{1-\rho^2}$). How does the PDF of the right factor / square-root term in Eq.A-9b look like? To me, this suggests that Eq.4 no longer should be interpreted as correlation.**

We agree with the reviewer that the introduction of the tolerance term modifies the strict interpretation of Eq. 4 as a conventional Pearson correlation test. However, we believe that the role of the Pearson correlation in the derivation of the criterion is important to explain, as it provides the basis for the formulation of the modified criterion used in MuscaDet. Importantly, Eq. 4 is not presented as a conventional correlation test, but as a decision criterion derived from the Pearson correlation coefficient:

Lines 214-215: *“As detailed in Appendix A, the expression for the Pearson correlation coefficient is reformulated to explicitly include σ_{tol} , leading to the following decision criterion.”*

The probability distribution of the right-hand term of Eq. A-9b is shown in Fig. 1 for each time scale. The distributions are skewed, with a pronounced peak at 0.999. At time scales of 15 and 30 min, a second mode is observed close to zero, corresponding to instants for which the variance of E_{meas} is lower than σ_{tol}^2 . The occurrence of the two modes

decreases with increasing ΔT , consistently with the decreasing probability of instants with low values of $\text{Var}(E_{\text{meas}})$ over longer time scales.

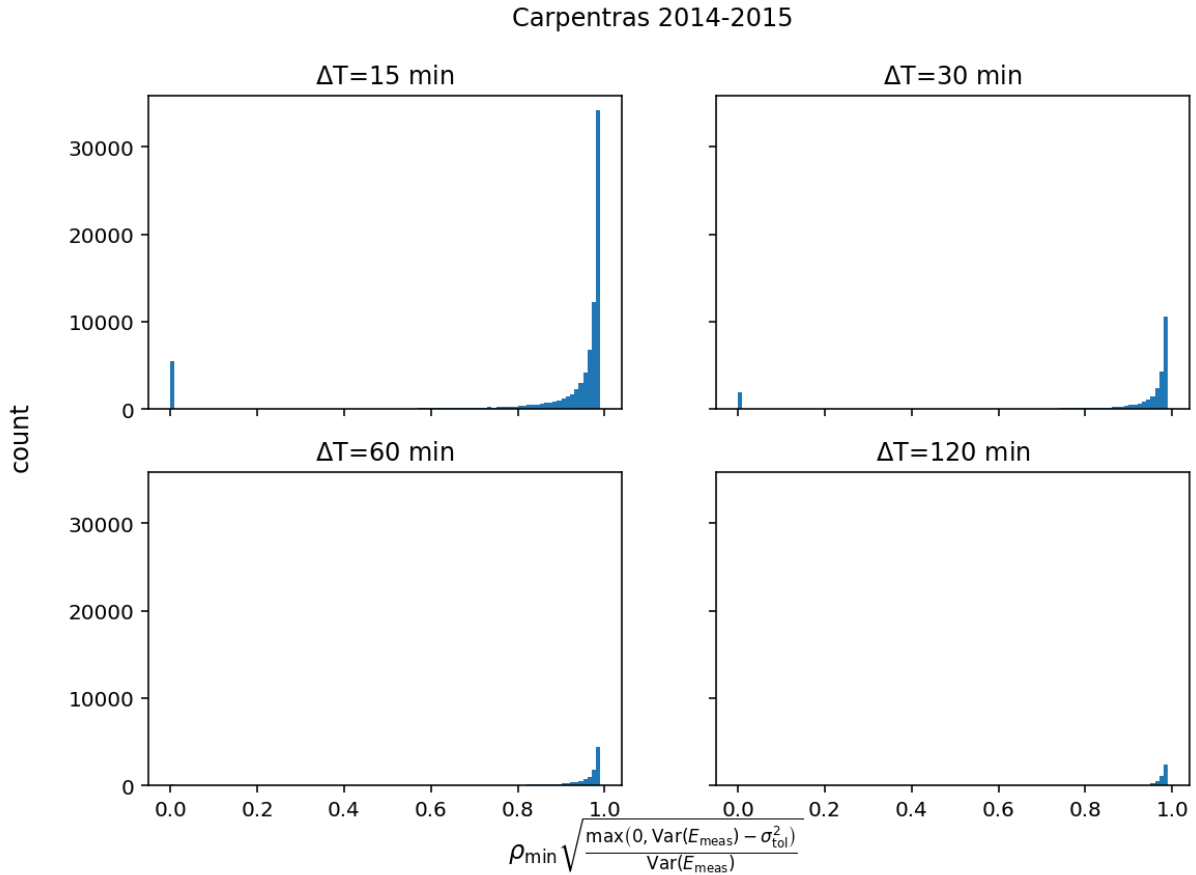


Figure 1 : Probability density distribution of the modified threshold applied to the correlation between E and E_{mlb} (right hand term in Eq. A9-b) for the four considered time scales.

*** Due to the division by zero in Eq.4 if $\text{Var}(E_{\text{meas}}) \leq \rho_{\min}^2$, Eq.4 essentially becomes a threshold test for low correlations / around noon. For which fraction of clear-sky cases is this threshold criterium met, thus Eq.4 acting as threshold test? My guess would be that this is the majority of cases.**

Before addressing the question of how frequently Eq. 4 effectively acts as a threshold test on the variance of E_{meas} , it is useful to clarify how this transition occurs. The formulation of σ_{tol} controls the transition between the two limiting cases of Eq. 4: a pure correlation test when $\sigma_{\text{tol}} = 0$, and a variance-based test when $\sigma_{\text{tol}} \gg \text{Var}(E_{\text{meas}})$. The value of σ_{tol} was empirically selected so that the transition between these two regimes remains balanced. As discussed in the Conclusions, we consider the physical definition of this tolerance to be one of the most important aspects to be addressed in future developments of MuscaDet.

The effect of this transition is illustrated in Fig. 2, which shows the time series of the correlation between E_{meas} and E_{MLB} , together with the corresponding modified correlation threshold, for a sequence of five days at Carpentras including two cloud-free

days. The correlation is calculated over a 15-min time scale. During the second and third days, which are cloud-free, the correlation decreases around noon as the variance of E_{meas} becomes small. At the same time, the modified correlation threshold (the right-hand term of Eq. A-9b, shown in red) decreases, making the correlation criterion less stringent. This illustrates that Eq. 4 does not abruptly switch between a correlation-based criterion and a variance-based criterion. Rather, σ_{tol} introduces a smooth transition between these two limiting behaviours.

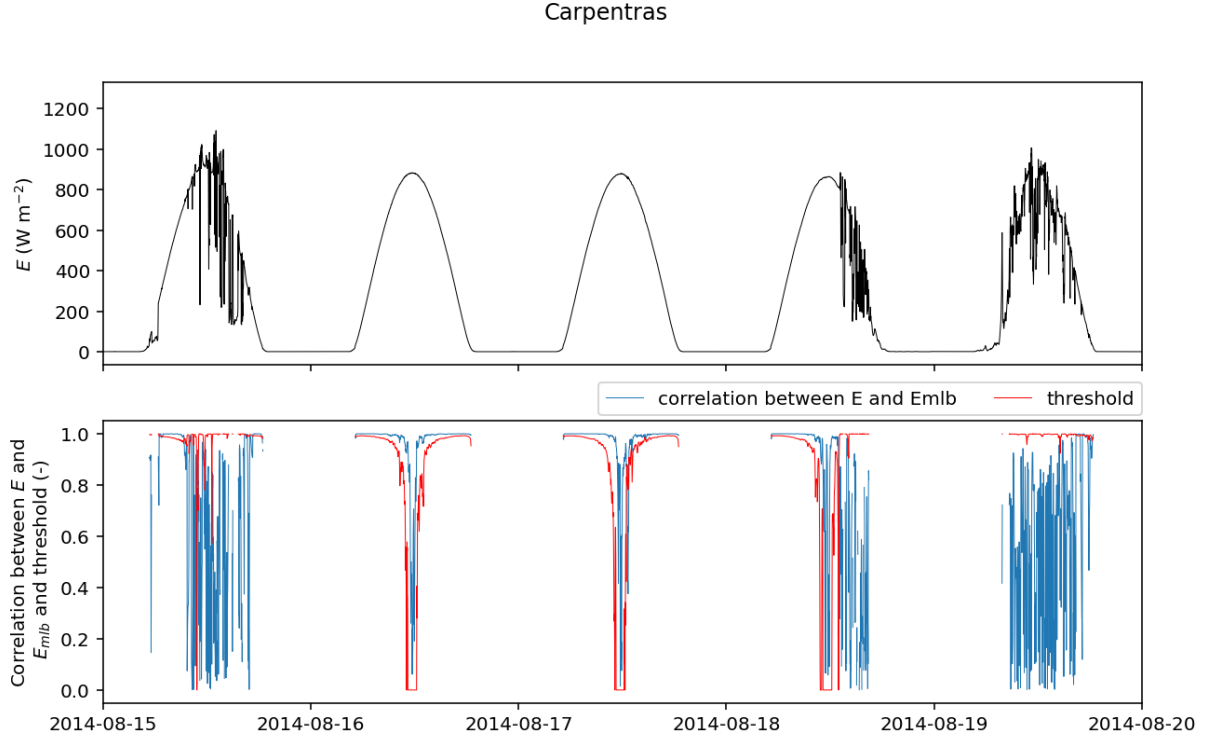


Figure 2 : Time series of E_{meas} (black line, upper panel), the correlation between E_{meas} and E_{mlb} (blue line, lower panel), and the modified correlation threshold, i.e. the right-hand term of Eq. A-9b (red line, lower panel), for a sequence of days at Carpentras including two cloud-free days.

To quantify the frequency with which Eq. 4 approaches the variance-based regime, we analysed the distribution of the modified correlation threshold,

$\rho_{min} \sqrt{\frac{\max(0, \text{Var}(E_{meas}) - \sigma_{tol}^2)}{\text{Var}(E_{meas})}}$. Figure 3 shows this quantity as a function of $\text{Var}(E_{meas})$ and μ for the four time scales considered in MuscaDet (left column). The corresponding joint distributions of $\text{Var}(E_{meas})$ and μ are shown in the right column. This representation allows the regions where the modified correlation threshold becomes low to be directly compared with their frequency of occurrence.

The results show that most observations at the Carpentras station correspond to modified correlation thresholds above 0.99. Thus, although the variance-based regime is reached under low-variance conditions, particularly around noon, it does not dominate the overall behaviour of the criterion.

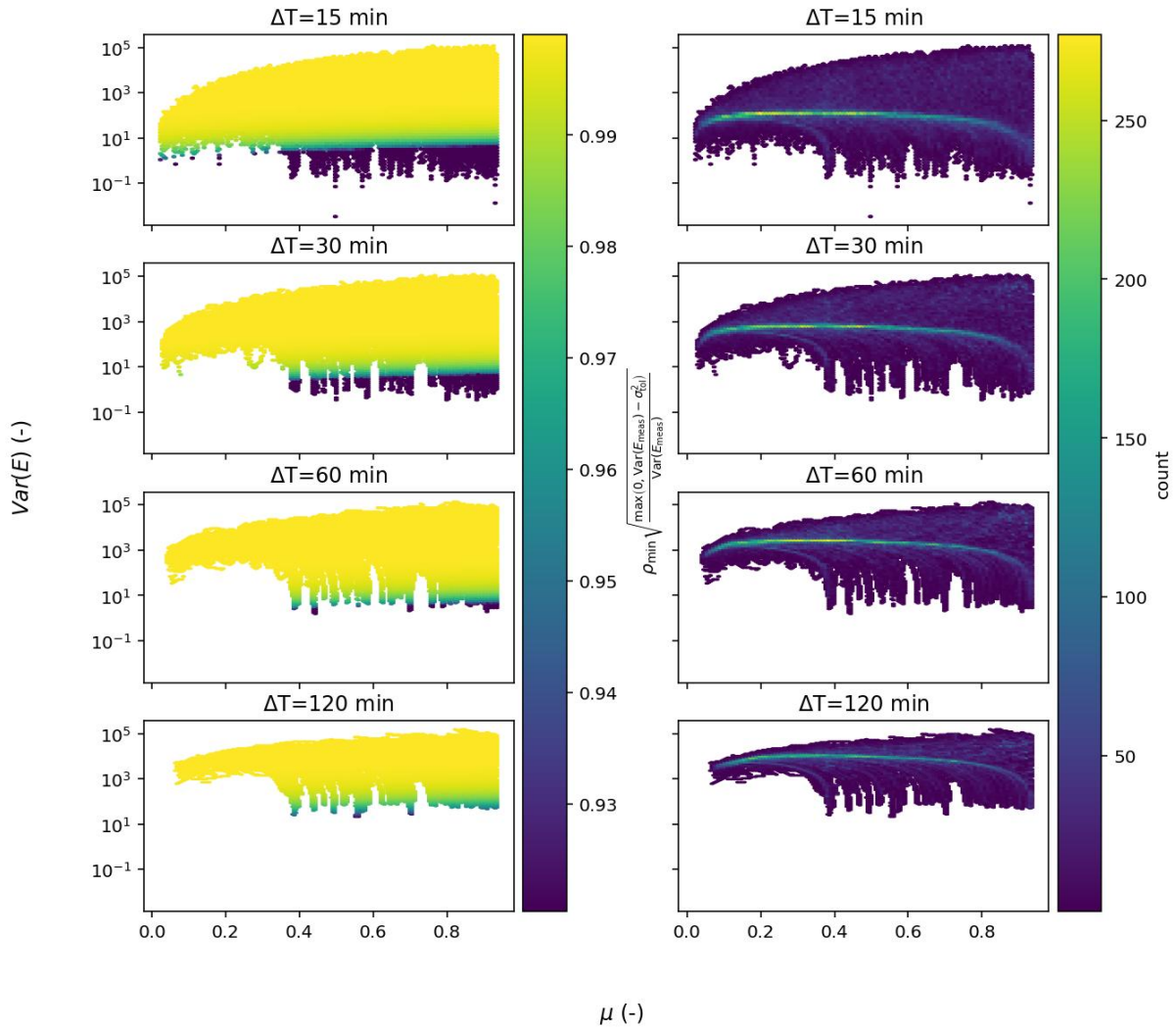


Figure 3 : Distribution of the modified correlation threshold as a function of the mean irradiance μ and the variance of E_{meas} (left column), and corresponding joint distribution of μ and $\text{Var}(E_{\text{meas}})$ (right column), for the four time-scales considered in MuscaDet at the Carpentras station.

*** One alternative suggestion: instead of the correlation / $\text{Var}(E_{\text{meas}})$, wouldn't it make sense to consider $\text{Var}(E_{\text{meas}} - F_{\text{MLB}})$, i.e. the residual of the MLB fit?**

Thank you for this suggestion. We considered this type of residual-based formulation during the development of MuscaDet but identified an important limitation.

The magnitude of $\text{Var}(E_{\text{meas}} - F_{\text{MLB}})$ is dependent on solar position and atmospheric conditions. It would therefore require a normalization to define a threshold that can be applied consistently throughout the day and across different atmospheric conditions. Avoiding such a dependence on absolute irradiance levels and solar geometry was an important consideration in the development of MuscaDet.

For this reason, we retained the correlation-based formulation, which provides a dimensionless and bounded quantity while allowing the tolerance to be explicitly incorporated into the decision criterion.

5) The article argues that the use of the correlation „allows the definition of a decision threshold that is independent of levels in irradiance (L593)“. However, in Eq.4, the threshold used is calculated from the cosine of the solar zenith angle. Doesn't this invalidate the stated advantage?

Indeed, this may appear contradictory at first sight, but the two stages of the proposed criterion should be clearly distinguished to avoid misunderstanding. The term σ_{tol} (Eq. A-4) represents a tolerance introduced to prevent measurement-related effects, such as thermal offsets or measurement noise, from being interpreted as cloud-induced variability. A simple formulation is currently proposed for this tolerance, which depends on the cosine of the solar zenith angle. We acknowledge that this formulation is heuristic, and we envisage replacing it in future developments by an explicit characterization of measurement uncertainty.

This tolerance is accounted for in the variance of the measurements before the correlation is calculated in the second stage of the criterion. The resulting “modified correlation” is a bounded and dimensionless quantity, which allows a fixed threshold to be defined independently of the absolute irradiance level.

The statement on line 593 refers to the general property of the Pearson correlation and not specifically to the complete criterion implemented in MuscaDet. The distinction between the tolerance parameter and the correlation threshold is already reflected in the manuscript:

L214: “ ρ_{min} is an adjustable parameter empirically set to 0.999 after sensitivity testing”

L209-210: “a tolerance parameter σ_{tol} is introduced, which accounts for both measurement noise and natural atmospheric variability.”

6) The article emphasizes the point that it does not rely on a clear-sky model. It does, however, make use of the MLB function to approximate observations (instead of the power law used by Long and Ackermann, 2000). What is the difference between this choice, and reliance on a clear-sky model? How does the algorithm performance depend on the choice of this function / its functional form? I do think this is an aspect which deserves a bit of discussion.

There is an important distinction to be made between using a clear-sky model as a functional form for fitting the observations and using the output of an externally driven clear-sky model as a reference. In the former case, the parameters of the function are estimated directly from the observations being classified. This is the approach followed by both Long and Ackermann (2000) and MuscaDet: the function is not used to provide an

a priori estimate of clear-sky irradiance, but rather to characterize the observed irradiance sequence and its dependence on the solar zenithal angle. In the latter case, the output of a clear-sky model is used as an external reference for identifying cloud-free conditions, with the potential risk that uncertainties or biases in the clear-sky model propagate directly into the cloud-free classification.

We chose the Modified Lambert-Beer (MLB) function rather than the power law used by Long and Ackermann (2000) because its functional form is more physically motivated for describing the interaction of solar radiation through the cloud-free atmosphere. The good performance of the MLB formulation for describing clear-sky irradiance has been extensively evaluated by Müller et al. (2004), whose results strongly informed the development of MuscaDet.

We agree that the sensitivity of MuscaDet to the choice of functional form of the clear sky model would be an interesting aspect to investigate. We expect, however, that other aspects of the detection procedure, as discussed in the conclusions, are likely to have a larger influence on the overall performance.

Specific comments:

*** L11: „for the quarterly verification“: Please explain what this actually means.**

We have reformulated the sentence to use the official terminology employed by CAMS (Evaluation and Quality Control, EQC) and to provide more context for readers who are not familiar with this type of activity:

Lines 11-13 *“...which introduces potential biases that are particularly problematic for the quarterly evaluation and quality control (EQC) of the McClear service against independent ground-based observations, conducted at our institute on behalf of Copernicus.”*

*** L278: „The Python implementation of MuscaDet is openly available on GitHub“. Please do mention its license here (LGPL), openly is ambiguous.**

...

The Python implementation of MuscaDet is publicly available on GitHub under the GNU Lesser General Public License (LGPL) (see Code availability section), ensuring transparency and reproducibility while allowing its reuse and modification under the terms of the license.

*** I suggest to add a DOI to the code / github repo, e.g. via Zenodo**

Thanks for this suggestion. A DOI has been added to the code shared on github ([10.5281/zenodo.23241191](https://doi.org/10.5281/zenodo.23241191)).

*** Finally, I encourage the authors to make available also the underlying data including the MuscaDet classification, to make it easier for subsequent studies to compare their results against the present work. At this stage, only the Python code and some example data are included in the github repository.**

Thank you for this excellent suggestion. We agree that making the underlying data, including the MuscaDet classification, publicly available will facilitate the comparison of future studies with our results. We have therefore made the data used for the evaluation and validation of MuscaDet publicly available on Zenodo and assigned them a DOI. We have also added the following sentences to the “Code availability” section (lines 664–666):

“The archived version of the code is available on Zenodo at <https://doi.org/10.5281/zenodo.23241191>. The data used for the evaluation and validation of MuscaDet are available on Zenodo at <https://doi.org/10.5281/zenodo.23241288>.”

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