Response to review 1

We wish to express our appreciation for the time and effort you have dedicated to providing feedback on our manuscript. The in-depth comments, suggestions, and corrections have been immensely helpful and have greatly improved the manuscript. We have incorporated changes to reflect the suggestions provided. Please see below, in blue, for a point-by-point response to the comments and concerns.

The authors explore the patterns of rainfall intensity-duration-area-frequency (IDAF) curves derived from adjusted weather data on the eastern Mediterranean region. IDAF curves at durations from 10min to 1 day and area from $0.25km^2$ to $500km^2$ are derived by applying the simplified meta-statistical extreme value analysis (SMEV) on 18 years of available weather radar data. Their study concludes that the simple scaling of rainfall intensities with duration is only valid for point scale, that area reduction factors are mainly useful for short durations (<3h), and that the reverse orographic effect is weaken with larger areas. Overall, I find the study relevant, very well written and easy to read/follow.

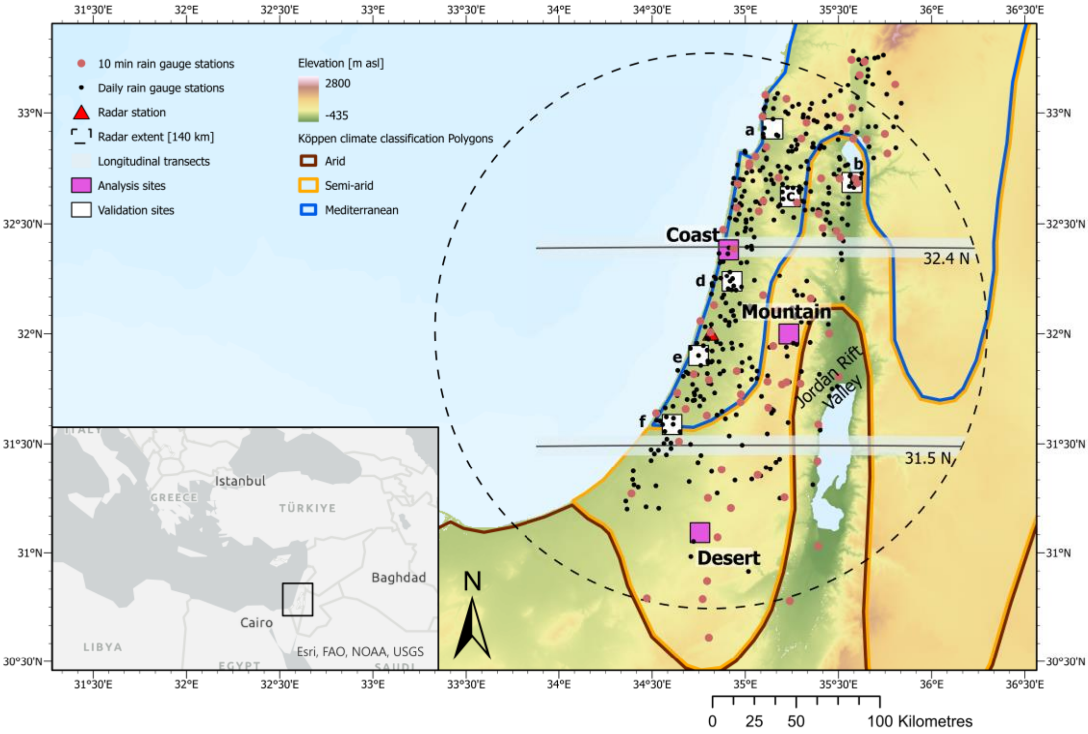
Thank you very much

However, I have still some recommendations or points that I would like to discuss with the authors regarding the study:

1. Figure 1 is a bit difficult to understand because it contains so much information. I would suggest that the background colour shows the land elevation and that the climate classification is given in semi-transparent polygons or lines. The size of the rain gauge-points can be a bit bigger so we can distinguish them better. Maybe the x and y axis for the right part of the figure can show the distance in meters from the weather radar location.

Author response: Thank you for the suggestions, we agree that the figure is busy and hard to understand. The size of the rain gauge markers has been increased and the background changed to show land elevation, with the climate classifications presented as lines legend (see figure below).

We prefer to keep the x- and y-axis as latitude and longitude as we feel that this is important information for the reader. However, we have moved the scale marker so that it aligns with the radar location, so that the distance from the radar can be better intuited. Additionally, we added the distance in km of the radar extent (140 km) to the figure's legend. We considered adding distance circles at 50 and 100 km from the radar, however we found this to be too busy.



Map of the study area

2. I'm a little bit confused with the correction and adjustment of the radar data. So as far as I understood there are in total 3 adjustments performed to radar data based on the rain gauge information. So with the two first adjustments you are trying to adjust rainfall intensities (using daily stations), and then with the third one you are adjusting directly the SMEV parameters (using the 10min stations). I am wondering if all three steps are necessary and not redundant, since in the end you adjust the SMEV radar parameters according to the 10min station parameters. Could you please comment a bit more on the necessity of these three adjustments? Do you know how much the SMEV radar parameters are changing due to the correction based on daily stations (i.e. if you do only adjustment 3 vs adjustment 2 and 3, vs all adjustments together?

Author response: Thank you for pointing this out. Indeed, there are three steps in the adjustment, but they are not redundant. The first two steps are done during the creation of the radar database. They optimise the radar archive in 'average' terms meaning that they aim at providing an archive that is as good as possible for (i) any moment and (ii) any location in the domain in terms of bias and dispersion of the daily precipitation amounts (see details in Marra and Morin, 2015 and Marra et al, 2022). These adjustments are not part of this study, they come with the radar archive and cannot be undone.

To make this aspect clearer, we rephrased the text of Section 2.1 to:

> *"The final radar archive was obtained after a two-step bias adjustment based daily rain gauge archive data (Morin and Gabella, 2007; Marra and Morin, 2015). This*

adjustment aimed at optimising the bias and dispersion of rainfall depths during independent meteorological events. A full description of the radar data elaboration procedure and overall quality is provided in Marra et al. (2022). Marra et al. (2022) demonstrated…”.

Clearly, an adjustment optimised for the average conditions will not necessarily be optimised also for extremes. The last adjustment we apply follows the approach by Marra et al. (2022) and aims at optimising the estimation of return levels from the radar based on ground “truth” from high-resolution rain gauge records. This adjustment operates in the SMEV parameter space and only adjusts the SMEV parameters and thus estimated return levels, not the weather radar estimates or the return levels estimated with any other extreme value method. We believe the text edit above clarifies this issue.

3. Also regarding the parameter scaling of different areas based on rainfall stations, do you know how drastic the change in the parameters of the bigger areas is? It would be interesting to see how the mean value of the parameters of different duration and area are changing after the adjustment. So to have an idea how “wrong” the radar parameters are, and which duration and areas are mostly affected by it. Maybe this could explain also the convergence of the IDAF curves for longer durations? On the other hand, it would be also interesting to see what parameters are mainly differing with station based parameters (either shape, or scale or the number of ordinary events). This is probably outside the scope of your study, but maybe you can give your insight in the discussion based on your experience so far.

Author response: The parameter scaling was developed originally for the pixel scale and has here been applied 'as is' to the areal scale – therefore the scaling is the same for each area size, and differs only for duration. Developing a scaling method for the areal scale would be preferable, but is not possible here due to the low density of rain gauges.

An analysis of the parameter correction factors shows that the mean of the absolute scaling factors over the study area for both the shape and scale parameters are slightly greater for smaller durations than larger durations, ranging from 1.33 (24 h) to 1.46 (10 min) for the mean scale correction factor and 1.23 (24 h) to 1.58 (10 min) for the mean shape correction factor. However, these differences are relatively minor. Additionally, the scaling is similar for the shape and the scale parameters. The correction factors for the number of ordinary events have a mean value of 1.75 (note that the correction factors for the number of ordinary events do not change with duration). The spatial distribution of the correction factors for the shape, scale, and n parameters varies across the study area. However, the patterns of variation are generally consistent for each duration.

Based on this it seems unlikely that the scaling of the parameters is causing the convergence observed at long durations.

4. Another thing that is not completely clear to me, is the identification of storms and ordinary events at the pixel scale. So you first determine the storm events based on daily average data (a total of 498 storm events). Then at each pixel for these storm events are you; a) either defining new "local" storm events, that can have completely different durations than the "regional" ones, or b) are you just checking which "regional" storms are manifested in this pixel and then decide whether to exclude them or not (but you keep the event duration same). I am asking because the events for each pixel are based on 10 min radar data, and it may be that the duration of such events is shorter than 24 hours (which would them compromise your fixed number of events over different durations).

Author response: The events are identified using method b. Indeed, it is likely that events are shorter than 24 hours, but this is not a problem with respect to the fixed number of events across durations. This is thanks to the unified approach we use to define the ordinary events, which goes through the identification of independent "storms" separated by at least 24 dry hours. This separation grants that, using a moving window of 24 hours (i.e. examining 24-hour durations), storms lasting for short (e.g., only for 1 hour in the pixel of interest) would still yield independent ordinary events for all durations up to 24 hours. Note that for storms lasting less than 24 h, when considering 24 h duration ordinary events the time window containing the maximal intensity will therefore include zero values. This holds true for all other durations as well.

Moreover, the annual maxima computed over moving windows of the desired duration would be a subset of the corresponding ordinary events. This approach is recently being widely adopted for multi-duration precipitation frequency analyses (e.g., Marra et al., 2020; Marra et al., 2021; Dallan et al, 2022; Marra et al., 2022; Formetta et al., 2022; Dallan et al., 2023; Araujo et al., 2023; Shmilovitz et al., 2023); we kindly refer to Marra et al. (2020), where it was introduced, for further details.

Throughout the paper the text was amended to emphasise the difference between storms and ordinary events. Additionally, the following text was added to clarify that the number of events is the same for all durations:

> *"Ordinary events of the spatial (area) and temporal (duration) scales of interest are then identified at each radar pixel for each storm, with one ordinary event calculated for each storm… It should be noted that for each area considered, the number of ordinary events at each pixel is consistent for all the examined durations. This is due to the unified approach used to define the ordinary events, which goes through the identification of independent "storms" separated by at least 24 dry hours."*

Araujo D, F Marra, H Ali, HJ Fowler, EI Nikolopoulos, 2023. Relation Between Storm Characteristics and Extreme Precipitation Statistics Over CONUS. Adv. Water Resour., 178, 104497, https://doi.org/10.1016/j.advwatres.2023.104497

Dallan E, F Marra, G Fosser, M Marani, G Formetta, C Shäer, M Borga, 2023. How well does a convection-permitting regional climate model represent the reverse orographic effect of extreme precipitation? Hydrol. Earth Sys. Sci., 27, 1133-1149, https://doi.org/10.5194/hess-27-1133-2023

Dallan E, M Borga, M Zaramella, F Marra, 2022. Enhanced summer convection explains observed trends in extreme subdaily precipitation in the Eastern Italian Alps. Geophys. Res. Lett., 49, e2021GL096727. https://doi.org/10.1029/2021GL096727

Formetta G, F Marra, E Dallan, M Zaramella, M Borga, 2022. Differential orographic impact on sub-hourly, hourly, and daily extreme precipitation. Adv. Water Resour., 149, 104085, https://doi.org/10.1016/j.advwatres.2021.104085

Marra F, M Armon, M Borga, E Morin, 2021. Orographic effect on extreme precipitation statistics peaks at hourly time scales. Geophys. Res. Lett., e2020GL091498, https://doi.org/10.1029/2020GL091498

Marra F, M Armon, E Morin, 2022. Coastal and orographic effects on extreme precipitation revealed by weather radar observations. Hydrol. Earth Syst. Sci., 26, 1439–1458, https://doi.org/10.5194/hess-26-1439-2022

Shmilovitz Y, F Marra, Y Enzel, E Morin, M Armon, A Matmon, A Mushkin, Y Levi, P Khain M Rossi, G Tucker, J Pederson, I Haviv, 2023. The impact of extreme rainstorms on escarpment morphology in arid areas: insights from the central Negev Desert. J. Geophys. Res.: Earth Surface, 128, e2023JF007093, https://doi.org/10.1029/2023JF007093

5. Following the explanation on line 210-211, is the number of ordinary events reduced according to the 55th percent, or just the input series for the CDF fitting is reduced to leave out the 55% of the events? Also, in Line 210 you mention than censoring between 55th to 80th quantile doesn't influence much the results, but then still why did you choose to censor below the 55th quantile?

Author response: From the referee's question we understand that the meaning of left censoring was not completely clear. As now better detailed in the text (see below) the left censoring procedure ignores the intensities of the censored events during the fitting of the CDF, but it is important to note that the weight of the censored events are retained in probability. The text has been revised to include this and reads as follows:

> *" The left censoring procedure ignores the intensities of the censored events while still retaining their weight in the probability. The study found that left-censoring values between the 55th quantile and the 80th quantile provide virtually indistinguishable results for the area. Following Marra et al., (2022) we here left-censor the lowest 55 % of the ordinary events."*

We selected the lower threshold (the 55th quantile) so as to include the maximum number of events in the data sample, to reduce uncertainty. The following was added to the text:

> *"The lower threshold was selected to include the maximum number of events in the data sample."*

6. Line 240, could you please describe shortly the bootstrapping from Overeem et al. 2008? Does it pool together all stations inside a region and samples from pooled storms, or is it just storm sampling with replacement from a single series?

Author response: The bootstrapping procedure performs sampling with replacement of years from a single series, and is applied independently to each pixel. The procedure is as follows:

The technique generates samples by selecting blocks (here blocks are defined as a hydrological year) randomly with replacement, so that the number of blocks is the same as in the original record. The ordinary events for each block are then concatenated to create the bootstrapped dataset, from which the Weibull parameters and quantiles are estimated, using the procedure described above. This enables the block structure of the original rainfall data to be preserved.

The above explanation has been added to the text.

7. Lines 251-252, why do you validate the radar data based on station data of another time period? Wouldn't this also punish more the radar data IDAF curves?

Author response: This is correct, however, we wanted to thoroughly asses the accuracy of the radar derived return levels and therefore wanted to ensure that the comparison rain gauge derived results were as accurate as possible. We thus decided to use the entire dataset. The following was added to explain this in the text:

"The rain gauge data spans a 30-year period, in contrast to the 12-year dataset used to derive the radar data results. We acknowledge that this adds some uncertainty to the comparison between the radar and gauge derived results, given the disparate data periods used. However, it was decided to use the whole timeseries, rather than matching the time periods, so as to produce the most accurate return levels against which to validate the radar derived results."

It is also correct that this will bias the rain gauge data towards producing better results than the radar data. However, as the results show (figure 3), generally the uncertainty of the radar derived results are comparable to the gauge derived results, despite using less data. This is noted in the next:

"This is encouraging as the radar results are computed using only 12 years of data and are adjusted using relations derived for the pixel-scale, whilst the gauge results utilise 30 years of data and direct precipitation observations."

8. At line 260, you mention the discrepancy between radar and daily station IDF curves due to different daily measurements. Since radar is at 10mins, wasn't it possible to calculate the daily maximum intensity according to the daily measurement times (between 6 am to 6 am)?

Author response: We thank the reviewer for the suggestion. We preferred presenting the maximal 24 h of the radar to match the entire analysis of this paper, but we will try to examine also the maximal 6 am – 6 am data for the radar and if it would be useful we will include it in the revised paper.

9. Figure 3 – c, I agree it might be the distance to the radar station that is causing such overestimation. However, this pattern is not consistent with Figure 4, as we see that in the region near to the radar station there is a clear underestimation (or very little rainfall). I was wondering if there is a specific parameter that is overestimated in this area that might be directly link with this IDF overestimation? Can it be that the adjustment to 10min station data parameters had something to do with the overestimation (like the density of 10min station data in the vicinity)?

Author response: The region around the radar station does have significant underestimation of the rainfall. However, the overestimation that can be seen in location e is the region of very high values just south of this area (visible in figure 4). This is stated in the text:

> *"Immediately south of the radar station there is also a distinct region of high values. This corresponds to the location of validation site e shown in Fig. 1, which exhibits precipitation intensities higher than those derived from gauge data (Fig. 3)."*

The scale parameter in this region is slightly higher than the surrounding regions, which could be causing the higher return level estimates, however, this was not caused by the scaling of the parameter.

The shape parameter is slightly lower than the surrounding regions, which could also cause higher values. For some areas and durations this decrease in values appears to correspond somewhat to a region with a scaling factor smaller than one, however this is not clear.

We considered that data from a specific rain gauge, in close proximity to the problematic area, was causing this problem. However, an analysis of the rain gauges in the region did not identify any issues.

10. At section 4.3 you explain how the figures are derived, however you mention in line 313 a 5 by 10 km^2 box, and then on line 319 a 10 by 10 km^2 Is this a typo, or these are actually two different types of box-sizes used for the investigation?

Author response: Thank you for pointing this out, it was a typo that has now been corrected. The correct size is 10 by 10 km^2.

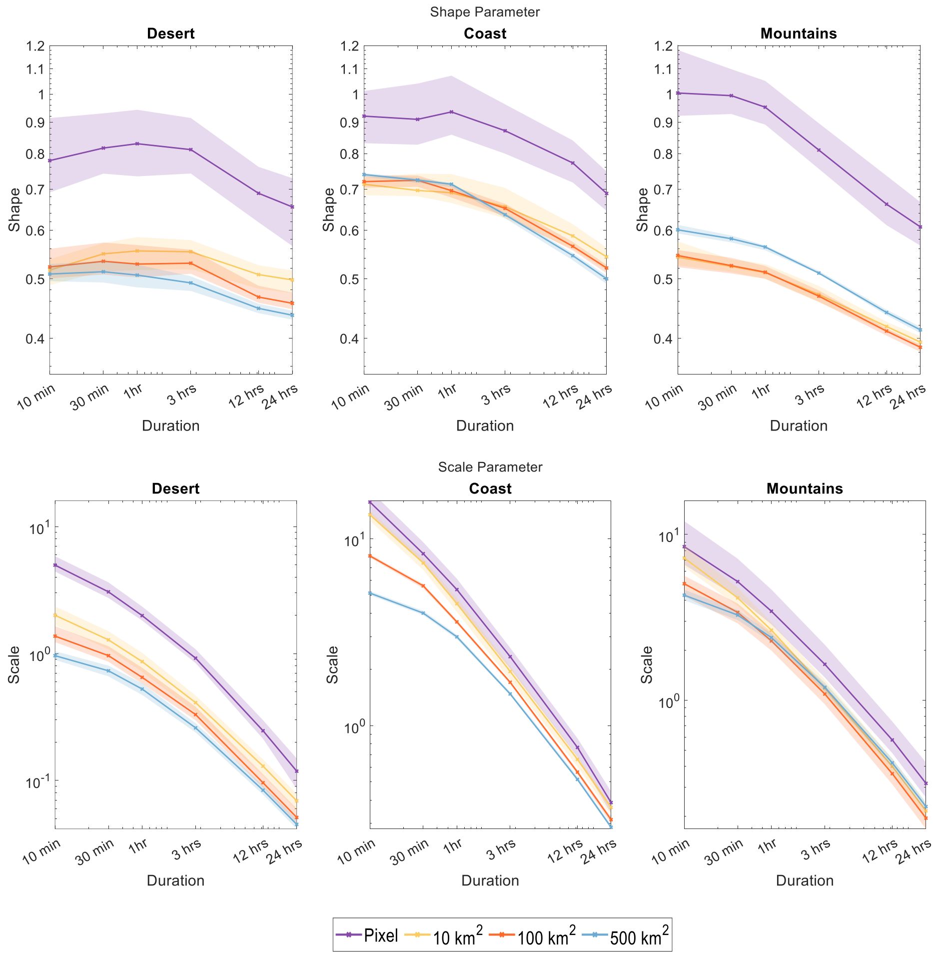
11. Figure 5 – I think it is also interesting to point out the duration when the areas converge for these three regions. In the desert the convergence happens at 1 hour, while at coast and mountains at 3 hours. Do you have any explanation for that? Maybe to explain why the IDAF curves are converging after a certain duration, it may be useful to have a look at the SMEV parameters and see how they are changing with duration and area, or even see the average characteristics of the ellipses for each duration and area; so for instance if for 24 h duration the axis ratio of the ordinary events is closer to 1 than those of 1h duration, or even the spatial variability of the rainfall within an ellipse for different durations and areas.

Author response: Yes, this is an interesting observation. We think it is probably to do with the nature of the rainfall in the different regions. The following was added:

> *"It is noteworthy that the estimated return levels for different spatial scales converge at different durations for the different regions (around 1 h over the desert and approximately 3 and 12 h over the coast and mountain regions, respectively). In desert areas rainfall primarily stems from highly localised small-scale convective rain cells, and events are generally short duration (Armon et al., 2020, Marra et al. 2017). Indeed for short durations, the highest rain intensity amounts in the region are located in the desert. Therefore, rainfall is very different at different spatial scales for short duration. At durations greater than 1 h rainfall becomes more homogenous in space, with less significant variations in rainfall intensity, causing this convergence. In contrast, rainfall events in the Mediterranean coastal and mountain regions generally have larger rainfall amounts for longer durations (Armon et al., 2020). The estimated return levels exhibit significant spatial differences for longer multi-hour durations, and do not show homogenous behaviour over different spatial scales until around 3 to 12 h. "*

A figure of the shape and scale parameters as a function of area and duration has been added to the supplement of the paper (see figure below), along with the following text added:

> *"The calculated shape and scale parameters, after correction factors have been applied, are presented in Fig. S4. The effect of both duration and area is clearly visible: the scale parameter decreases with increasing duration and increasing area, with the values converging at long durations – mirroring the behaviour of the return levels presented in Fig. 5. Unlike the scale parameter, the values of the shape parameter do not become more similar for long durations. The parameter displays non-monotonic behaviour, with generally minimal change for durations between 10 min and 1 h, and decreasing for durations between 1 and 6 h (implying an increasing tail heaviness). Very low parameters, between 0.4 and 0.75 (indicating heavy tails), are observed for area sizes greater than the pixel scale, especially over the desert and mountains, while exponential tales (i.e. values close to 1) are observed for the pixel scale."*



Shape and scale parameters (after correction factors have been applied) as a function of area and duration estimated for the desert, coast, and mountains. Shaded areas represent the 90 % confidence interval from 100 bootstrap samples.

12. Also the results from Figure 5 are a bit controversial, as I would expect that the ARF are dependent on duration and area (see for instance Overeem et al. 2010), and in my opinion these results should be discussed more. Line 375-397 – here you are discussing about other studies that have more or less contrary results to your investigation. The main reason for this contrast, you list the different study areas. However, might there be other factors like the methodology applied or the data used that might explain the difference in the results (i.e. use of ellipses instead of circles, use of SMEV instead of GEV and so on). Lastly is the same pattern as shown in Figure 5 also valid for other locations, i.e. the validation sites or other random sites?

Author response: Thank you for pointing this out. In general, all the studies on ARF show that ARF values increase with increasing duration, indicating more similar behaviour between the point and the areal scale for longer durations. This agrees with the results of figure 5 - for 24 h durations rainfall intensity is very similar for all areal scales, while for 10 min rainfall there is a large spread of values.

The disagreement in the studies is the extent of this similarity - which is described by the value of the ARF. The studies mentioned show a range of results - e.g. Pavlovic produces values of 0.95 for 24 h 500 km^2 rainfall, while Biondi et al. (2021) derive a figure of only 0.45 for 24 h 500 km^2 rainfall. The text was revised to make this clearer and now reads:

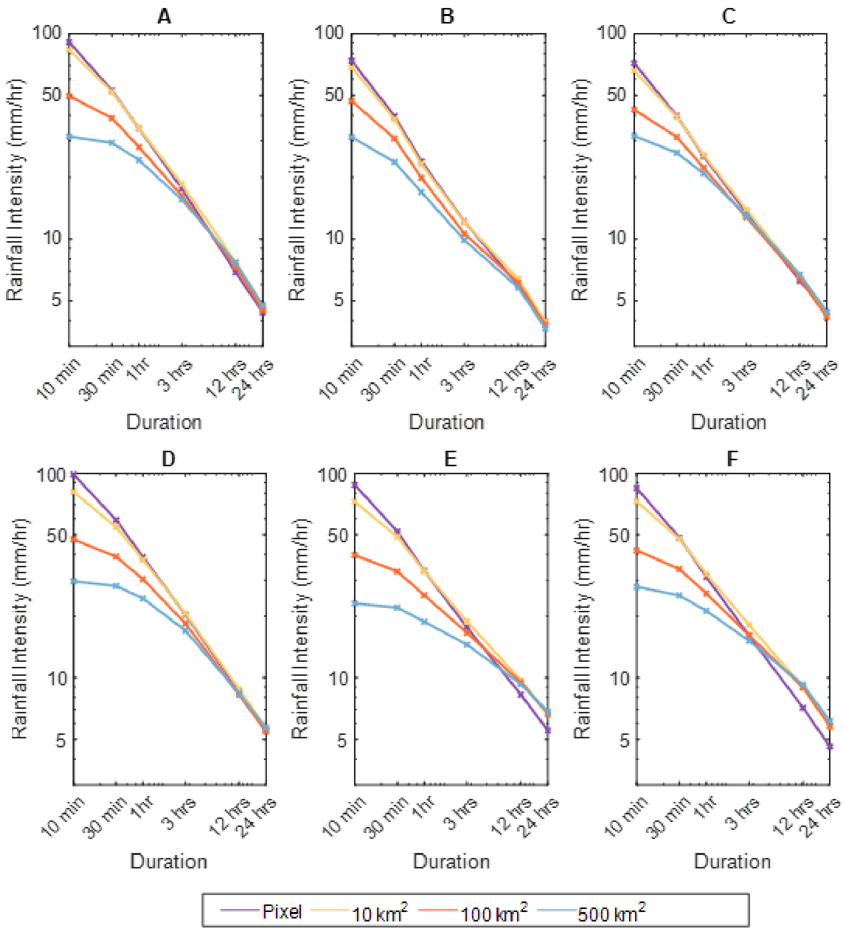
> *"Conversely, a study by Biondi et al. (2021), who estimated ARF values derived for the Calabria region in southern Italy using both a fixed and moving-centre approach, found that although ARF values increase with increasing duration, the estimated ARF values for 24 h precipitation at large areas are still low – thus indicating a large difference between point and large-scale areal precipitation. They derived values of approximately 0.27 and 0.45 for 1 and 24 h duration rainfall over a 500 km^2 area using a fixed centre approach, and values of 0.34 and 0.53 when applying a moving centre approach. They do note, however, that ARF values show a much sharper decrease for shorter durations due to the small areal extent of the short-duration events, while events with a long duration tend to be characterised by sustained rain rates over larger areas as expected.*
>
> *Kim et al. (2019) derived ARF values of approximately 0.89 and 0.37 for 1 h duration precipitation over areas of 10 km^2 and 530 km^2 respectively, and values of 0.92 and 0.7 for 24 h precipitation over the same area sizes. These results again demonstrate that rainfall becomes more similar with duration, but still indicate differences between the small and large-scale areal precipitation.*

It is very likely that the different methodologies used to derive the ARF values, as well as a number of other factors, will affect the results – this has been demonstrated in a number of papers. The following was added to the paper:

> *"It should be noted that there are several factors which may influence the variability in these ARF values. The studies are focused on different locations, characterised by varying seasonality, rainfall types and geographical characteristics, all of which have been demonstrated to affect ARF estimates (Kao et al., 2020). Moreover, the studies apply different methodologies for ARF calculation (moving centre vs fixed centre approach), different precipitation data sources (radar data vs rain gauge) and varying record lengths, all of which have demonstrated effects on ARF values."*

To investigate if the same pattern seen in figure 5 is present for other locations the IDAF curves were plotted for the 6 validation sites (see figure below). It is evident that the same pattern exists. The following was added to the paper (without the figure):

> *"Additionally, return levels were examined for the six validation sites to verify that this pattern is consistent throughout the study region, and the same pattern was observed."*



25 year return period IDAF curves estimated for the six validation sites.

13. In Section 5.2 (more specifically starting from Line 410 and on) you mention that the power-law relation weakens as the area size increases. Do you know of any other study that might back you up in this conclusion?

Author response: The power law relation between intensity and duration is well covered in the literature. However, as far as we can tell the influence of area on the intensity duration relationship has not been previously studied. Similarly, there are also studies on the power law between intensity and area, related to the spatial scaling of rainfall, however, they do not consider the impact of duration.

A number of papers look at the effect of area and duration on areal reduction factors – for example Kim et al. (2019) show that ARF generally increases with duration, and that this phenomenon becomes pronounced as the area becomes larger, however they do not relate it to the power-law relationship.

14. It seems that this works is largely based on the previous work of Marra et al. 2022. Maybe you can consider to join this paper with the previous one, so readers will go directly to the previous one if they have any questions.

Author response: Thank you for the suggestion. Part of the methods are indeed taken from the work by Marra et al, 2022, but the scientific objective here is different as we focus on the areal dimension. For this reason, and since the above mentioned paper was published over 1 year ago by a slightly different team, we believe it is not appropriate to join the two papers (even if at all possible).