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Discussions

Interactive comment on "Little evidence for super Clausius–Clapeyron scaling of intense rainstorm properties with air temperature" *by* P. Molnar et al.

P. Molnar et al.

molnar@ifu.baug.ethz.ch

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The main question raised by this comment is whether our results support the statement that super-CC scaling rates result from mixing stratiform and convective events. Loriaux points to a recent paper by herself and co-authors (Loriaux et al. 2014) where the argument is that super-CC rates are a real feature of extreme convective precipitation, and the change in slope from CC to 2CC rate at a given temperature is determined by the dominance of convective precipitation at a given time resolution and temperature. This argument is supported by data from the Netherlands and expected rates (above CC) are also theoretically shown from an entraining plume model under certain assumptions. The critical question raised by the comment of Loriaux is that "...no results

[in our paper] are presented to clearly back up the claim that the slope of the full set is inflated by storm cloud mixing."

To address this question we lay out first some methodological issues, we present an example of the results for one station, and summarize them for all stations, with the aim to explain clearly what the inflation by storm cloud mixing means. These considerations and statements will be reflected in the revision of our manuscript.

1. Analysis methodology

The aim of our paper is to demonstrate the variability in precipitation intensity-air temperature scaling rates obtained from data for many stations in different geo-climatic settings across a region with local orographic effects on precipitation formation as well as different large-scale atmospheric moisture flux patterns (e.g. south-north of the main Alpine divide). Compared to previous studies we have two significant methodological differences which have to be clearly stated.

First, we chose not to analyze all intervals of rain (at a given temporal resolution) as if they were independent samples, because we know they are not. Our independent unit is the rainfall event separated by dry periods. For each event we identify event properties, rainfall depth R, duration td, mean event intensity (Im=R/td), and peak intensity (Ip) at the given time resolution, and we relate these to the mean air temperature on the day that the rainfall event occurred. In the revised manuscript we have recomputed all results for 10-min (new) and 1-hr (previous manuscript) rainfall data, with allows us to highlight some important differences related to temporal resolution. We omit snowfall and mixed events by only taking events in the warm season period April-September and ensuring that event temperature was never below 4C. These are generally convective and stratiform events with the highest rainfall intensities during the year. More details on the event selection procedure can be found in Gaal et al. (2014).

Second, we chose not to search for a perceived change in the slope of the rainfall-temperature relation at a certain threshold temperature, but rather we fit a CC (exponential) relation to the data for the entire range of temperatures above 4C. We do this because we have stations covering altitudes from 300 to about 2200 m, with large differences in air temperature; where there is no good reason to argue that the same temperature threshold would apply. In the revised manuscript we compare a traditional binning approach (but no overlapping bins again for reasons of independence) with quantile regression without binning, which was shown by Wasko and Sharma (2014) to be a more robust estimation procedure. In our revised manuscript we report results only for quantile regression and the binning estimators will be provided in the supplementary material in the revised manuscript. Because our sample size is smaller than studies using all rain intervals (see above), we report results only up to the 95-percentile in our study.

Because we only take independent rainfall events above 4C and do not search for a break in slope, but estimate a single best relation between rain intensity and air temperature at each station, our scaling slopes are not directly comparable with those of previous studies, including those of Loriaux et al. (2014).

2. Scaling slope effects of stratiform and convective rain

We divide all events into two exclusive subsets: those accompanied by lightning and those that are not. Overall between 25-50% of the events are accompanied by lightning, depending on station location. We recognize that the division of all events into the two subgroups lightning and no-lightning only roughly approximates convective-stratiform rain, but we believe this to be a good first order approximation insofar as heavy convective summer thunderstorms are concerned. No-lightning and lightning events occur over a similar temperature range, but of course no-lightning events are associated with lower mean intensities and lightning events with higher mean intensities and shifted towards hotter days.

If we estimate the scaling slope of the log-intensity versus temperature relation for both lightning and no-lightning subsets and for all events together we get the results shown

in Figure 1 for most stations (example shows the Wynau station). The scaling slopes for no-lightning and lightning sets are practically identical at 6%/C, while when both sets are treated together we get the rate 10%/C at this station. The results for the temperature binning method were practically the same. So our answer to the comment by Loriaux is that over the ranges of air temperature where both stratiform and convective rain may occur (overlap), which is dependent on latitude, local climatology, orography, etc., both storm types may scale with a CC-like rate when analysed separately, but their combination seems to scale with a rate greater than CC because the two subsets have different mean event intensities and temperatures. This explanation is not ours, it was put forward by Haerter and Berg (2009) and Berg and Haerter (2013) and supported in their case by cloud observations instead of lightning. We fully acknowledge that in our analysis this separation is good insofar as the presence of lightning is able to separate convective and stratiform rain.

3. How systematic is this result?

The next question is how systematic is this result when all stations are considered. Figure 2 shows the scatter plot of scaling slopes of lightning and no-lightning subsets for all stations in our dataset for the 95-percentile of events. It is evident that the slopes are generally between CC and 2CC for convective (lightning) events and slightly lower for mean than for peak intensity. The values for stratiform (no-lightning) events are slightly lower and on the average around the CC-rate. Notably, there are very few stations that exhibit rates greater than the 2CC-rate in each subset, despite the variability between stations. When we plot the same scaling rates for all events versus no-lightning and lightning events separately we get quite a different picture (Figure 3). The scaling rates for all events are systematically higher than those of lightning and no-lightning subsets. This is true for both peak and mean intensity. For mean intensity (top row) the highest scaling rates for all events reach up to 2CC, while for peak 10-min intensity (bottom row) they can be greater than that.

Therefore we conclude that the statement that the CC-scaling rates for all events may be different from that estimated for stratiform and convective subsets individually, and in fact higher than the individual subset rates, is true and substantiated by our data. Perhaps the phrasing that a super-CC rate (meaning greater than CC-rate) is the result of event type mixing (only) is misleading, because indeed we do find super-CC rates at our stations as well, both in no-lightning and lightning subsets. We will revise this accordingly.

There is an important consequence of this result with regard to the statement about rainfall intensity increases under a (much) warmer climate, in the sense that, if a shift towards more convective rainfall occurs at a site, predictions about higher rainfall intensities made from scaling slopes of all events may be incorrect. The relevance of this problem is illustrated in Figure 4 where we show how the contribution of convective (lightning) events at our stations increases with air temperature. The proportion of convective events on warm days (e.g. greater than 25C) is almost 90% on the average and their scaling slope will determine the rate of increase in rainfall intensity with temperature on hot days.

4. Contradiction with Loriaux et al. (2014)?

The question that remains is if our results contradict the findings of Loriaux et al. (2014). We think they do not for the following reasons.

First, we never claimed that physical (dynamic and thermodynamic) arguments do not support the existence of higher than CC scaling or super-CC scaling, we just claim that 2CC rates found by some authors in the literature are not common in the Swiss dataset. They do not occur at the hourly scale or at the 10-min scale for the estimation of mean event intensity. They are only visible at some stations in the peak 10-min intensity during a storm. We will be more explicit in the revised manuscript regarding this result. The additional combined analyses at 10-min and 1 hour that we carried out during the revision of our paper will serve as further support for resolution effects. Like previous authors, we find that 10-min resolution data allow a more accurate represen-

tation of storm duration, especially in strong convective storms on hot days which are shorter than 1 hr. As a result, the 10-min derived scaling slopes are generally greater than those derived from hourly data. This will be shown and discussed in the revised manuscript.

Second, it is not entirely clear to us how Loriaux et al. (2014) generated their Figure 1, but it seems that all station-years were pooled together into a single dataset for the Netherlands where they report a 2CC rate for very extreme 10-min rain. Also in our dataset 10-min peak intensities scale at some stations with rates close to (even greater than) 2CC, so we see no contradiction there. It is important to point out that in the complex topography of Switzerland we have a large spatial variability in precipitation properties. For this reason we insist on analyzing stations separately to quantify the variability in the resulting intensity-temperature scaling rates.

Third, the separation of thermodynamic and dynamic components of the expected scaling of precipitation intensity with temperature controlled by the flux of moisture at the cloud base and in-cloud lateral moisture convergence in the plume model of Loriaux et al. (2014) shows that under no moisture limitations the scaling rate can be about 10%/C, composed of 7%/C due to thermodynamic effects (perturbed humidity) and 3%/C related to dynamic effects (perturbed vertical updraft velocity). Considering additional effects of vertical velocity on lateral moisture flux can theoretically lead to scaling rates between CC and 2CC (Loriaux et al., 2014, p.3654). Our data in Figures 2 and 3 show that indeed most stations exhibit scaling rates, especially for convective events, in the CC-2CC range for mean event intensity. Thus we believe that our results do not contradict the results of Loriaux et al. (2014), we rather see added value in the spatial variability in scaling slopes which our data demonstrate.

The figures and arguments presented in this response will be part of the revised manuscript.

References

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Figure Captions

Figure 1: Mean event intensity as a function of daily air temperature for lightning (red) and no lightning (green) events with their scaling rates for the 95-percentile (quantile regression) for the station Wynau. The scaling relation for joint analysis of the two sets is shown with the black line. Reported CC-slopes are in %/100/C.

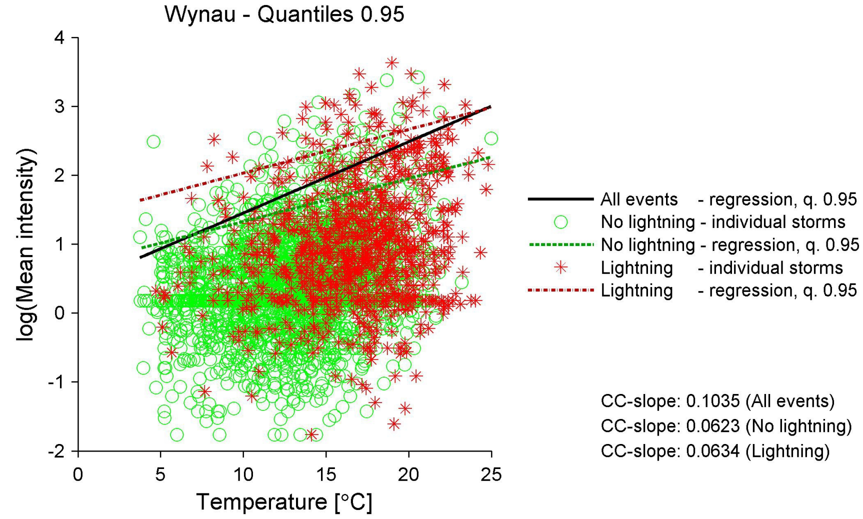
Figure 2: Scatterplot of lightning versus no-lightning scaling rates in %/100/C for mean event intensity (left) and peak 10-min event intensity (right) for the 95-percentile. Lines show the CC (7%/C) and 2CC (14%/C) rates.

Figure 3: Scatterplot of all events versus no-lightning scaling rates (left) and lightning scaling rates (right) in %/100/C (right) for mean event intensity (top row) and peak 10-min rainfall intensity (bottom row) for the 95-percentile. Lines show the CC (7%/100/C) and 2-CC (14%/100/CC) rates.

Figure 4: The ratio of events with lightning as a function of air temperature. The mean

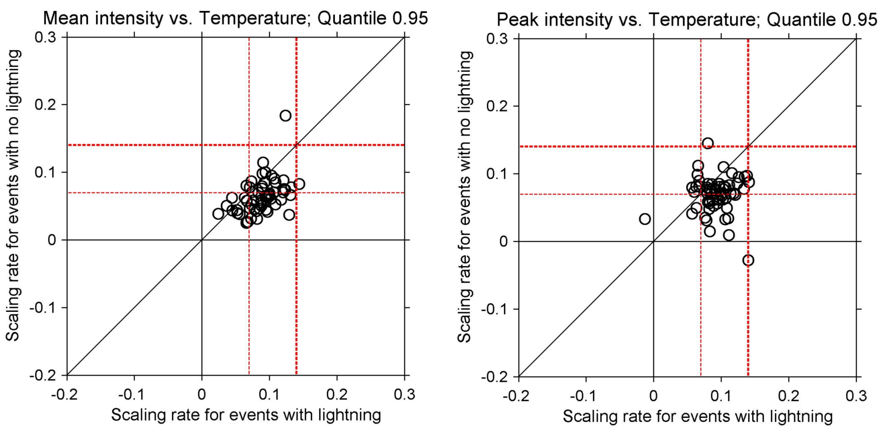
and standard deviation were computed from the set of all 59 stations.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 11, 8923, 2014.



Wynau - Quantiles 0.95
log(Mean intensity)
Temperature [°C]
All events - regression, q. 0.95
No lightning - individual storms
No lightning - regression, q. 0.95
Lightning - individual storms
Lightning - regression, q. 0.95
CC-slope: 0.1035 (All events)
CC-slope: 0.0623 (No lightning)
CC-slope: 0.0634 (Lightning)

Fig. 1.



Mean intensity vs. Temperature; Quantile 0.95
Peak intensity vs. Temperature; Quantile 0.95
Scaling rate for events with no lightning
Scaling rate for events with lightning

Fig. 2.

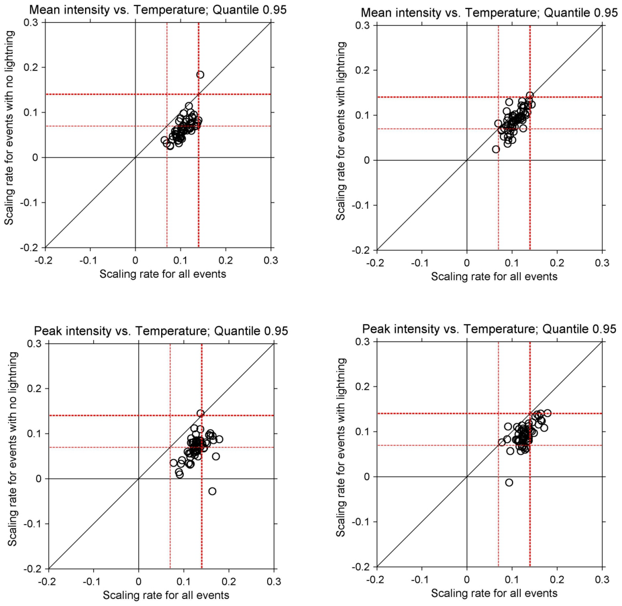

Mean intensity vs. Temperature; Quantile 0.95
Scaling rate for events with no lightning
Scaling rate for all events
Mean intensity vs. Temperature; Quantile 0.95
Scaling rate for events with lightning
Scaling rate for all events
Peak intensity vs. Temperature; Quantile 0.95
Scaling rate for events with no lightning
Scaling rate for all events
Peak intensity vs. Temperature; Quantile 0.95
Scaling rate for events with lightning
Scaling rate for all events

Fig. 3.

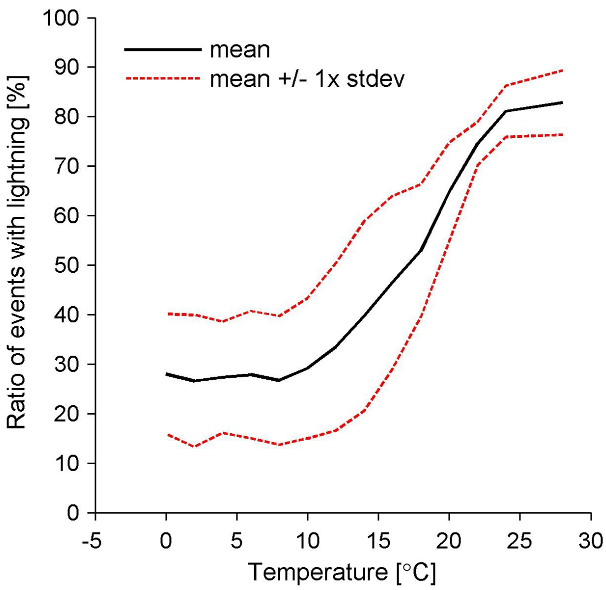

mean
mean +/- 1x stdev
Ratio of events with lightning [%]
Temperature [°C]

Fig. 4.