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Storm type effects on super Clausius-Clapeyron scaling of intense rainstorm properties with air temperature

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Summary Response to Editor/Reviewers:

The paper has been reviewed in line with our responses provided in the HESS Discussion phase. The main changes requested/summarized by the Editor have been as follows.

(1) *Suggestion: Reanalyse with 10-min data*. We have done this and provide now a comparison of 1-hr and 10-min results, with a focus on the more accurate 10-min results and comparing the results. The effect of the resolution on the results is in the direction reported by previous studies, i.e. higher scaling slopes are found for higher resolutions. Indeed as one referee points out, the effect of 10-min resolution on mean event intensity is only through a more accurate definition of the true event duration, thereby affecting short events, while the effect on peak 10-min intensity is greater because at this resolution bursts of high intensity during an event can be captured. We address these issues now in the revised manuscript in the Section 3.2 Effect of storm type mixing.

(2) *Suggestion: Add figures with fitting*. We have done this step and present now a new Figure 3 where the fitting for both quantile regression QR and temperature binning TB methods for one example station are shown (see also answer to question 5). We have also added a new Figure 1 which provides a revised map of all the stations used in our analysis, divided into four geo-climatic regions.

(3) *Suggestion: The analysis on other variables than temperature should be clarified or removed*. With the new 10-min results and the question of J. Loriaux to our HESS Discussion paper on the effect of mixing event types, we have expanded the discussion of the paper in this direction, i.e. analyzing the details of the intensity-temperature scaling rates for stratiform and convective subsets. Because of this new added focus we think the original analysis with atmospheric variables from radio-sounding data is not adding new information and in fact distracting from the main message. We have decided to remove this section from the revised paper.

(4) *Suggestion: Application of the presented methodology to the dataset used by Lenderink and van Meijgaard (2009)*. Our methodology cannot easily be applied to the De Bilt dataset without apriori knowledge of storm type, or lightning data used to separate convective from stratiform rain, as we have done. We do not have access to such data for the Netherlands, and it would be better that the KNMI scientists conduct this analysis should they see it as being important. Furthermore, the station in De Bilt is close to the sea and we think from the climatic point of view, not really comparable with our dataset for 59 stations in Switzerland. We think that adding another station from a different part of Europe to our paper would not really add more clarity. In the revised manuscript we now clearly show the magnification of slopes that comes from storm type mixing at the Swiss stations. This is a conceptually a possible explanation of the high 2CC scaling rates at De Bilt as well.

(5) *Suggestion: Use of other methods for assessing the scaling coefficients (such as quantile regression)*. We have adopted this suggestion and in the revised manuscript now report and compare results for both quantile regression (QR) and the traditional temperature binning (TB) methods. In the revised paper we present mostly the QR results, but a comparison between the estimation methods is also presented in a new Figure 7, and TB results are also shown with new Figures in Supplementary materials.

(6) *Suggestion: The use of the presence of lightning data to discriminate different storm types may lead to overestimates in scaling coefficients at low precipitation intensities and underestimates at high intensities*. This statement made by J. Loriaux in her comment in the HESS Discussion phase led us to conduct a station-by-station assessment of the no-lightning, lightning, and combined slopes.

The results are clearly showing the inflation effect by mixing and are now presented as scatter-plots in new Figures 4 and 5 in our revised manuscript. We have also addressed this issue in depth in our response in the Discussion phase. We think this information and the discussion thereof in the revised manuscript answers the question of J. Loriaux.

<u>Additional major changes to the manuscript in the revision were</u>

(7) In light of the stronger focus on storm type mixing we have decided to slightly change the title of the paper from “Little evidence of...” to „Storm type effects on the scaling of heavy rainfall event intensities with air temperature“. Since Section 3.3 with the radio-sounding data was removed, we also removed the two student co-authors who performed that part of the analysis, and placed them in the acknowledgement list.

(8) Because of the re-computation with the 10-min data, we decided to expand the station dataset from 50 to 59 stations. Out of the original dataset of Gaal et al. (2014) we removed only three stations at highest elevations because the lightning data are not reliable there – the fraction of lightning strikes in the vicinity of the stations are too high and this gives us an unbalanced no-lightning-lightning subset division. Apart from these three stations we chose not to remove any additional stations, even if their scaling slopes were outliers. In fact we point to and discuss the main outlier in the text in Section 3.3 Regional variability.

(9) We added altogether 5 new figures to the revised manuscript, updated the reference list, and substantially rewrote Section 1 Introduction and the entire Section 3 Results and Discussion. We also updated the Conclusions to reflect better the main focus of the paper—which is a demonstration of the effect of storm type mixing on the rainfall intensity-temperature scaling rates and their spatial variability in an orographically and climatologically complex region.

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~~Little evidence for~~ Storm type effects on super Clausius-Clapeyron scaling of intense rainstorm properties with air temperature

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Abstract. Extreme precipitation is thought to increase ~~proportionally to the rise in the~~ with warming at rates similar to or greater than the water vapor holding capacity of the air at ~~roughly~~ ~$7\,\%\,^{\circ}\mathrm{C}^{-1}$, the so-called Clausius-Clapeyron (CC) rate. We present an empirical study of the variability in the rates of increase in precipitation intensity with air temperature using 30 years of ~~hourly data from 50 stations in an Alpine environment~~10-min and 1-hr data from 59 stations in Switzerland. The analysis is conducted on storm events rather than fixed ~~time resolutions~~interval data, and divided into ~~event~~ storm type subsets based on ~~concurrent lightning strikes indicating~~ the presence of lightning which is expected to indicate convection. The average rates of increase in extremes (95th percentile) of mean event intensity ~~(7.4~~computed from 10-min data are $6.5\,\%\,^{\circ}\mathrm{C}^{-1}$ (no-lightning events), $8.9\,\%\,^{\circ}\mathrm{C}^{-1}$ ~~) and peak hourly intensity (5.1~~(lightning events) and $10.7\,\%\,^{\circ}\mathrm{C}^{-1}$ ~~) for 90th percentiles are close to the CC rate expected under fully saturated conditions. Super-CC rates reported by other studies are an exception in our dataset. Events accompanied by lightning~~ (all events combined). For peak 10-min intensities during an event the rates are $6.9\,\%\,^{\circ}\mathrm{C}^{-1}$ ~~(convective events) exhibit significantly higher rates of increase than stratiform rain~~no-lightning events), $9.3\,\%\,^{\circ}\mathrm{C}^{-1}$ (lightning events) and $13.0\,\%\,^{\circ}\mathrm{C}^{-1}$ (all events combined). Mixing of the two storm types exaggerates the relations to air temperature. Doubled CC rates reported by other studies are an exception in our dataset even in convective rain. The large spatial variability in scaling rates across Switzerland suggests that both local (orographic) and regional effects limit moisture ~~availability and supply~~ supply and availability in Alpine environments especially in mountain valleys. ~~A trend analysis shows that our estimate of the number of convective events across Switzerland~~ The number of estimated convective events has steadily increased across Switzerland in the last 30 years~~. This significant~~ , with 30% of the stations showing statistically significant changes. The shift towards more convective storms ~~in a warming climate may as a consequence lead to stronger storm intensities and therefore~~ with higher temperatures may be relevant for heavy rain intensities and a higher risk connected with those events in the future.

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1 Introduction

The ~~rise in the~~ water vapor holding capacity of the air ~~at roughly~~ increases with temperature by about $7\,\%\,^{\circ}\mathrm{C}^{-1}$, the so-called Clausius-Clapeyron (CC) rate~~, is the rate at which precipitable water increases under fully saturated conditions with~~ . Consequently, precipitation is also expected to increase with air temperature. While changes in mean precipitation are constrained by the energy budget at the Earth surface and are typically smaller than the CC rate, e.g. 2–$3\,\%\,^{\circ}\mathrm{C}^{-1}$ ~~(??)~~ (e.g. **???**) , changes in extreme precipitation ~~on the ground~~ from fully saturated air masses have been postulated to ~~increase~~ occur at the CC rate, or ~~higher,~~ even higher if local moisture convergence takes place ~~(??) .~~ (e.g. **???**) .

Simulations of daily extreme precipitation by climate models have shown ~~different sensitivities globally~~ a range of sensitivities to air temperature ~~, with generally higher scaling rates in the tropics than the extra-tropics~~ globally. Extratropical precipitation was shown to increase at about the thermodynamically constrained CC rate, while tropical precipitation change varied widely between models because of the dependence of tropical rainfall on moist convective processes in the atmosphere, especially vertical velocity (e.g. ????). These results were complemented by satellite observations for high daily percentiles (e.g. ?) as well as by ground observations of daily precipitation in different regions and seasons which capture the seasonally varying atmospheric circulation and moisture supply (e.g. ??) Satellite observations indicate that the rate of increase in extreme daily rainfall with a warming climate in the tropics may be greater than that simulated by some models (?) , while ground observations have also shown a decrease in extreme rainfall in some parts of the tropics (?) . Overall, local responses are strongly dependent on changes in large scale circulation patterns and the physical nature and seasonality of rainfall regimes (e.g. ??) .

Investigations of sub-daily precipitation focused on the scaling relations for very high rain intensities for which we expect no limitations in moisture availability and supply, and therefore saturated water vapor conditions, and a scaling rate which may reach CC or even exceed itAnalyses of precipitation data at sub-daily resolutions generally show strong rates of increase in intensity with temperature. Data demonstrations started with the De Bilt dataset where ? found that a CC rate of increase in extreme hourly intensities accelerated to a super-CC doubled CC rate of approximately 14%°C^{-1} for temperatures above 12°C. The super-CC relation was explained by This 2CC rate was attributed to a positive feedback between water vapor and the dynamics of precipitation formation in convective clouds (?) . A super-CC rate was (??) . 2CC rates were subsequently found in other studies using hourly and higher resolution datawhere it . It was also argued that at very high temperatures the relation between precipitation intensity and temperature may become negative due to atmospheric moisture supply limitations (e.g. ??) (e.g. ?????) .

Available observational evidence to-date suggests that precipitation-temperature scaling rates vary from station to station, may vary widely in space and are time resolution dependent , and that super-CC scaling is not found everywhere (e.g. ????) . In fact, an (e.g. ??????) . An alternative (statistical) explanation for super-CC rates has been put forward, that mixing storm types–stratiform low intensity rainfall at low temperatures and convective high intensity rainfall at high temperatures–may lead to the appearance of super-CC rates (??). ? demonstrated on a large dataset in Germany that super-CC scaling is in fact dominated by convective rain which is more sensitive to increases in air temperature. Quantifying the effect of storm type mixing remains an important and open problem (e.g. ???) .

In this article we add empirical evidence to the picture of variability in scaling slopes between intense rainstorm properties and air temperature from observations of hourly precipitation and temperature at 50 at 10-min and 1-hr resolutions at 59 stations with 30 years of record in an Alpine environment in Switzerland. We aim focus only on rainfall events, aiming to address three key questions which complement previous studies:

(a) Is the rate of increase in rainfall extremes with temperature affected by storm type (stratiform or convective) and what is the frequency of occurrence of super-CC rateseffect of combining storm types on the estimated scaling slopes across many stations? For the storm type separation we used a classification of events with lightning data (?) and a convectivity index (?). We also looked at evidence of possible shifts in the stratiform–convective event split in the past 30 years.

(b) Are CC super-CC rates evident when integral storm event properties (e.g. total depth, mean and peak intensity, and duration) are related to air temperature, as opposed to using fixed time resolutions intervals (e.g. daily or hourly) like in most previous studies? It has been cautioned that a fixed temporal resolution (coarse) time interval may not provide an accurate picture of temperature relations (?) . rainfall variability (?) . Most notably, the temporal resolution has a strong impact on event duration, which especially for short heavy rain spells can only be resolved accurately by 10-min and higher resolution data.

(c) Is Are there coherent spatial variability patterns in the rates of increase in event intensity (mean and extreme) with air temperature in a region of complex topography? We complement this question with a preliminary investigation of which other atmospheric variables in addition to ground temperature may be good (better)predictors of precipitation on the ground from radio-sounding dataacross Switzerland? With many 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), Switzerland offers the possibility to investigate the spatial variability in the relations of extreme rainfall to air temperature (e.g. ?) . To address this question we divided the stations into four distinct geo-climatic regions and looked for differences between them.

2 Data and Methods

2.1 Meteorological Data

We used hourly 10-min and 1-hr precipitation, air temperature, relative humidity and lightning strike measurements at 50 and relative humidity measurements at 59 stations of the SwissMetNet network (MeteoSwiss) for the period 1982–2011 (30 yrs) 1981–2011 (31 yrs) and 10-min lightning strike data for the period 1987–2011 (25 yrs). The stations were selected based on adequate record length without missing data, excluding stations at highest altitude altitudes where precipitation measurement is less reliable. The stations ranged from 203 m a.s.l (Magadino) to 2287 m a.s.l. (Goetsch) in altitudeand covered the pre-Alpine as well as Alpine regions. For the purpose of the analysis, the air temperature and relative humidity data were aggregated to mean daily values. . The stations were divided into four geo-climatic regions: Plateau in northern Switzerland ($n = 25$), pre-Alps north of the main Alpine divide ($n = 10$), high Alps ($n = 14$), and Tessin in southern Switzerland ($n = 10$) (Fig. 1).

Precipitation ~~is~~ at SwissMetNet stations was recorded by a heated tipping-bucket raingauge (Lambrecht) with orifice area 200 cm^2 and tip resolution 0.1 mm. The data are quality checked and have been used in previous studies by the authors (**????**). Intensity correction is applied, but correction for wind is not~~(?) . Because we focus on high intensity rain we are of the opinion that~~ . The wind-driven ~~undercatch~~ undercatch is lower for higher intensity rain (**?**) , and we assume that it does not affect the correlations ~~to~~ of extremes with air temperature appreciably. Air temperature is a standard measurement by a ventilated thermometer at 2 m height. Relative humidity is measured by a dew point mirror (Thygan). Lightning strike count is derived from the induced electric charge by ground antennas at the stations. Separation between cloud-to-ground and intra-cloud lightning is not possible. We use close ~~strikes around the station (< 3 km)~~ and distant (< 30 km) strikes as an indication of convective potential of the atmosphere in the vicinity of the station. More information about the lightning strike data can be found in **?**.

~~As supporting data we also used atmospheric radio-soundings by weather balloon at midday (12:00 UTC) from the Payerne station in western Switzerland where we extracted convective available potential energy (CAPE), convective inhibition (CIN), an integrated estimate of the precipitable water in the air column (PW) and upper air temperature at 500 hPa (TAIR) for each sounding on a rainy day for the period 1982–2011. These data were used to check for correlations with precipitation measured on the ground in the vicinity of the station.~~

2.2 Selection of Rainfall Events

Our main unit of analysis in this study is the rainfall event. We defined independent ~~storms with a fixed inter-arrival time $t_i = 3$ hrs following the work of **?** . This separation time is a balance between statistical considerations of dependence between events (e.g. **??**) and the need to limit intra-event gaps and ensure that extreme hourly intensities are indeed related to the actual event itself and mean event intensity is not biased (e.g. **?**) .~~

events as wet periods separated by a continuously dry interval with duration greater than t_i. For each defined event we determined four main properties: total rainfall depth R, event duration d, mean rainfall intensity $I_m = R/d$, and peak (maximum) ~~hourly~~ intensity during the event I_p ~~.~~ at a given temporal resolution. In the identification of events we ignored single-tips, i.e. intervals with 0.1 mm of measured rainfall.

To each event we assigned a mean daily air temperature and relative humidity on the day of the event, or over several days if the event spread over more than one day. Because we are interested in intense rainfall events only and want to avoid snow and mixed rain-snow events~~especially at higher altitudes~~, we limit the analysis to events in the warm season ~~only~~ (April–September) ~~at all stations. To each event we assigned a mean daily air temperature and relative humidity on the day of the event, or over several days if the event spread over more than one day.~~ and with temperature during the events exceeding 4°C. The time used to separate events was chosen as $t_i = 2$ hrs following the work of **?** . This separation time is a balance between statistical considerations of independence between events (e.g. **??**) and the need to limit intra-event gaps and ensure that peak event intensities are indeed related to the actual storm (e.g. **?**) .

~~We subsequently divided the events into several subsets. The first division aimed to capture the distinction between stratiform and convective rain insofar as it is captured by lightning. To this end we took the presence or absence of lightning during the event and not the count as a discriminatory variable. The second division aimed to capture the degree of convectiveness of each event for which we used~~ The temporal resolution has a strong effect on event d and I_p. Event duration is better resolved with 10-min than with 1-hr data, and this effect is particularly important for short duration convective summer events which are often shorter than 1 hr. Peak intensity during the event is also greater at 10-min than 1-hr resolutions because of intra-event intensity fluctuations. In the article we focus mostly on the results with 10-min data but we also present some results with 1-hr data to quantify the effect of temporal resolution.

2.3 Convective-Stratiform Rain

We divide all events in the period 1987–2011 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. Insofar as heavy convective summer thunderstorms are associated with lightning, we consider the presence of lightning as a good first order discriminator between convective and stratiform rain. In the 10-min data we associated events to the convective set if they were preceded by lightning strikes within 30-min of the beginning of rainfall.

The convective-stratiform rain separation by lightning is based on observed associations between intra-cloud and cloud-to-ground lightning and the type and amount of rain (e.g. **?????**) . Other methods exist for the identification of convective rain from ground synoptic observations of clouds, state of weather and/or rain intensity fluctuations, radar observations, and event duration (e.g. **????????**) . We also recognize that embedded convection may also occur in cold fronts outside of the warm season. Despite these limitations, we nevertheless think that the occurrence of lightning is a reasonable discriminator for the presence of convection in the warm season in Switzerland.

For the entire record 1981–2011 we used an additional method to classify events by their convective nature using the convectivity index β of ?, which is defined as the ratio between the rainfall depth that fell with hourly intensities $i_h > I^*$ intensities $i > I^*$ to the total event depth R. We then classified events as non-convective if $\beta = 0$ $\beta < 0.2$, moderately convective if $0 < \beta < 0.8$ $0.2 < \beta < 0.8$ and strongly convective if $\beta > 0.8$ (?).

The threshold intensity I^* is a parameter which needs to be estimated for every station. We use the method of ? which uses the presence of lightning to classify convective events as those where $I_p > I^*$ with a chosen misclassification rate. This means, that the . The threshold I^* is increased until found with an acceptable error α of non-lightning events classified as convective is reached (false positives, Type I error) . This decision is based on the argument that we want to minimize (not remove) the cases where high rain intensities are observed without lightning strikes in the vicinity of a raingauge in our convective subset. In this paper we use a misclassification rate $\alpha = 15\%$. from the period with available lightning data. By choosing the same α for all stations we have an objective way to compare the properties of the events and their relation to temperature across stations. For more details on calibrating I^* see ? .

The assumption behind our event selection is that summer thunderstorms with convective activity are associated with lightning and there is a relation between intra-cloud and cloud-to-ground lightning and the amount of rain (e.g. ?????) . Although other methods exist for the identification of convective rain from ground synoptic observations of clouds, state of weather and/or rain intensity fluctuations, and radar observations (e.g. ???????) we think that the occurrence of lightning is a reasonable discriminator for the presence of convection, especially in the warm season.

between stations. To analyze possible changes in storm type and intensity in the instrumental record the frequency of convective events we applied a non-parametric Mann-Kendall trend test (e.g. ?) to the number of events per year during which the rainfall intensity exceeded the intensity threshold I_p exceeded I^* over the period 1982–2012. These are events that according to our selection procedure exhibit at least a moderate degree of convectivity as measured by the convectivity index of ? 1981–2012 using 10-min data. For more details on calibrating I^* see ? .

2.4 Correlation with Air Temperature

Most previous studies have correlated precipitation intensities with air temperature investigated precipitation intensities at fixed time intervals (resolution).Event-based relations were only studied by ? to our knowledge. In this paper we estimate the correlations of event properties with dailyair temperature , with a special focus on mean event intensity I_m and peak hourly intensity I_p. To obtain the slope, i. e. percent rise in the tested variable with an increase in air temperature, we used exponential regression rather than linear fitting in the semilog domain which is more biased. The fitting procedure itself may indeed be relevant for the slope estimation as has been shown by ? e.g. 10-min, hourly, daily) by binning the data into temperature ranges, the so-called temperature binning (TB) method. In each temperature bin a precipitation intensity quantile is found and the intensity-temperature data pairs are used to search for CC or super-CC scaling rates for different temperature ranges often starting at cold temperatures (e.g. see review in ?) .

In our article we chose not to search for a perceived change in the slope of the intensity-temperature relation at a certain threshold temperature, but rather we find a scaling slope for the entire range of temperatures above 4°C at each station. We do this because we want to avoid the effect of snowfall at low temperatures, and we have stations covering altitudes from 200 to about 2300 m where it is unreasonable to expect a break in slope at the same temperature. We estimated the slope for the different event subsets, by fitting to all events and to selected percentiles estimated from databinned into temperature classes by 2°C. Results are reported here for the entire sample and the 90th percentile to focus on the peculiarities of extreme events.

The relations between precipitation intensity on the ground and radio-sounding data for the Payerne station were explored directly on hourly data scaling slope by the quantile regression (QR) method applied to logarithmically transformed intensity data. We used principle component analysis to estimate the groupings in the different sounding data (CAPE, CIN, PW, TAIR) and multivariate linear and nonlinear regression to estimate their contribution to the observed variance in hourly precipitationintensityThis method does not require binning and is unbiased with respect to sample size (?) . The results of the QR the TB method by exponential regression of intensity-temperature data pairs were compared.

Since we do not use fixed time intervals, we estimate the scaling slopes for quantiles of event properties (R, d, I_m, I_p) and mean air temperature on the day of the event. Event variables have been used in some recent studies (????) and have the advantage of being statistically independent outcomes of the precipitation process at the event scale. We focus in particular on mean and peak event intensity and on the 95th percentile, although we report results for other percentiles as well. I_m reflects the mean atmospheric conditions leading to precipitation, while I_p represents short (10-min or 1-hr) periods of maximum intensity during an event.

3 Results and Discussion

3.1 ~~Effect~~ Analysis of ~~Storm Type~~All Events

Histograms of the estimated ~~regression~~ slopes fitted to ~~the 90th percentile~~ event d, R, I_m and I_p with air temperature for the 95th percentile of all storms regardless of storm type, i.e. ~~, the 10% threshold of the most extreme events for each temperature class, from all stations~~ the 5% largest values in the sample of all events (quantile regression method) are shown in Fig. ~~1 for the four event properties~~2 for 10-min and 1-hr data. There is a clear and consistent negative relation ~~of~~ between event duration d ~~to air temperature also found by ?~~ and air temperature visible in both 10-min and 1-hr data, indicating that shorter storms consistently take place during warmer days. The total event depth R is ~~negatively~~ poorly related to air temperature~~but this relation is not as strong as the previous one and is more variable among stations . When all of the storms are considered, the 90th percentiles of mean~~ , with large variability among stations (see also **?**) .

As expected, the strongest relations to air temperature come from mean and peak event intensity~~I_m and peak hourly intensityI_p are positively related to air temperature with a station mean of 7.4%°~~. The average scaling slopes from all stations substantially exceed the CC rate. For mean event intensity these are 10.7%°C^{-1} for ~~I_m and 5.1%°~~10-min data and 9.5%°C^{-1} for ~~I_p, which are close to the CC rate. However, there is clearly variability among stations. Although scaling rates above 10%°~~1-hr data. For peak event intensity the scaling slopes are 13.0%°C^{-1} ~~are detected at some stations, we do not observe widespread super-CC rates in our dataset like some previous studies have found (e.g. ???) .~~ for 10-min data and 8.9%°C^{-1} for 1-hr data. Although peak event intensity increases with temperature at a significantly higher rate than mean event intensity using 10-min data, this effect is not visible or is even reversed in the hourly data. This indicates the limitations of the coarse hourly resolution in capturing peak intensity fluctuations.

~~How does storm type contribute to the rainfall-temperature slope? The boxplots for all of the events and the different event subsets are shown in Fig. 2 for I_m and Fig. 3~~

3.2 Effect of Storm Type Mixing

One of the key questions here is how storm type contributes to the rainfall intensity-temperature slope. An example of the estimated scaling slopes by the quantile regression and temperature binning methods are shown for ~~I_p and the station mean and standard deviation for~~ the ~~90th percentile are also reported in Table 1. The separation of events into the different storm subsets clearly highlights that events accompanied by lightning and those with the highest convectivity index exhibit the highest rates of increase with air temperature, while less convective and stratiform rain is marginally related to air temperature and only for I_m~~station Wynau (WYN, Plateau region) for all events and subsets with and without lightning (Fig. 3). The scaling slopes for no-lightning and lightning sets are practically identical at 6%°C^{-1}, while when both sets are analyzed together we obtain a rate 10–11%°C^{-1}% at this station by both QR and TB estimation methods.

Analyzing all stations shows that this is in fact a systematic result. In accordance with the findings of **?** and **?** ~~, all events exhibit higher slopes than lightning events only~~ the scaling rates for all events are systematically higher than those of the individual lightning and no-lightning subsets because of the mixing of stratiform events at low temperatures and convective events at high temperatures. This ~~implies that the scaling of~~ is true for both mean (Fig. 4) and peak (Fig. 5) event intensity and for both 10-min and 1-hr resolutions as demonstrated by the bias in the scatter-plots between the slopes obtained for lightning and no-lightning subsets and all events. The bias is most evident for the no-lightning subset, where the rates are substantially lower than those for all events. Importantly, while the convective lightning subsets shows slopes for peak intensity from 10-min data generally constrained in the CC-2CC range for individual stations, mixing events results in several stations having slopes in excess of the 2CC rate. There are practically no stations that exhibit rates greater than 2CC in each individual storm type subset, despite the variability between stations.

The boxplots for all events and the different event subsets are summarized in Fig. 6 for I_m and I_p ~~close to the CC rate for all events is inflated by storm type mixing and smaller rates are observed when only convective (lightning) events are considered (6.3 and 2.7~~for the 95th percentile and the station mean and standard deviation are also reported in Tables 1 and 2. The mean slope for I_m for the no-lightning subset is 6.5%°C^{-1} ~~, respectively) , and rates are even smaller for stratiform (no lightning) events (2.9 and 1.1%°C^{-1}, respectively).~~

~~It follows that, not surprisingly, when the mean intensities of all eventsare analyzed together,~~ which is close to the ~~assumption of fully saturated air contributing to precipitation formation is violated and the rates of increase are generally much below the CC rate(at 94% of the stations) even for the events with the highest convectivity index $\beta > 0.8$ (at 73% of the stations). For extreme events represented by the 90th percentile , the air saturation assumption may be less limiting and the rates are higher, but on the average still around the~~ CC rate, ~~41% of the stations had rates lower than CC~~ the lightning subset slope is 8.9%°C^{-1} which is greater than the CC rate, while for all events ~~and 55% for the events with $\beta > 0.8$ (Fig. 2). When even higher percentiles were analyzed, the proportion of scaling rates higher than CC increased, but super-CC rates were exceeded for the 99th percentile only 6% of the time for all events and 18% in the evens with the highest convectivity . Overall, this supports the fact that super-CC rates are rare even~~ the resulting slope is 10.7%°C^{-1}. For peak event intensity the rates are slightly higher but the same amplification effect of mixing event types applies. The convective lightning subset slope for 10-min I_p is 9.3%°C^{-1}. Analyzing the different subsets based on the convectivity index β also shows that only the most convective range has a strong relation to air temperature.

The rates for convective events which finds support in climate model simulations (??) . in our dataset are mostly in the CC-2CC range for 10-min data for both mean and peak event intensities, and slightly lower if a coarser 1-hr resolution was used (Fig. 6). The rates are in agreement with the steady-state entraining plume model of **?** who showed that the scaling rate in convective systems can be about 10%°C^{-1}, composed of 7%°C^{-1} due to thermodynamic effects and 3%°C^{-1} related to dynamic effects (vertical updraft velocity). Considering additional effects of varying vertical velocity on lateral moisture flux can lead to scaling rates between CC and 2CC for convective storms (**?**) , which is supported by our data.

Interestingly, I_m increases at a considerably stronger rate than I_p. When all events are considered, peak hourly intensity I_p is practically independent of air temperature, while for extreme events there is a positive relation but less strong than for I_m for all event subsets, and can also be negative The results using both slope estimation methods for the 50th, 90th, 95th, 99th percentiles show that overall the QR and TB methods provide very similar slope estimates, with a higher variability between stations in the TB method (Fig. 3). We argue that this is because for extreme storms, the mean event intensity better reflects the water vapor content of the atmosphere leading to precipitation including the supply of moisture than 7). Any differences between the QR and TB methods are smaller than the differences between the lightning and no-lightning subsets. The sensitivity of the results to the single maximal hourly rainfall pulse. The latter is likely more affected by local conditions and cloud and precipitation physics beyond CC scaling10-min data is reflected in higher overall slopes than for 1-hr data due to the higher accuracy in determining storm duration and high peak 10-min intensities (see also **?**) . However also this effect is smaller than the difference between lightning and no-lightning subsets. Even for the highest analyzed quantile (99th percentile) it is clear that the convective set of events provides slopes in the CC-2CC range and we do not observe widespread 2CC rates.

3.3 Regional Variability

The results indicate a large variability in precipitation-temperature relations across Switzerland. A regional division of stations and the regression slope for the 90th The scaling slopes for the 95th percentile of I_m for all events is lightning and no-lightning events are shown in Fig. 4 and the mean slopes are listed for all four regions in Table 1. 8 and summarized in Tables 1 and 2 for the four studied regions. Overall, the lowest rates in I_m and I_p are found in the Alpine region and in Tessin south of the main Alpine divide (6.1–6.3%°C^{-1} on the average)Plateau and Alpine stations, while the rates highest rates are on the average in the pre-Alps and in the plateau and especially in the prealpine area are much greater (∼8.3%°C^{-1} on the average)Tessin south of the main Alpine divide. This suggests a regional effect on precipitation intensity strongly influenced not only by local surface-atmosphere feedbacks temperature but also by local and general circulation patternsand , advection of moisture conditioned by topography, and local surface-atmosphere feedbacks (see also **?**) .

It is notable that Some of the lowest rates of precipitation increase with air temperature are observed in the main Alpine valleys (Fig.4e.g. Rhone Valley), where probably both lower temperatures and heating of the atmosphere common inversions combine with complex orographically driven patterns of moisture flow, condensation, and rainfall formation (e.g. **?**). Similarly, high rates in the pre-Alps may be conditioned by moisture convergence and windward ascent leading to enhanced orographic effects on precipitation in this area (e.g. **?**) . Outliers are also evident, like the station Cimetta (CIM) in Tessin with very high scaling rates for non-lightning events. This is a very exposed station on a mountain hillslope where we have concerns about the quality and representativeness of the rainfall and lightning measurements.

The issue of moisture availability has been raised as a possible limitation on the rates of precipitation increase and can be seen by plotting relative humidity as a function of air temperature (e.g. **?**) or analyzing dew point temperature (e.g. **?**) at high temperatures (e.g. **????**) . The relation of mean daily relative humidity to air temperature for nine stations in our dataset representative of the different regions shows that there are indeed possible limitations of moisture availability at high temperatures ($>$ 20°C) in Alpine climates (Fig. 5higher temperatures when relative humidity on rainy days drops (Fig. 9). Stations in the mountain valleys (e.g. Davos, Zermatt) are typically moisture limited at a lower temperature temperatures which suggests that there could be an orographic shielding of inner Alpine valleys, with the moisture content of the warmer air being depleted before arriving to these valleys. These are sites where I_m increases with temperature much less than for the other stations (Fig. 4).

3.4 Relation to Atmospheric Variables

The assumption of available moisture to saturate the air mass is key to the expectation that precipitation intensity should scale with air temperature at (or close to) CC rates. It has been suggested that ground air temperature may not be a sufficient measure of moisture availability, or that more complex relations with temperature and humidity profile of the troposphere exist (**??**) . The question is if temperature higher up in the atmosphere or other atmospheric variables which capture properties of the vertical energy and humidity profile may be even better predictors of ground precipitationSimilar moisture limitations have been described on a larger continental scale in the US and Canada (**??**) .

The analysis of radio-sounding data and ground precipitation measured at Payerne (and stations in the immediate vicinity) showed that this is indeed not the case. Principle component analysis grouped the variables in two major classes. Precipitable water (PW) and upper air temperature at 500 hPa (TAIR) together with temperature on the ground had the strongest explanatory power, while CAPE and CIN had a very weak relation to precipitation. Others have also found atmospheric variables such as CAPE and CIN to be poor predictors of precipitation on the ground in different climates (e.g. **?????**) . We found that ground air temperature was in fact the single best predictor of precipitation intensity for a range of quantiles followed by upper air temperature, which suggests that results gleaned from previous studies using ground temperature are indeed robust.

3.4 Evidence of Change in Convective Events

The presented positive relations of precipitation intensity to with temperature across Switzerland, regardless of the actual rate of increase, are suggesting that precipitation should exhibit some signal of change in a warming climate. Previous studies have found that precipitation (especially winter precipitation) and air temperature have increased in the last century in the wider European Alpine region and in Switzerland (e.g. **???**). However, changes in extreme rainfall from daily precipitation records have been rather small and spatially inconsistent (e.g. **??**).

The Mann-Kendall trend test for The interesting question is if there have been changes in the frequency and intensity of convective events, since these produce the highest rainfall intensities. In this dataset, the proportion of convective events, i.e. those accompanied by lightning, is strongly dependent on air temperature and varies between 30% at low temperatures to more than 80% at temperatures above 25°C (Fig. 10).

The change in the frequency of convective events in our study quantified by upward or downward trends in the number of events per year during which the precipitation peak 10-min intensity exceeded the threshold I^* suggests shows that 90% of the stations exhibited upward trendsin this metric, and 30% were statistically significant in the period 1981–2011 (Fig. 6). In this analysis we used the full set of 62 stations and higher resolution 10-min rainfall data to identify storms and classify them following the study of (**?**) . 11). Statistically significant trends (Mann-Kendall test) were distributed across the country, suggesting that a widespread shift towards more convective storms in a warming climate in this part of Europe in the April–September period over the last 30 years may have taken place (**?**) . In the US changes in convective events connected to an increase in the frequency of lightning strikes have been projected under a future warmer climate (e.g. **?**) . It will be important to assess if the observed changes in convective events are a signal of climate change in the Alpine area as well. Further evidence of these trends and their sensitivity to the methods of extracting convective storms will be explored in more detail in future research.

4 Conclusions

This study complements previous data-based investigations of extreme hourly precipitation increases with air temperature with an analysis of 30 years of hourly records from 50 10-min and 1-hr records from 59 stations in an area with high relief and complex topography. Scaling of extreme precipitation rainfall on an event basis is analyzed to find evidence for CC (7%°C^{-1}) or super-CC scaling rates. The novelty in our work compared to previous studies, with the exception of **?** , is that we used storm event properties, rather than fixed time intervalsin our analysis, and we separated events into stratiform and convective sets based on lightningand quantified their degree of convectivity. Our main conclusions are:

(1) Mean Station mean event intensity I_m and peak hourly 10-min intensity I_p of all the extreme events extremes increased with air temperature at a station mean scaling rate of 7.4%°C^{-1} for I_m and 5.1%°C^{-1} for I_p which is close to the CC rate. These are rates which are exaggerated super-CC rates. However, these rates are amplified by the mixing of storm types as already discussed by **?**. Events accompanied by lightning (convective events) exhibit significantly consistently higher rates of increase with air temperature than stratiform rainevents, but both storm types have lower rates than when all of the events are combined. Although individual scaling rates greater than 10%°C^{-1} are observed for certain stations, super-CC rates in our dataset Rates exceeding 2CC observed in some previous studies are an exception in our dataset, even for the 90th and higher percentiles of I_m and I_p99th percentiles in convective storms.

(2) The large spatial variability in precipitation-temperature relations across Switzerland, especially the low scaling rates in deep Alpine valleys and high rates in the prealpspre-Alps, suggests that precipitation-temperature relations are influenced not only by local surface-atmospheric feedbacks temperature itself but also by general circulation patterns and local advection of moisture conditioned by topography. We demonstrate on selected some representative stations that there are possible limitations of moisture availability at high temperaturesin Alpine climates. Stations located in inner Alpine valley exhibits moisture limitation at

~~a lower temperature, suggesting that topographic shielding can be an important factor in smoothing the effect of air warming on extreme precipitation.~~ .

(3) The ~~analysis of radio-sounding data and ground precipitation at Payerne showed that temperature measured at the ground was the single best predictor of precipitation intensity for a range of quantiles followed by integrated precipitable water and upper air temperature at 500 hPa. Variables capturing the energetic state of the atmosphere, such as CAPE and CIN, had very low predictive power. This suggests that results gleaned from previous studies using ground temperature are indeed robust.~~

~~(4) Changes in the~~ number of convective events as identified by lightning across Switzerland in the past 30 years ~~, insofar they are identified by our classification which selects convective events as those during which precipitation intensity at a given resolution exceeds a threshold $i > I^*$, are an important feature in a warming climate~~have changed. We found that the majority of the stations exhibited upward trends in the number of convective events in the period 1981–2011 (30% were statistically significant). ~~Our results suggest that this significant~~ The shift towards more convective storms at higher temperatures may as a consequence lead to ~~stronger rainstorms and therefore~~ higher risk connected with ~~those events~~short-duration extreme rainfall.

Overall, our main finding is that ~~super-CC~~ 2CC rates of increase in rainfall with temperature ~~($\sim$14%°C^{-1})~~ reported by others ~~(e.g. ?????) ,~~ (e.g. **?????**) are rare and rather an exception ~~than the norm~~in our dataset, even for ~~extreme~~ convective rainfall. ~~We also demonstrate~~ Mixing of storm types has an important impact on the scaling rates. While increases in convective (lightning) events are between 8–9%°C^{-1} and in stratiform (no-lightning) events between 6–7%°C^{-1} for mean and peak 10-min intensity, the mixing of events resulted in scaling rates between 11–13%°C^{-1} on the average. Which scaling rates apply to extreme precipitation in a warmer future depends on the air temperature at which these events will occur and on the relative proportion of storm types at that temperature.

We also observe large variability in the ~~rates in space that~~ scaling rates between stations, which are likely connected with ~~local moisture availability and~~ atmospheric moisture supply dynamics combined with topographic effects. Uncertainties on the estimate of the slopes from ~~scattered~~ data and the inherent stochasticity of the rainfall process can be additional causes of ~~the variabilityin the results~~variability. However, we ~~argue that the sub-CC scaling and more~~ think that the storm type effects and heterogenous patterns in extreme ~~precipitation with temperature observed in Switzerland~~ rainfall intensity-temperature relations are robust results ~~and can be related to the complex orography and relatively large distance from the major source of water vapor (oceans). A possible hypothesis, to be explored in future studies, is a decreasing gradient of precipitation scaling with temperature as the distance from the moisture source increases geographically or because of topographic blocking~~indicative of the complex topography and atmospheric moisture supply patterns in Switzerland and possibly other regions.

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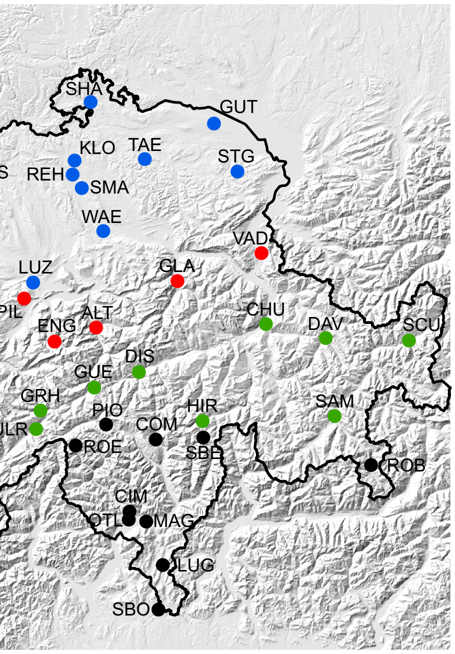


Figure 1. ~~Histograms~~ Map of the ~~regression slopes fitted to~~ 59 analyzed stations in Switzerland divided into 4 regions: Plateau, pre-Alps, Alps and Tessin. The labels list station codes. The Tessin region represents all stations that are in valleys facing south of the ~~90th percentiles~~ main Alpine divide.

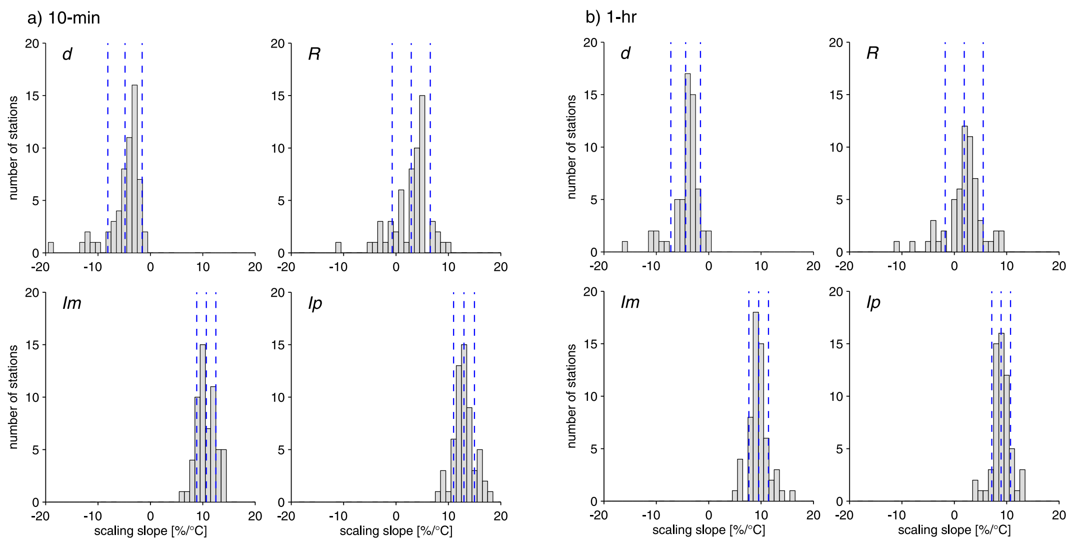


Figure 2. Histograms of the ~~event data for all stations~~ scaling slopes in %~~/100~~°C^{-1} ~~. Event~~ fitted to the 95th percentiles of event duration d~~(top left)~~, total storm depth R~~(top right)~~, mean intensity I_m ~~(bottom left)~~ and peak intensity I_p ~~(bottom right~~for 59 stations with the quantile regression method. Data are shown for a) 10-min and b) 1-hr resolutions. Vertical dashed lines indicate the mean $\pm$ 1 standard deviation. The same figure for the temperature binning method is the Supplementary materials.

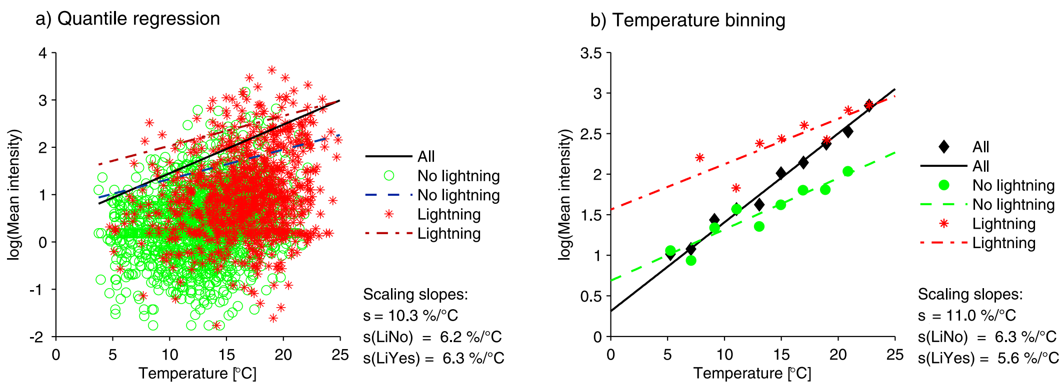


Figure 3. ~~Boxplots showing~~ Example of the ~~distributions~~ estimates of ~~slope magnitude~~ scaling slopes by a) the quantile regression method and b) the temperature binning method for the station Wynau. Slopes for no-lightning (green, s(LiNo)) and lightning (red, s(LiYes)) events as well as all events together (s) are shown and their magnitudes in $\%{}^{\circ}\mathrm{C}^{-1}$ are reported.

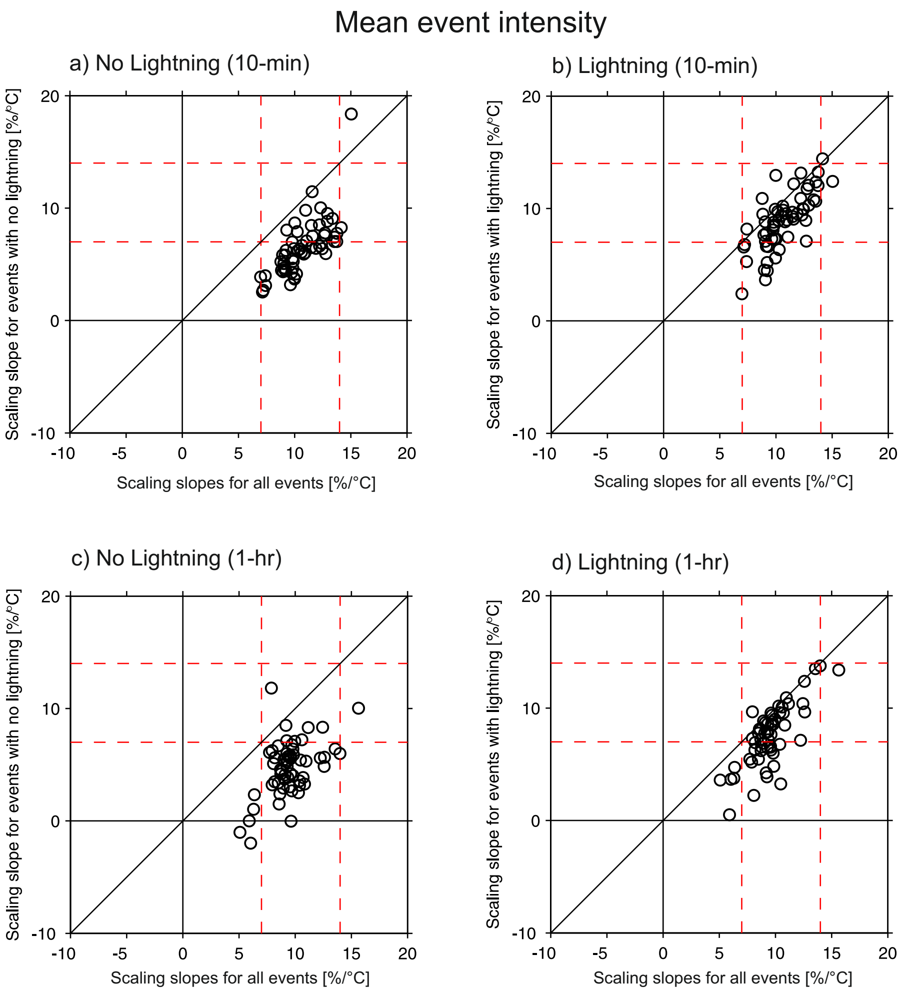


Figure 4. Scatterplots of station-derived estimates of scaling slopes for mean event intensity I_m relation to temperature in different subgroups: using lightning and no-lightning events versus all events , three convectivity levels, at the a-b) 10-min and events with and without lightning for c-d) 1-hr resolution using the quantile regression method (a95th percentile). Red dashed lines indicate the entire sample, CC rate (7%$^\circ$C^{-1}) and 2CC rate (b14%$^\circ$C^{-1})the 90th percentile of the binned data. The red line shows same figure for the median, temperature binning method is the upper Supplementary materials.

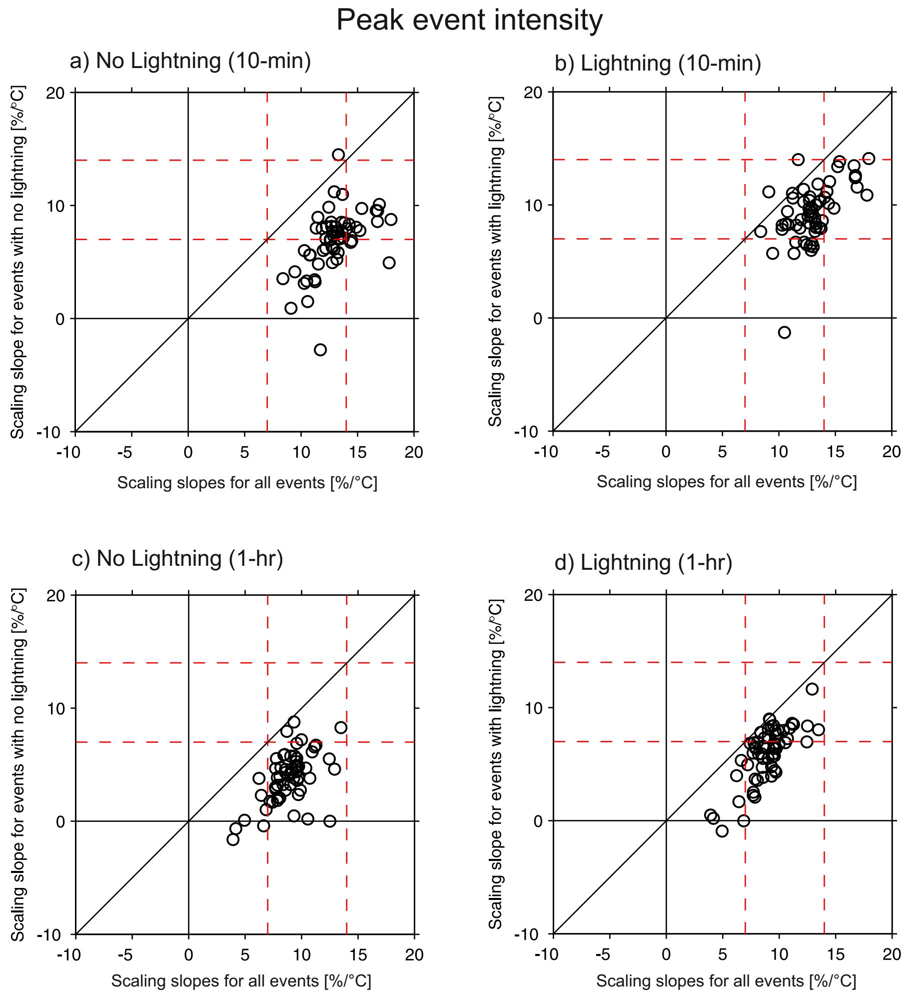
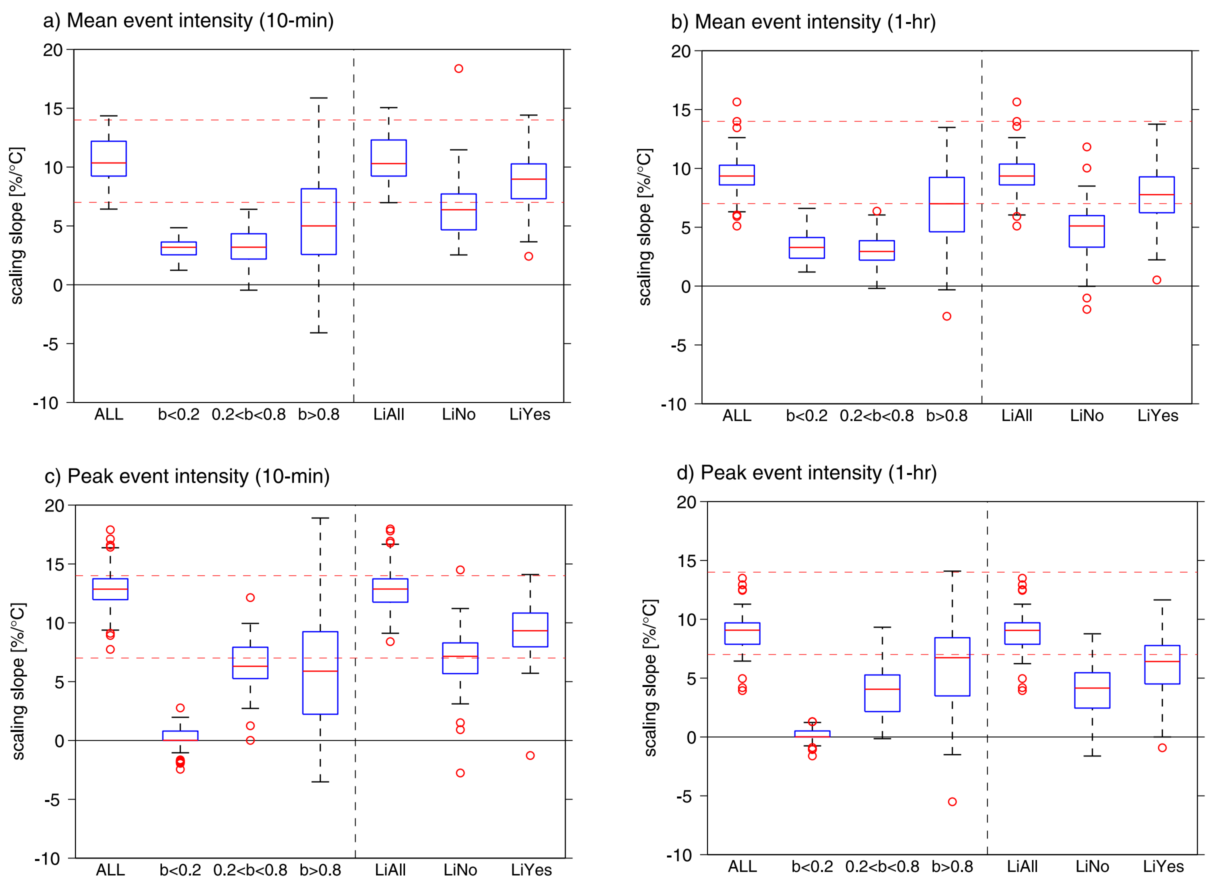


Figure 5. Scatterplots of station-derived estimates of scaling slopes for peak event intensity I_p in lightning and ~~lower bound are~~ no-lightning events versus all events at the ~~25th~~ a-b) 10-min and ~~75th percentiles~~ c-d) 1-hr resolution using the quantile regression method (~~25P and 75P~~95th percentile). ~~The whiskers are calculated as w_{top}=75P+1.5~~Red dashed lines indicate the CC rate (~~75P-25P~~7%°C^{-1}) ~~, w_{bot}=25P-1.5~~and 2CC rate (~~75P-25P~~14%°C^{-1}). ~~Outliers are plotted as red crosses~~The same figure for the temperature binning method is the Supplementary materials.

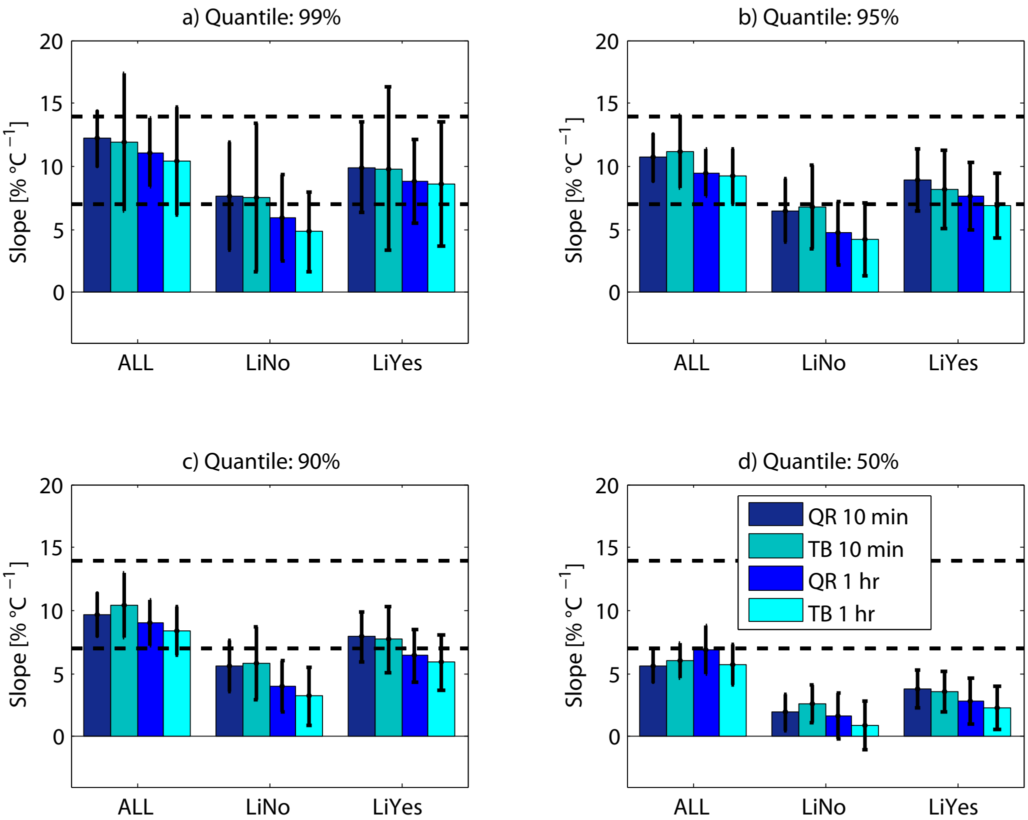


a) Analyzed station locations in 4 regions of Switzerland following roughly The horizontal dashed line shows the division of ? . b) Regression slopes fitted to the 90th percentiles of the event mean precipitation I_m including all events in 1CC rate (7%°C^{-1}) and 2CC rate (see Table 114%°C^{-1}). The same figure for the temperature binning method is the Supplementary materials.

a) Analyzed station locations in 4 regions of Switzerland following roughly The horizontal dashed line shows the division of ? . b) Regression slopes fitted to the 90th percentiles of the event mean precipitation I_m including all events in 1CC rate (7%°C^{-1}) and 2CC rate (see Table 114%°C^{-1}). The same figure for the temperature binning method is the Supplementary materials.

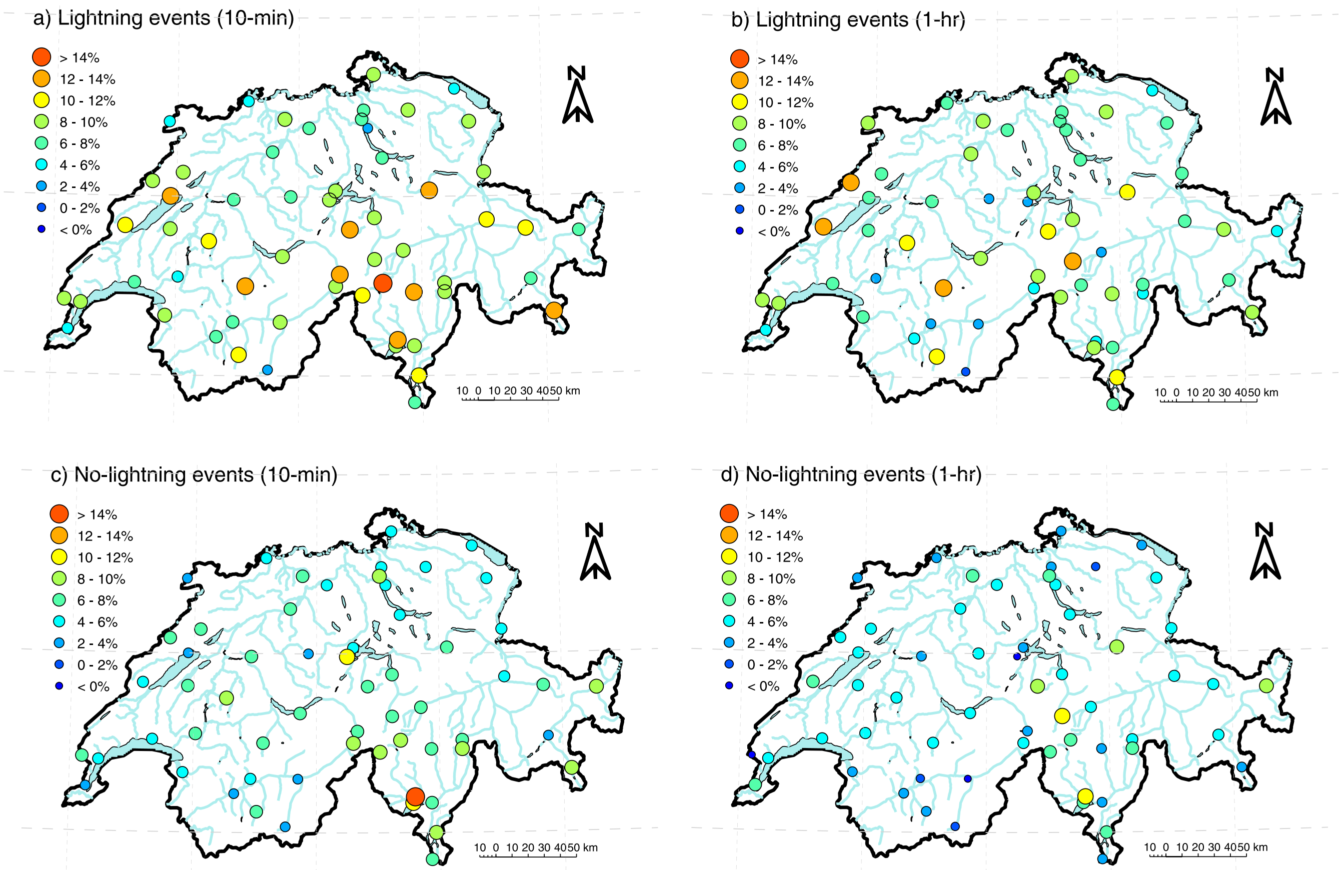
Figure 6. Boxplots showing the distributions of scaling slope magnitude for mean event intensity I_m at the a) 10-min scale and b) 1-hr scale; and for peak event intensity I_p relation to temperature in at the c) 10-min scale and d) 1-hr scale. The slopes were estimated using the quantile regression method for the 95th percentile. The data are organized into different subgroups (from left): using all events (1981–2011, ALL), three convectivity levels, and ; all events with and without lightning for data (a1987–2011, LiAll)the entire sample, and the division into no lightning (bLiNo) the 90th percentile of the binned dataand lightning (LiYes) subsets. The red line shows the median, the upper and lower bound are the 25th and 75th percentiles (25P and 75P). The whiskers are calculated as w_{top}=75P+±1.5(75P-25P), w_{bot}=25P-1.5(75P-25P). Outliers are plotted as red crossescircles.

a) Analyzed station locations in 4 regions of Switzerland following roughly The horizontal dashed line shows the division of ? . b) Regression slopes fitted to the 90th percentiles of the event mean precipitation I_m including all events in 1CC rate (7%°C^{-1}) and 2CC rate (see Table 114%°C^{-1}). The same figure for the temperature binning method is the Supplementary materials.



~~Mean daily relative humidity plotted against mean daily air temperature for wet (precipitation larger than 1 mm.day^{-1}) and dry days at nine representative stations in the four regions in Fig. 4.~~

Figure 7. The mean and ± 1 standard deviation of the scaling slope estimates for mean event intensity I_m for all events (ALL) consisting of lightning (LiYes) and no-lightning (LiNo) subsets for the quantile regression method (QR) and the temperature binning method (TB) and both studied resolutions 10-min and 1-hr. Results are reported for (a) 99th; (b) 95th; (c) 90th; and (d) 50th percentile.



~~Trends in the number of events per year that exceeded the threshold I^* over the period 1981–2012 estimated by the non-parametric Mann-Kendall trend test. Upward trends are blue, downward trends are red, statistically significant trends at the $\alpha = 10\%$ significance level have filled markers.~~

Figure 8. Spatial maps of scaling slopes for lightning events at the a) 10-min and b) 1-hr resolution; and no-lightning events at the c) 10-min and d) 1-hr resolution for the 95th percentile estimated with the quantile regression method. The color and size of the legend markers indicate the scaling slope magnitude in $\%°C^{-1}$. The same figure for the temperature binning method is the Supplementary materials.

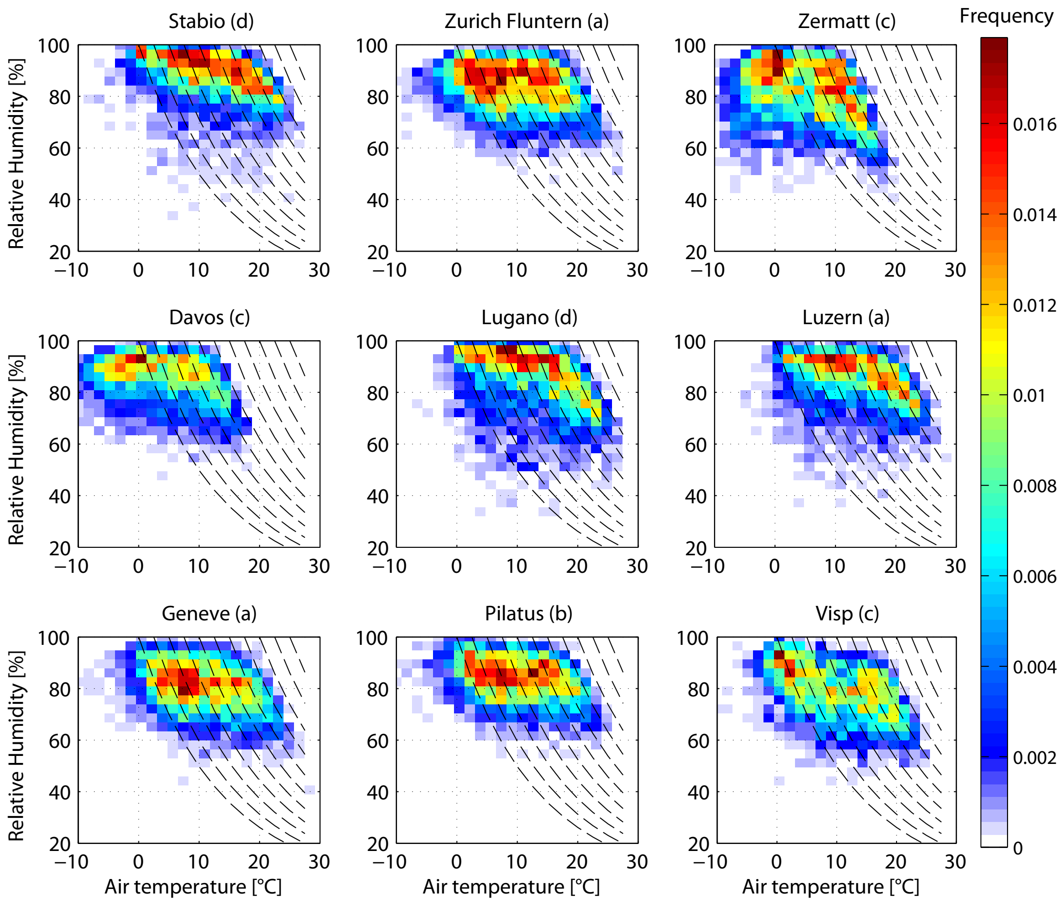


Figure 9. Relative frequency of mean daily relative humidity as a function of mean daily air temperature for wet days (precipitation larger than 1 mm day^{-1}) at nine representative stations in the four regions in our dataset: (a) Plateau, (b) pre-Alps, (c) Alps, (d) Tessin. Constant vapor pressure relations are shown with dashed lines.

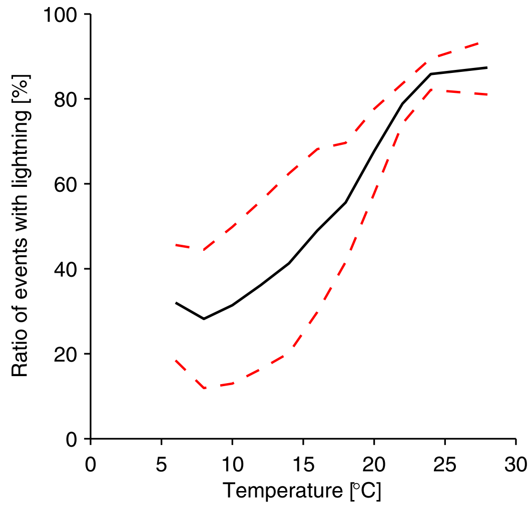


Figure 10. The average percentage of lightning events in the set of all events as a function of air temperature for the 59 studied stations. Red lines give bounds ± 1 standard deviation.

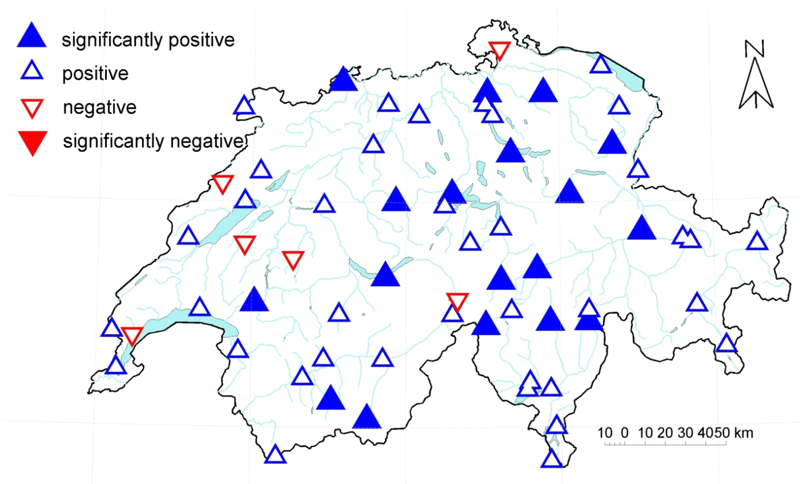


Figure 11. Trends in the number of events per year in which the peak 10-min intensity $I_p > I^*$ over the period 1981–2011 estimated by the non-parametric Mann-Kendall trend test. Upward trends are blue, downward trends are red, statistically significant trends at the $\alpha = 10\%$ significance level have filled markers.

Table 1. Expected values of the regression slopes in $\%^{\circ}C^{-1}$ fitted to the ~~90th~~ 95th percentiles ~~of binned storm data~~ by quantile regression ± 1 standard deviation. Slopes are reported for mean I_m ~~and peak I_p storm~~ event intensity for ~~different regions~~10-min and 1-hr time resolutions for all events, ~~convectivity index β~~no lightning events, lightning events, and storms grouped by ~~lightning~~the convectivity index β.

I_m (10-min)	all events	~~β=0 0< β <0.8 β >0.8~~ no lightning	lightning	$\beta < 0.2$	$0.2 < \beta <$
All stations ($n = 59$)	~~7.4~~ 10.7 ± ~~2.8~~ 1.9	6.5 ± 2.5	8.9 ± 2.5	3.1 ± 0.9	3.2 ± 1.5
Plateau ($n = 25$)	10.1 ± 1.3	~~5.8~~ 5.5 ± 1.4	7.9 ± 2.2	2.8 ± 0.9	~~7.0~~ 2.7 ± ~~5.7~~
pre-Alps ($n = 10$)	~~6.3~~ 11.2 ± 1.8	7.2 ± 2.0	9.8 ± 2.3	3.3 ± 0.9	3.3 ± 1.8
~~0.5exPlateau~~ Alps ($n = 14$)	~~8.3~~ 9.9 ± ~~3.3~~ 2.3	~~2.7~~ 5.7 ± ~~0.8~~ 2.1	~~6.9~~ 8.6 ± 2.6	~~7.5~~ 3.4 ± ~~4.1~~ 0.8	~~2.7~~ 3.2 ± ~~1.6~~
~~0.5exPrealps~~ Tessin ($n = 10$)	~~8.3~~ 12.8 ± ~~1.5~~ 1.2	~~3.5~~ 9.4 ± ~~1.0~~ 3.4	~~6.2~~ 10.9 ± ~~3.1~~ 2.2	~~5.8~~ 3.4 ± ~~3.0~~ 0.9	~~3.9~~ 4.1 ± ~~1.9~~
~~0.5exAlps~~	~~6.1~~				
I_m (1-hr)	all events	no lightning	lightning	$\beta < 0.2$	$0.2 < \beta <$
All stations ($n = 59$)	9.5 ± ~~2.4~~ 1.9	~~3.7~~ 4.7 ± ~~1.7~~ 2.5	~~3.7~~ 7.6 ± ~~2.4~~ 2.7	~~7.3~~ 3.3 ± ~~9.6~~ 1.2	3.0 ± ~~1.7~~ 1
~~0.5exTicino~~ Plateau ($n = 25$)	~~6.3~~ 9.4 ± 1.3	4.4 ± 1.7	7.8 ± 2.1	2.7 ± 0.8	3.4 ± 1.3
pre-Alps ($n = 10$)	10.3 ± 2.1	5.0 ± 2.9	8.5 ± ~~1.6~~ 3.2	~~6.1~~ 3.5 ± ~~2.2~~ 1.0	~~6.3~~ 3.0 ± ~~2.5~~
Alps ($n = 14$)	~~5.9~~ 9.3 ± 2.9	4.1 ± 3.1	6.2 ± 3.5	3.9 ± 1.3	2.4 ± 1.2
Tessin ($n = 10$)	9.4 ± 1.0	5.9 ± 2.7	8.1 ± 1.7	3.9 ± 1.3	3.1 ± 1.5

Table 2. Expected values of the regression slopes in $\%^{\circ}C^{-1}$ fitted to the 95th percentiles by quantile regression ± 1 standard deviation. Slopes are reported for peak I_p event intensity for 10-min and 1-hr time resolutions for all events, no lightning events, lightning events, and storms grouped by the convectivity index β.

I_p (10-min)	all events	~~β=0 0< β <0.8 β >0.8~~ no lightning	lightning	$\beta < 0.2$	$0.2 <$
All stations ($n = 59$)	~~5.1~~ 13.0 ± ~~2.1~~ 2.0	~~0.6~~ 6.9 ± ~~0.9~~ 2.7	~~2.5~~ 9.3 ± ~~2.3~~ 2.6	~~3.3~~ 0.1 ± ~~5.0~~ 1.0	~~1.1~~ 6.4
~~0.5exPlateau~~ Plateau ($n = 25$)	~~5.7~~ 12.6 ± ~~2.0~~ 1.0	~~0.5~~ 7.1 ± ~~0.7~~ 1.5	8.4 ± 1.4	0.6 ± 0.6	6.0
pre-Alps ($n = 10$)	13.7 ± ~~2.4~~ 2.6	~~4.0~~ 7.6 ± ~~4.2~~ 2.1	11.0 ± 2.6	0.5 ± 1.1	6.6 ±
Alps ($n = 14$)	12.0 ± 2.6	4.4 ± 3.3	9.2 ± 3.5	0.1 ± 0.3	6.6
~~0.5exPrealps~~ Tessin ($n = 10$)	~~5.6~~ 14.4 ± ~~1.2~~ 1.4 ~~2.0~~	~~0.9~~ 9.0 ± 2.3	10.0 ± 2.7	-1.4 ± 0.8	~~2.8~~ 5.6
I_p (1-hr)	all events	no lightning	lightning	$\beta < 0.2$	$0.2 <$
All stations ($n = 59$)	8.9 ± 1.8	3.9 ± 2.3	5.9 ± 2.5	~~3.5~~ 0.1 ± 0.6	3.8 ± 2.
Plateau ($n = 25$)	~~1.0~~ 9.1 ± 0.9	~~0.8~~ 4.6 ± ~~1.4~~ 1.5	~~5.5~~ 6.7 ± ~~4.4~~ 1.3	0.1 ± ~~1.5~~ 0.4	~~1.3~~ 4.7 ± ~~5.9~~
pre-Alps ($n = 10$)	~~-0.5~~ 9.5 ± ~~0.8~~ 1.9	5.3 ± 2.1	7.0 ± ~~2.0~~ 3.1	0.4 ± 0.6	4.7
Alps ($n = 14$)	~~-0.2~~ 8.2 ± ~~0.9~~ 3.1	2.2 ± ~~2.2~~ 2.8	3.7 ± 3.0	0.5 ± 0.5	1.8
~~1ex~~ Tessin ($n = 10$)	8.7 ± 1.2	3.1 ± 1.5	5.8 ± 1.5	-0.7 ± 0.6	3.7