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Little evidence for 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 water vapor holding capacity of the air at roughly 7 % °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 yr of hourly data from 50 stations in an Alpine environment. The analysis is conducted on storm events rather than fixed time resolutions, and divided into event subsets based on concurrent lightning strikes indicating the presence of convection. The average rates of increase in mean event intensity (7.4 % °C^{-1}) and peak hourly intensity (5.1 % °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 (convective events) exhibit significantly higher rates of increase than stratiform rain. Mixing of the two storm types exaggerates the relations to air temperature. The large spatial variability in scaling rates across Switzerland suggests that both local (orographic) and regional effects limit moisture availability and supply in Alpine environments especially in mountain valleys. A trend analysis shows that our estimate of the number of convective events across Switzerland has steadily increased in the last 30 yr. This significant shift towards more convective storms in a warming climate may as a consequence lead to stronger storm intensities and therefore higher risk connected with those events.

1 Introduction

The rise in the water vapor holding capacity of the air at roughly 7 % °C^{-1}, the so-called Clausius–Clapeyron (CC) rate, is the rate at which precipitable water increases under fully saturated conditions with 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 % °C^{-1} (Schneider et al., 2010; Roderick et al., 2014), changes in extreme precipitation on the ground have been postulated to increase at the CC rate, or higher, if local moisture convergence takes place (Trenberth, 1999; Trenberth et al., 2003). Simulations of daily extreme precipitation by climate models have shown different sensitivities globally to air temperature, with generally higher scaling rates in the tropics than the extra-tropics (e.g. Pall et al., 2007; O'Gorman and Schneider, 2009a, b; O'Gorman, 2012). These results were complemented by satellite observations for high daily percentiles (e.g. Allan and Soden, 2008) 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. Berg et al., 2009; Utsumi et al., 2011).

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 it. Data demonstrations started with the De Bilt dataset where Lenderink and van Meijgaard (2008) found that a CC rate of increase in extreme hourly intensities accelerated to a super-CC rate of approximately 14 % $^\circ\mathrm{C}^{-1}$ for temperatures above 12 °C. The super-CC relation was explained by a positive feedback between water vapor and the dynamics of precipitation formation in convective clouds (Lenderink and van Meijgaard, 2009). A super-CC rate was subsequently found in other studies using hourly and higher resolution data where it was also argued that at very high temperatures the relation between precipitation intensity and temperature may become negative due to moisture supply limitations (e.g. Hardwick Jones et al., 2010; Lenderink et al., 2011).

Available observational evidence to-date suggests that precipitation–temperature scaling rates vary from station to station, are time resolution dependent, and that super-CC scaling is not found everywhere (e.g. Haerter et al., 2010; Hardwick Jones et al., 2010; Shaw et al., 2011; Mishra et al., 2012). In fact, 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 (Haerter and Berg, 2009;

Berg and Haerter, 2013). Berg et al. (2013) 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.

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 stations with 30 yr of record in an Alpine environment in Switzerland. We aim to address three key questions which complement previous studies: (a) is the rate of increase affected by storm type (stratiform or convective) and what is the frequency of occurrence of super-CC rates? For the storm type separation we used a classification of events with lightning data (Gaál et al., 2014) and a convectivity index (Llasat, 2001). We also looked at evidence of possible shifts in the stratiform–convective event split in the past 30 yr. (b) Are CC rates evident when integral storm event properties (e.g. total depth, mean and peak intensity, duration) are related to air temperature, as opposed to using fixed time resolutions (e.g. daily or hourly) like in most previous studies? It has been cautioned that a fixed temporal resolution may not provide an accurate picture of temperature relations (Haerter et al., 2010). (c) Is there coherent spatial variability 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 data.

2 Data and methods

2.1 Meteorological data

We used hourly precipitation, air temperature, relative humidity and lightning strike measurements at 50 stations of the SwissMetNet network (MeteoSwiss) for the period 1982–2011 (30 yr). The stations were selected based on adequate record

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length without missing data, excluding stations at highest altitude where precipitation measurement is less reliable. The stations ranged from 203 m a.s.l. (Magadino) to 2287 m a.s.l. (Goetsch) in altitude and 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.

Precipitation is 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 (Molnar and Burlando, 2008; Paschalis et al., 2012, 2013, 2014). Intensity correction is applied, but correction for wind is not (Chvila et al., 2005). Because we focus on high intensity rain we are of the opinion that wind-driven undercatch does not affect the correlations to 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) as an indication of convective potential of the atmosphere. More information about the lightning strike data can be found in Gaál et al. (2014).

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 $t_\mathrm{i} = 3$ h following the work of Gaál et al. (2014). This separation time is a balance between statistical considerations of dependence between events (e.g. Grace and Eagleson, 1967; Restrepo-Posada and Eagleson, 1982) 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. Dunkerley, 2010).

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. Because we are interested in intense rainfall events only and want to avoid 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.

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 convectivity index β of Llasat (2001) which is defined as the ratio between the rainfall depth that fell with hourly intensities $i_h > I^*$ to the total event depth R. We then classified events as non-convective if $\beta = 0$, moderately convective if $0 < \beta < 0.8$ and strongly convective if $\beta > 0.8$ (Llasat, 2001).

The threshold intensity I^* is a parameter which needs to be estimated for every station. We use the method of Gaál et al. (2014) 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 threshold I^* is increased until an acceptable error 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 $\alpha = 15\,\%$. By choosing

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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 Gaál et al. (2014).

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. Tapia et al., 1998; Petersen and Rutledge, 1998; Price and Federmesser, 2006; Grungle and Krider, 2006; Yair et al., 2010). 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. Pešice et al., 2003; Lang et al., 2003; Rigo and Llasat, 2004; Llasat et al., 2005, 2007; Berg et al., 2013; Rulfová and Kyselý, 2013) we think that the occurrence of lightning is a reasonable discriminator for the presence of convection, especially in the warm season.

To analyze possible changes in storm type and intensity in the instrumental record we applied a non-parametric Mann–Kendall trend test (e.g. Fatichi et al., 2009) to the number of events per year during which the rainfall intensity exceeded the intensity threshold 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 Llasat (2001).

2.3 Correlation with air temperature

Most previous studies have correlated precipitation intensities with air temperature at fixed time intervals (resolution). Event-based relations were only studied by Haerter et al. (2010) to our knowledge. In this article we estimate the correlations of event properties with daily air 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 Wasko and Sharma

(2014). We estimated the slope for the different event subsets, by fitting to all events and to selected percentiles estimated from data binned 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. 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 precipitation intensity.

3 Results and discussion

3.1 Effect of storm type

Histograms of the estimated regression slopes fitted to the 90th percentile, i.e., the 10 % threshold of the most extreme events for each temperature class, from all stations are shown in Fig. 1 for the four event properties. There is a clear and consistent negative relation of event duration d to air temperature also found by Haerter et al. (2010), indicating that shorter storms take place during warmer days. The total event depth R is negatively 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 event intensity I_m and peak hourly intensity I_p are positively related to air temperature with a station mean of 7.4 $\%\,^{\circ}\mathrm{C}^{-1}$ for I_m and 5.1 $\%\,^{\circ}\mathrm{C}^{-1}$ for I_p, which are close to the CC rate. However, there is clearly variability among stations. Although scaling rates above 10 $\%\,^{\circ}\mathrm{C}^{-1}$ are detected at some stations, we do not observe widespread super-CC rates in our dataset like some previous studies have found (e.g. Lenderink and van Meijgaard, 2008, 2009; Lenderink et al., 2011).

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 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. In accordance with the findings of Haerter and Berg (2009) and Berg et al. (2013), all events exhibit higher slopes than lightning events only because of the mixing of stratiform events at low temperatures and convective events at high temperatures. This implies that the scaling of 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 $\%\,^\circ\mathrm{C}^{-1}$, respectively), and rates are even smaller for stratiform (no lightning) events (2.9 and 1.1 $\%\,^\circ\mathrm{C}^{-1}$, respectively).

It follows that, not surprisingly, when the mean intensities of all events are analyzed together, 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 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 ($\geq 12\,\%$) rates were exceeded for the 99th percentile only 6 % of the time for all events and 18 % in the events with the highest convectivity. Overall, this supports the fact that super-CC rates are rare even for convective events which finds support in climate model simulations (O'Gorman and Schneider, 2009a, b).

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 (Fig. 3). We argue that this is because for

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extreme storms, the mean event intensity better reflects the water vapor content of the atmosphere leading to precipitation including the supply of moisture than the single maximal hourly rainfall pulse. The latter is likely more affected by local conditions and cloud and precipitation physics beyond CC scaling.

3.2 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 percentile of I_m for all events is shown in Fig. 4 and the mean slopes are listed for all four regions in Table 1. Overall, the lowest rates in I_m are found in the Alpine region and in Tessin south of the main Alpine divide (6.1–6.3 $\%\,^\circ\mathrm{C}^{-1}$ on the average), while the rates in the plateau and especially in the prealpine area are greater ($\sim 8.3\,\%\,^\circ\mathrm{C}^{-1}$ on the average). This suggests a regional effect on precipitation intensity strongly influenced not only by surface-atmosphere feedbacks but also by local and general circulation patterns and advection of moisture conditioned by topography.

It is notable that the lowest rates of precipitation increase with air temperature are observed in the main Alpine valleys (Fig. 4), where probably both lower temperatures and heating of the atmosphere combine with complex orographically driven patterns of moisture flow, condensation, and rainfall formation (e.g. Panziera and Germann, 2010). 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. Hardwick Jones et al., 2010) or analyzing dew point temperature (e.g. Lenderink et al., 2011). 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 ($> 20\,^\circ\mathrm{C}$) in Alpine climates (Fig. 5). Stations in the mountain valleys (e.g. Davos, Zermatt) are typically moisture limited at a lower temperature 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).

3.3 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 (O'Gorman and Schneider, 2009a, b). 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 precipitation.

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. Zawadski et al., 1981; McBride and Frank, 1999; Dixon, 2008; Adams and Souza, 2009; Barkidija et al., 2013). 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 temperature across Switzerland, regardless of the actual rate of increase, are suggesting that precipitation

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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. Beniston et al., 1994; Widmann and Schaer, 1997; Brunetti et al., 2009). However, changes in extreme rainfall from daily precipitation records have been rather small and spatially inconsistent (e.g. Frei and Schaer, 2001; Birsan et al., 2005).

The Mann–Kendall trend test for changes in the number of events per year during which the precipitation intensity exceeded the threshold I^* suggests that 90 % of the stations exhibited upward trends in this metric, and 30 % were statistically significant (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 Gaál et al. (2014). Statistically significant trends were distributed across the country, suggesting that a widespread shift towards more convective storms in a warming climate in the April–September period over the last 30 yr may have taken place. 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 yr of hourly records from 50 stations in an area with high relief and complex topography. Scaling of extreme precipitation on an event basis is analyzed to find evidence for CC (7 % °C^{-1}) or super-CC rates. The novelty in our work compared to previous studies, with the exception of Haerter et al. (2010), is that we used storm event properties, rather than fixed time intervals in our analysis, and we separated events into stratiform and convective sets based on lightning and quantified their degree of convectivity. Our main conclusions are:

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1. Mean event intensity I_m and peak hourly intensity I_p of all the extreme events 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 by the mixing of storm types as already discussed by Berg et al. (2013). Events accompanied by lightning (convective events) exhibit significantly higher rates of increase with air temperature than stratiform rain, 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 are an exception, even for the 90th and higher percentiles of I_m and I_p.

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 prealps, suggests that precipitation–temperature relations are influenced not only by local surface-atmospheric feedbacks but also by general circulation patterns and local advection of moisture conditioned by topography. We demonstrate on selected representative stations that there are possible limitations of moisture availability at high temperatures in 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 across Switzerland in the past 30 yr, 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. We found that the majority of the stations exhibited upward trends in the number of convective events (30 % were statistically significant). Our results suggest that this significant shift towards more convective storms at higher temperatures may as a consequence lead to stronger rainstorms and therefore higher risk connected with those events.

Overall, our main finding is that super-CC rates of increase in rainfall with temperature ($\sim 14\,\%\,^{\circ}\mathrm{C}^{-1}$) reported by others (e.g. Lenderink and van Meijgaard, 2008; Allan and Soden, 2008; Lenderink and van Meijgaard, 2009; Hardwick Jones et al., 2010; Lenderink et al., 2011), are rare and rather an exception than the norm, even for extreme convective rainfall. We also demonstrate large variability in the rates in space that are likely connected with local moisture availability and 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 variability in the results. However, we argue that the sub-CC scaling and more heterogenous patterns in extreme precipitation with temperature observed in Switzerland 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.

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Table 1. Expected values of the regression slopes in % °C^{-1} fitted to the 90th percentiles of binned storm data ±1 standard deviation. Slopes are reported for mean I_m and peak I_p storm intensity for different regions, convectivity index β, and grouped by lightning.

I_m	All events	$\beta = 0$	$0 < \beta < 0.8$	$\beta > 0.8$	No lightning	Lightning
All stations	7.4 ± 2.8	3.2 ± 1.3	5.8 ± 2.8	7.0 ± 5.7	2.9 ± 1.7	6.3 ± 3.3
Plateau	8.3 ± 3.3	2.7 ± 0.8	6.9 ± 2.6	7.5 ± 4.1	2.7 ± 1.6	5.9 ± 2.1
Prealps	8.3 ± 1.5	3.5 ± 1.0	6.2 ± 3.1	5.8 ± 3.0	3.9 ± 1.9	8.0 ± 3.9
Alps	6.1 ± 2.4	3.7 ± 1.7	3.7 ± 2.4	7.3 ± 9.6	3.0 ± 1.7	5.8 ± 4.8
Ticino	6.3 ± 1.3	2.9 ± 1.6	6.1 ± 2.2	6.3 ± 2.5	1.8 ± 0.9	5.9 ± 1.2

I_p	All events	$\beta = 0$	$0 < \beta < 0.8$	$\beta > 0.8$	No lightning	Lightning
All stations	5.1 ± 2.1	0.6 ± 0.9	2.5 ± 2.3	3.3 ± 5.0	1.1 ± 2.0	2.7 ± 3.5
Plateau	5.7 ± 2.0	0.5 ± 0.7	3.6 ± 2.4	4.0 ± 4.2	1.1 ± 2.1	3.3 ± 1.9
Prealps	5.6 ± 1.2	0.9 ± 0.8	2.8 ± 1.7	−0.5 ± 6.2	2.0 ± 2.5	3.5 ± 2.1
Alps	4.1 ± 2.4	1.0 ± 0.9	0.8 ± 1.4	5.5 ± 4.4	1.3 ± 1.5	1.3 ± 5.9
Ticino	4.5 ± 1.5	−0.5 ± 0.8	2.1 ± 2.0	2.4 ± 4.4	−0.2 ± 0.9	2.2 ± 2.2

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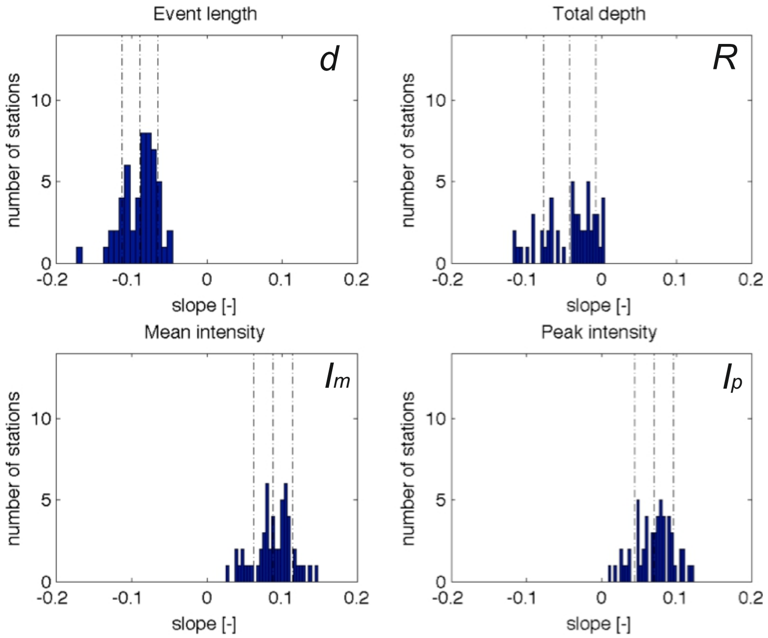

Figure 1. Histograms of the regression slopes fitted to the 90th percentiles of the event data for all stations in %/100 °C^{-1}. Event duration *d* (top left panel), total storm depth *R* (top right panel), mean intensity I_m (bottom left panel) and peak intensity I_p (bottom right panel). Vertical dashed lines indicate the mean ±1 standard deviation.

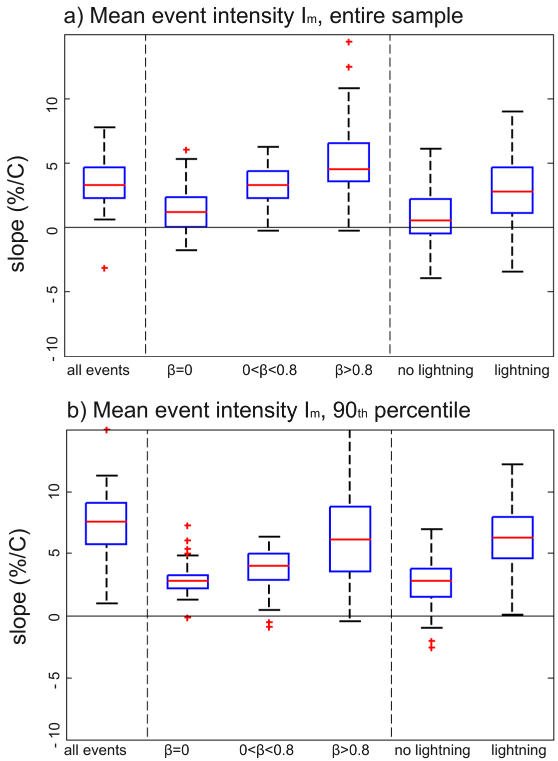

Figure 2. Boxplots showing the distributions of slope magnitude for mean event intensity I_m relation to temperature in different subgroups: using all events, three convectivity levels, and events with and without lightning for **(a)** the entire sample, and **(b)** the 90th percentile of the binned data. The red line shows the median, the upper and lower bound are the 25th and 75th percentiles (25 P and 75 P). The whiskers are calculated as $w_\mathrm{top} = 75\,\mathrm{P} + 1.5(75\,\mathrm{P} - 25\,\mathrm{P})$, $w_\mathrm{bot} = 25\,\mathrm{P} - 1.5(75\,\mathrm{P} - 25\,\mathrm{P})$. Outliers are plotted as red crosses.

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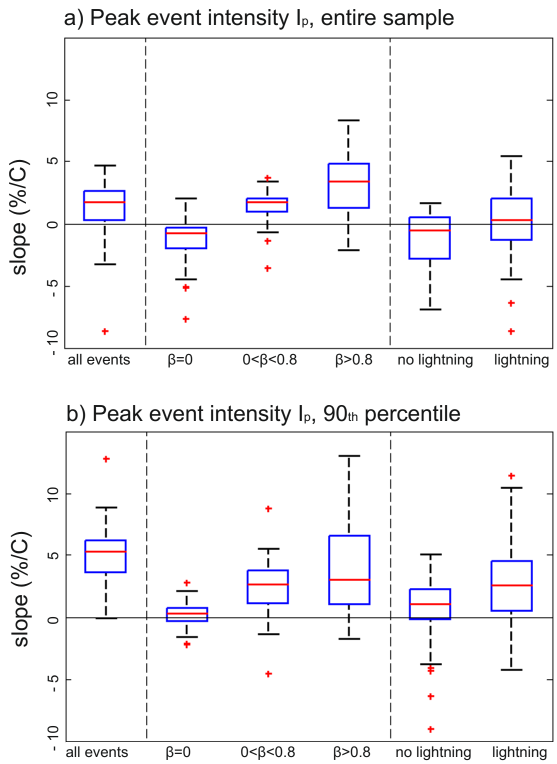

Figure 3. Boxplots showing the distributions of slope magnitude for peak event intensity I_p relation to temperature in different subgroups: using all events, three convectivity levels, and events with and without lightning for **(a)** the entire sample, and **(b)** the 90th percentile of the binned data. 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 crosses.

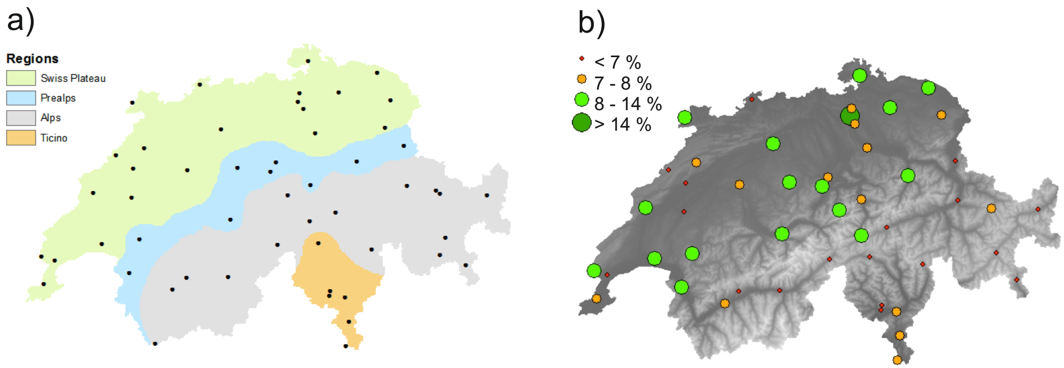

Figure 4. (a) Analyzed station locations in 4 regions of Switzerland following roughly the division of Schüepp and Gensler (1980). **(b)** Regression slopes fitted to the 90th percentiles of the event mean precipitation I_m including all events in % °C^{-1} (see Table 1).

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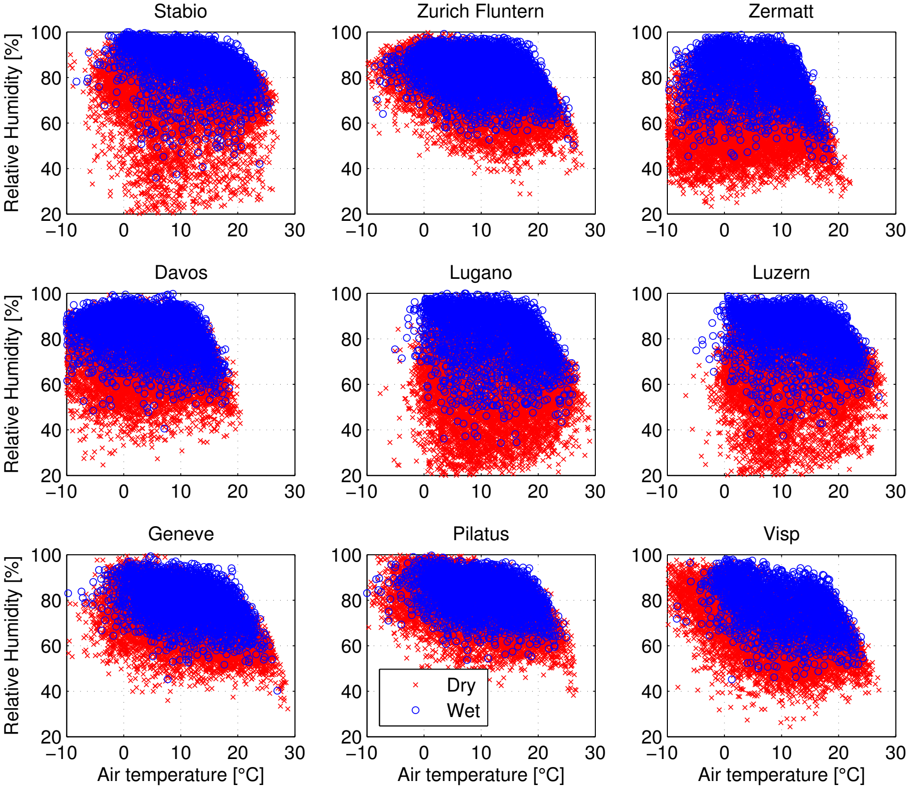

Figure 5. Mean daily relative humidity plotted against mean daily air temperature for wet (precipitation larger than 1 mm day^{-1}) and dry days at nine representative stations in the four regions in Fig. 4.

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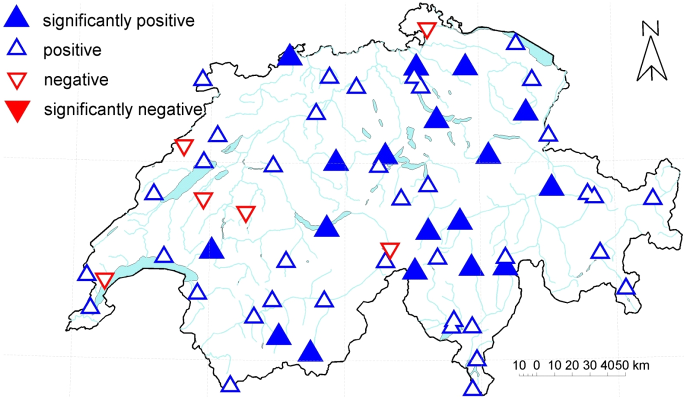

Figure 6. Trends in the number of events per year that exceeded the threshold I^* over the period 1981–2012 estimated by the non-parametric Mann–Kendall trend test. Upward trends are blue, downward trends are red, statistically significant trends at the $\alpha = 10\,\%$ significance level have filled markers.