Selection of intense rainfall events based on intensity thresholds and lightning data in Switzerland

Ladislav Gaal[1,2,3]**, Peter Molnar**[1]**, and Jan Szolgay**[2]

[1]Institute of Environmental Engineering, ETH Zurich, Switzerland
[2]Slovak University of Technology, Bratislava, Slovakia
[3]now at: Technical University of Vienna, Vienna, Austria

Abstract. This paper presents a method to identify intense warm season storms with convective character based on intensity thresholds and the presence of lightning, and analyzes their statistical properties. Long records of precipitation and lightning data at 4 stations and 10-min resolution in different climatological regions in Switzerland are used. Our premise is that thunderstorms associated with lightning generate bursts of high rainfall intensity. We divided all recorded storms into those accompanied by lightning and those without lightning and found the threshold I^* that separates intense events based on peak 10-min intensity $I_p \geq I^*$ for a chosen misclassification rate α. The performance and robustness of the selection method was tested by investigating the inter-annual variability of I^* and its relation to the frequency of lightning strikes. The probability distributions of the main storm properties (rainfall depth R, event duration D, average storm intensity I_a and peak 10-min intensity I_p) for the intense storm subsets show that the event average and peak intensities are significantly different between the stations. Non-parametric correlations between the main storm properties were estimated for intense storms and all storms including stratiform rain. The differences in the correlations between storm subsets are greater than those between stations, which indicates that care must be exercised not to mix events of different origin when they are sampled for multivariate analysis, e.g. copula fitting to rainfall data.

1 Introduction

Rainfall is one of main causes of natural hazards in hydrological systems (e.g. Vörösmarty et al., 2013; Wilhelmi and Morrs, 2013; Kyselý et al., 2013), and is inseparably related to flood risk (e.g. Hlavcova et al., 2005; Blöschl, 2008; Borga

Correspondence to: Peter Molnar
(molnar@ifu.baug.ethz.ch)

et al., 2011; Winsemius et al., 2013). Storms associated with high rainfall intensities often lead to severe flooding in catchments and urban areas, accelerated hillslope and channel erosion, triggering of landslides, mud and debris flows (e.g. Llasat, 2009; Brunetti et al., 2010; Badoux et al., 2012). The severity of storms and their damage potential is dependent not only on the total rainfall amount but also on other storm characteristics such as peak rainfall intensity and event duration. The statistical properties of these storm characteristics and their inter-dependencies are fundamental descriptors of intense storms for both practical (design) and scientific purposes. That is the general aim of this paper.

The first question we address is how to select intense storms out of all events based on some common property. A good example is the distinction of precipitation into convective and stratiform rain which captures two different cloud dynamical processes (e.g. Houze, 1997). Convective rain is associated with higher rainfall intensities and is commonly identified from ground synoptic observations of clouds, state of weather and/or rain intensity fluctuations (e.g. Pešice et al., 2003; Chvila et al., 2005; Tremblay, 2005; Llasat et al., 2007; Berg et al., 2013; Ruiz-Leo et al., 2013; Rulfová and Kyselý, 2013). Weather radar provides additional information, e.g. updraft velocities and cloud water content, which aid the identification of convective rain (e.g. Rigo and Llasat, 2004; Llasat et al., 2005; Rigo and Llasat, 2007). Although formal convective-stratiform separation techniques (see comparison in Lang et al., 2003) are inherently limited because they do not directly quantify the origin and type of convection (Zimmer et al., 2011) they have one thing in common – that a locally high rainfall intensity is expected in events where convection is present even if embedded in stratiform systems. It is this extremity of rainfall intensity during a storm which we would like to capture in our selection of intense events, regardless of their exact meteorological origin and genesis.

The second question we address in this paper is how to

define a threshold intensity for the identification of intense storms. This choice is rather arbitrary and depends on the time resolution used, i.e. the duration for which the intensity exceeds the threshold (e.g. Llasat, 2001). There are very few objective methods to estimate the threshold intensity, one notable exception is Tremblay (2005) who partitions rain into stratiform and convective components with the latter being anomalies in the relation between total precipitation and precipitation intensity (e.g. Ruiz-Leo et al., 2013). This method is based on a global classification from raingauges and provides time-dependent but not station-specific thresholds. It was developed for 6-h aggregations which are not always sufficient to capture short-term variations in rain intensity during convective storms.

One of the main goals in this paper is to develop a station-based method to choose the intensity threshold based on long records of lightning strike data and precipitation measured at a high resolution (10 min). The premise is that summer thunderstorms with convective activity are commonly associated with lightning (e.g. Tapia et al., 1998; Rivas Soriano et al., 2001; Rivas Soriano and De Pablo, 2003; Barnolas et al., 2008; Tadesse and Anagnostou, 2009; Yair et al., 2010; Koutroulis et al., 2012). A number of recent studies have demonstrated the connection between intra-cloud and cloud-to-ground lightning and convective precipitation using rainfall yield, i.e. the amount of rain per lightning flash, as a measure (e.g. Petersen and Rutledge, 1998; Grungle and Krider, 2006; Price and Federmesser, 2006; Pineda et al., 2007; Kochtubajda et al., 2013). Tapia et al. (1998) developed a model to predict the space-time distribution of rainfall as a function of rainfall yield and lightning strikes. However, the predictive strength of lightning count as an explanatory variable on a regional scale in these studies is not very strong.

The approach we take instead is that the simple presence of lightning in the vicinity of a raingauge is indicating the existence of convective activity. We find the rainfall intensity threshold that gives us an acceptable separation error between events accompanied by lightning and those that are not, and study their statistical properties. Although we use accurate station-based lightning data, the same approach applies to lightning data from long-range lightning detection ground networks or satellites (e.g. Defer et al., 2005; Price and Federmesser, 2006; Kotroni and Lagouvardos, 2008). Our study complements other recent efforts focused on using lightning observations to better understand and predict convective storms and their consequences, e.g. flash floods (Price et al., 2011a,b; Koutroulis et al., 2012).

The main contributions of this paper are threefold: (a) We provide a new method to identify intense warm season rainfall events as those in which the maximum intensity exceeds a threshold by using lightning strike data as an explanatory variable. We analyze the performance and robustness of this method by investigating the relations between the estimated threshold and lightning statistics. (b) We show the probability distributions of main storm properties for the intense storm subset identified by our method and discuss the differences between the studied stations. (c) We present non-parametric correlation coefficients between the main storm properties for the intense storm subset and contrast these with the correlations for all storms to highlight the particular inter-dependencies (or lack thereof) in intense storm properties. The analysis is conducted on 4 stations in different climatological regions in Switzerland and provides a basis for a follow-up regionalization effort.

2 Data

2.1 Meteorological data and study sites

The data used in this study are from stations of the Swiss-MetNet network (MeteoSwiss). These are automatic weather stations recording a range of hydroclimatic data at a 10-min sampling resolution. Our main data are precipitation and air temperature for the period 1981-2012 (32 years) and lightning strikes for the period 1987 to 2005 (19 years) at 62 stations with about 3000 meter altitude difference (Figure 1).

Precipitation is recorded by a heated tipping-bucket rain-gauge (Lambrecht) with orifice area 200 cm^2 and tip resolution 0.1 mm. The data are quality checked and corrected at the hourly resolution. The 10-min precipitation data have been analysed for their scaling-based properties (Molnar and Burlando, 2008) and short-term oscillations (Paschalis et al., 2012) and we are confident in their good quality. Air temperature is a standard measurement by a ventilated thermometer at 2 m height.

Four of the 62 stations are chosen as examples of different climatological regions in this paper (Figure 1): Geneve-Cointrin (GVE, 420 m a.s.l.) in the lowland region north of the Alps, Napf (NAP, 1404 m a.s.l.) in the Swiss pre-Alpine region in central Switzerland, Scuol (SCU, 1304 m a.s.l.) in the Graubünden region in the East of Switzerland where substantial blocking of precipitation is observed, and Lugano (LUG, 273 m a.s.l.) in the Tessin region to the south of the main Alpine divide which is significantly affected by Mediterranean weather patterns and orographic forcing, especially in the summer and fall seasons (Panziera and Germann, 2010).

2.2 Event definition

Our analysis is based on precipitation events which we identify separately for the warm (April-September) and cold (October-March) half-years, which we also call seasons in this paper. For the selection of potentially intense rainfall events we limit ourselves to the warm season only and add a constraint that the air temperature during an event $T > 4°C$ to ensure liquid precipitation and minimize the likelihood of snow or mixed events at high altitude stations. In the determination of individual events we disregarded all intervals with

only 1 tip in 10-min (0.1 mm/10-min) because these are often artifacts of condensation and funnel drainage at the end of events and increase the duration of events with minimal increase in rainfall depth.

In practice it is common to define individual rainfall events by rainless intervals exceeding a selected duration called the inter-arrival time (also inter-event time, inter-storm period) t_i (Figure 2). Many application-based criteria for identifying rainfall events using a fixed t_i have been presented in the literature, with values ranging from 3 min to 24 hours (e.g. Dunkerley, 2008, 2010). In our study we have chosen $t_i = 2$ hrs based on the de-correlation time in the rainfall records (see next section for details).

For each event we determined four main event properties: total rainfall depth (R), event duration (D), average rainfall intensity ($I_a = R/D$), and peak (maximum) 10-min intensity during the event (I_p) (Figure 2). Table 1 summarizes the final number of events per warm season for the four stations, which ranged from an average of 84 (0.46 per day) at Scoul to 98 (0.54 per day) at Napf in the pre-Alpine area.

2.3 Inter-arrival time

An objective approach to choose t_i is to ensure that subsequent events are independent. Independence can be evaluated on a conceptual basis or statistically. The conceptual basis may for example be a model of the interception process which would identify independent events as those where t_i exceeds the time scale of evaporation from a fully saturated canopy (e.g. Lloyd, 1990; Zeng et al., 2000), or a time period during which soil wetness decreases sufficiently not to impact the subsequent flood runoff (e.g. Bracken et al., 2008). The statistical basis may for example be that t_i is sufficiently long for the autocorrelation in rainfall to become statistically insignificant (Grace and Eagleson, 1967), or the probability distribution of t_i closely exponential, like that of independent events in a Poisson process (Restrepo-Posada and Eagleson, 1982). Selecting long t_i may prove useful for ensuring the identification of statistically independent events, but in turn, it has a negative effect on storm properties by creating extensive intra-event gaps, leading to a strong bias in storm duration and average intensity (e.g. Restrepo-Posada and Eagleson, 1982; Dunkerley, 2010).

We chose a combination of conceptual and statistical considerations in identifying t_i, bearing in mind that we want to preserve the extremal properties of intense rain events. Conceptually the values of t_i were a-priori restricted to the order of the usual time scale of summer thunderstorms, and statistical independence of the events was ensured by analyzing the autocorrelogram of the sequences of 10-min rainfall. The lag at which the autocorrelation coefficient became statistically insignificantly different from zero for a chosen significance level indicates the inter-arrival time at which the storm events may be regarded as independent.

The autocorrelogram, i.e. the Pearson correlation coefficient as a function of time lag was determined for each station and each warm season separately. The autocorrelation functions for individual seasons were then averaged and are shown as dots in Figure 3. The statistical significance was tested at the significance level 10%. The de-correlation time ranged between 2 and 3 hr, and this was similar for the majority of the 62 SwissMetNet stations. Some mountain stations, such as Scuol in Figure 3, show slightly longer de-correlation times. From this result we conclude that $t_i = 2$ hrs gave us an appropriate de-correlation time in the rainfall records. Moreover it also matches the order of lifespan of thunderstorms in general.

2.4 Lightning strikes

Lightning-induced electric charge was measured locally at each SwissMetNet station by a ground antenna from 1987 to 2005 (19 years). After 2005 the data are obtained under the Europe-wide EUCLID network (http://www.euclid.org) and are extrapolated to the stations. To ensure homogeneity of the records we only consider the earlier period of local station measurements in this paper.

Lightning data are reported as the number of strikes within a certain range from the station at a 10-min time resolution. The sensitivity of the antenna allows an identification of close ($< \sim 3$ km) and distant (between $\sim 3 - 30$ km) lightning. Separation between cloud-to-ground and intra-cloud lightning is not possible. Figure 4 shows the most interesting statistics of lightning data at the Geneve station. Because this data has to our knowledge not yet been reported in the literature we highlight the following main features which were common among all stations.

There are clearly many more distant strikes than close ones. However, their ratio remains rather stable across years. The occurrence and actual sum of strikes in the cold (CHY) and warm (WHY) half-years are dramatically different, with more than 90% of the strikes in the warm season indicating the connection between convectivity, ice-build up in cloud systems, electrification, and thunderstorm activity. The monthly distribution of lightning shows that the three most active months are June-July-August. The hourly distribution of lightning further indicates that lightning has a clear diurnal pattern with maxima between 15:00 and 18:00 hours UTC in the afternoon when convective activity is highest. There were some small differences at the Napf, Scuol and Lugano stations but the general tendencies were identical. Even if we do not take into account the actual count of lightning strikes, because this is a highly uncertain and site-dependent quantity, and only the presence or absence of lightning, the seasonal and diurnal statistics do not change appreciably.

Lightning data sheets like that in Figure 4 for Geneve are available from the authors for all 62 stations of the SwissMetNet network.

3   Method of intense storm event selection

The method to select intense warm season storms out of our set of all storms is based on identifying events during which the peak 10-min intensity exceeds a threshold $I_p \geq I^*$. This subset of intense storms can be assigned a convectivity index for every event j as the fraction of the event total rainfall depth that falls with intensities greater than I^* (Llasat, 2001),

$$\beta_j = \frac{\int_{\tau=0}^{D_j} \{i; i \geq I^*\} d\tau}{R_j} \qquad (1)$$

All events belonging to the set of intense events then have $0 < \beta \leq 1$ and those that are not considered intense $\beta = 0$.

Based on the findings that the occurrence of intense summer rainfall is indeed well correlated with lightning activity, especially over land (e.g. Petersen and Rutledge, 1998; Rivas Soriano et al., 2001; Rivas Soriano and De Pablo, 2003; Pineda et al., 2007; Barnolas et al., 2008; Tadesse and Anagnostou, 2009; Yair et al., 2010; Koutroulis et al., 2012), we propose to calibrate the threshold parameter I^* at every station as a function of the presence or absence of lightning. In Section 3.1 we first analyze the storm properties for all events with and without lightning, and in Section 3.2 we then develop a statistical approach to estimate I^* based on lightning data.

3.1   Storm properties and lightning

All storms in our dataset were divided into those that were accompanied by lightning and those that were not. In this step we did not consider the actual count of lightning strikes but only the presence of lightning, similar to Katsanos et al. (2007) who used a fixed 6-h accumulation step for stations in the Mediterranean. We chose to include distant strikes as well as close strikes because we are defining a property of the events which is dependent on a larger scale propensity of the atmosphere around the station to generate extreme rainfall. In associating lightning with storm rainfall we also considered strikes that occurred up to 20 min before the actual rainfall event began, which captures commonly observed time lags in pre-storm lightning-rainfall correlations (e.g. Grungle and Krider, 2006; Koutroulis et al., 2012).

We found that 31% (Scuol), 39% (Napf), 40% (Geneve), and 62% (Lugano) of the events were associated with lightning (Table 1). In this statistic Lugano was an exception and most stations in the SwissMetNet network had between 30–40% of storms with lightning on the average. Naturally stations at higher elevations and/or in valleys surrounded by mountain peaks have a higher proportion simply because lightning strikes are more frequent there.

Histograms of the four main rainfall event properties (R, D, I_a, I_p) were compared for the subsets of events with and without lightning for the period 1987-2005. The differences in the distributions were objectively assessed with statistical tests (Kolmogorov-Smirnov). Figure 5 shows the results for

Geneve. The results were consistent for the other stations and show that rainfall duration D and total rainfall depth R are not statistically significantly related to the occurrence of lightning, except for very short durations and low rainfall totals. However, average rainfall intensity I_a and especially peak rainfall intensity I_p were consistently different for events accompanied by lighting.

The main difference in I_p was that events accompanied by lightning had higher peak intensities in general and the largest peak intensities were in fact observed only in storms with lightning. Also very low peak intensities were much more prevalent in storms without lightning. This result was true for all analyzed stations. We conclude that the short term peak 10-min intensity I_p during an event is indeed the most useful variable to separate intense summer storm events of a mostly convective character from our event dataset.

3.2   Calibrating the intensity threshold

The threshold intensity I^* is an unknown parameter in our approach which selects intense storms of a mostly convective character out of all storms as those for which $I_p \geq I^*$. This is our model under the assumption that lightning data is indicative of convective activity. We can then use the two subsets of storms with and without lightning for the calibration of the intensity threshold. For any I^* we can compute the sensitivity, i.e., the fraction of events accompanied by lightning which are identified as intense storms (true positives), and specificity, i.e., the fraction of events not accompanied by lightning which are identified as not intense storms (true negatives). Plotting sensitivity versus specificity for a range of I^* (see Figure 6 for Geneve) gives us a complete indication of how good our model is because the departure of the data points from the diagonal indicates the power of the model to make a reliable selection (e.g. Begueria, 2006).

We choose an acceptable misclassification error α of no lightning events as convective (false positives, Type I error) to make a decision for I^* as the threshold where specificity $= 1 - \alpha$. This decision is based on the argument that when lightning occurs in the vicinity of the gauge but we do not measure high intensity rain this could be caused by sampling the edge of a passing convective cell. While when lightning does not occur but we do measure high intensity rain this is indeed an error in our model which we would like to minimize. This error contains all the physical processes that may lead to intense precipitation in the absence of lightning, e.g. embedded convection in stratiform systems, low updraft velocities and ice build-up, etc. By choosing the same α for all stations we have an objective way to compare the properties of the intense storms between stations. In this study we take $\alpha = 0.1$, and the corresponding I^* values are between 5.8 and 9.2 mm/h at the four stations (Table 1).

4   Results

We present the results by first discussing the calibrated intensity thresholds I^* with regard to some previous studies. We then analyze the performance of the method to select intense warm season rainfall events, and finally present the basic statistics of the main storm properties for this set of events and their cross-correlations.

4.1   Comparison of intensity thresholds

The calibrated thresholds to identify intense warm season storms with convective character at the four studied stations (between 5.8 and 9.2 mm/h) are lower than what is reported in most climatological and engineering hydrology literature for extreme convective rain. For example, Dutton and Dougherty (1979) and Watson et al. (1982) present a threshold of 48-50 mm/h for considering rainfall to be all of convective origin. Llasat (2001) considers that convective rain events exceed a peak 5-min intensity of 35 mm/h, and a threshold for average hourly intensities for heavy rainfall defined by the Spanish National Meteorological Institute is 15 mm/h. Earlier studies, like Wussow (1922) developed an empirical formula for Germany which gives 7.1 mm for strong rainfall of 10-min duration, i.e., 43 mm/h, and Reinhold (1940) classified heavy rainfall when intensities for 10-min durations exceeded 40 mm/h. Velikanov (1964) describes a classification where the threshold for 10-min intensive rainfall is given as 3.8 mm, i.e., 23 mm/h. This classification was also used in former Czechoslovakia by Dub and Němec (1969). Dunkerley (2010) reports that in the context of erosion an event was only significant by Wischmeier and Smith (1978) if either the rain depth was larger than 12.5 mm or the rain rate exceeded 6.5 mm in 15 min, i.e., 26 mm/h (Kinnell, 2003).

A direct comparison of our thresholds with the above (and other) studies is not possible for several reasons. First is that these studies are generally focused at identifying very heavy convective rainfall events only, while we are interested in selecting a larger set of storms which are of convective character and not only the most extreme of them. Second is that many of these studies use different temporal resolutions of the rainfall data which strongly affects the threshold intensities (e.g. Llasat, 2001), and naturally the results vary considerably from one region to another based on the local climate. In our work it is the misclassification rate α which determines I^*. If we are stricter on the acceptable Type I error in our model (lower α) then the threshold I^* increases. However, this goes at the expense of increasing Type II error, i.e. our model will have a lower sensitivity with respect to identifying events accompanied by lightning as convective (see Figure 6).

4.2   Testing the robustness of the method

Because lightning data which are key in our method to estimate I^* may vary strongly in time and space and be non-homogeneous, a question to be answered is how robust the results are with respect to lightning variability. We examine two aspects: the inter-annual variability of I^* and its relation to the frequency of lightning strikes.

Inter-annual variability in I^* estimated on a bi-annual basis is shown together with the estimate for the entire 18-year record (until 2004) with reliable lightning data for all four stations in the left panel in Figure 7. The result is that there is no evident trend in the estimate of I^*, although the local station inter-annual variability in lightning strikes, as seen for instance in Lugano, may lead to larger variability in the estimate. We also plot the corresponding bi-annual estimate of sensitivity in the right panel in Figure 7. If lightning was not a predictor of intense events in our model, the sensitivity would be equal to the chosen misclassification rate $\alpha = 0.1$. The results show that the sensitivity at all stations is in fact much greater than α and is in the range ~ 0.4 on the average. There is some inter-annual variability in model performance, however, it is not unacceptable. In fact in Lugano the performance is practically constant, which is a good indication of the robustness of the connections between lightning and intense rain over time at this station.

The second aspect to test is whether I^* is related to the frequency of lightning strikes and its variability from year to year. We would like to clarify if it is possible that the frequency of storms with lightning changes in time and thereby affects the estimate of I^*. The number of storms with and without lightning estimated on a bi-annual basis are shown in the left panel in Figure 8. The proportion of storms with lightning remains reasonably consistent between years at all stations. More importantly, I^* is clearly independent of the frequency of storms with lightning shown in the right panel in Figure 8, which allows us to conclude that we have a robust method to extract intense storms from our dataset based on peak 10-min intensity alone, which at the same time coincide well with those which are accompanied by lightning.

4.3   Properties of selected storms

Because the subset of intense summer storms should mostly contain intensities associated with convective events, we use the convectivity index defined by Llasat (2001) in Eq. (1) to quantify the strength of convection on an event basis. The cumulative probability distributions of β in Figure 9 show an almost uniform shape at all stations. As expected, the highest convectivity overall was observed in Lugano in southern Switzerland. Llasat (2001) identified events with $\beta > 0.8$ as strongly convective in Spain, which would correspond to 18% (Napf and Scuol), 20% (Geneve) and 30% (Lugano) of the events in our dataset.

The cumulative distributions of the main storm properties of the events are shown in Figure 10 and some basic statistics are listed in Table 1. The exceedance probability is shown to accentuate the behaviour of extremes. The stations show a very similar distribution of storm duration, except for Lugano which has the longest events. Storm duration is not a variable that is very strongly affected by the different regional climates. However, the other variables are statistically significantly different between the stations. Average event intensity is higher in Lugano than in the other stations, leading to the highest event rainfall depths. Also peak 10-min intensity during an event is highest in Lugano, followed by Napf and Geneve. Extremes are particularly affected. For example an event from our subset with a probability of exceedance of 20%, that is an event that occurs about 5-6 times a year, has a peak 10-min intensity of about 40 mm/h in Lugano, 25 mm/h in Napf and 20 mm/h in Geneve.

One of our main aims was to quantify the correlations between main storm properties for the intense storm subset and contrast these with the correlations for all storms, to highlight the particular inter-dependencies (or lack thereof) in intense storm properties. We chose all storms instead of the subset of less intense storms since we would like to show the differences between our selection and a traditional choice where all storms are used regardless of their meteorological origin. To quantify the correlations we use the Spearman rank correlation coefficient because we intend to use the relations between storm properties for statistical multivariate analysis with the method of copulas. Copula parameters depend on the correlations between the variables, which are generally quantified with a non-parametric correlation like Spearman (or alternatively Kendall) in the literature (e.g. Genest and Favre, 2007; Serinaldi, 2008; Vandenberghe et al., 2010).

The Spearman rank correlation coefficient estimated for all 6 pairs of variables and all stations is shown in Figure 11. The results show that the intense summer storm events have practically no correlation between peak intensity I_p and the duration of the event D, while when all storms are considered including stratiform rain this correlation was significantly positive. Another interesting observation is that I_p is less strongly correlated to total rainfall depth R in our intense storm subset than in all events. In other words, in events with intensities associated usually with convection, a high intensity over a short period of time does not necessarily lead to a high overall event total, while in events with stratiform rain rates that is generally the case. As expected, average storm intensity I_a is negatively correlated with duration D in the convective intense event set but not for all storms.

Some of the correlation coefficients in the event sets are statistically significant (Figure 11) and they suggest that a multivariate approach, for instance on the basis of copulas, is advised for probabilistic modelling of extreme storm properties (e.g. Kao and Govindaraju, 2007; Serinaldi, 2008; Bardossy and Pegram, 2009; Vandenberghe et al., 2010). Overall the differences in the correlation coefficients between sta-

tions are much smaller than between the convective event set and the entire set of events, which means that it is of first order importance to select wisely the sample of intense events for multivariate analysis.

5   Discussion of selection method and extremes

The traditional approach to the analysis of extreme rainfall is the depth-duration-frequency (DDF) curve applied to annual maxima or peaks over a threshold (POT), where for a given duration, the most extreme rainfall depths (intensities) in a year are selected and their probability of occurrence is estimated. Estimation methods for the analysis of annual and POT extremes are well known and reported in the literature (e.g. Katz et al., 2002) as well as the mathematical framework for studying DDF curves (e.g. Koutsoyiannis et al., 1998). Estimation uncertainties are related to fitting an extreme value distribution to the selected data (mostly GEV-type) and functional forms for the DDF relation parameters, and these may be quantified from station as well as weather radar data (e.g. Overeem et al., 2008, 2009). The result is an estimated rainfall intensity for a given duration and return period. The threshold intensity comes from the minimum observed annual extreme in the record (annual maxima), or the choice of the average number of events per year (POT). Its basis is purely statistical – it is record period and duration-dependent.

Our approach is different in two main ways: (1) We are looking at rainfall events as independent outcomes of atmospheric water vapour fluxes and precipitation formation processes. We do not fix a-priori a given rainfall duration in the analysis (like in DDF curves) but we study several event properties and their statistics. (2) We select events which have a common physical origin and genesis, i.e. the presence of convection, insofar as it is reflected in a high peak 10-min intensity during the event. In this way we select many events, which are both short and long, with different rainfall totals, for the analysis, in contrast to only extreme intensities for DDF curves. Our threshold I^* is calibrated with lightning data, which are independent measurements. To us this threshold has a physical meaning, as a short-term rain intensity which was exceeded in most convective rainfall events at a given station.

The consequence is that our threshold I^* is not in fact directly comparable with POT or any other intense rainfall thresholds which are purpose-driven. Most studies define subjective thresholds based on hydrological risk, monitoring issues, or meteorological considerations. Some of these are discussed in Section 4.1. At this point we can say that despite the fact that our thresholding is different from the DDF approach, the statistics of extremes in our selection of intense storms agree reasonably well with the HADES (Hydrological Atlas of Switzerland) estimates from DDF analysis, where the 1 hr duration extremes with a return period 2.33 yr

ranged between 18-34 mm/h at our four study sites (Jensen et al., 1997), while our selection gave peak 10-min rainfall intensities with a non-exceedance probability $p = 0.8$ (i.e., the largest 5-6 events per year) between 20-40 mm/h. In a subsequent study we will explore the full spatial distribution of event properties across all 62 stations in Switzerland.

6   Conclusions

Properties of intense storms, such as total rainfall depth, storm duration, average intensity and peak intensity are important descriptors of the rainfall regime at a site. For the statistical analysis of rainfall events and extremes it is often important that the storms in the analyzed sample have a common meteorological origin, for instance convective rain, stratiform rain, hail, snowfall, etc. A similar concept may also be found in catchment hydrology where on the basis of meteorological conditions and catchment state different flood types are defined (Merz and Blöschl, 2003) and statistically analyzed (e.g. Gaál et al., 2012). In this paper we took this common property of intense warm season storms to be the short term (10 min) peak in rainfall intensity. It is this extremity of rainfall intensity during a storm which we would like to capture in our selection of intense events. We estimated the threshold intensity with the help of a unique lightning dataset, thereby capturing the convective character of these intense events.

The main conclusions of the paper are:

(1) We developed a new method to identify intense warm season rainfall events as those in which the peak 10-min intensity exceeds a threshold $I_p \geq I^*$ by using lightning data as an external variable for the presence of convection. We divided all storms into those accompanied by lightning and those without lightning and found the threshold I^* that separates intense events for a chosen misclassification rate α. Altogether 31% (Scuol), 39% (Napf), 40% (Geneve), and 62% (Lugano) of the events were associated with lightning at our studied stations and the calibrated I^* values are between 5.8 and 9.2 mm/h at the four stations (Table 1).

(2) The performance and robustness of the selection method was tested by investigating the inter-annual variability of I^* and its relation to the frequency of lightning strikes. We found that there is no evident trend in the estimate of I^* and the performance of the model in time. I^* is independent of the absolute frequency of storms with lightning at all stations, which allows us to conclude that our method to extract intense storms, which at the same time coincide well with those which are accompanied by lightning and therefore have a convective character, is robust.

(3) We analyzed the probability distributions of the main storm properties (rainfall depth R, event duration D, average intensity I_a and peak 10-min intensity I_p) for the intense storm subset and found that while storm duration did not vary significantly between stations, the other properties did. Average event and peak intensity was much higher in Lugano in southern Switzerland, than in the other stations. The strength of convection measured by the convectivity index (Llasat, 2001) β was also highest in Lugano where 30% of the events would be considered strongly convective.

(4) We presented non-parametric correlation coefficients between the main storm properties for the intense storm subset and compared them with the correlations for all storms to highlight the particular inter-dependencies in intense storm properties. The results show that the intense warm season storm events have practically no correlation between peak intensity I_p and event duration D, I_p is less strongly correlated to total rainfall depth R, and average storm intensity I_a is more strongly negatively correlated with duration D in our intense event set than for all events, including those of a stratiform nature. The differences in the correlations between storm subsets were significant and greater than those between stations, which indicates that care must be exercised not to mix events of different origin when they are sampled for multivariate analysis, e.g. copula fitting to rainfall data.

The analysis in this paper was reported for 4 representative stations in different climatological regions in Switzerland to illustrate the selection methodology. In a follow-up effort we will extend the analysis to all 62 stations of the SwissMetNet network and develop regionalization approaches which will allow the estimation of spatially-distributed I^* in Switzerland to be used where lightning data are not available.

References

Badoux, A., Turowski, J. M., Mao, L., Mathys, N., and Rickenmann, D.: Rainfall intensity-duration thresholds for bedload transport initiation in small Alpine watersheds, *Nat. Hazards Earth Syst. Sci.*, *12*, 3091–3108, doi:10.5194/nhess-12-3091-2012, 2012.

Bardossy, A. and Pegram, G. G. S.: Copula based multisite model for daily precipitation simulation, *Hydrol. Earth Syst. Sci.*, *13*, 2299–2314, doi:10.5194/hess-13-2299-2009, 2009.

Barnolas, M., Atencia, M., Llasat, M. C., and Rigo, T.: Characterization of a Mediterranean flash flood event using rain gauges, radar, GIS and lightning data, *Adv. Geosci.*, *17*, 35–41, doi:10.5194/adgeo-17-35-2008, 2008.

Begueria, S.: Validation and evaluation of predictive models in hazard assessment and risk management, *Nat. Hazards*, *37*, 315–329, doi:10.1007/s11069-005-5182-6, 2006.

Berg, P., Moseley, C., and Haerter, J. O.: Strong increase in convective precipitation in response to higher temperatures, *Nat. Geosci.*, *6*, 181–185, doi:10.1038/NGEO1731, 2013.

Blöschl, G.: Flood warning - on the value of local information, *Int. J. River Basin Manage.*, *6*, 41–50, doi:10.1080/15715124.2008.9635336, 2008.

Borga, M., Anagnostou, E. N., Blöschl, G., and Creutin, J.-D.: Flash flood forecasting, warning and risk management: the HYDRATE project, *Environ. Sci. Policy*, *14*, 834–844, doi:10.1016/j.envsci.2011.05.017, 2011.

Bracken, L. J., Cox, N. J., and Shannon J.: The relationship between rainfall inputs and flood generation in south-east Spain, *Hydrol. Process.*, *22*, 683–696, doi:10.1002/hyp.6641, 2008.

Brunetti, M. T., Peruccacci, S., Rossi, M., Luciani, S., Valigi, D., and Guzzetti, F.: Rainfall thresholds for the possible occurrence of landslides in Italy, *Nat. Hazards Earth Syst. Sci.*, *10*, 447–458, doi:10.5194/nhess-10-447-2010, 2010.

Chvila, B., Sevruk, B., and Ondras, M.: The wind-induced loss of thunderstorm precipitation measurements, *Atmos. Res.*, *77*, 29–38, doi:10.1016/j.atmosres.2004.11.032, 2005.

Defer, E., Lagouvardos, K., and Kotroni, V.: Lightning activity in the eastern Mediterranean region, *J. Geophys. Res.*, *110*, D24210, doi:10.1029/2004JD005710, 2005.

Dub, O. and Němec, J.: Hydrologie, Technicky pruvodce, SNTL, Prague, 380 pp., 1969.

Dunkerley, D. L.: Rain event properties in nature and in rainfall simulation experiments: a comparative review with recommendations for increasingly systematic study and reporting, *Hydrol. Process.*, *22*, 4415–4435, doi:10.1002/hyp.7045, 2008.

Dunkerley, D. L.: How do the rain rates of sub-event intervals such as the maximum 5- and 15-min rates (I_5 or I_{30}) relate to the properties of the enclosing rainfall event?, *Hydrol. Process.*, *24*, 2425–2439, doi:10.1002/hyp.7650, 2010.

Dutton, E. J. and Dougherty, H. T.: Year-to-year variability of rainfall for microwave applications in the USA, *IEEE T. Commun.*, *5*, 829–832, doi:10.1109/TCOM.1979.1094464, 1979.

Gaál, L., Szolgay, J., Kohnová, S., Parajka, J., Merz, R., Viglione, A., and Blöschl, G.: Flood timescales: Understanding the interplay of climate and catchment processes through comparative hydrology, *Water Resour. Res.*, *48*, W04511, doi:10.1029/2011WR011509, 2012.

Grace, R. A. and Eagleson, P. S.: A model for generating synthetic sequences of short-time-interval rainfall depths, in: Proceedings of International Hydrology Symposium, Fort Collins, Colorado, 268–276, 1967.

Genest, Ch. and Favre, A.: Everything you always wanted to know about copula modeling but were afraid to ask. *J. Hydrol. Eng.*, *12*, Special Issue: Copulas in Hydrology, 347–368, doi:10.1061/(ASCE)1084-0699(2007)12:4(347), 2007.

Grungle, B., and Krider, P.: Cloud-to-ground ligtning and surface rainfall in warm-season Florida thunderstorms, *J. Geophys. Res.*, *111*, D19203, doi:10.1029/2005JD006802, 2006.

Hlavcova, K., Kohnova, S., Kubes, R., Szolgay, J., and Zvolensky, M.: An empirical method for estimating future flood risk for flood warnings, *Hydrol. Earth Syst. Sci.*, *9*, 431–448, doi:10.5194/hess-9-431-2005, 2005.

Houze, R. A.: Stratiform precipitation in regions of convection: A meteorological paradox? *B. Am. Meteorol. Soc.*, *78*, 2179–2196, doi:10.1175/1520-0477(1997)078<2179:SPIROC>2.0.CO;2, 1997.

Jensen, H., Lang, H., and Rinderknecht, J.: Extreme point rainfall of varying duration and return period 1901-1970, in: Hydrological Atlas of Switzerland, Plate 2.4.2, Federal Office for the Environment FOEN, Berne, Switzerland, 1997.

Kao, S.-C. and Govindaraju, R. S.: A bivariate frequency analysis of extreme rainfall with implications for design, *J. Geophys. Res.*, *112*, D13119, doi:10.1029/2007JD008522, 2007.

Katsanos, D., Lagouvardos, K., Kotroni, V., and Argiriou, A.: Combined analysis of rainfall and lightning data produced by mesoscale systems in the central and eastern Mediterranean, *Atmos. Res.*, *83*, 55–63, doi:10.1016/j.atmosres.2006.01.012, 2007.

Katz, R. W., Parlange, M. B., and Naveau, P.: Statistics of extremes in hydrology, *Adv. Water Resour.*, *25*, 1287–1304, doi:10.1016/S0309-1708(02)00056-8, 2002.

Kinnell, P. I. A.: Event erosivity factor and errors in erosion predictions by some empirical models, *Aust. J. Soil Res.*, *41*, 991–1003, doi:10.1071/SR02123, 2003.

Kochtubajda, B., Burrows, W. R., Liu, A., and Patten, J. K.: Surface rainfall and cloud-to-ground lightning relationships in Canada, *Atmos. Ocean*, *51*, 226–238, doi:10.1080/07055900.2013.780154, 2013.

Kotroni, V. and Lagouvardos, K.: Lightning occurrence in relation with elevation, terrain slope, and vegetation cover in the Mediterranean, *J. Geophys. Res.*, *113*, D21118, doi:10.1029/2008JD010605, 2008.

Koutroulis, A. G., Grillakis, M. G., Tsanis, I. K., Kotroni, V., and Lagouvardos, K.: Lightning activity, rainfall and flash flooding - occasional or interrelated events? A case study in the island of Crete, *Nat. Hazards Earth Syst. Sci.*, *12*, 881–891, doi:10.5194/nhess-12-881-2012, 2012.

Koutsoyiannis, D., Kozonis, D., and Manetas, A.: A mathematical framework for studying rainfall intesity-duration-frequency relationships, *J. Hydrol.*, *206*, 118–135, doi:10.1016/S0022-1694(98)00097-3, 1998.

Kyselý, J., Gaál, L., Picek, J., and Schindler, M.: Return periods of the August 2010 heavy precipitation in northern Bohemia (Czech Republic) in present climate and under climate change, *J. Water Clim. Change*, *4*, 265–286, doi:10.2166/wcc.2013.051, 2013.

Lang, S., Tao, W. K., Simpson, J., and Ferrier, B.: Modeling of convective-stratiform precipitation processes: Sensitivity to partitioning methods, *J. Appl. Meteor.*, *42*, 505–527, doi:10.1175/1520-0450(2003)042<0505:MOCSPP>2.0.CO;2, 2003.

Llasat, M. C.: An objective classification of rainfall events on the basis of their convective features: application to rainfall intensity in the Northeast of Spain, *Int. J. Climatol.*, *21*, 1385–1400, doi:10.1002/joc.692, 2001.

Llasat, M. C.: High magnitude storms and floods, in: The Physical Geography of the Mediterranean, edited by: Woodward, J. C., Oxford University Press, Oxford, 513–540, 2009.

Llasat, M. C., Ceperuelo, M., and Rigo, T.: Rainfall regionalization on the basis of the precipitation convective features using a rain-gauge network and weather radar observations, *Atmos. Res.*, *83*, 415–426, doi:10.1016/j.atmosres.2005.08.014, 2007.

Llasat, M. C., Rigo, T., Ceperuelo, M., and Barrera, A.: Estimation of convective precipitation: the meteorological radar versus an automatic rain gauge network, *Adv. Geosci.*, *2*, 103–109, doi:10.5194/adgeo-2-103-2005, 2005.

Lloyd, C. R.: The temporal distribution of Amazonian rainfall and its implications for forest interception, *Q. J. Roy. Meteorol. Soc.*, *116*, 1487–1494, doi:10.1002/qj.49711649612, 1990.

Merz, R. and Blöschl, G.: A process typology of regional floods, *Water Resour. Res.*, *39*, 1340, doi:10.1029/2002WR001952, 2003.

Molnar, P. and Burlando, P.: Variability in the scale properties of high-resolution precipitation data in the Alpine climate of Switzerland, *Water Resour. Res.*, *44*, W10404, doi:10.1029/2007WR006142, 2008.

Overeem, A., Buishand, A., and Holleman, I.: Rainfall depth-duration-frequency curves and their uncertainties, *J. Hydrol.*, *348*, 124–134, doi:10.1016/j.jhydrol.2007.09.044, 2008.

Overeem, A., Buishand, A., and Holleman, I.: Extreme rainfall analysis and estimation of depth-duration-frequency curves using weather radar, *Water Resour. Res.*, *45*, W10424, doi:10.1029/2009WR007869, 2009.

Panziera, L. and Germann, U.: The relation between airflow and orographic precipitation on the southern side of the Alps as revealed by weather radar, *Q. J. Roy. Meteorol. Soc.*, *136*, 222–238, doi:10.1002/qj.544, 2010.

Paschalis, A., Molnar, P., and Burlando, P.: Temporal dependence structure in weights in a multiplicative cascade model for precipitation, *Water Resour. Res.*, *48*, W01501, doi:10.1029/2011WR010679, 2012.

Pešice, P., Sulan, J., and Řezáčová, D.: Convection precursors in the Czech territory, *Atmos. Res.*, *67–69*, 523–532, doi:10.1016/S0169-8095(03)0007, 2003.

Petersen, W. A. and Rutledge, S. A.: On the relationship between cloud-to-ground lightning and convective rainfall, *J. Geophys. Res.*, *103*, 14025–14040, doi:10.1029/97JD02064, 1998.

Pineda, N., Rigo, T., Bech, J., and Soler, X.: Lightning and precipitation relationship in summer thunderstorms: Case studies in the North Western Mediterranean region, *Atmos. Res.*, *85*, 159–170, doi:10.1016/j.atmosres.2006.12.004, 2007.

Price, C. and Federmesser, B.: Lightning-rainfall relationships in Mediterranean winter thunderstorms, *Geophys. Res. Lett.*, *33*, L07813, doi:10.1029/2005GL024794, 2006.

Price, C., Yair, Y., Mugnai, A., Lagouvardos, K., Llasat, M. C., Michaelides, S., Dayan, U., Dietrich, S., Di Paola, F., Galanti, E., Garrote, L., Harats, N., Katsanos, D., Kohn, M., Kotroni, V., Llasat-Botija, M., Lynn, B., Mediero, L., Morin, E., Nicolaides, K., Rozalis, S., Savvidou, K., and Ziv, B.: Using lightning data to better understand and predict flash floods in the Mediterranean, *Surv. Geophys.*, *32*, 733–751, doi:10.1007/s10712-011-9146-y, 2011.

Price, C., Yair, Y., Mugnai, A., Lagouvardos, K., Llasat, M. C., Michaelides, S., Dayan, U., Dietrich, S., Galanti, E., Garrote, L., Harats, N., Katsanos, D., Kohn, M., Kotroni, V., Llasat-Botija, M., Lynng, B., Mediero, L., Morin, E., Nicolaides, K., Rozalis, S., Savvidou, K., and Ziv, B.: The FLASH Project: using lightning data to better understand and predict flash floods, *Environmental Science and Policy*, *14*, 898–911, doi:10.1016/j.envsci.2011.03.004, 2011.

Reinhold, F.: Regenspenden in Deutschland (Grundwerte fr die Entwsserungstechnik, GE 1940), Archiv für Wasserwirtschaft, Heft Nr. 56, Reichsverband der Deutschen Wasserwirtschaft, Berlin, 1940.

Restrepo-Posada, P. J. and Eagleson, P.S.: Identification of independent rainstorms, *J. Hydrol.*, *55*, 303–319, doi:10.1016/0022-1694(82)90136-6, 1982.

Rigo, T. and Llasat, M. C.: A methodology for the classification of convective structures using meteorological radar: Application to heavy rainfall events on the Mediterranean coast of the Iberian Peninsula, *Nat. Hazards Earth Syst. Sci.*, *4*, 59–68, doi:10.5194/nhess-4-59-2004, 2004.

Rigo, T. and Llasat, M. C.: Analysis of mesoscale convective systems in Catalonia using meteorological radar for the period 1996-2000, *Atmos. Res.*, *83*, 458–472, doi:10.1016/j.atmosres.2005.10.016, 2007.

Rivas Soriano, L. and De Pablo, F.: Analysis of convective precipitation in the western Mediterranean Sea through the use of cloud-to-ground lightning, *Atmos. Res.*, *66*, 189–202, doi:10.1016/S0169-8095, 2003.

Rivas Soriano, L., De Pablo, F., and Garcia Diez, E.: Relationship between convective precipitation and cloud-to-ground lightning in the Iberian peninsula, *Mon. Weather Rev.*, *129*, 2998–3003, doi:10.1175/1520-0493(2001)129<2998:RBCPAC>2.0.CO;2, 2001.

Ruiz-Leo, A. M., Hernandez, E., Queralt, S., and Maqueda, G.: Convective and stratiform precipitation trends in the Spanish Mediterranean coast, *Atmos. Res.*, *119*, 46–55, doi:10.1016/j.atmosres.2011.07.019, 2013.

Rulfová, Z. and Kyselý, J.: Disaggregating convective and stratiform precipitation from station weather data, *Atmos. Res.*, *134*, 100–115, doi:10.1016/j.atmosres.2013.07.015, 2013.

Serinaldi, F.: Analysis of inter-gauge dependence by Kendall's tau, upper tail dependence coefficient, and 2-copulas with application to rainfall fields, *Stoch. Env. Res. Risk A.*, *22*, 671–688, doi:10.1007/s00477-007-0176-4, 2008.

Schüepp, M. and Gensler, G.: Klimaregionen der Schweiz, in: Die Beobachtungsnetze der Schweizerischen Meteorologischen Anstalt, Konzept 1980, edited by Müller, G., Arbeitsberichte der Schweizerischen Meteorologischen Anstalt Nr. 93, Anhang Ib. Zürich, 1980.

Tadesse, A. and Anagnostou, E. N.: Characterization of warm season convective systems over US in terms of cloud to ground lightning, cloud kinematics, and precipitation, *Atmos. Res.*, *91*, 36–46, doi:10.1016/j.atmosres.2008.05.009., 2009.

Tapia, A., Smith, J. A., and Dixon, M.: Estimation of convective rainfall from lightning observations, *J. Appl. Meteorol.*, *37*, 1497–1509, doi:10.1175/1520-0450(1998)037<1497:EOCRFL>2.0.CO;2, 1998.

Tremblay, A.: The stratiform and convective components of surface precipitation, *J. Atmos. Sci.*, *62*, 1513–1528, doi:10.1175/JAS3411.1, 2005.

Vandenberghe, S., Verhoest, N. E. C., and De Baets, B.: Fitting bivariate copulas to the dependence structure between storm characteristics: A detailed analysis based on 105 year 10 min rainfall, *Water Resour. Res.*, *46*, W01512, doi:10.1029/2009WR007857, 2010.

Velikanov, M. A.: Gidrologia susi. Gidrometeoidzat, Leningrad, 1964.

Vörösmarty, Ch. J., de Guenni, L. B., Wollheim, W. M., Pellerin, B., Bjerklie, D., Cardoso, M., D'Almeida, C., Green, P., and Colon, L.: Extreme rainfall, vulnerability and risk: a continental-scale assessment for South America, *Philos. T. Roy. Soc. A*, *371*, 20120408, doi:10.1098/rsta.2012.0408, 2013.

Watson, P. A., Gunes, M., Potter, B. A., Sathiaseelan, V., and Leitas, D. J.: Development of a climatic map of rainfall attenuation for Europe. Final Report of the European Space Agency, ESTEC

CONTR. No. 4162/79/NL, Postgraduate School of Electrical and Electronic Engineering, University of Bradford, UK, 1982.

Wilhelmi, O. V. and Morrs, R. E.: Integrated analysis of societal vulnerability in an extreme precipitation event: A Fort Collins case study, *Environ. Sci. Policy*, *26*, 49–62, doi:10.1016/j.envsci.2012.07.005, 2013.

Winsemius, H. C., Van Beek, L. P. H., Jongman, B., Ward, P. J., and Bouwman, A.: A framework for global river flood risk assessments, *Hydrol. Earth Syst. Sci*, *17*, 1871–1892, doi:10.5194/hess-17-1871-2013, 2013.

Wischmeier, W. H. and Smith, D. D.: Predicting rainfall erosion losses-a guide to conservation planning, Agriculture Handbook, No. 537, US Department of Agriculture, Washington, DC, 1978.

Wussow, G.: Untere Grenzwerte dichter Regenfälle, Meteorol. Z., *39*, 173–178, 1922.

Yair, Y., Lynn, B., Price, C., Kotroni, V., Lagouvardos, K., Morin, E., Mugnai, A., and Llasat, M. C.: Predicting the potential for lightning activity in Mediterranean storms based on the Weather Research and Forecasting (WRF) model dynamic and microphysical fields, *J. Geophys. Res.*, *115*, D04205, doi:10.1029/2008JD010868, 2010.

Zeng, N., Shuttleworth, J. W., and Gash, J. H. C.: Influence of temporal variability of rainfall on interception loss. Part I. Point analysis, *J. Hydrol.*, *228*, 228–241, doi:10.1016/S0022-1694(00)00140-2, 2000.

Zimmer, M., Craig, G. C., Keil, C., and Wernli, H.: Classification of precipitation events with a convective response timescale and their forecasting characteristics, *Geophys. Res. Lett.*, *38*, L05802, doi:10.1029/2010GL046199, 2011.
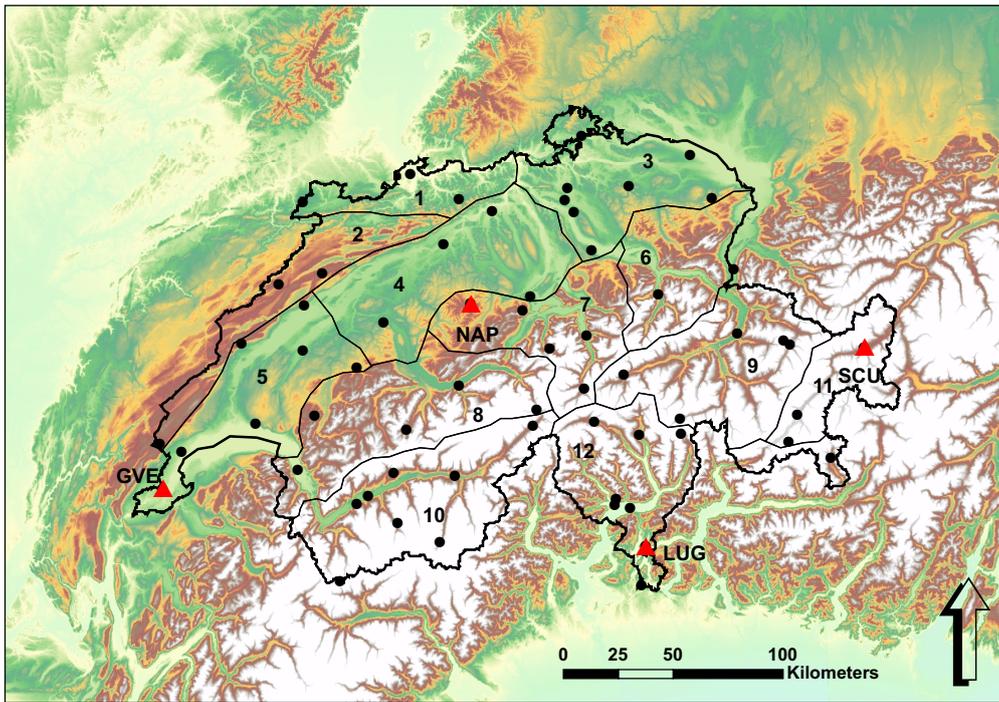
Fig. 1. The SwissMetNet stations in 12 climatic regions defined by Schüepp and Gensler (1980). The four selected stations in this paper are marked by red triangles: GVE - Geneve-Cointrin, NAP - Napf, SCU - Scuol, LUG - Lugano.
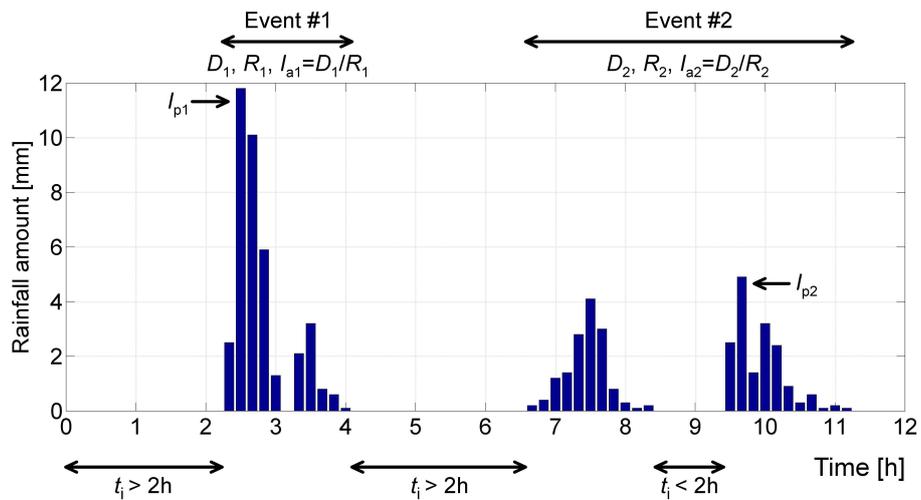

Fig. 2. A schematic to illustrate the identification of independent rainfall events (storms). Symbols: D - event duration, R - total rainfall depth, I_a - average rainfall intensity, I_p - peak 10-min intensity, t_i - inter-arrival time.
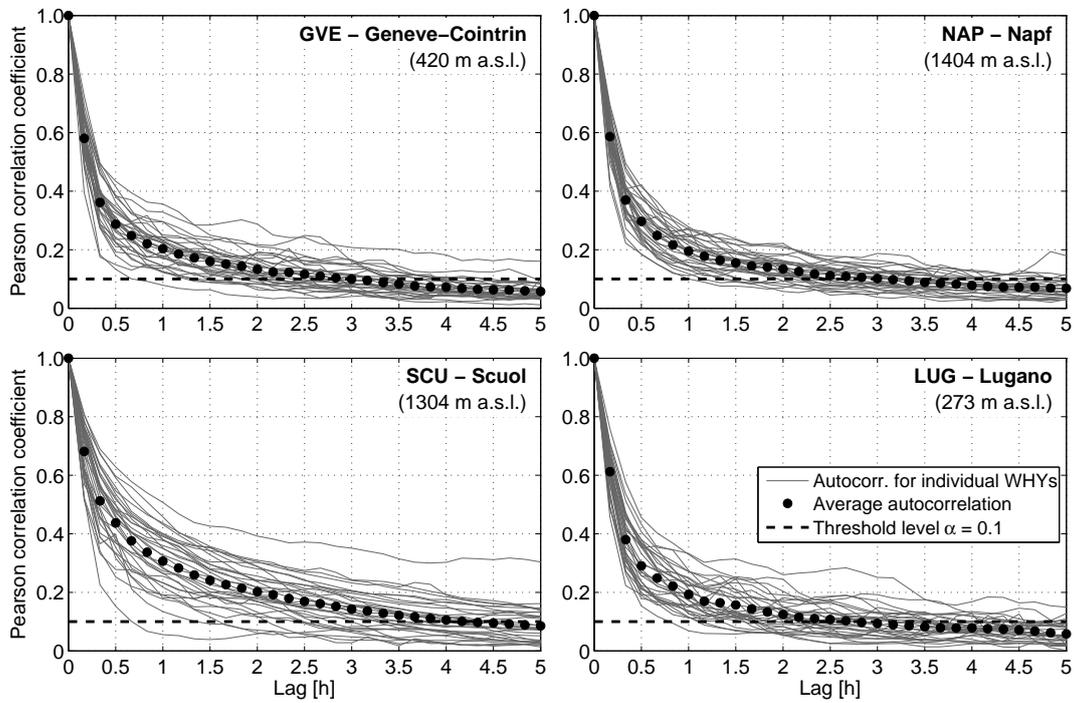
Fig. 3. Autocorrelograms for the selected 4 stations. Solid lines represent the autocorrelation coefficients for the individual warm half-years (abbr. WHY) with lags of 10 mins. The dots show the average of the autocorrelation functions over all years. The dashed horizontal straight line is the critical correlation for the significance level 10%.
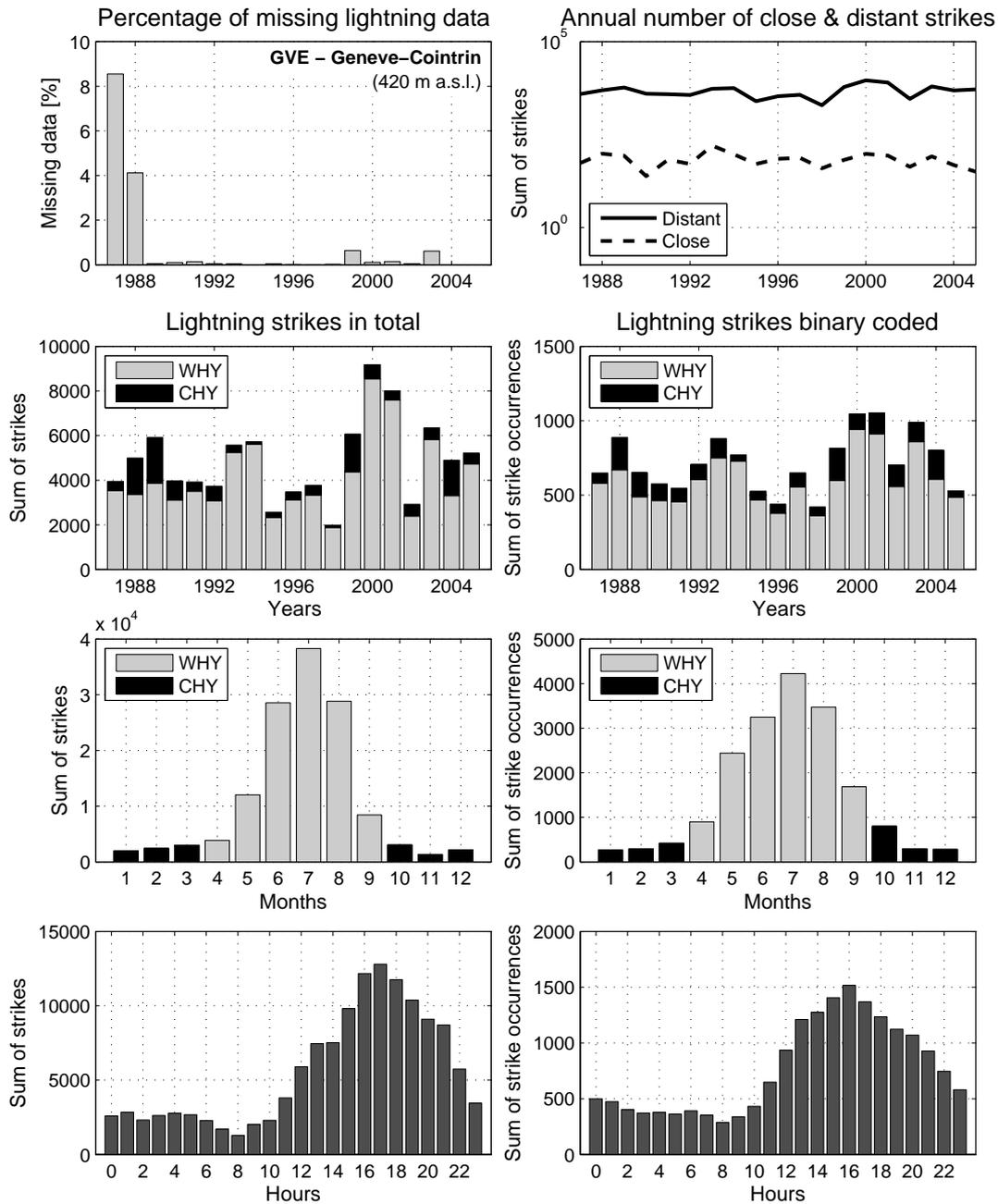
Fig. 4. Lightning data statistics for the station Geneve - Cointrin. Top left: percentage of missing (N/A) lightning data in each year. Top right: annual sums of close and distant lightning. The remaining figures show the distribution of all the observed lightning (regardless whether close or distant) from an annual (row 2), seasonal (row 3) and daily (row 4) perspective. Left panels show the actual number of lightning strikes, right panels show the sums of the lightning occurrence (binary per 10 min interval). WHY (CHY) stands for warm (cold) half-year. Time is in UTC, which is -2 h LT (summer) and -1 h LT (winter).
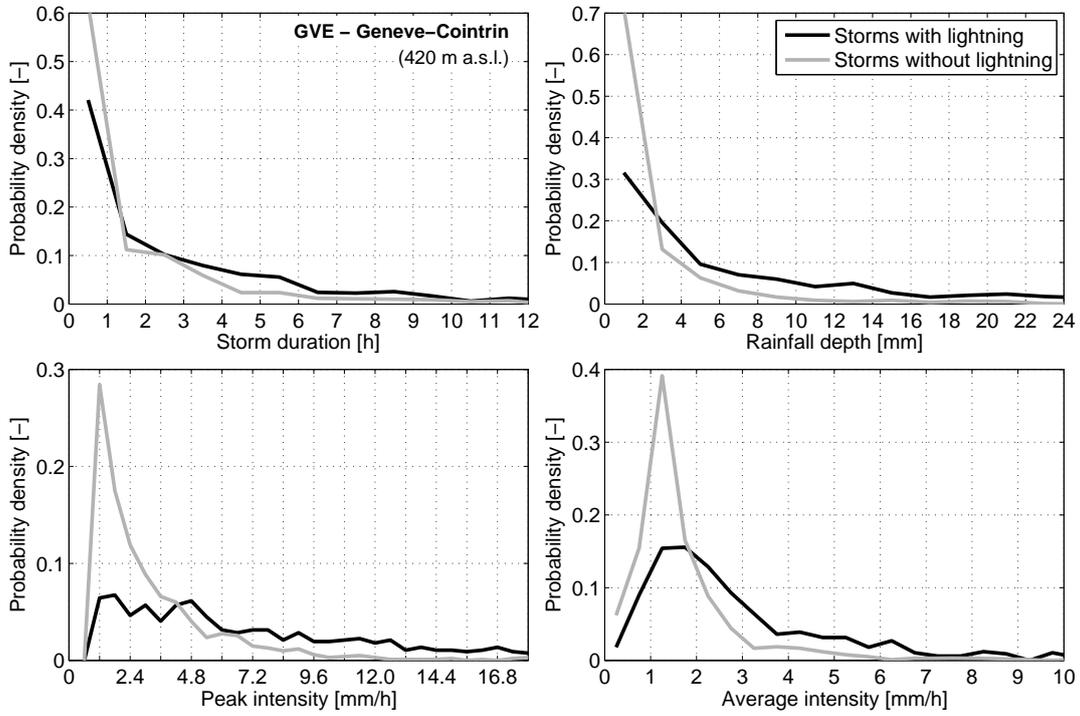
Fig. 5. Empirical probability density functions (PDFs) for the main storm properties: total rainfall depth R (top left), storm duration D (top right), peak intensity I_p (bottom left) and average storm intensity I_a (bottom right), differentiated by lightning, for station Geneve - Cointrin.
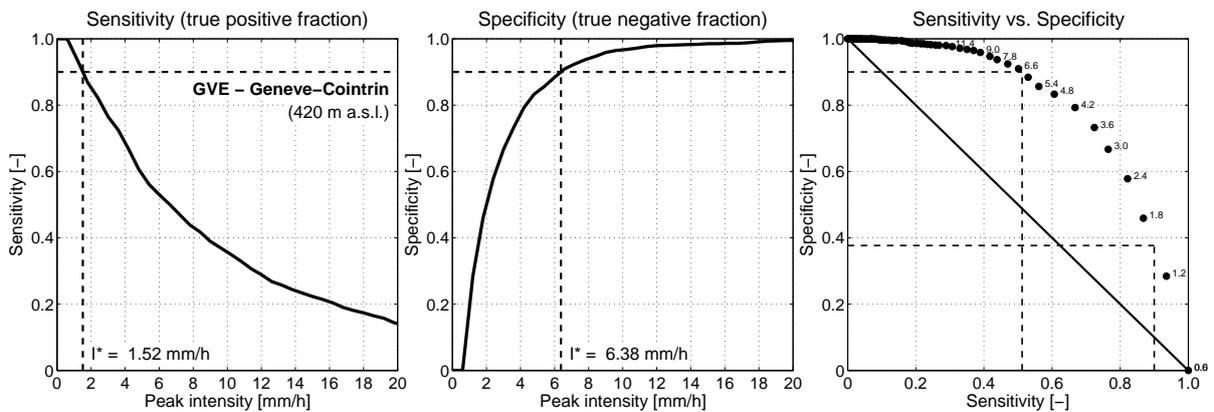

Fig. 6. Estimation of the threshold peak intensity I^* on the basis of sensitivity (left) and specificity (center) at station Geneve - Cointrin. The plot on the right shows the inter-relation of sensitivity and specificity at the same station. The numbers within the plot indicate the corresponding value of peak intensity in mm/h.
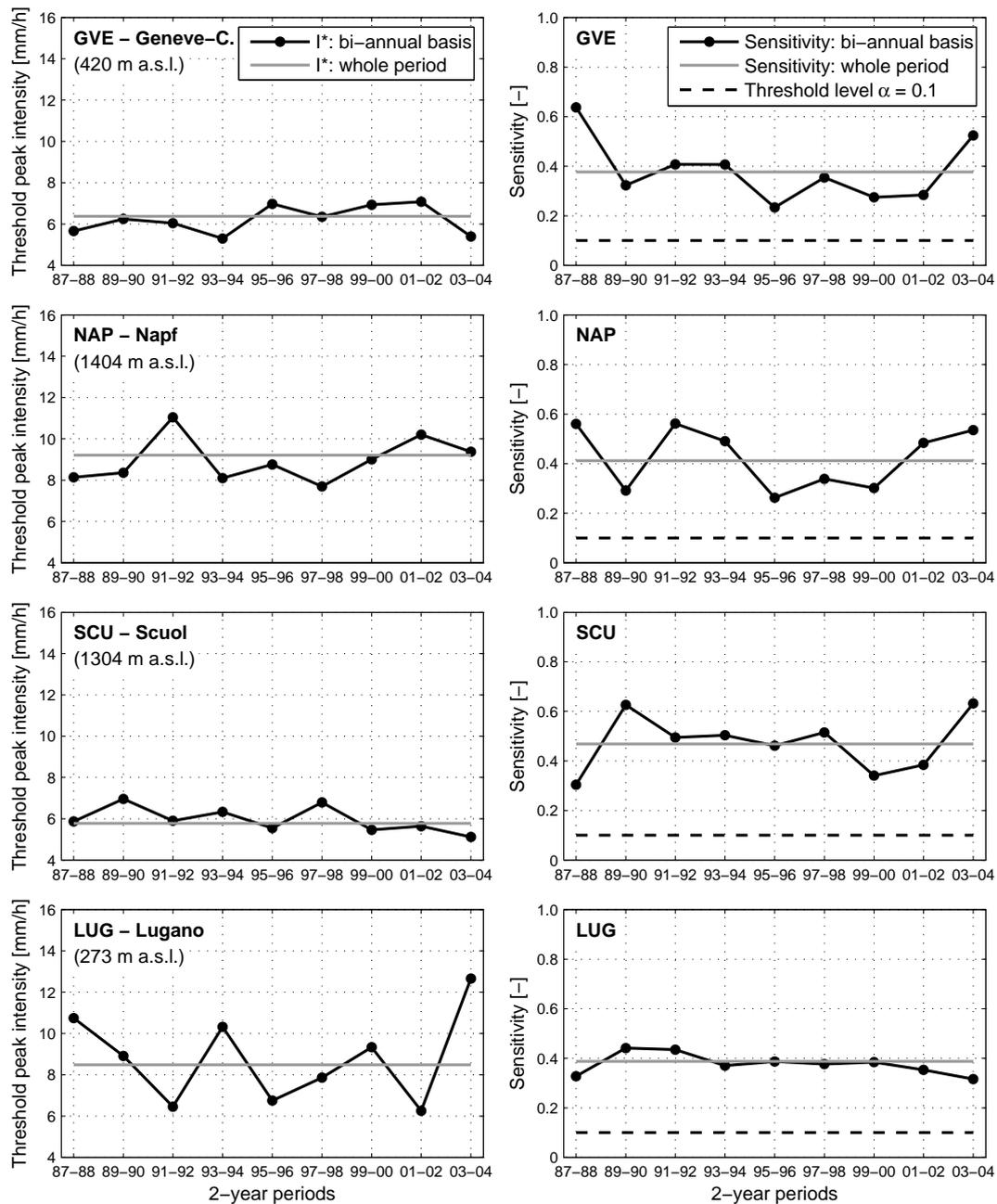
Fig. 7. Threshold peak intensity I^* estimated on a bi-annual basis (left) and the sensitivity corresponding to I^* on a bi-annual basis (right) at the studied stations. The dashed horizontal line on the right panels denotes the chosen misclassification error $\alpha = 0.1$.
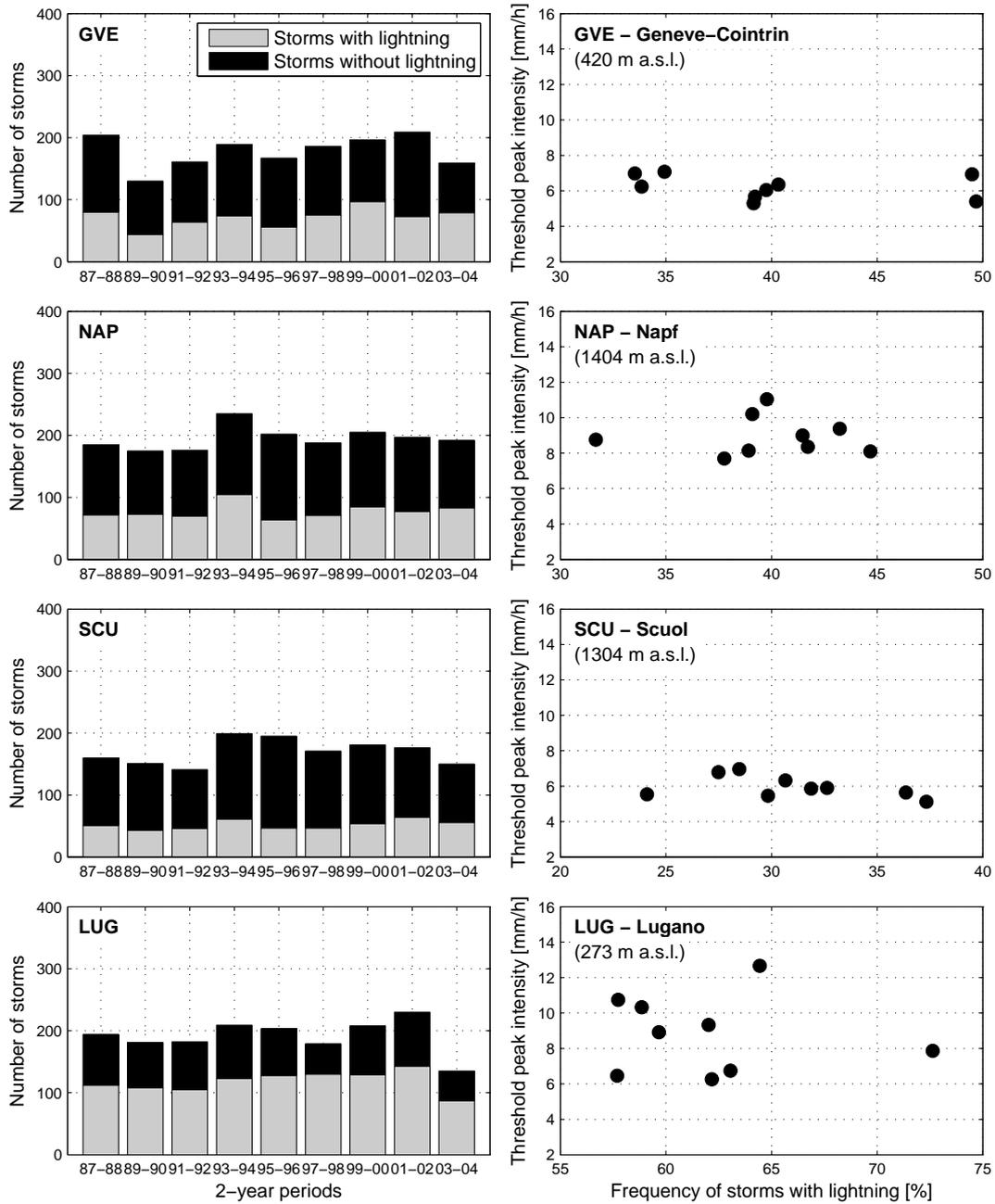
Fig. 8. Number of storms with and without lightning on a bi-annual basis (left) and the relationship between threshold peak intensity I^* and the frequency of storms with lightning on a bi-annual basis (right) at the studied stations. Note the different scale of x axes for the stations.
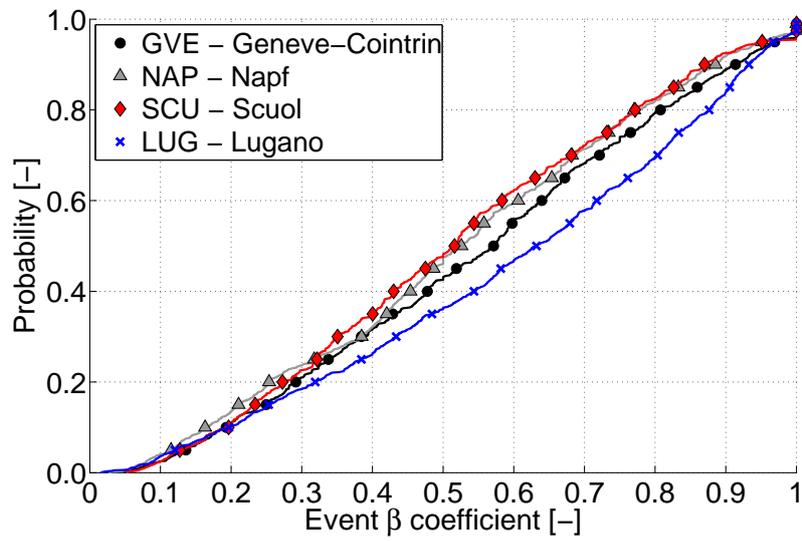
Fig. 9. Cumulative distributions (non-exceedance probability) of event β coefficients for all the storms with $I_p \geq I^*$ (i.e., $\beta > 0$), for the studied stations.
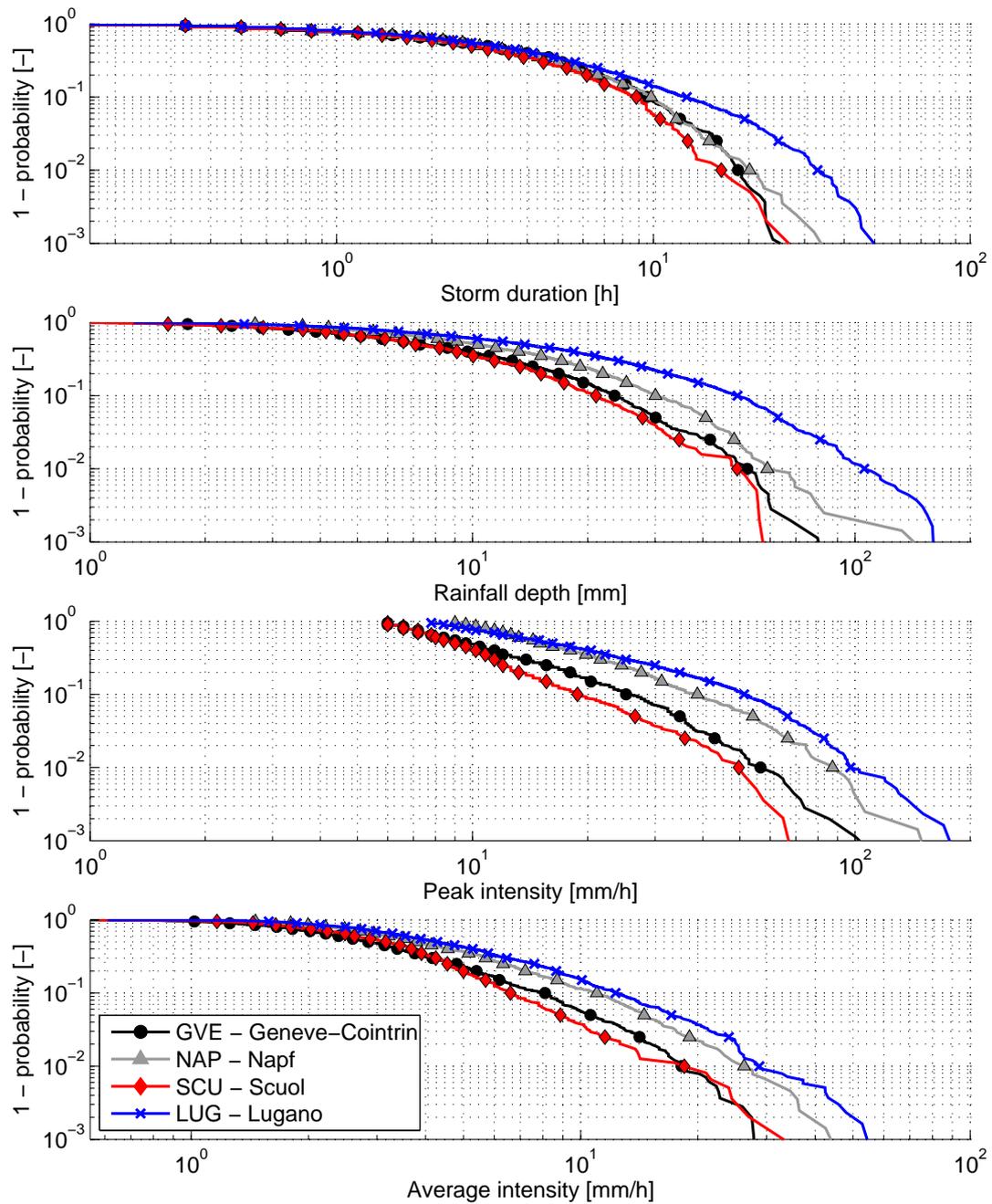
Fig. 10. Cumulative distributions (exceedance probability) of main storm properties for intense warm season storms: storm duration D, total rainfall depth R, peak intensity I_p and average storm intensity I_a (from top to bottom) at the studied stations.
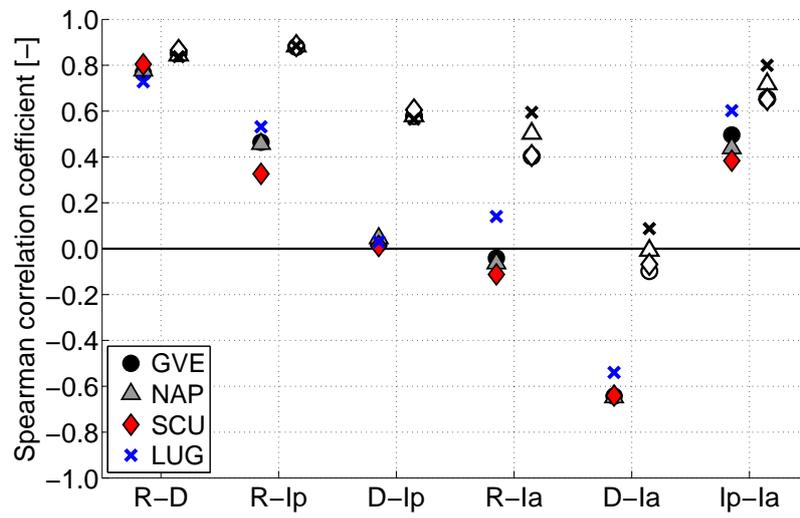
Fig. 11. Spearman rank correlation coefficients between pairs of main storm properties (storm duration D, total rainfall depth R, peak intensity I_p and average storm intensity I_a) for intense warm season storms (filled, color markers) and all storms (empty markers) at the studied stations.

Table 1. Main properties of the four selected SwissMetNet stations in this analysis: Geneve-Cointrin (GVE), Napf (NAP), Scuol (SCU) and Lugano (LUG). The storm statistics shown are for the warm season (April-September) with an additional constraint that air temperature $T > 4°C$ during an event.

Station	GVE	NAP	SCU	LUG
Station properties				
Altitude [m a.s.l.]	420	1404	1304	273
Mean annual precipitation (1961–1990) [mm]	822	1736	693	1454
Climatological region (Schüepp and Gensler, 1980)	5	4	11	12
Event statistics (1987–2005)				
Mean number of events [no/yr]	88.7	98.0	84.0	94.9
Mean number of events with lightning [no/yr and %]	35.1 (39.6)	38.6 (39.4)	25.8 (30.8)	58.5 (61.6)
Threshold peak intensity I^* [mm/h]	6.4	9.2	5.8	8.5
Storm characteristics (1981–2012)				
Mean number of events $I_p > I^*$ [no/yr and %]	24.6 (28)	26.8 (28)	19.6 (24)	34.3 (37)
Total rainfall depth, mean (stdev) [mm]	11.1 (10.5)	14.8 (14.2)	9.8 (8.7)	21.1 (21.3)
Storm duration, mean (stdev) [h]	3.7 (3.9)	4.1 (4.3)	3.6 (3.4)	4.6 (5.4)
Average storm intensity, mean (stdev) [mm/h]	4.7 (4.0)	5.6 (5.2)	3.9 (3.3)	7.0 (6.5)
Peak 10-min intensity, mean (stdev) [mm/h]	15.8 (12.3)	21.9 (16.5)	11.6 (8.2)	27.8 (22.7)