

Selection of intense storms by rainfall intensity and lightning

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

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Abstract

This paper presents a method to identify intense warm season storms of convective character based on intensity thresholds and 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 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, and highest in Lugano in southern Switzerland. Non-parametric correlations between the main storm properties were estimated for the subsets of 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 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 Morris, 2013; Kysely et al., 2013), and is inseparably related to flood risk (e.g. Hlavcova et al., 2005; Blöschl, 2008; Borga 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

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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 and should be known with the highest possible reliability both for 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; Tremblay, 2005; Llasat et al., 2007; Berg et al., 2013; Ruiz-Leo et al., 2013; Rulfová and Kyselý, 2013). Weather radar provide 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

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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 SwissMetNet 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 yr) and lightning strikes for the period 1987 to 2005 (19 yr) at 62 stations with about 3000 m altitude difference (Fig. 1).

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 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 (Fig. 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,

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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, 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 within an event $T > 4^\circ\text{C}$ 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 ($0.1\text{ mm } 10\text{ min}^{-1}$) because these are often artifacts of condensation and water 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 (Fig. 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 h (e.g. Dunkerley, 2008, 2010). In our study we have chosen $t_i = 2\text{ h}$ 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) (Fig. 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 Scuol to 98 (0.54 per day) at Napf in the pre-Alpine area.

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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 to ensure 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 Pearson correlation coefficient 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 Fig. 3. The statistical significance was tested at the significance level 10%. The de-correlation time ranged between 2 and 3 h, and this was similar for the majority of the 62 SwissMetNet stations. Some mountain stations,

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such as Scuol in Fig. 3, show slightly longer de-correlation times. From this result we conclude that $t_i = 2$ h 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 yr). 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 (≈ 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.

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 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

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quantity, and only the presence or absence of lightning, the seasonal and diurnal statistics do not change appreciably.

Lightning data sheets like that in Fig. 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),

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

All events belonging to the set of intense events then have $0 < \beta \leq 1$ and those that are less 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 Sect. 3.1 we first analyze the storm properties for all events with and without lightning, and in Sect. 3.2 we then develop a statistical approach to estimate I^* based on lightning data.

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3.1 Storm properties and lightning counts

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 % (Scul), 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 lightning.

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

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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 vs. specificity for a range of I^* (see Fig. 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⁻¹ at the four stations (Table 1).

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4 Results

We present the results by first discussing the calibrated intensity thresholds I^* with regard to previous studies of rainfall extremes. 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⁻¹) are lower than what is reported in most climatological and engineering hydrology literature for extreme events. For example, Dutton and Dougherty (1979) and Watson et al. (1982) present a threshold of 48–50 mm h⁻¹ 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⁻¹, and a threshold for average hourly intensities for heavy rainfall defined by the Spanish National Meteorological Institute is 15 mm h⁻¹. 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⁻¹, and Reinhold (1940) classified heavy rainfall when intensities for 10 min durations exceeded 40 mm h⁻¹. Velikanov (1964) describes a classification where the threshold for 10 min intensive rainfall is given as 3.8 mm, i.e. 23 mm h⁻¹. 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⁻¹ (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 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

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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 Fig. 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 yr record (until 2004) with reliable lightning data for all four stations in the left panel in Fig. 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 Fig. 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

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are shown in the left panel in Fig. 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 Fig. 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 Fig. 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 Fig. 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^{-1} in Lugano, 25 mm h^{-1} in Napf and 20 mm h^{-1} in Geneve. In a subsequent study we will

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explore the full spatial distribution of event properties across all 62 stations in Switzerland.

One of our main aims was to quantify the correlations 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. 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. The Spearman rank correlation coefficient estimated for all 6 pairs of variables and all stations is shown in Fig. 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, and this correlation is strongest in the convective intense event set.

Some of the correlation coefficients in the event sets are statistically significant (Fig. 11) and they suggest that a multivariate approach, for instance on the basis of copulas, is necessary 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 stations 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.

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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⁻¹ 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 based on peak 10 min intensity, which at the same time coincide

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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 affected by the Mediterranean, than in the other stations. An event from our subset with an exceedance probability of 20 %, that is an event that occurs about 5–6 times a year, has $I_p = 40 \text{ mm h}^{-1}$ in Lugano, $I_p = 25 \text{ mm h}^{-1}$ in Napf and $I_p = 20 \text{ mm h}^{-1}$ in Geneve. 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 finally 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 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 are significant and greater than those between stations, which indicates that care must be exercised not to mix events when they are sampled for multivariate analysis, e.g. copula fitting to rainfall data.

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

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Table 1. Main properties of the four selected SwissMetNet stations in this analysis: Geneva-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 mean event temperature $T > 4^\circ\text{C}$.

Station	GVE	NAP	SCU	LUG
<i>Station properties</i>				
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
<i>Storm event statistics</i>				
Mean number of events [noyr^{-1}]	88.7	98.0	84.0	94.9
Mean number of events with lightning [noyr^{-1} and %]	35.1 (39.6)	38.6 (39.4)	25.8 (30.8)	58.5 (61.6)
Threshold peak intensity I^* [mm h^{-1}]	6.4	9.2	5.8	8.5
<i>Storm characteristics (1981–2012)</i>				
Mean number of events $I_p > I^*$ [noyr^{-1} 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^{-1}]	4.7 (4.0)	5.6 (5.2)	3.9 (3.3)	7.0 (6.5)
Peak 10 min intensity, mean (stdev) [mm h^{-1}]	15.8 (12.3)	21.9 (16.5)	11.6 (8.2)	27.8 (22.7)

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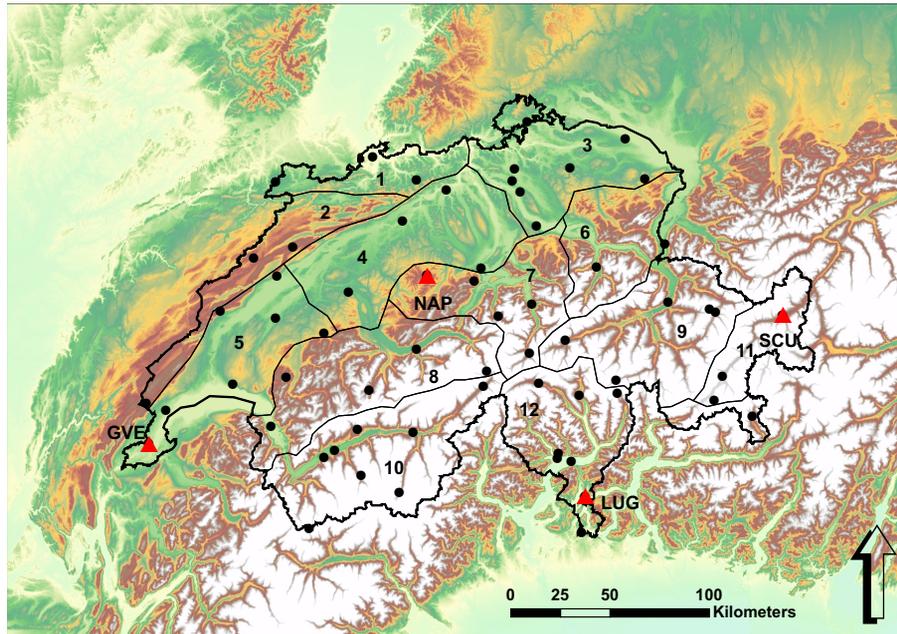


Fig. 1. The SwissMetNet stations in 12 climatic regions defined by Schüepp and Gensler (1980). The four selected stations in this paper are marked by red triangles: GVE – Geneve-Cointrin, NAP – Napf, SCU – Scuol, LUG – Lugano.

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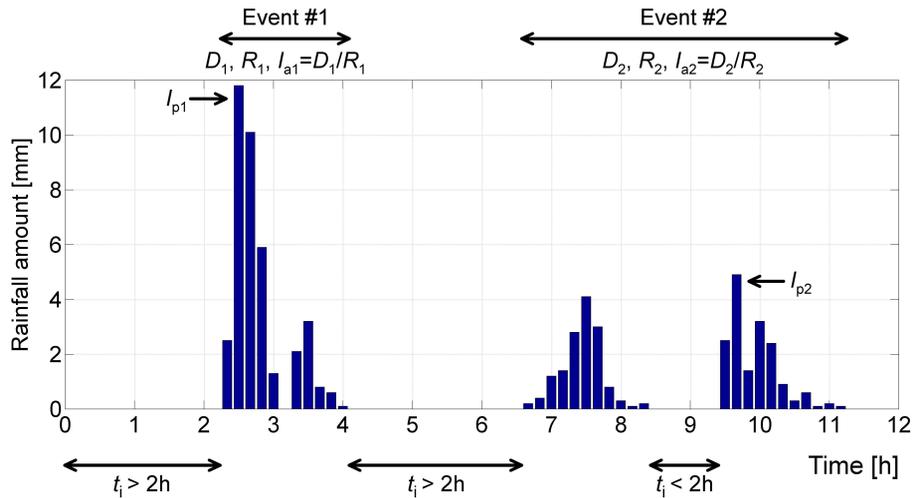


Fig. 2. A schematic to illustrate the identification of independent rainfall events (storms). Symbols: D – event duration, R – total rainfall depth, I_a – average rainfall intensity, I_p – peak 10 min intensity, t_i – inter-arrival time.

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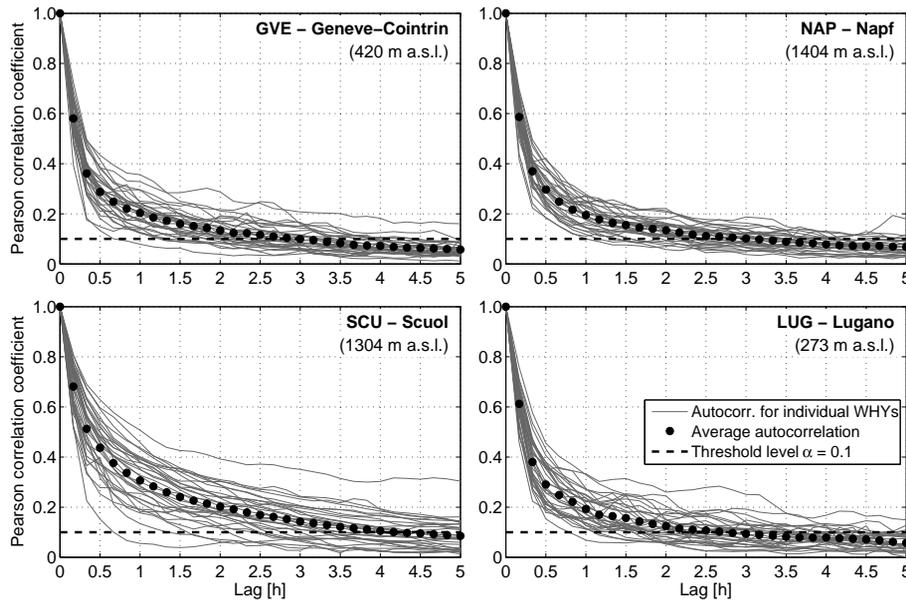


Fig. 3. Autocorrelograms for the selected 4 stations. Solid lines represent the autocorrelation coefficients for the individual warm half-years (abbr. WHY) with lags of 10 min. The dots show the average of the autocorrelation functions over all years. The dashed horizontal straight line is the critical correlation for the significance level 10%.

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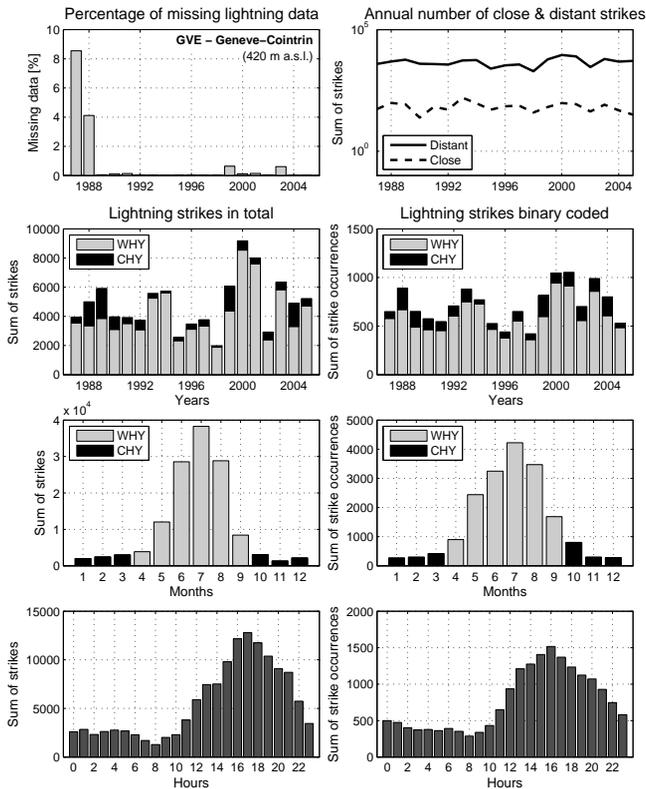


Fig. 4. Lightning data statistics for the station Geneve-Cointrin. Top left: percentage of missing (N/A) lightning data in each year. Top right: annual sums of close and distant lightning. The remaining figures show the distribution of all the observed lightning (regardless whether close or distant) from an annual (row 2), seasonal (row 3) and daily (row 4) perspective. Left panels show the actual number of lightning strikes, while 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).

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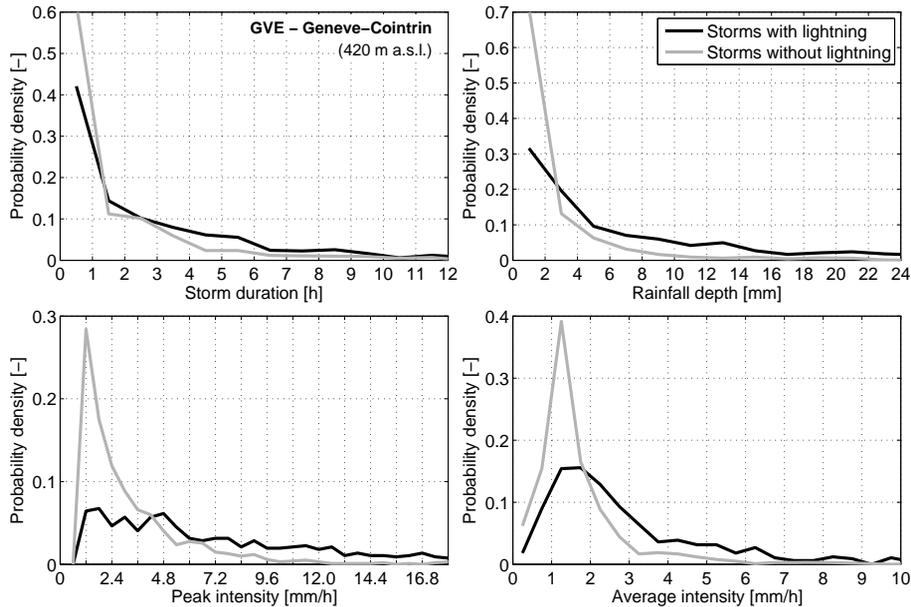


Fig. 5. Empirical probability density functions (PDFs) for the main storm properties: total rainfall depth R (top left panel), storm duration D (top right panel), peak intensity I_p (bottom left panel) and average storm intensity I_a (bottom right panel), differentiated by lightning, for station Geneve-Cointrin.

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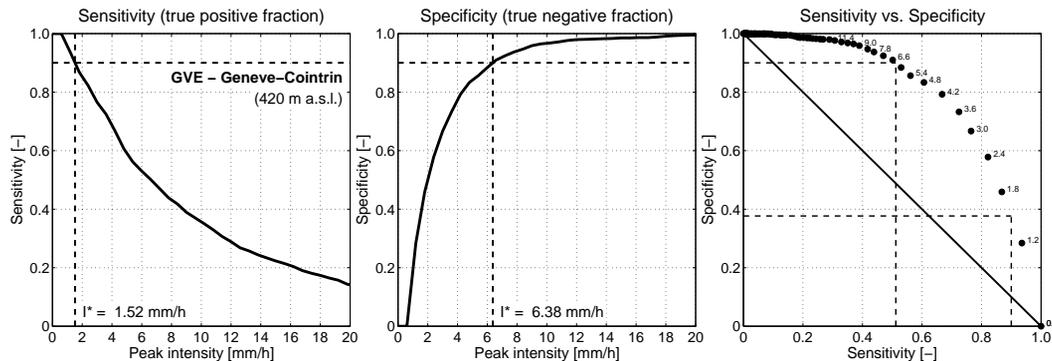


Fig. 6. Estimation of the threshold peak intensity I^* on the basis of sensitivity (left panel) and specificity (middle panel) at station Geneve-Cointrin. The right panel shows the inter-relation of sensitivity and specificity at the same station. The numbers within the plot indicate the corresponding value of peak intensity in mm h^{-1} .

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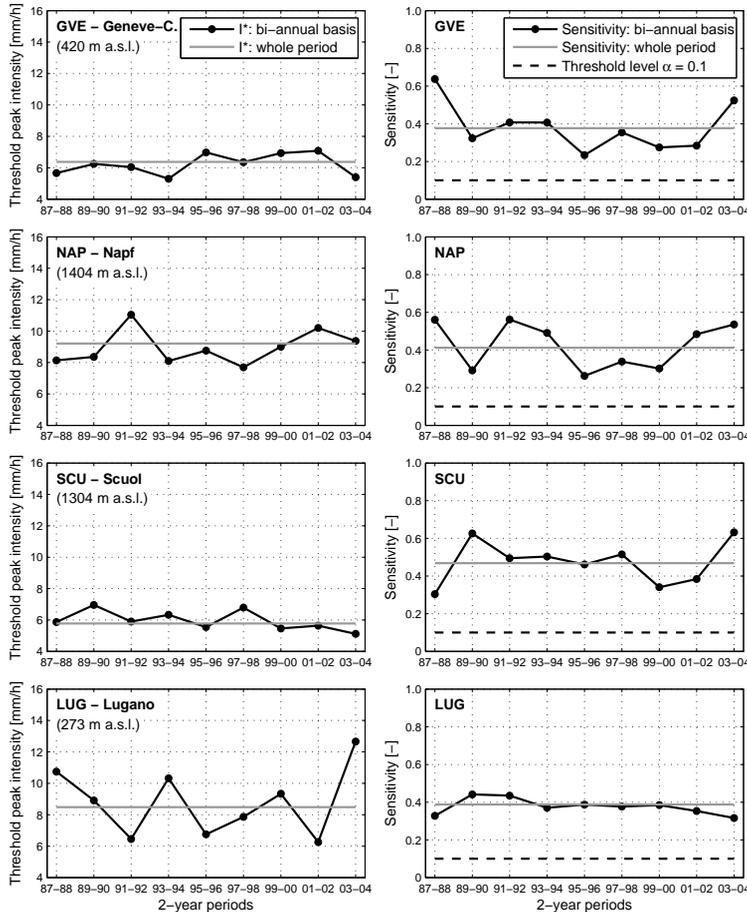


Fig. 7. Threshold peak intensity I^* estimated on a bi-annual basis (left panel) and the sensitivity corresponding to I^* on a bi-annual basis (right panel) at the studied stations. The dashed horizontal line on the right side denotes the chosen misclassification error $\alpha = 0.1$.

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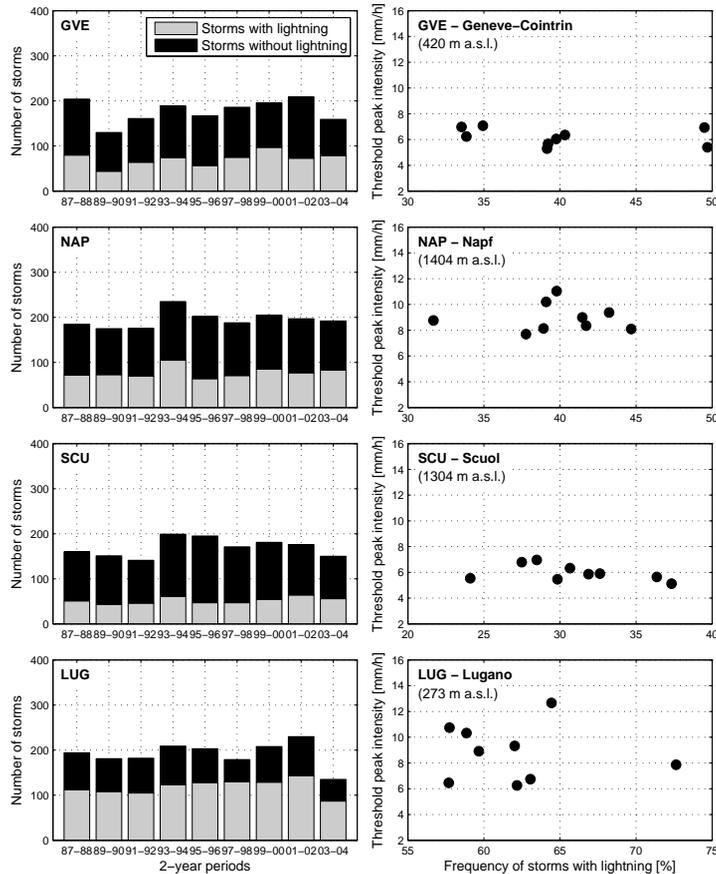


Fig. 8. Number of storms with and without lightning on a bi-annual basis (left panels) and the relationship between threshold peak intensity I^* and the frequency of storms with lightning on a bi-annual basis (right panels) at the studied stations. Note the different scale of x axes for the stations.

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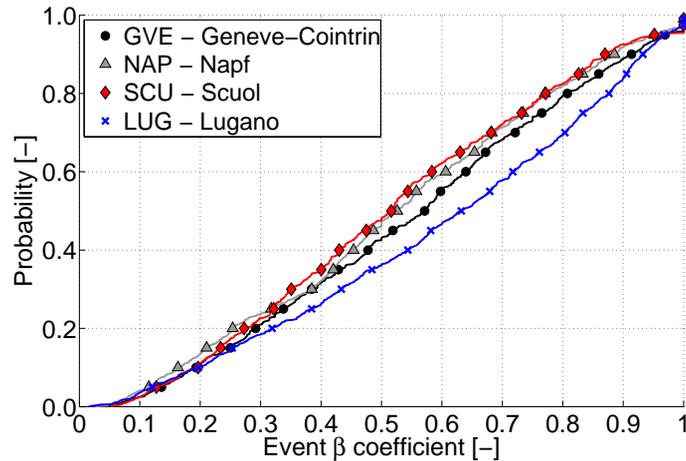


Fig. 9. Cumulative distributions (non-exceedance probability) of event β coefficients for all the storms with $I_p \geq I^*$ (i.e. $\beta > 0$), for the studied stations.

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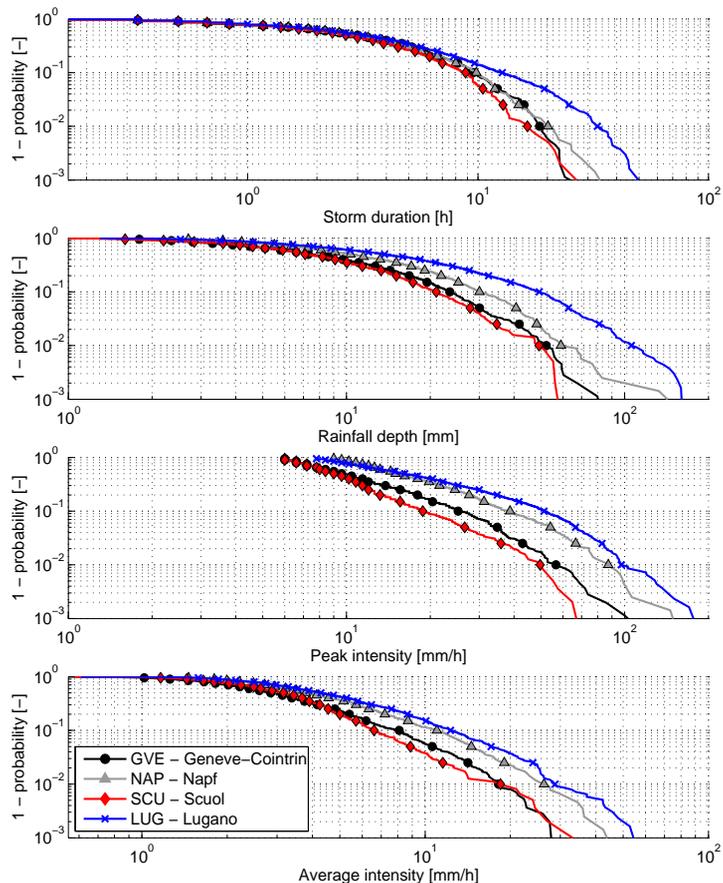


Fig. 10. Cumulative distributions (exceedance probability) of main storm properties for intense warm season storms: storm duration D , total rainfall depth R , peak intensity I_p and average storm intensity I_a (from top to bottom panels) at the studied stations.

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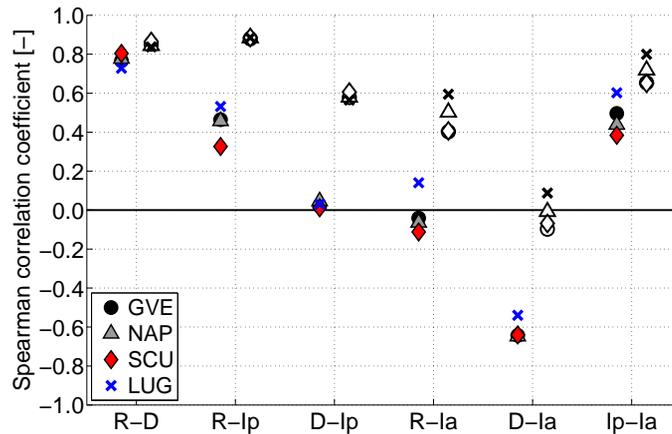


Fig. 11. Spearman rank correlation coefficients between pairs of main storm properties (storm duration D , total rainfall depth R , peak intensity I_p and average storm intensity I_a) for intense warm season storms (filled, color markers) and all storms (empty markers) at the studied stations.

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