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Technical note: Space-time analysis of rainfall extremes in Italy: clues from a reconciled dataset

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Abstract. Like other Mediterranean areas, Italy is prone to the development of events with explosive rainfall intensity, lasting for several hours. The main triggering mechanisms of these events are quite well known but the aim of developing rainstorm hazard maps compatible with their actual probability of occurrence is still far from being reached. A systematic frequency analysis of these occasional highly intense events would require a complete countrywide dataset of sub-daily rainfall records, but this kind of information was still lacking for the Italian territory. In this work several sources of data are gathered, for assembling the first comprehensive and updated dataset of extreme rainfall of short duration in Italy. The resulting dataset, referred to as Italian Rainfall Extreme Dataset (*I-RED*), includes the annual maximum rainfalls recorded in 1 to 24 consecutive hours from more than 4500 stations across the country, spanning the period between 1916 and 2014. A detailed description of the spatial and temporal coverage of the *I-RED* is presented, together with an exploratory statistical analysis aimed at providing preliminary information on the climatology of extreme rainfall at the national scale. Taking into account the potentialities emerging from the analysis, a description of the ongoing and planned future work activities on the database is provided.

1 Introduction

Italy can boast of a role at the highest level in the development of meteorological observations (Brunetti et al., 2006), with 6 meteorological stations operating since the eighteenth century (Bologna, Milano, Roma, Padova, Palermo and Torino), and 15 stations with observation starting in the first half of the nineteenth century. First attempts of performing a systematic collection of monthly rainfall data go back to as early as 1880 when the National Office for Meteorology and Climate was funded. The National Hydrographic Service (*SIN*) and the National Hydrographic and Mareographic Service (*SIMN*) collected annual maxima values for 1-3-6-12 and 24 hours durations in the Hydrological Yearbooks from 1917 to early 2000s (the final publication year depends on the local agencies of the *SIMN*). The Legislative Decree 112/1998 dismantled the *SIMN*, transferring its tasks to the 19 administrative regions and the 2 autonomous provinces of Trento and Bolzano. These authorities were designated as local Operational Centres and Regional Environmental Agencies to deal with hydro-meteorological monitoring and civil protection issues.

In spite of the huge heritage of data, only a small fraction of the Italian rainfall data is available in a computer-readable format. Moreover, the dismantledment of the National Service led to a lack of update of the national database of extreme rainfall that is still stucked, for some regions, at the beginning of the '90s. This has led to a very fragmented framework:

updated rainstorm hazard assessments are actually only available for some regions and only at the regional scale (see, e.g., Uboldi et al. (2014); Libertino et al. (2017)). Various regional studies present different metodologies and are sometimes based on very different data densities and record lengths (e.g., Claps et al., 2016), but only few updated analyses on short-duration rainfall in a over-regional framework are available (e.g., Rudari et al., 2005; Allamano et al., 2009).

In view of the assembling of the first comprehensive dataset of extreme rainfall of short duration in Italy several major sources of data have been analysed. The resulting dataset, referred to as Italian Rainfall Extremes Database (*I-RED*), includes data from more than 4500 stations across the country, spanning the period between 1916 and 2014, and refers to annual maximum rainfall recorded in 1 to 24 consecutive hours (exact durations available are 1-3-6-12 and 24 hours).

The following sections describes the sources of the data, the work carried out for the merging of the database and the operations that are still required for making it suitable for a nationwide robust rainfall frequency analyses. A preliminary analysis of the extreme rainfall regime at the national scale is also presented.

2 Merging the *I-RED* Dataset

2.1 Data sources

As a follow-up of the activities of the Italian National Group for the Prevention of the Hydrogeological Disasters ($GNDCI$) a comprehensive nationwide hydrological information system has been set up, within the "*CUBIST* project", funded by the Italian Ministry of Education and Research (*PRIN* 2005). The database includes about 6000 pluviographs and pluviometers, 700 temperature stations and about 400 river basins (Claps et al., 2008) and is available at: http://www.cubist.polito.it; accessed: 2017-10-26. In the detail, the database includes rainfall data from 1900 to 2001 (depending on the region) and constitute the first important attempt of making the large Italian hydrological heritage freely available in a computer-readable format.

The number of data per year is not constant across the analysed period, being increasing in time as more stations have been installed in the recent years. Data availability decreases in the period of the Second World War, as many records have been missed in that period. After 1980, with the progressive dismissal of the *SIMN* and the development of the local hydrographic authorities, data availability decreases rapidly until 2001, when the rain gauges still under the *SIMN* were taken over by the local Operational Centres.

After the late '80s the local Environmental Agencies started to support the *SIMN* in its work. Gradually, the 21 regional hydrological services took over the networks and the tasks of the national one. Each hydrological service adopted its own rules for the publication of the collected data and, even if the Italian law adopted an Open Source policy for the public data, an updated database of the annual rainfall maxima for sub-daily duration at the national scale is still lacking. For the scopes of this research, the different agencies have been contacted, requesting the regional annual maxima datasets for sub-daily durations. The regions of Italy are shown in Figure 1 together with the type of data provided, that will be described in the following section. Table 1 lists the name of the local authorities and the regional codes, aimed at identifying them in the database. The public availability of the original dataset is also reported. The different providers adopt various data policies, raising significant problems with the publication of the merged dataset.

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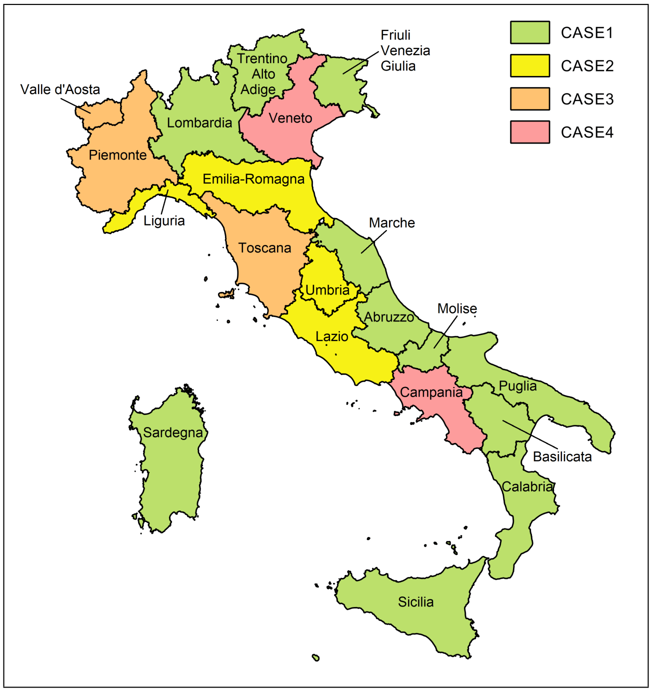

Figure 1. Names of the Italian regions and type of datasets provided by the regional authorities. The cases refer to the bulleted list of section 2.2.

2.2 Cleaning and merging operations

Merging and harmonizing the different datasets is a quite long and difficult operation, that is still ongoing. The different Operational Centres provided different types of datasets, with different temporal coverages and spatial reference systems. Duplicate stations are often present in the databases of neighboring regions.

The first steps of this work have been carried out at the regional scale. For each region all the data falling inside the regional boundaries have been considered. These data, according to the setting of the databases of the local Operational Centers, could belong to one of these 3 categories:

a) Data from the *CUBIST* database for the 1900-2001 period already available from the former national service

b) Data provided by the regional authority

c) Data provided by the regional authorities of the neighboring regions, falling out of their regional borders

Observations dating before 1916 have been discarded, as considered not significant and too unevenly distributed. Considering that most of the provided data have been validated from the related authorities, they are considered reliable and, at first, included directly in the *I-RED*. In presence of inconsistencies between the type b) and type c) data, preliminary manual merging was carried out. If the same station was found in the database of more neighboring regions a first attempt of merging the series

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Table 1. Regions of Italy with the assigned code and the related local Operational Center with references to the availability of digitized data.

CD	Region	Operational Center	Digitized data availability
01	Abruzzo	Ufficio Idrografico e Mareografico Regione Abruzzo	Under request
02	Basilicata	Dipartimento Protezione Civile Regione Basilicata	Available in [1]
03	Calabria	Centro Funzionale Multirischi - ARPACAL	Available at [2]
04	Campania	Centro Funzionale Regione Campania	Under request
05	Emilia-Romagna	ARPA Emilia-Romagna	Under request
06	Friuli Venezia Giulia	Ufficio Idrografico Regione Autonoma Friuli Venezia Giulia	Under request
07	Lazio	Centro Funzionale Regione Lazio	Under request
08	Liguria	ARPAL-CFMI-PC	Partially available at [3]
09	Lombardia	ARPA Lombardia	Available at [4]
10	Marche	Dipartimento di Protezione Civile Regione Marche	Available at [5]
11	Molise	Centro Funzionale Regione Molise	Under request
12	Piemonte	ARPA Piemonte	Partially available at [6]
13	Puglia	Dipartimento di Protezione Civile Regione Puglia	Available at [7]
14	Sardegna	ARPAS	Under request
15	Sicilia	Osservatorio delle Acque Regione Siciliana	Under request
16	Toscana	Servizio Irdrografico Regionale Toscana	Available at [8]
17	Trento *	Centro Funzionale Provincia Autonoma di Trento	Available at [9]
18	Bolzano - Alto Adige *	Ufficio Idrografico Provincia Autonoma di Bolzano - Alto Adige	Under request
19	Umbria	Regione Umbria	Under request
20	Valle d'Aosta	Centro Funzionale Regione Autonoma Valle d'Aosta	Under request
21	Veneto	ARPAV	Under request

* the Autonomous Provinces of Trento and Bolzano - Alto Adige, together, constitute the region Trentino Alto Adige (CD: 22)
[1] Manfreda, S., Sole, A. and De Costanzo, G.: Le precipitazioni estreme in Basilicata, Editrice Universo Sud, 2015.
[2] ARPACAL: Centro Funzionale Multirischi, http://www.cfd.calabria.it/, accessed: 2016-08-01
[3] ARPAL: Consultazione Dati Meteoclimatici, http://www.cartografiarl.regione.liguria.it/SiraQualMeteo/Fruizione.asp, accessed: 2016-08-01
[4] ARPA Lombardia: Progetto Strada, http://idro.arpalombardia.it/pmapper-4.0/map.phtml, accessed: 2016-08-01
[5] Protezione Civile Regione Marche: Annali Idrologici Regione Marche, http://console.protezionecivile.marche.it, accessed: 2016-08-01
[6] ARPA Piemonte: Banca dati meteorologica, http://www.regione.piemonte.it/ambiente/aria/rilev/ariaday/annali/meteorologici, accessed: 2016-08-01
[7] Protezione Civile Puglia: Annali Idrologici - Parte I, http://www.protezionecivile.puglia.it/centro-funzionale/analisielaborazione-dati, accessed: 2016-08-01
[8] SIR Toscana: Settore Idrologico Regionale, http://www.sir.toscana.it/, accessed: 2016-08-01
[9] Centro Funzionale di Protezione Civile Provincia Autonoma di Trento: Meteotrentino, http://www.meteotrentino.it/, accessed: 2016-08-01

together was carried out, by analysing the data recorded year by year. If the merging was not feasible, higher priority was given to the data provided by the authority of the considered region (that is usually also the owner of the network). This allowed to avoid the presence of duplicate series in the *I-RED*.

Once merged, for each region, type b) and type c) datasets, the resulting dataset has to be merged with the type a) dataset. This operation has been quite complex, as the overlapping period between the different dataset was different for each region

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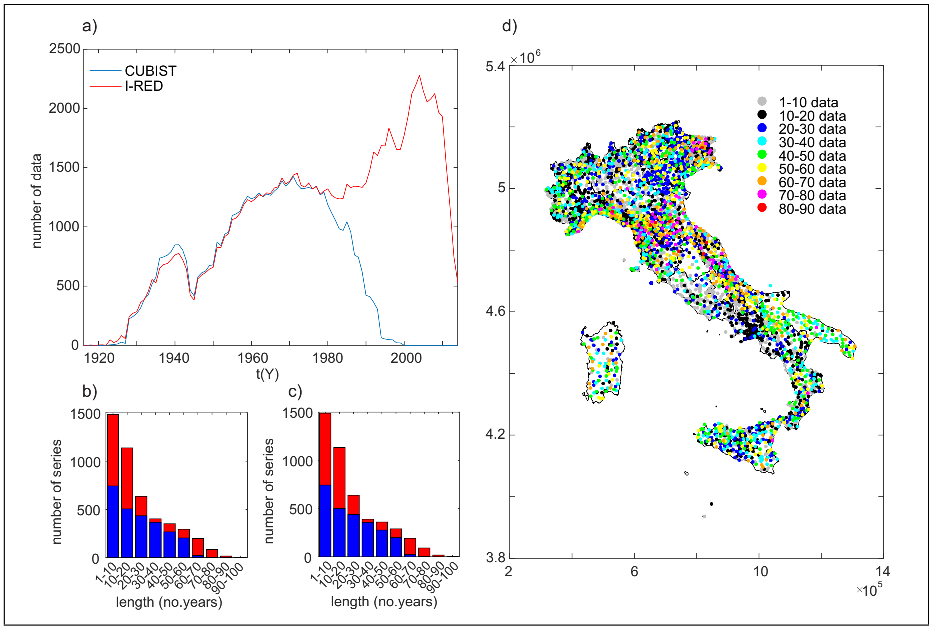

Figure 2. (a) Data availability per year in the *I-RED* and *CUBIST* databases (the smallest value across the 5 considered duration is reported per each year). Number of series per length class in the *I-RED* (red) and *CUBIST* (blue) databases for durations 1 (b) and 24 (c) hours. (d) Length of the series in the *I-RED* database represented in space: the color refers to the minimum length among the 5 available durations. If more stations overlap due to the resolution of the picture, the one with the longer series appears on the top.

and because most of the authorities did not tracked the change in the name/code of the stations. The different procedures performed, according to the type of the dataset that the region has provided (as reported in figure 1) can be summarized as follows:

1. *Regions that digitized the whole SIMN database for their areal domain and provide a complete merged database.* The provided data were inserted in the *I-RED* without editing and without considering the *CUBIST* series. Only for the Abruzzo and Molise regions some preliminary refinement was needed, as the two regions were divided in 1963, and the databases of the two regions partially overlap. The stations were then divided according to the actual regional boundaries and the duplicate series removed.

2. *Regions that provided datasets including data from their actual regional network partially merged with subsets of digitized data from the SIMN Hydrological Yearbooks.* As not all the *SIMN* datasets were digitized from the local authorities, the dataset lacked part of the stations included in the *CUBIST* database. To maximize the available information, data from the regional databases and the *CUBIST* one were manually analyzed and merged, in order to avoid duplicate values. Stations with same name and similar coordinates were merged together in the presence of a two-year consistent overlapping period. In the presence of inconsistencies between the values recorded by the two stations two stations in the overlapping period, they were treated as different stations and renamed. If that was not possible to unravel any doubt, the stations

were considered as separate entities. For the Liguria region, the information in ARPAL (2013) was used to overcome the lack of information on the continuity of the series.

3. *Regions that provided two different datasets: one containing the whole digitized data from the SIMN stations and another containing the digitized data from their actual networks.* The data of the two databases were merged together, the overlapping period manually analyzed to avoid overlapping, and the *CUBIST* database ignored. The operation was made possible by the collaboration of $ARPA$ Piemonte, for Piemonte and Valle d'Aosta, and of the Università degli Studi di Firenze, for Toscana.

4. *Regions that provided only the data recorded from the network they actually manage.* All the information concerning the *SIMN* stations was lacking. The provided dataset was therefore merged with the whole *CUBIST* database for the considered regions. Duplicate values were excluded analyzing manually the overlapping period, if present.

With the application of the above described rules, 20 complete regional datasets have been obtained. The regional datasets were finally merged together to generate the *I-RED*. After the merging phase some reliability check has been performed, in order to detect any problematic or incorrect information. They includes the identification and removal of the duplicate data/stations and reliability checks on the larger values of the dataset, comparing them to the absolute record-breaking events for all the durations (see Libertino (2017)), aimed at detecting inconsistencies in rainfall series. If any suspect value was found, its year of occurrence was compared, when referring to recent years, with the data from event reports or newspapers. If the data refers to a *SIMN* station, the Hydrological Yearbooks were consulted. If no evidence was found, the related authority was contacted. Most of the operations need human supervision, and a thorough verification work. If it is not possible to unravel any doubt the suspect value is discarded.

Due to the complexity of the check operations, further efforts and collaborations with the regional authorities are still ongoing to increase the consistency of the database. Nevertheless, to date (October 2017) the *I-RED* includes more than 4500 stations nationwide and constitute the largest updated dataset of annual maxima for Italy. In the following, the spatio-temporal distribution of the assembled data will be described.

3 Main features of the *I-RED* database

The number of data available per year in the *I-RED* is reported in figure 2a, as compared with that of the *CUBIST* database. As every station is related to an unique value of annual maxima for a given duration, the presence of a measurement implies the presence of a station. The number of available stations increases with time, and drastically grows after the dismissal of the *SIMN* and the development of the local agencies. The decrease after 2010 can be attributed to the fact that not all the regions have published the data for the most recent years.

The smaller size of the *I-RED* compared the *CUBIST* database in some years can be due to:

- The presence, before 1945, in the *CUBIST* database of data from territories lost by Italy after World War II (e.g. , Istria) or from neighboring countries, not included in the *I-RED*;

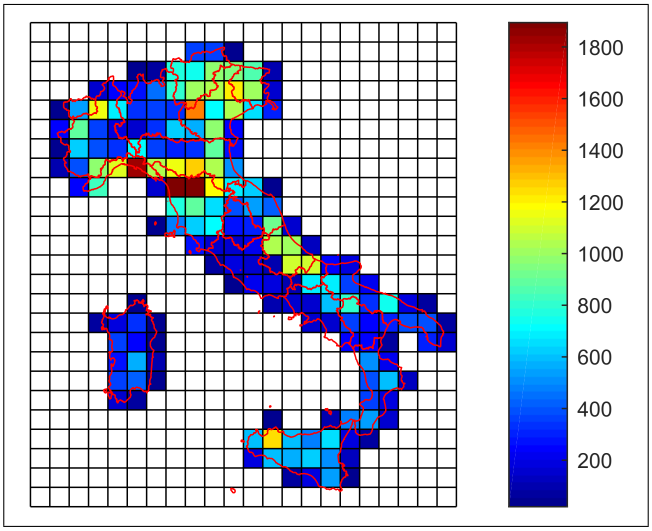

Figure 3. Number of station-year per cell over a 50 km grid.

– The fact that regional agencies could have decided for different reasons not to include data or stations from the *SIMN* dataset in their database. Part of these data could therefore be lost not considering the *CUBIST* database for these regions.

Considering the limited significance of the information loss, further efforts for including these data will be planned only in a future stage of the development of the database.

For a descriptive analysis of the rainfall data, all the assembled time series are classified according to their length. Results are shown in Figure 2b and 2c for the 1 and 24 hours durations, respectively. The other durations (not shown) report a similar behaviour. Considering the short life of the regional Operational Centers, most of the new series are shorter than 20 years but the contribution of the *CUBIST* database allows for a significant amount of longer series (see, e.g., the 60-70 data class).

The spatial distribution of the stations is shown in figure 2d. The color scale refers to the number of the available data per each series. The minimum number across the 5 duration is considered. One can clearly distinguish that, even if the whole national territory is represented, the density of the stations widely changes across the nation. To show the relevance of the non-uniformity, a gridded domain with a mesh size of 50 km is introduced. Figure 3 shows the number of station-year, i.e., the total number of data per cell, showing all the available data of the stations located within the cell. If data consistency changes for the different durations, the shortest one is considered. The non uniformity of the network density clearly emerges at first sight, with some cells presenting almost 10 times the number of data of other cells. The most densely gauged cells can be found in the North-West of the country, in particular in Liguria region, in the northern Toscana and, in the North-East.

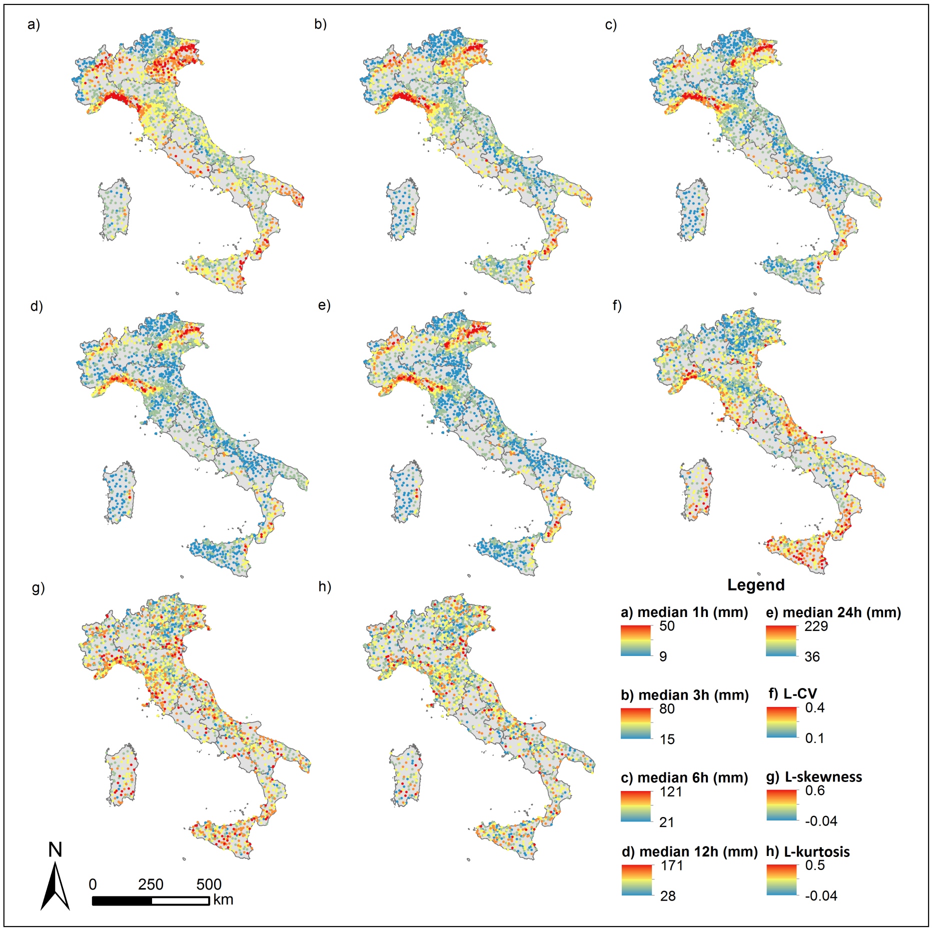

Figure 4. Median values of the *I-RED* series from 1 (a) to 24 (e) hours. Average statistics for the five durations considered: (f) *L-CV*, (g) L-skewness and (h) L-kurtosis. Series with more than 20 data are considered.

4 Descriptive statistical analysis of rainstorms in Italy

A preliminary descriptive analysis of the characteristics of extreme rainfalls at the national scale has been carried out on the newly developed *I-RED* database. Series with a minimum length of 20 years of data have been considered in this analysis. This length constraint leads to a subset of 1974 series available for the analysis, out of the original 4686. For each duration, the median of the series is depicted in figure 4. The median is used as a robust estimator of the central tendency of a series, less sensitive than the mean to the presence of outliers.

When short durations are considered, stations with larger median values seem to be evenly distributed across the country. Moving to longer durations, a marked spatial clusterizations of the series with larger median value appears.

For each series, the sample L-moments (Hosking and Wallis, 1997) have then been computed to describe the shape of the empirical distribution of the records. The mean L-moments ratios among the different durations give information respectively

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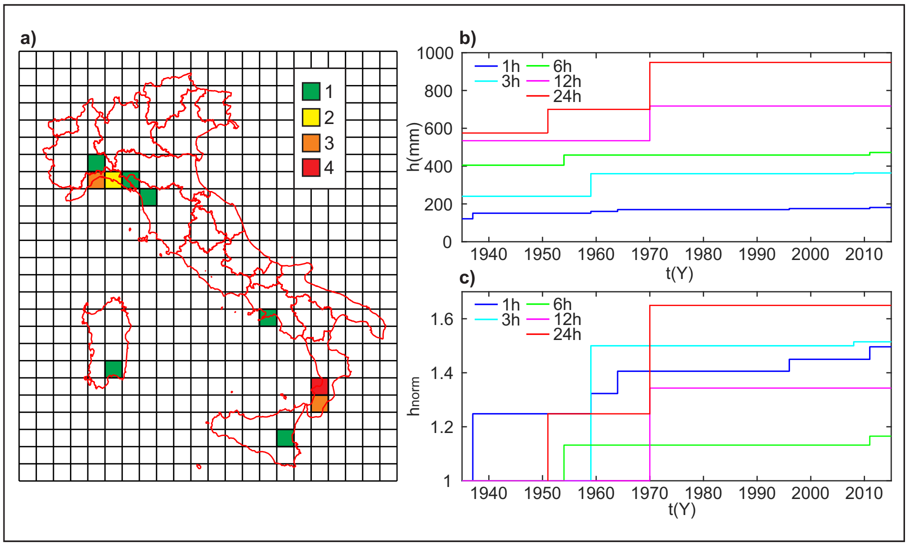

Figure 5. (a) Number of record-breaking events per cell over a 50 km grid. Record breaking rainfall depths for the 5 considered durations from 1935 to 2015 (b) in absolute values and (c) normalized on the 1935 values.

on the dispersion (L-CV), skewness (L-skewness) and "peakedness" (L-kurtosis) of the empirical distributions. All the above statistics are mapped in figure 4. Panel (f) shows that the coastal areas and the islands are generally characterized by a higher variability in the annual maxima series, presenting larger L-CV values. The northern part of the peninsula, even if characterized by large median values, shows lower L-CV, which is typical of areas with large average rainfall values. It is harder to identify a precise spatial pattern in the distribution of the skewness and kurtosis values (panels (g) and (h)). Coastal and island areas seem to generally show larger skewness values, confirming the influence of the Mediterranean sea on the climate of these areas.

The significance of the developed dataset allows also to preliminary explore the rainfall events sometimes referred to as "black swans" (Blöschl et al., 2015), showing extraordinary intensities even when compared with the population of annual maxima. In Italy, many of these events have been studied as individual extraordinary events (e.g., Rebora et al., 2013; Fiori et al., 2014), due to the large recorded intensities and to their severe consequences, but the fragmented configurations of the national database have prevented a systematic treatment of this population of "extremes of the extremes" (Snorrason et al., 2002). A preliminary investigation on the occurrence of very-extreme events at the national scale has been performed and summarized in figure 5a that shows the spatial distribution of the record-breaking rainfall events for the considered durations from 1935 to 2015. A record-breaking event is defined as the annual value that exceeds all the previous ones. At this stage, only nationwide record-breakings are considered, pulling up all the data together year by year. Record breaking rainfall amounts can provide a picture of the spatio-temporal distribution of the major weather anomalies in the country. Analysing record-breaking events has some advantages from both an operational and a statistical point of view. Due to the significant amounts recorded, these events can be easily verified combining different sources of information, and, moreover, this kind of analysis does not require any assumption on the underlying probability distribution (Coumou et al., 2013). The spatial distribution of the events seems to suggest a clusterization of these phenomena in some areas of the country: the eastern part of Liguria and northern part of Toscana and the extreme south of Calabria. Localized events also occurred in Campania, Sicilia and Sardegna. All of these areas are generally characterized by complex orography in the proximity of the coastline: a framework that can promote the development of particularly intense phenomena (Furcolo et al., 2015). At-site systematic analysis of the record breaking events, which are expected to provide useful information for characterizing the extreme rainfall regime in the country (Lehmann et al., 2015), is now possible thanks to the consistency of the new *I-RED* database. Figure 5b shows the record-breaking evolution in time (for each duration); the occurrence of a new record-breaking is represented by an increasing step in the line. Panel (c) report the same record-breakings, whose values are normalized by the 1935 values.

5 Conclusions

The first comprehensive dataset of extreme rainfall in Italy, called *I-RED*, has been presented here. It is a significant source of information, able to provide unprecedented knowledge on the characteristics of heavy precipitation in Italy and on the possible rainfall regime changes in the last century. Further efforts will be addressed to increase the spatial data homogeneity and coverage in time, by including the data of the most recent years and, eventually, by contacting the local authorities for requesting assistance in the merging of the series. The final aim is to make the update of the database systematic and unsupervised. In the meanwhile the *I-RED* will be used for exploring the different outcomes provided by this preliminary analysis, e.g., assessing the influence of the spatial distribution of the stations on the observation of record-breaking extreme events, evaluating the presence of trends in the temporal distribution of the "black swans" and analysing the statistical predictability of these kind of events on such a wide and complex domain.

Data availability. Some of the agreements signed with the data providers restrict the use of the data to the aims of this project. Due to these legal restrictions, the full database can not be actually made freely available. The original data can be requested to the authorities reported in table 1. Please, contact the corresponding author for further information.

Competing interests. No competing interests are present.

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