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Title: Storminess and geo-hydrological events affecting small coastal basins in a terraced Mediterranean environment

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Storminess and geo-hydrological events affecting small coastal basins in a terraced Mediterranean environment

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Abstract

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1. Introduction

In Mediterranean river-torrential landscapes, long phenomena-free periods can be suddenly interrupted by storms from which accelerated erosion, landslides and floods derive (Diodato, 2004). This is particularly evident in landscapes affected by land use conflicts (Pacheco et al., 2014; Valle Junior et al., 2014). Severe weather conditions characterised by intense rainfall causing simultaneous events such as landslides, floods, accelerated erosion and resulting in economic damage and human injury were defined by Petrucci and Polemio (2003) as Damaging geo-Hydrological Events (DHEs). Northern coastal zones of the Mediterranean Sea are particularly exposed to the occurrence of high intensity rainfalls that might cause flash flooding and landslides (Barriendos Vallve and Martin-Vide, 1998; Rusjan et al., 2009; Llasat et al., 2010). As known, climatically-induced mass movements (e.g. debris slides, debris avalanches, debris flows) can damage roads, villages and infrastructures (Revellino et al., 2008; 2010, Fiorillo et al., 2013; Guerriero et al., 2013; D'Amato Avanzi et al., 2013b; Galve et al., 2015; Bordoni et al., 2015) and frequently, together with accelerated erosion, they can supply large sources of solid materials to drainage networks. Sediments coming from slopes increase the magnitude and energy of stream flow and, especially in small mountain basins, play a fundamental role in generating flooding phenomena at the basin mouth (Gutierrez et al., 1998; Brandolini et al., 2012). Flash floods are very dangerous, often resulting in the loss of life due to the fact that they can deliver enormous amounts of water and debris in a very short space of time (Gaume et al., 2009; Tarolli et al., 2012). These events, normally, have a special impact in mountain areas, where the effects of extreme precipitations are heightened by slope steepness (Fiorillo et al., 2001; Lebel et al., 2011; Pereira et al., 2010; Perriello Zampelli et al., 2012). However, coastal environments with mountain-like geomorphological features can also be seriously exposed to accelerated erosion and landslide and flood risks (Guthrie and Evans, 2004; Cevasco et al., 2010; Santo et al., 2012). In such a case, risk conditions are increased by both the high economic value of coastal areas and the large number of tourists that visit these areas (Guadagno et al., 2005; De Vita et al., 2012; McCullough et al., 2013; Revellino et al., 2013; Martino and Mazzanti, 2014).

Several studies have dealt with both the recent changes in rainfall characteristics (Frich et al., 2002; Trenberth, 2011) and their effects on the occurrence of rainfall-induced phenomena, such as landslides and floods. The majority of these studies focused on mountain regions, where rainfall-induced phenomena are more common than in coastal areas (e.g. Jomelli et al., 2004; Pelfini and Santilli, 2008; Floris et al., 2010). On the other hand, many recent studies have focused on storm erosivity, that can be considered as the "power of the rainfall" to produce slope processes (landsliding and erosion) and, therefore, represents an environmental indicator of many geo-hydrological phenomena (e.g. Davison et al., 2005; Diodato, 2006; De Luis et al., 2010; Diodato and Bellocchi, 2010; Xin et al., 2011; Angulo-Martínez and Beguería, 2012; Panagos et al., 2015; Sadeghi and Hazbavi, 2015). Despite this, no study attempting to relate DHEs with storm erosivity changes has been reported in literature.

This study was prompted by the occurrence, on 25th October 2011, of a very intense rainfall event which affected a wide area between the eastern Liguria and the northern Tuscany coast (north-western Italy), causing 13 fatalities and severe damage to villages, cultivations, infrastructures and essential services (Cevasco et al., 2012; D'Amato Avanzi et al., 2013a). Some small coastal basins of the easternmost Ligurian Riviera suffered major damage due to the occurrence of hundreds of shallow landslides, widespread erosional phenomena and flash floods. Starting from an analysis of the October 25th 2011 rainfall event, this paper investigates historical rainfall and the related damaging effects on the abovementioned small coastal basins. In addition to having almost homogeneous geomorphological and climatic features, these basins show similar problems with regard to the occurrence of DHEs. In fact, the local microclimate, which favours high intensity rainfall, and the mountain-like geomorphologic features, make the coastal basins of eastern

Liguria prone to shallow landsliding and rapid flooding (Cevasco et al., 2008; Brandolini et al., 2012). With the aim of contributing to a better understanding of the relationships between extreme events, climate change and geomorphic phenomena, and bearing in mind the risks that such phenomena represent both for resident people and tourists, we investigated the response of the environment to severe rainfall over time and the time-scale at which changes on extreme rainfall events occur. In this way, the study analyses changes in storm erosivity and their relationships with the occurrence and severity of DHEs. Additionally, the study discusses the related upcoming trends, also taking into account a more enlarged view on the Mediterranean central area.

2. Study area

The study area is located along the easternmost Ligurian coast, within the border of the La Spezia province (Fig. 1a), and it is formed by the Tyrrhenian basins between the village of Deiva Marina and the city of La Spezia. These basins mainly extend between the coastline and the Cinque Terre/Vara valley watershed, reaching altitudes of approximately 700-800 m a.s.l. The study area includes the famous Cinque Terre, a UNESCO World Natural Heritage Site since 1997 and a national park since 1999.

From a geological point of view, the study area is part of the northern Apennines, a mountain belt formed during the Tertiary by the tectonic superimposition of the Ligurid units onto the Adria plate margin (Alvarez et al., 1974). The area can be divided into three geological sectors (Giammarino et al., 2002): i) ophiolite rocks - relicts of the Jurassic oceanic crust - outcrop between Framura and Levanto; ii) sedimentary rock formations, mainly made up of clay-shales and sandstones (Upper Jurassic-Cretaceous), which are present between Framura and Deiva Marina; and iii) sedimentary rock formations mainly constituted by limestone and sandstone (Upper Trias – Miocene) and clay-shale and limestone (Paleogene) which outcrop between Monterosso and La Spezia. The ophiolitic slopes are usually lacking of soil mantle or it is very thin; conversely, sedimentary rock slopes are covered by 0.5–2.5 m thick eluvial-colluvial soil. The soil covers are characterized by wide heterogeneous grain size, generally consisting in mixtures of gravel and sand with a subordinate fine fraction (Cevasco et al. 2013b; 2014). Often, soils covering slopes do not present the original setting as they have been reworked during the past centuries for agricultural purposes.

The proximity of the Cinque Terre/Vara valley watershed to the coastline does not allow a well-developed hydrographic network typical of coastal areas and, where this happens, the coastal plains have limited extent and only briefly interrupt the continuity of the high rocky coast (Corradi et al., 2013). Coastal basins are usually characterized by narrow and deep-cut valleys, steep slopes and short streams with an ephemeral hydrological regime. The morphological features of the study area strongly controlled the development of urbanization. The most populated villages were built on small coastal plains (Deiva Marina, Bonassola, Levanto) or on the floor of deep-cut valleys (Monterosso, Vernazza, Manarola, Riomaggiore) reducing, over time, natural areas at the mouth of streams. This often resulted in the embanking of the final tracts of the streams or, in some cases, coverage or deviation from their original path. Human activity also affected the steep slopes behind the coast and most of them were terraced in historical times for agricultural purposes. In this area, terracing of slopes can be considered a real geomorphologic value that has few equals of similar magnitude in the world. The abandonment of rural areas following socio-economic changes since the 1950s, which resulted in a general lack of maintenance of dry stone masonries, has led to the loss of many terraced areas with increasing slope instabilities (Terranova et al., 2002). At the same time, given the high environmental, historic and cultural value of the eastern Ligurian Riviera, tourism has significantly increased.

Due to its geographical and morphological features, the study area has a mild Mediterranean climate. Southerly exposition, the vicinity of the sea and mountains acting as a barrier, which protect the coast from continental influxes, are all factors that most contribute to making the climate particularly mild. Moreover, the humidifying action of the sea on the air masses coming from the southern quadrants and the Alpine-Apennine chains effect, which frequently divert Atlantic perturbations towards the Gulf of Genoa, produces relatively abundant rainfalls (Fig. 1b). Along the coast, between Deiva Marina and La Spezia, the mean annual rainfall value ranges between 900 and 1100 mm, with minimum and maximum values towards Portovenere and in the coastal stretch to the west of Cinque Terre, respectively (Pedemonte, 2005). A sudden increase of the mean annual precipitation (MAP) with altitude was observed, with values reaching approximately 1500-1600 mm in the immediate and higher inland Vara/Magra valleys. Precipitation is more abundant in autumn and winter. Very intense rainstorms, which can originate from self-regenerating storm cells or a persistent cyclonic Thyrrenian circulation (Crosta, 1998; Cevasco et al., 2009), can affect, prevalently in autumn, the northeastern coast of Ligury and Tuscany (Van Delden, 2001). Despite their short duration, the storms are capable of triggering simultaneous geomorphic processes that pose a great hazard to the safety of people.

3. The 25th October 2011 event

On October 25th 2011, after a long dry period, a rainfall event hit a wide area between eastern Liguria and north-western Tuscany (Fig. 2a). After a few hours of low intensity rainfall, a violent storm system with a “self-healing” structure originated in the Cinque Terre area, in a very short time interval. Huge amounts of rainfall fell between 9 and 15 (Universal Time Coordinated, UTC) on the coastal area of the Cinque Terre and the Vara valley and, subsequently, on Lunigiana. Rainfall was recorded by several rain gauges located in eastern Liguria (ARPAL-CFMI-PC, 2012) and northern Tuscany (CFRT, 2011).

As shown in Table 1, in eastern Liguria, very high cumulative rainfall amounts were recorded in the inland Vara valley at the Brugnato and Calice al Cornoviglio rain gauges and, along the coast, at the Levanto San Gottardo and Monterosso rain gauges with 539 mm, 454 mm, 333 mm and 382 mm respectively. Hourly intensity rainfall peaks recorded at Brugnato, Calice al Cornoviglio, Levanto San Gottardo and Monterosso, were 153 mm/h, 129 mm/h, 111 mm/h and 92 mm/h respectively (Fig. 2b). Rainfall intensities at 3, 6 and 12 hours were also extremely high. The higher values (e.g. 472 mm/6h) were recorded at the Brugnato rain gauge. Moreover, in Lunigiana (northwestern Tuscany) rainfall amounts reached their maximum at the S.Giustina rain gauge, with 376 mm; lower, but significant values of cumulative rainfall were also recorded at Rocca Sigillina (318 mm), Pontremoli (366 mm) and Parana (315 mm). The highest hourly intensity was recorded at the Parana rain gauge (88 mm). Rainfall intensities at 6 and 12 hours were lower than those recorded in eastern Liguria, but nevertheless were significant (Table 1).

The 25th October 2011 rainfall triggered hundreds of shallow landslides and floods affecting the Tyrrhenian basins between Bonassola and Manarola and the Magra river basin (Cevasco et al., 2012; D'Amato Avanzi et al., 2013a). The event caused 13 casualties, severe damage to villages and infrastructures (the collapse of bridges, interruption of provincial and municipal roads, and stretches of highways and railways, and the temporary interruption of essential services such as gas, water, telephone and sewerage).

In the study area, the basins of Vernazza, Monterosso, Levanto and Bonassola suffered considerable damage. This damage was particularly severe in the inhabited historic centres of Vernazza and Monterosso (Fig. 3), where enormous amounts of material were mobilized on the slopes by shallow landslides and accelerated erosional processes and subsequently charged by torrents downhill, originating hyperconcentrated flows and mud/debris floods. Three casualties occurred in Vernazza, one in Monterosso. These two villages are typical examples of anthropic transformations, which mainly occurred in the past century, leading to flood risk increase; in fact, in both cases, the main urban street was built by covering the final tract of the valley floor along which the stream originally flowed. In both cases, the covered tract of the stream beds was filled by debris and the above urban streets suddenly turned into raging torrents. As a result, the central streets of Vernazza and Monterosso were buried by mud and debris up to 4 m and 3 m thick, respectively.

Recent detailed studies on the relationships between slope processes induced by the intense rainfall of October 25th 2011 on the Vernazza basin and land-use (Cevasco et al., 2013a; 2013b; 2014) highlighted that the rainfall event triggered more than 500 shallow landslides on an area of approximately 5.8 km^2 (about 1.5% of the basin area); additionally 1.65% of the basin area was affected by very intense accelerated erosion. These studies pointed out the extreme vulnerability of terraced slopes which, due to the lack of maintenance of dry stone masonries, currently represent the main areas prone to landsliding and accelerated erosion. An even more recent study (Cevasco and Brandolini, 2015) has shown that the anthropic modifications which occurred in the Vernazza basin during the 1970s (e.g. roads construction), played a negative role, especially in increasing the effects of the October 25th 2011 debris flows and debris flood.

Damage in the Levanto basin was prevalently due to shallow landslides, which caused the disruption of many stretches of roads. Local breaking of the levees of the Ghiararo stream and local floods affected the centre of the Levanto village and its outskirts. The Bonassola basin, on the other hand, suffered minor damage, essentially due to local floods or roads interruptions.

4. Methods

4.1. Historical rainfall analysis

The analysis of historical rainfall series was constrained by the availability, within the study area, of meteorological stations with continuous rainfall data records for a long-term period, as long and continuous as possible. Therefore, only the representative coastal rain gauge of Levanto (4 km northwest of Monterosso and 7 km northwest of Vernazza) was chosen for analysing historical rainfall. The available data records for annual, monthly, daily and maximum intensity (in 1, 3, 6, 12 and 24 h) rainfall cover a period of 58 years between 1954 and 2012. Some missing data regarding maximum intensity rainfall (1954, 1957, 1960, 1965 and 1993) was filled by using records from the neighbouring rain gauges near Levanto. In particular, we referred to Montale di Levanto for 1954, 1957 and 1960, La Spezia for 1965 and, given the unavailability of recordings from stations located within the study area, we referred to the nearby Sarzana station for 1993 (Fig. 1b).

4.2. Storminess and Damaging geo-Hydrological Events (DHEs) analysis

In order to evaluate if storm erosivity may represent a measure of the response of the environment to severe rainfall over time, storm erosivity was calculated over the longest period possible. Additionally, an investigation on the DHEs which occurred in the study area during the same period was also carried out; DHEs were also classified on the basis of their severity. Finally, the storm erosivity pattern was compared to DHE distribution and severity. Based on the availability of rainfall data, the period between 1954 and 2012 was investigated. The adopted methodologies for storminess estimation and DHE identification and classification are illustrated below.

4.2.1. Storm erosivity

In order to obtain rain-erosivity values according to the RUSLE (Revised Universal Soil Loss Equation) methodology (Renard et al., 1997), accurate rainfall measurements on short time scales are required (e.g. sub-hourly time-scales).

This is problematic for long-term studies (e.g., 1954-2012) due to the fact that records of this type are not available for years antecedent to the modern digital-instrumental period (1994-2010). Alternative models were developed to estimate rainfall erosivity using more readily available precipitation data, such as annual amount, daily maximum and hourly annual maximum (Diodato, 2004). However, when erosivity is required to be estimated at a specific location, the estimate can be improved with a calibration against actual rain-erosivity data for determining site-specific coefficients around a considered location.

In this study, annual storm erosivity was estimated starting from the seminal R-factor equation (Diodato, 2004), which was calibrated for Italy at a regional scale using data at an hourly and sub-hourly scale (Fig. 4a). The model takes into account three annual variables: annual precipitation (*Pa*), annual 24-hours maximum precipitation (*d*), and annual 1-hour maximum rainfall (*h*). Subsequently, the original R-factor model was modified for local scale application across the study area (Fig. 4b) and a new equation was recalibrated using data at an hourly scale for the San Piero a Grado meteorological station, which is the nearest station to Levanto, for which hourly data is available. The new R-factor equation is the following:

$$\mathrm{Ra} = 0.05 \cdot Pa \cdot \left(\sqrt{d} + h \right) \qquad [1]$$

where Ra (Annual Rainfall Erosivity) is expressed in MJ mm ha^{-1} h^{-1} y^{-1}.

The best fit was obtained by an iterative procedure to attain the best result with R^2=0.92 (Fig. 4c).

4.2.2. Damaging geo-Hydrological Events

Information on past events was mainly collected by using the “Italian archive of historical information on landslides and floods” (Guzzetti et al., 1994; Guzzetti and Tonelli, 2004) for the period 1954-2001. The ISPRA database, newspapers, scientific and popular publications and field observations provided information on the events which occurred in the 2001-2012 period. Due to the organization of the archive data, it was necessary to confine the research within administrative boundaries. Nevertheless, the entire study area falls within the administrative boundaries for which data has been retrieved. Therefore, the study was carried out by considering landslide and flood events that affected the coastal municipalities between Deiva Marina and La Spezia (that is Deiva Marina, Framura, Bonassola, Levanto, Monterosso, Vernazza, Riomaggiore, Portovenere, La Spezia). The landslide events affecting the territory of the immediate inland (the municipalities of Carrodano, Pignone, Borghetto, Riccò del Golfo and Beverino) were also included in the research.

After collecting data on landslides and floods, rainfall triggering events were identified. The study revealed the occurrence of 44 DHEs in the reference period. A classification of their severity was made taking into account: i) the number of landslides/floods; ii) the extent of the area on which landslides/floods occurred; and iii) damage to people. Due to the limitations of the accessed databases and archives, which tended to underestimate the events of low magnitude or those that did not cause extensive or well-defined damage (Guzzetti et al., 1994), the number of landslides which actually occurred in the study area, in the reference period, was most probably greater than those reported in catalogues. However, the data obtained from catalogues, especially the data regarding the high-magnitude events, can be considered reliable. Four classes of event severity were established, similar to those obtained by Giannecchini and D'Amato Avanzi (2012) for the nearby Versilia River basin:

E1: Low severity - local floods/landslides, no damage to people;

E2: Medium severity - floods/landslides affecting wide areas, no damage to people; floods/landslides affecting local areas, severe damage to people;

E3: High severity - floods/landslides affecting wide areas, severe damage to people;

E4: Very high severity - floods/landslides affecting wide areas, very severe damage to people.

With regards to the classification of damage to people, the difference between "severe" and "very severe" was based on the number of sites where fatalities occurred. In particular, the term "very severe" was used if one or more fatalities occurred in more than one municipality.

5. Results and discussion

5.1. Contextualizing the magnitude of the October 25th 2011 event in the rainfall time series

The Mean Annual Precipitation (MAP), based on the 1954-2012 data (Fig. 5a), was 1033 mm with a minimum of 668 mm in 1989 and a maximum of 1542 mm in 1979. The rainiest month was October, with a mean precipitation of 154 mm whereas the driest month was July, with a mean precipitation of 25 mm (Fig. 5b).

The analysis of maximum intensity rainfalls (Fig. 5c) showed that only one event with an intensity of about 100 mm/1h (in 2011), 2 events with intensities greater than 150 mm /3 h and 200 mm /6 h (in 1981 and 2011), and only one event with an intensity greater than 250 mm/12 h or 250 mm/ 24 h (both in 2011) were recorded in the reference period. With regards to the 1981 event (which occurred on September 22nd), return times higher than 200 years and higher than 100 years were calculated for the maximum intensity rainfalls in 3, 6, 12 h and in 24 h, respectively (ARPAL-CFMI-PC, 2013). Instead, return times higher than 500 years were calculated for the maximum intensity rainfalls in 3, 6, 12, 24 h recorded on October 25th 2011. Considering the distribution of these two events in the analyzed time period (both occurred after 1980), their return times (in any case greater than 100 years) and the restricted time interval between their occurrence (just 30 years), it would appear that extreme events are more frequent in recent times. However, the reliability of this observation can only be confirmed via an analysis of a longer series of data or by future observations. The exceptionality of the magnitude of the October 25th 2011 rainfall event in the study area was also highlighted by comparing the rainfall intensities values recorded at different rain gauges with the historical maximum intensity rainfall recorded at the reference rain gauge of Levanto. For example, at the Levanto San Gottardo rain gauge (approximately 1 km northeast of the Levanto rain gauge, Fig. 2) the maximum intensity rainfall in 1, 3, 6, 12 and 24 h (Table 1) exceeded all records from 1954 to 2011 (Fig. 5c), the 3 hours rainfall intensity (204 mm) exceeded the mean value of the rainiest month (154 mm) and the 24 hours rainfall intensity (333 mm) exceeded the double of the mean value of the rainiest month. Values of maximum intensity rainfall in 6, 12 and 24 h at Levanto San Gottardo were even exceeded at Monterosso (Table 1).

5.2. Storm erosivity pattern during 1954 – 2012

The interannual pattern of Ra anomalies per year of the Levanto rain gauge from 1954 to 2012 is shown in Fig. 6. The long-term mean of the Ra is 2,582 MJ mm ha^{-1} h^{-1} y^{-1}, with a strong temporal variability being the standard deviation equal to 1,263 MJ mm ha^{-1} h^{-1} y^{-1}. It is also possible to note that in some years (1954, 1959, 1960, 1991, 1999, 2000, 2010 and 2011) the annual values of storm erosivity largely exceed the one standard deviation. In order to discover whether storm-erosivity was affected by any type of trend or discontinuity across time, the *cumulative deviation test* (Buishand, 1982) was applied. Figure 6 shows the obtained results from the Buishand test application (blue curve). A change point (red arrow) in the trend of Ra anomaly appeared in correspondence to the year 1990. The thirty-seven year period 1954-1990 was rather quiet, with 62% of the years with a Ra value below the mean of the Ra, 5% of the years with a Ra value equal to the mean of the Ra and 32% of the years exceeding the mean of Ra. Only in 13.5% of the years (1954, 1959, 1960, 1964 and 1984) did the Ra value exceed the one standard deviation. In the twenty-two year period 1991-2012, the series was affected by more pronounced impulsive storminess, with a Ra value standing above the mean of Ra in 55% of the years and exceeding the one standard deviation in 27% of the years (1991, 1999, 2000, 2009, 2010 and 2011).

As shown in Fig. 6, a very high percentage (84%) of the annual amount of erosivity reached in 2011 was due to the daily storm erosivity amount related to the 25th October 2011 event. In order to evaluate the extreme value of erosivity that affected the area around Levanto in the year 2011, the Gumbel plot (GEV-based) of the annual storm erosivity versus return times at the Levanto station (1954-2012 period) was developed. Data was elaborated via generalized extreme value (GEV) distributions as Gumbel plots via a Climate Explorer. The results showed that the return period of the storm erosivity amount in 2011 was approximately 50 years, while the single storm erosivity of October 25th recorded a return period of 1000 years.

In addition to the above considerations, the annual mean of the Ra value obtained in this study (2,582 MJ mm ha^{-1} h^{-1} y^{-1}), which largely exceeded the mean value of rainfall erosivity in Europe of 911 MJ mm ha^{-1} h^{-1} y^{-1} (Panagos et al., 2015), confirms the study area as being one of the European regions at the highest rainfall erosivity level. However, at a national scale, the obtained mean value of the Ra is fairly typical of westerly Italian regions facing the Tyrrhenian Sea, that are characterized by quite high long-term average rain-erosivity (approximately 3,000 MJ mm ha^{-1} h^{-1} y^{-1}) due to their exposition to frontal systems connected to Mediterranean depressions (Diodato et al., 2014).

Several studies aimed at detecting time trends in the rainfall erosivity time series have been carried out, especially in the last decade, in other areas. The recent great deal of attention focused on this aspect is related to the assessment of observed changes in the natural and human environment due to global warming. The rainfall erosivity trends observed in different areas, being related to precipitation variability, can be various; differences were observed, sometimes, also at a regional scale. Capolongo et al. (2008) investigating the magnitude, frequency and trends of the rainfall erosivity index in Basilicata (southern Italy) during 1951-2000, obtained conflicting results since more than half of the 53 stations did not show a statistical trend; 6% of the stations showed an upward trend and 23% of the stations showed a downward trend in seasonal and annual erosivity, the trends becoming stronger during the last 30-year (1971–2000) when compared to the overall 50-year period. De Luis et al. (2010) analysing a dataset including 1113 monthly rainfall series from the Mediterranean Iberian Peninsula, covering the period 1951–2000, detected decreases in rainfall erosivity under semiarid conditions and increases mainly occurring in dry and subhumid areas. Angulo-Martinez and Begueria (2012), analysing time variation of rainfall erosivity in the Ebro valley (NE Spain) for the period 1955–2006, detected a general decrease in annual and seasonal rainfall erosivity. Sadeghi and Hazbavi (2015) reported general decreasing trends at monthly, seasonal and annual time scales of storm erosivity in Iran during 1970–1992. They concluded that the observed changes in storm erosivity were probably affected by some climatic trends. Similar results, showing that annual rainfall, annual erosive rainfall and interannual rainfall erosivity had a decreasing trend for 1956–2008, were found by Xin et al. (2011) who evaluated the spatiotemporal variation in rainfall erosivity for the Chinese Loess Plateau. An opposite trend of the rainfall erosivity index was found by Lee et al. (2011) for different regions of South Korea from 1973 to 1999, with an increase in the middle-western region and a decrease in the eastern and southern coastal regions.

Our results indicate that, despite the fact that the rainfall erosivity trend in the study area was substantially flat during 1954-2012, the 1991-2012 period showed a more pronounced impulsive storminess when compared to the 1954-1990 period.

5.3. Damaging geo-Hydrological Events during 1954 – 2012

The distribution of the severity classes of the DHEs is shown in Fig. 7a. In the reference period, only the event which occurred on October 25th 2011, was classified as E4. The other events were distributed in the E3 (4 events, 9.1% of the total), E2 (12 events, 27.3% of the total) and E1 (27 events, 61.4% of the total) classes. Besides the exceptional rainfall, it was observed that the severity degree of the DHE which occurred on October 25th 2011 was most probably influenced by land use changes and human modifications which occurred during the past century (e.g. lack of maintenance of dry stone walls retaining terraces, construction of roads, restriction of flow sections). It is also likely that land use changes affected the severity of other DHEs which occurred during the reference period. However, quantifying the degree of influence of land use on the severity of a DHE is a complex issue, as the role played could be contrasting. For example, land use changes leading to the lack of maintenance of terraces and human activity causing the restriction of flow sections or the construction of roads have been recognized as negative factors causing an increase of damage related to heavy/intense rainfall (Cevasco et al., 2014; Cevasco and Brandolini, 2015); on the other hand, the growth of vegetation as the consequence of the abandonment of terraced areas probably has had a positive role in preventing major damage.

The analysis of the distribution of the DHEs on a seasonal basis (Fig. 7b) highlighted a maximum in autumn, with occurrence of 50% of total number of DHEs (22 events in E1, E2, E3 and E4 severity classes). About 30% of the total number of DHEs (13 events in E1, E2 and E3 classes) occurred in winter. The remaining 20% of DHEs (9 events, mainly E1-class) occurred in spring and summer. Among the autumn and winter months, October and January are clearly the most exposed to DHEs occurrence (22.7% and 15.9% of total number of DHEs, respectively).

With regards to the seasonal distribution and severity of the DHEs, the results obtained in this study generally agree with the findings of Giannecchini and D'amato Avanzi (2012), which analysed 152 DHEs which had occurred over a long time period between 1328 to 2009 in the Versilia river basin (northern Tuscany coastal region, and very close to the study area). In particular, regarding seasonal distribution, the months of late summer and autumn were identified as the most prone to DHE occurrence whereas, regarding DHE severity, October, September and November respectively were identified as the months most exposed to the occurrence of the highest severity DHE. This is also in good agreement with the findings of Esposito et al. (2003) who, analysing the occurrence of the main historical DHEs during the period 1700-2000 in the Bonea River Basin (southern Tyrrhenian coast), found November, October, September and December as the months most prone to DHE occurrence. Barriendos Vallve and Martin-Vide (1998), studying catastrophic floods in the Spanish Mediterranean coastal area from the 14th to the 19th centuries, also identified autumn as the season of most frequent flooding, with October being the outstanding month, while September and November registered slightly lower levels.

5.4. Relationships between Ra and DHEs

Ra anomalies previously calculated over the 1954-2012 period were compared with the distribution and the severity of DHEs that affected the study area during the same period. With regards to DHE severity, in the case of the occurrence of more DHEs within the same year, we referred to that of maximum severity. Results are shown in Fig. 8. In general, a quite good agreement was found comparing Ra anomalies with DHE distribution and severity. In particular, in all cases, it was observed that the highest severity DHEs (5 events, 100% of the total number of E3- and E4 classes) occurred in the years (1954, 1966, 1981, 1992 and 2011) for which positive anomalies of Ra were calculated. Most of the medium severity DHEs (6 events, 67% of the total number of E2-class DHEs) occurred in the years for which positive anomalies of Ra were calculated; the remaining E2-class DHEs (3 events, 33% of the total number of E2-class DHEs) occurred in the years for which the Ra is equal (1 event) or below the average value (2 events). Most of the lowest severity DHEs (9 events, 56% of the total number of E1-class) occurred in the years for which negative anomalies of the Ra were calculated; the remaining E1-class DHEs (7 events, 44% of the total number of E1-class DHEs) occurred in the years for which the Ra is equal (1 event) or above the average value (6 events). Only about 14% of the years in which no DHEs occurred (1959, 1973, 1995 and 2009) showed positive anomalies of the Ra. In the remnant 86% of cases (25 years) the Ra was approximately equal (3 years) or below (22 years) the average value. However, some anomalies were also detected. In some cases, despite the Ra largely exceeding the average value, only a few low severity DHEs (1960, 1991, 1999 years), or none (1959 and 2009 years), were detected. This can be due to the incompleteness of the landslide/flood reference data or to other causes (e.g. daily storm erosivity amount in relation to annual amount of erosivity). On the other hand, there were years in which DHEs occurred despite the fact that negative Ra anomalies were calculated. The most relevant example is related to 2001, in which a DHE of E2-class occurred despite the fact that a strong negative Ra anomaly (-1867 MJ mm ha^{-1} h^{-1} y^{-1}) was calculated for that year. In this case the severity degree of the DHE, which occurred in early January, can not be related to the Ra value of 2001 but rather it was affected by the effects of antecedent heavy rainfall (December 2000). However, the most severe DHEs (E3-, E4-class) show a good consistence with Ra extremes and a quite regular distribution within the entire reference period can be identified (Fig. 8); instead, the less severe DHEs (E2-, E1-class) become more irregular. Within certain limits, it is possible to assume a direct relationship between the most severe DHEs and Ra extreme values, although human activity can play an important role in determining the severity degree of DHEs.

Through the ratio between the duration of the reference period and the number of events of each severity class, an average recurrence time was calculated in 11.6 years for the E3- and E4-class DHE occurrence, in 6.4 years for the E2-

class DHE occurrence, and approximately 3.6 years for the E1-class DHE occurrence. Moreover, although the number of DHEs is rather limited, a threshold of the Ra with regards to the most severe DHE classes (E3-, E4-class) occurrence was identified as approximately 3,300 MJ mm ha^{-1} h^{-1} y^{-1}. This value corresponds to the minimum value of the Ra (referred to the year 1992) among those calculated for the years in which a DHE of E3- or E4 class occurred. However, if this threshold is exceeded, it does not necessarily imply that a greater severity DHE occurs. Despite this, the above threshold value could be helpful for management purposes.

As previously stated, a change point in the trend of storm erosivity anomaly was observed in correspondence to the year 1990, with most of the years below the Ra average value during 1954-1990 and most of the years above the Ra average value during 1990-2012. With regards to DHE distribution over these periods, three events of the E3-class and three events of the E2-class occurred between 1954 and 1990. On the other hand, one E4-class event, one E3-class event and five E2-class events occurred during the 1991-2012 period. By applying the ratio between the duration of the reference period and the number of DHEs occurred, a preliminary recurrence time for DHE occurrence was calculated. The frequency of the most severe DHEs (E3-, E4-class) occurring in 1954-1990 and 1991-2012 is similar as the average recurrence time was 12.3 years and 11years respectively. Moreover, a higher frequency of E2-class DHEs was observed in the last twenty-two years with respect to the previous period (recurrence time of 4.4 years and 12.3 years respectively). Therefore, an increase of the geo-hydrological risk is potentially expected in the next future.

5.5. Seasonal timing of the intensifying storminess

A more enlarged view of the Mediterranean Central Area (MCA) over the recent decades shows that autumn seasons are prone to intensified precipitation rates with positive anomalies over many zones. Increased temperatures may result, paradoxically, in a generally decreasing trend of total annual rainfall in spite of the fact that daily rainfall increases (Alpert et al., 2002; Frich et al., 2002). In this context, it is relevant to learn how past warming has affected the changes of extreme precipitations (Klein Tank and Können, 2003; Trenberth, 2011).

In order to identify which monthly or seasonally rain might have led to a major increase in annual storm erosivity along the easternmost Ligurian Riviera, we compared the rainfall rate of the recent decades (1991-2012) with that of the previous period (1951-1990) across the MCA. The most positive anomalies of precipitation rate were observed especially during September, October and December (Fig. 9), respectively. A positive core was extended from central Italy toward northern Italy in these months, which might have triggered high-velocity slope failures, such as soil slips, debris flows, debris avalanches, etc., and heavy rain in the months in which the higher frequency of geo-hydrological phenomena was detected in the study area.

The observed increasing trend in the rain rates corresponds to climate change prognosis that predict reductions in average summer and autumn precipitation combined with an increase in high-intensity rainy events for many parts of Central Europe and also the Alps (Christensen and Christensen, 2003; Meusburger et al., 2012). However, it is interesting to note that the Atlantic Multi-decadal Oscillation (AMO, Schlesinger and Ramankutty, 1994; Trenberth and Shea, 2006) becomes positive around the Ra change point, which was detected in 1990 (Fig. 6). In this way, the possibility that our observations are an effect of large-scale global climate cycles (e.g. AMO) casts doubt on the suggestion that results, indicating a post-1990 shift in storminess, are related only to anthropogenic climate change.

6. Conclusions

In the Mediterranean area, it is acknowledged that rain storms can suddenly interrupt long phenomena-free periods. These events (known as DHEs), although not very frequent, are capable of triggering simultaneous slope processes and phenomena such as flash floods, landslides and accelerated erosion, producing damage to cultivations, settlements and posing a great risk to the safety of people.

A very severe DHE which occurred in eastern Liguria and northern Tuscany on October 25th 2011 was the starting point for conducting this study, which is aimed at a better understanding of the relationships between extreme events, climate change and geomorphic phenomena in view of the risks that such phenomena represent for both people and tourists. A coastal sector of eastern Liguria Riviera, with high environmental and tourist value and prone to shallow landsliding and flash floods, was selected. Related to the 1954-2012 period, the study included: i) an analysis of the time series of precipitation; ii) an evaluation of storm erosivity; iii) an identification and classification of past DHEs; and iv) a comparison of the interannual evolution of storm erosivity with DHE distribution and severity.

Some concluding remarks from the previous analysis can be summarized as follows.

The results of the analysis of precipitation time series, related to one representative station located within the study area, showed that the values of the October 25th 2011 event, both in terms of cumulative precipitation and rainfall intensity records, have never been achieved in the reference period. The comparison between the rainfall data recorded on October 25th 2011 by two coastal stations and the historical analysis also pointed out the uniqueness of this event since the 3-hour rainfall intensity exceeded the mean value of the rainiest month and the 24-hour rainfall intensity exceeded the double of the mean value of the rainiest month.

The analysis of the Ra pattern over time showed a strong temporal variability in the study area, with mean values of 2,582 MJ mm ha^{-1} h^{-1} y^{-1} that are typical of the highest erosivity levels of Europe. A rather quiet period of thirty-seven years (1954-1990) and an increase of the extreme values of the erosivity amount for 1991-2012, with a peak corresponding to the event of October 25th 2011, were identified. The exceptionality of this event was further confirmed by the results of the analysis of storm erosivity, whose daily amount represented 84% of the annual amount reached in 2011, and by the single storm erosivity event return period, estimated at approximately 1000 years. However, it is unclear whether the observed post-1990 shift in storminess is related to anthropogenic climate change or to the effects of large-scale global climate cycles (e.g. AMO).

The investigation on past DHEs and related landslides and floods which occurred in the study area during the 1954-2012 period, led to the identification of 44 DHEs, which were classified in four severity classes. The October 25th 2011 event was classified as the most severe DHE which had occurred in the study area in the reference period. Apart from the triggering rainfall, that was exceptional, the severity of that event could also be attributed, at least in part, to human influence, which made damage even more severe. A preliminary recurrence time was calculated in approximately 12 years for the highest severity DHE occurrence; likewise the most hazardous seasons can be recognized in months between late Summer and Autumn.

Moreover, results from the comparison of the inter-annual pattern of storm erosivity and DHE distribution and severity showed, in general, a good consistency, confirming that annual storm erosivity is an important environmental indicator of many geo-hydrological phenomena. Despite the limited number of DHEs in the reference period, a threshold of the Ra with regards to the most severe DHE class (the E3- and E4-classes) occurrence was identified in approximately 3,300 MJ mm ha^{-1} h^{-1} y^{-1}.

In conclusion, the more pronounced impulsive storminess observed after 1991, with erosivity exceeding in various years the one standard deviation in the last two decades, and evidence of more frequent extreme events in recent times, with two rainfall events with return periods higher than 100 years since 1980, indicate a potential increase in the frequency of DHEs. Taking into account the above, effective land and urban planning strategies have to be undertaken in the study area, on the one hand for preserving its high environmental, historical and cultural values and, on the other hand, for securing effective geo-hydrological risk reduction.

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Table caption

Table 1 Cumulated rainfall on 25th October 2011 and maximum rainfall intensity in 1, 3, 6, 12, 24 h recorded by some rain gauges of eastern Liguria and northern Tuscany (elaborated from data from the Regione Liguria, 2012 and CFRT, 2011). Bold type indicates rain gauges and data regarding the study area.

Figure captions

Fig. 1. a) Location of the study area. The Red line marks the boundaries of the coastal Tyrrhenian basins to which the study is related. b) Map of mean annual precipitations (after Pedemonte, 2005; modified and redrawn). The Blue points indicate the rain gauges that provided data for the historical rainfall analysis (Le: Levanto; Mn: Montale di Levanto; Sp: La Spezia; Sr: Sarzana); the dark grey points mark the location of the photographs portrayed in Fig. 3.

Fig. 2. a) Spatial pattern of cumulated rainfall around and across the study area (bounded in black) between 02.00 UTC of October 25th 2011 and 02.00 UTC of October 26th 2011 (after ARPAL-CFMI-PC 2012, modified). The Grey points mark the rain gauges cited in the text. LSG: Levanto San Gottardo; MO: Monterosso; BR: Brugnato; CA: Calice al Cornoviglio; PA: Parana; SG: Santa Giustina; PO: Pontremoli; RS: Rocca Sigillina. b) Hyetographs (blue bars) and cumulative rainfall plots (red lines) of the Borghetto, Calice al Cornoviglio, Levanto San Gottardo and Monterosso rain gauges (data from the Regione Liguria – ARPAL, 2011).

Fig. 3. Some damage suffered in the Vernazza and Monterosso basins due to the October 25th 2011 rainfall. The location of the photographs is shown in Fig. 1b. a) destruction of roads (Vernazza basin); b) accelerated erosion on cultivated terraces (Vernazza basin); c-d) the main street of Vernazza buried by mud and debris immediately after the rainfall (photo c from http://www.youreporter.it, integrated) and after the removal of the debris flood deposits; e) destruction of a part of the covered tract of the Canale Pastanelli at Monterosso; f) the main street of Monterosso during the works for removing the debris flood deposits.

Fig. 4. Downscaling scheme illustrating how R-factor was rearranged to be used in reconstructing rainfall erosivity in historical times at Levanto station. a) seminal R-factor (Diodato, 2004) calibrated for Italy at regional scale (in Diodato, 2004 the variables *P*, *p* and *h* were indicated as *a*, *b* and *c*, but they are respectively the same); b) R-factor rearranged (based on Diodato, 2004) for local scale application across the study area; the equation was recalibrated using data at hourly scale for S. Piero a Grado station; since the variables are the same used in Diodato (2004), only a different composition of the predictors was need to assure the calibration for S. Piero a Grado station; c) R-factor applied for Levanto station for reconstructing annual storm erosivity in historical times.

Fig. 5. Historical rainfall data at Levanto (1954-2012 period). a) mean annual precipitation; b) mean monthly precipitation; c) maximum intensity rainfall in 1, 3, 6, 12 and 24 h.

Fig. 6. Temporal pattern of annual storm erosivity (Ra) anomalies (grey bars) with overimposed one standard deviation (red line) and cumulative deviation (blue curve) at the Levanto station; annual Atlantic Multi-decadal Oscillation (AMO) is also represented (green curve). The red arrow in 1990 indicates a change point in the time-series. The daily storm erosivity amount of 25th October 2011, representing 84% of the annual amount of erosivity reached in 2011, is also marked (black bar). AMO was provided by Trenberth and Shea (2006) via Climate Explorer.

Fig. 7. a) Distribution of the severity of DHEs. b) Monthly distribution of the DHEs.

Fig. 8. Comparison between the temporal patterns of the Ra and DHEs. The bars indicate Ra anomalies; the grey scale filling indicates the years in which DHEs of different severity occurred. The white bars indicate the years in which no DHEs occurred.

Fig. 9. Monthly rainfall rate anomalies (1991-2012) compared with the period 1951-1990 over the Mediterranean Central Area in (a): September; (b): October and c): December. The little square indicates the study area (from National Centers for Environmental Prediction reanalysis, NOAA-ESRL: through http://www.cdc.noaa.gov).

Rain gauge	Cumulated rainfall Oct. 25, 2011 [mm]	Maximum rainfall intensity [mm]				
		1h	**3h**	**6h**	**12h**	**24h**
Brugnato	538.2	153.4	328.4	472.0	511.0	538.8
Calice al Cornoviglio	452.8	129.2	228.4	365.4	404.0	453.8
Levanto San Gottardo	**333.0**	**111.0**	**204.0**	**282.4**	**312.0**	**333.4**
Monterosso	**381.8**	**91.8**	**197.0**	**348.8**	**362.0**	**382.2**
Parana	315.2	88.0	164.8	230.4	265.6	315.2
Santa Giustina	374.4	72.8	177.2	260.8	323.0	376.2
Rocca Sigillina	315.4	68.8	163.2	239.6	279.2	318.4
Pontremoli	365.8	67.0	164.8	251.4	319.8	366.0

Table 1

Figure 1

Click here to download high resolution image

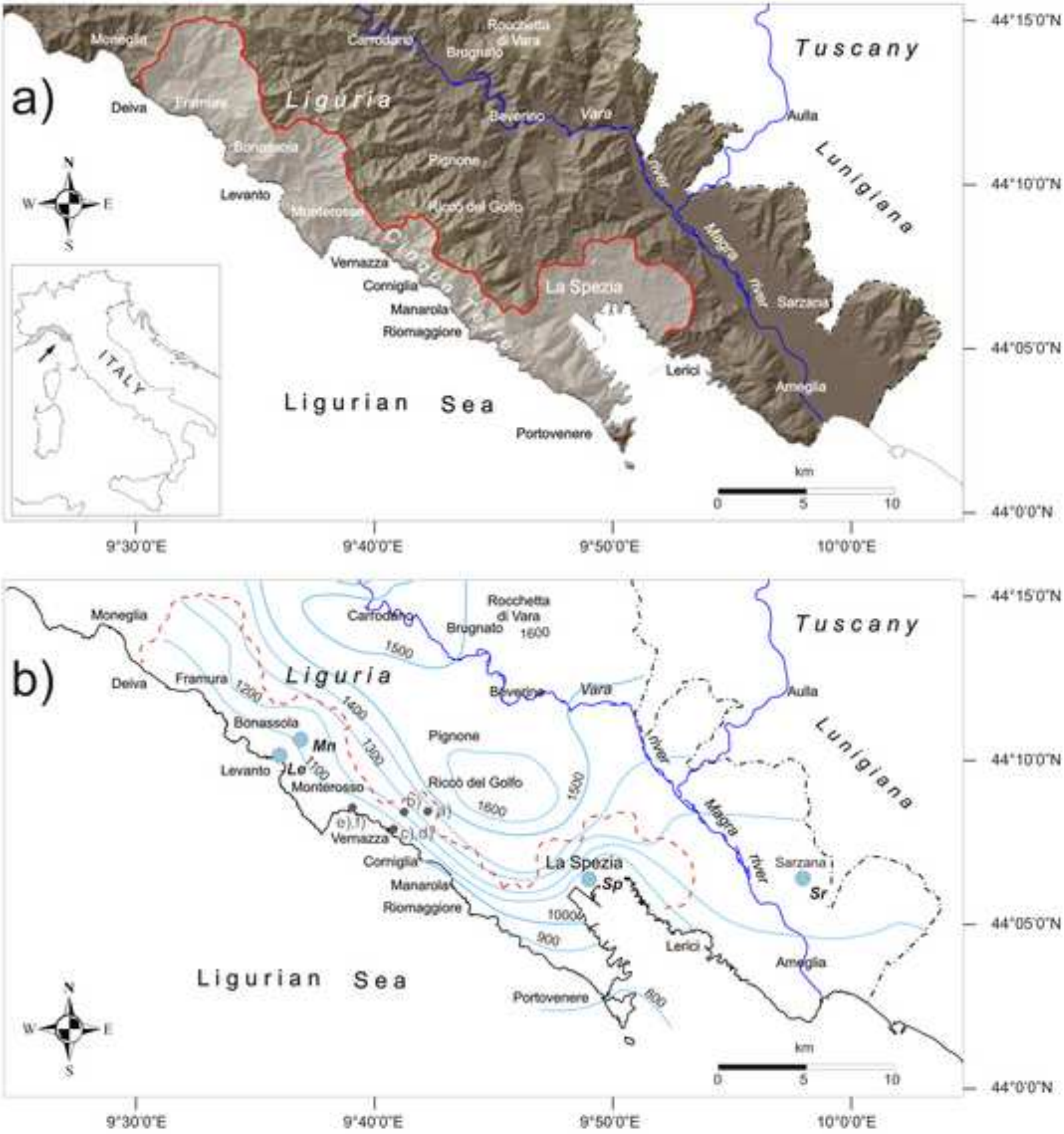

Figure 2

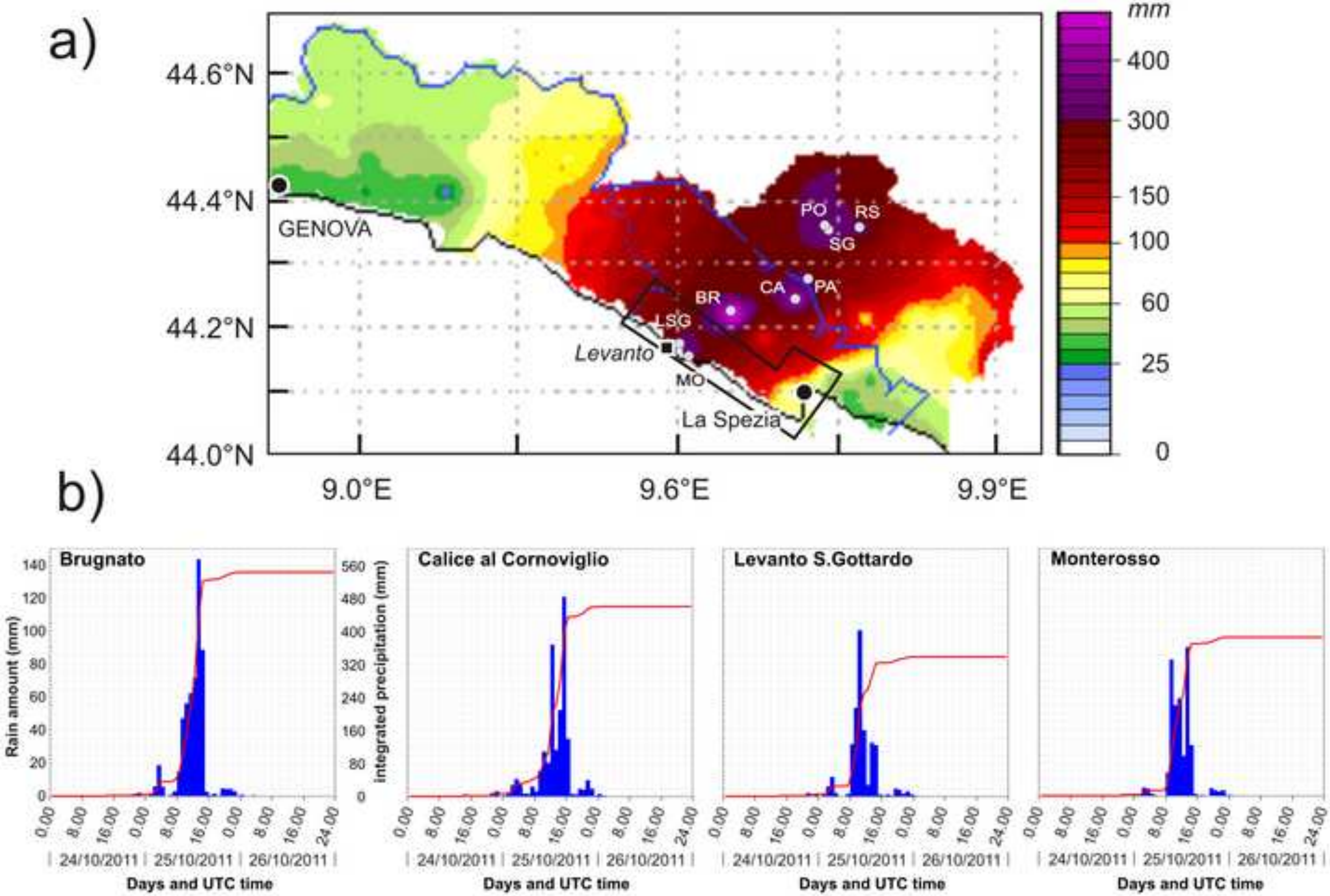
a)
mm
400
300
150
100
60
25
0
44.6°N
44.4°N
44.2°N
44.0°N
9.0°E
9.6°E
9.9°E
GENOVA
PO
RS
SG
CA
PA
BR
LSG
Levanto
MO
La Spezia
b)
Brugnato
Calice al Cornoviglio
Levanto S.Gottardo
Monterosso
Rain amount (mm)
0
20
40
60
80
100
120
140
integrated precipitation (mm)
0
80
160
240
320
400
480
560
0.00
8.00
16.00
0.00
8.00
16.00
0.00
8.00
16.00
24.00
24/10/2011
25/10/2011
26/10/2011
Days and UTC time

Figure 3

Figure 4

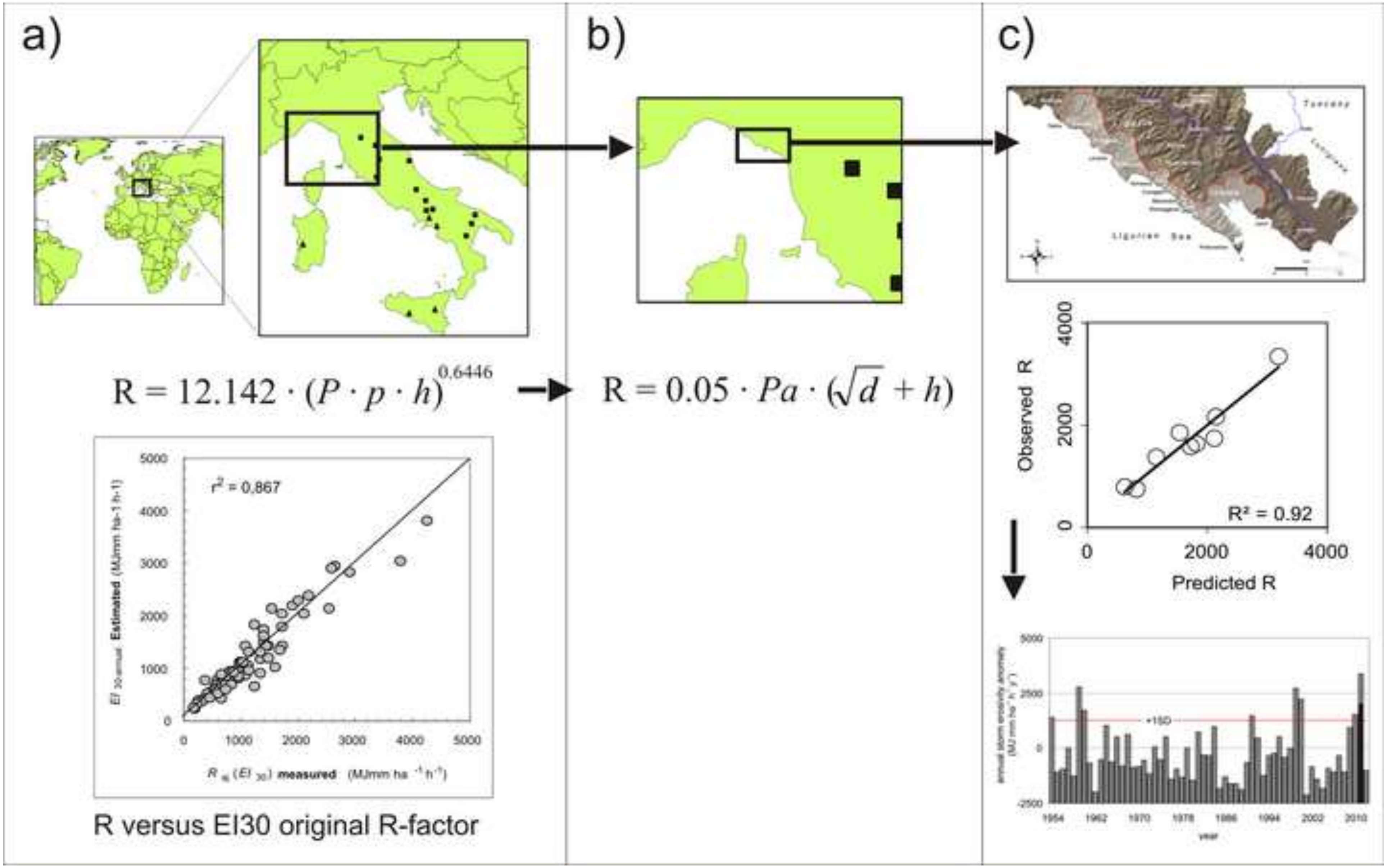
a)
b)
c)
$R = 12.142 \cdot (P \cdot p \cdot h)^{0.6446}$
$R = 0.05 \cdot Pa \cdot (\sqrt{d} + h)$
$r^2 = 0,867$
$EI_{30annual}$ Estimated (MJmm ha-1 h-1)
R_{w} (EI_{30}) measured (MJmm ha^{-1} h^{-1})
0
1000
2000
3000
4000
5000
R versus EI30 original R-factor
Tuscany
Ligurian Sea
Observed R
Predicted R
R² = 0.92
0
2000
4000
annual storm erosivity anomaly (MJ mm ha^{-1} h^{-1} y^{-1})
+1SD
5000
2500
0
-2500
1954
1962
1970
1978
1986
1994
2002
2010
year

Figure 5

Click here to download high resolution image

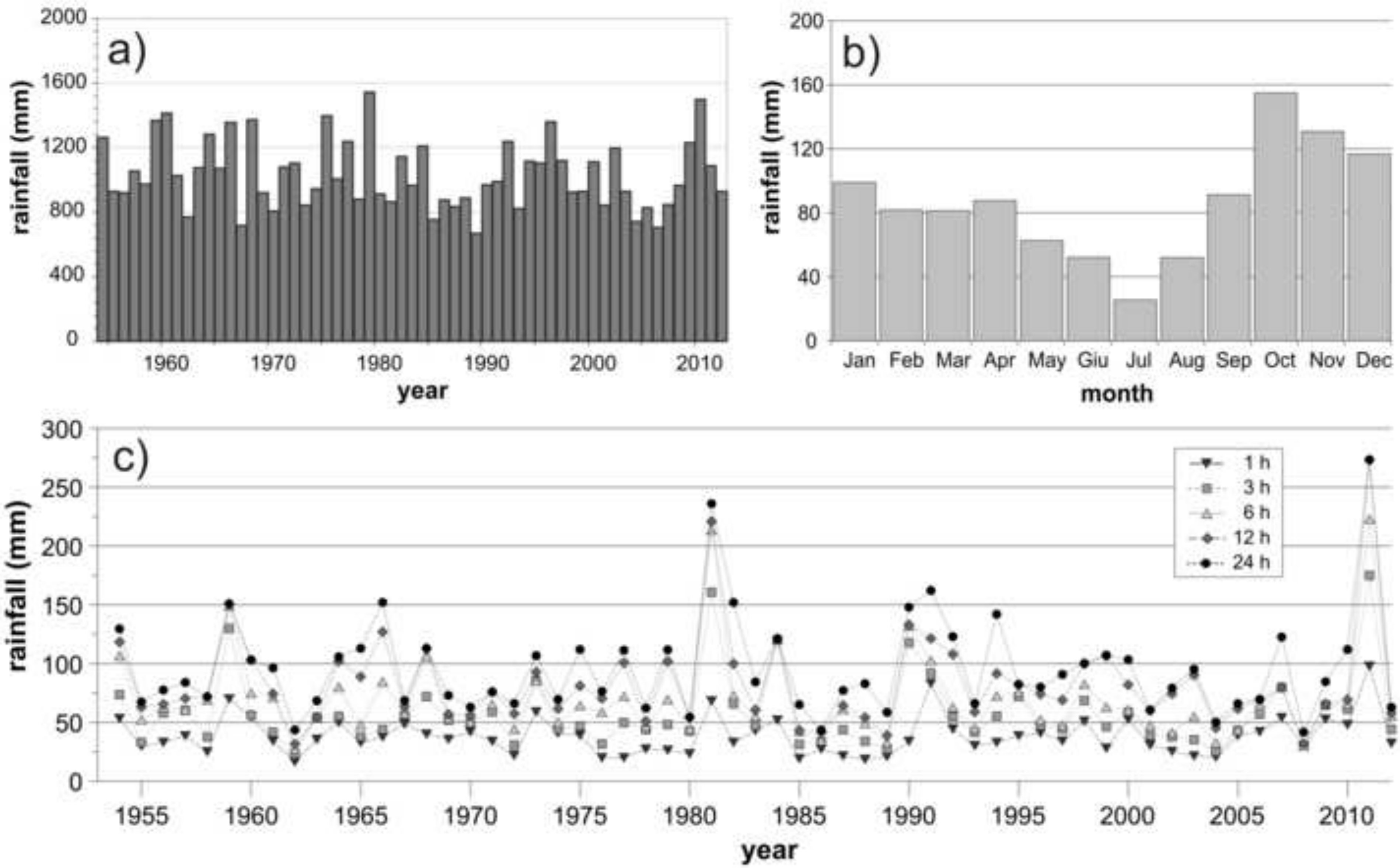

Figure 6

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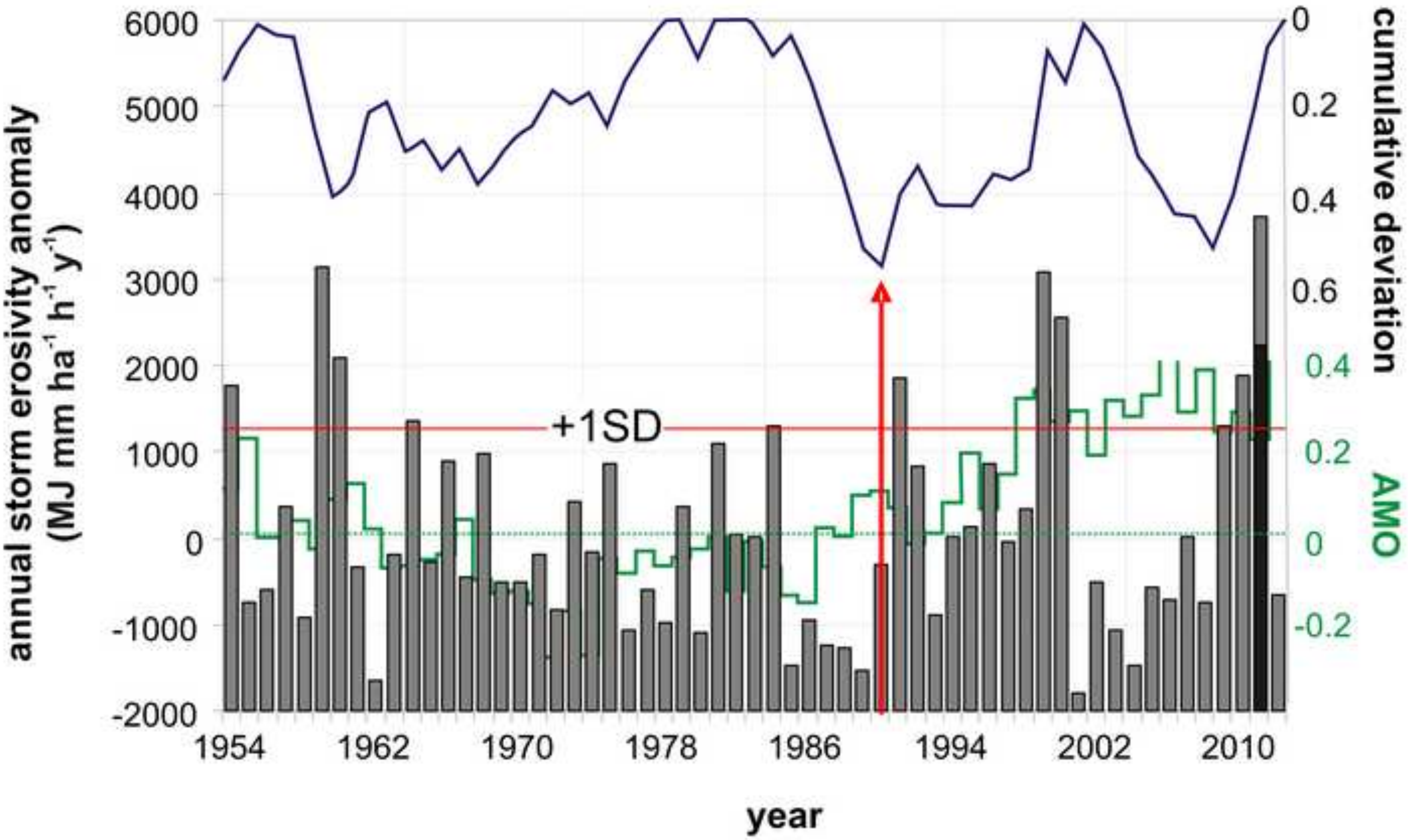


Figure 7

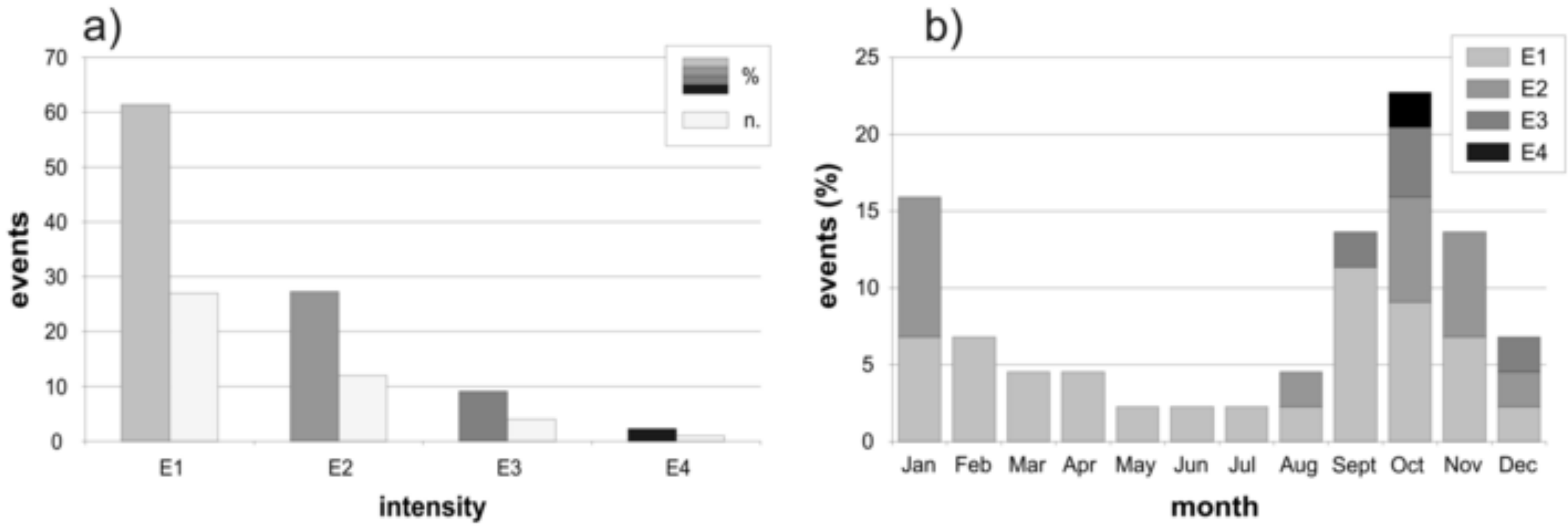

a)
events
70
60
50
40
30
20
10
0
%
n.
E1
E2
E3
E4
intensity
b)
events (%)
25
20
15
10
5
0
E1
E2
E3
E4
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec
month

Figure 8

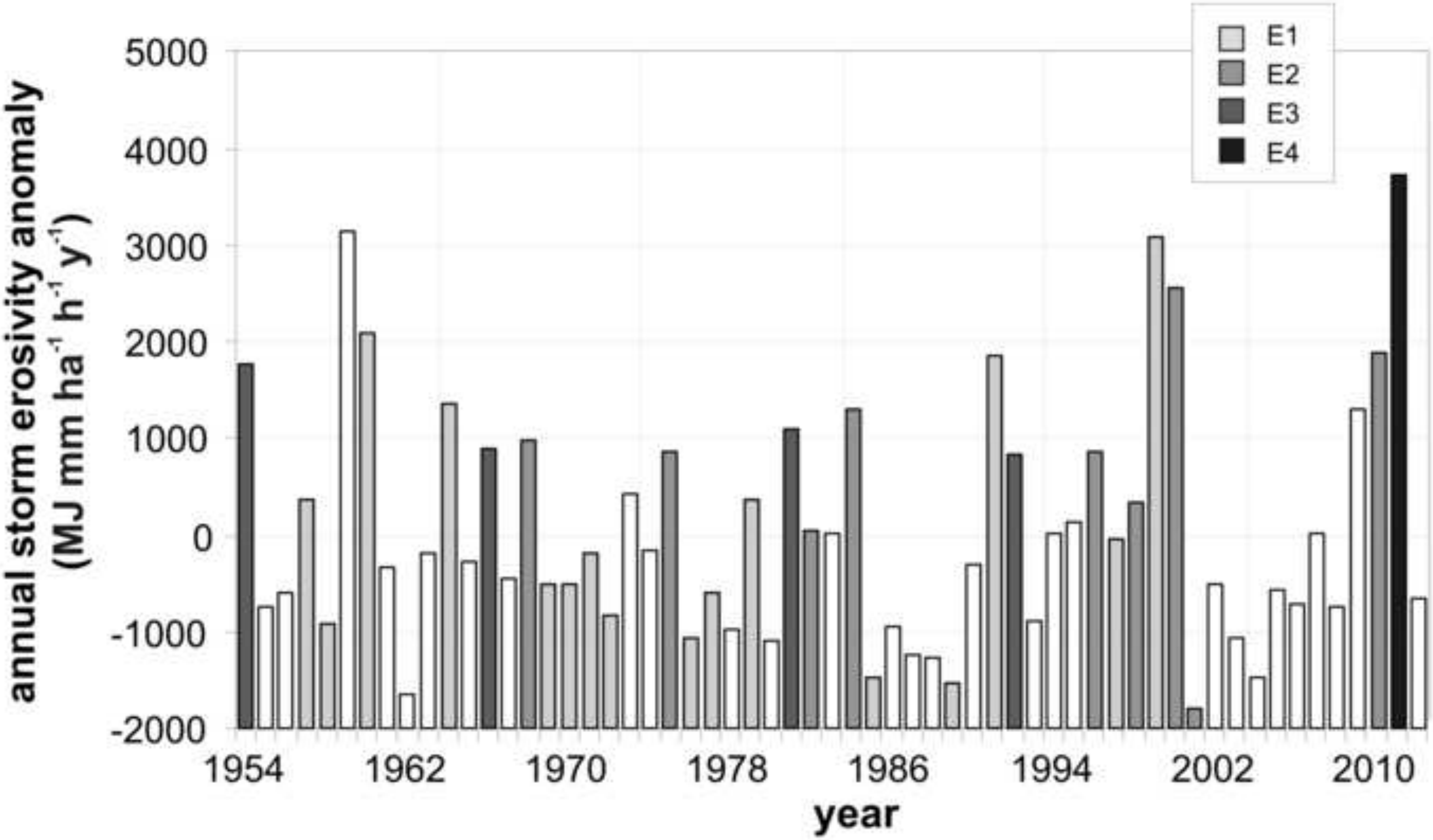
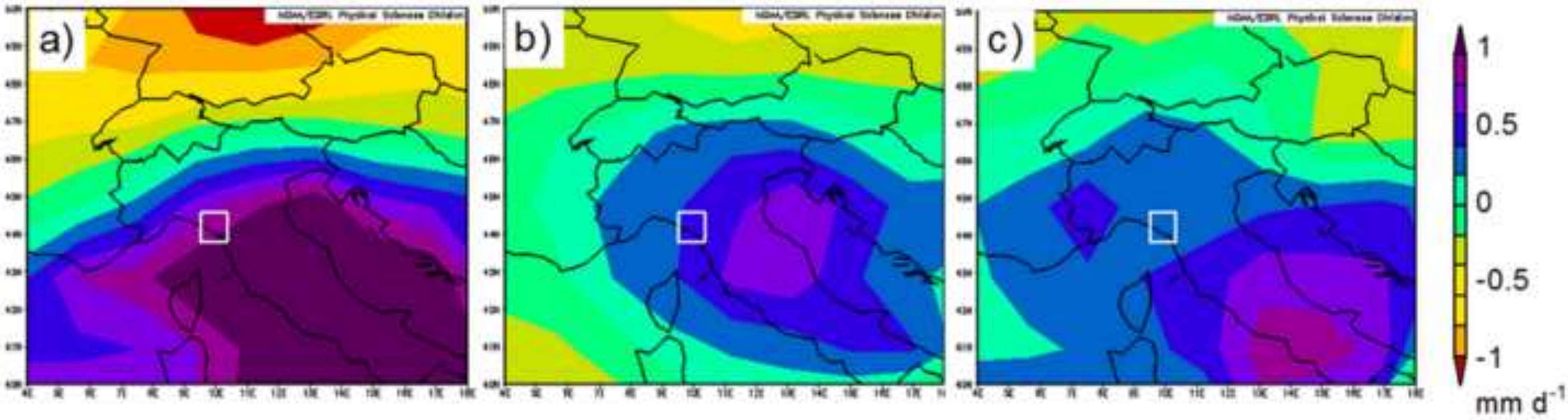

E1
E2
E3
E4
5000
4000
3000
2000
1000
0
-1000
-2000
annual storm erosivity anomaly
(MJ mm ha^{-1} h^{-1} y^{-1})
1954
1962
1970
1978
1986
1994
2002
2010
year

Figure 9


a)
NOAA/ESRL Physical Sciences Division
b)
NOAA/ESRL Physical Sciences Division
c)
NOAA/ESRL Physical Sciences Division
1
0.5
0
-0.5
-1
mm d^{-1}