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The Potential Role of Climate Indices to Explain Floods, Mass-Movement Events and Wildfires in Southern Italy

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Abstract: Climate variability can be the source of several multiple hazards and damaging phenomena, such as flash floods, debris flows, landslides, forest fires, etc. In this study the response in the frequency of landslides, floods and forest fires to a set of climate indices is studied, referring to a region of southern Italy (Calabria) located in the center of the Mediterranean basin, a hot-spot for climate change. For these comparisons, 5022 landslides and 1584 flood occurrences for a 29-year period (1990–2018) have been selected for the whole Calabria; the burnt areas have been analyzed for the same territory from 2008 to 2018. The climate indices have been calculated by means of daily rainfall and temperature data registered in 93 stations. The results showed that landslide occurrences are more linked with climate indices describing not very intense rainfall. Conversely, floods show best matches with climate indices representative of more extreme precipitation. Regarding the burnt areas, the results confirmed that very dry climate conditions, modifying the moisture content of the soil, can change the intensity and the extension of fires.

Keywords: climate indices; sectorial indices; comparison; Calabria (southern Italy)

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1. Introduction

Climate variability may cause several impacts, particularly cold and warm, dry and wet, severe snowfall events, wind storms, etc. [1–3]. Intense rain events are a source of multiple hazards: they can simultaneously trigger different types of damaging phenomena (flash, river or urban floods) and the development of Damaging Hydro Geological Events (DHEs) [4], e.g., mass-movements as debris-flows, landslides, etc. [5–7]. Societal significance of these events becomes visible through their effects on human society, its assets and activities, as significant economic losses, severe damage to buildings and transport assets, and losses of human life [8,9]. DHEs are different in terms of mechanisms, dynamics and effects on mankind and environment, and their simultaneous occurrence may lead to damage that cannot be properly assessed when phenomena are considered separately. The combined activation of floods and landslides may both amplify damage and hint emergency management actions, in a sort of cascading effect (i.e., the interruption of roads and power supply), which obstruct both emergency management and post-event recovery [10]. In the last 20 years, DHEs have produced damages estimated more than USD 650 billion, affecting millions of people around the world [11]. The impact of rain events can be exacerbated by concurrent variations in the precipitation regimes, foreseen under the effects of the changing climate, that is leading to an increase of both frequency and intensity of these events [12]. In some areas (i.e., north-eastern Europe), the increase of air temperature causes severe floods due to earlier spring snowmelt [13]. Moreover, the variations in the seasonal distribution of precipitation and evaporation also affect the soil moisture conditions of flood events [12]. Actually, the period 1990–2016 represents one of the most flood-rich periods in Europe, if compared to similar flood-rich periods over the past 500 years [13]. Regarding the landslides, even though the relation between the increase of these phenomena and climate changes remains a difficult and uncertain task, in some areas global warming with the consequent increase of the rainfall event intensity represents a primary trigger of shallow and rapid landslides and thus a principal cause of landslide fatalities [9,14].

On the other hand, long and severe dry periods have serious effects on crop yields, forest growth and mortality, availability of water resources, forest fires, etc. [15–17]. As representative examples, a widespread reduction of vegetation production was recorded in central Europe after the 2003 drought [18]; large agricultural and hydrological impacts were verified in 2017 after very dry periods in several parts of the world, especially in Asian countries [19]; losses in agriculture and forestry were recorded in large areas of Europe after the 2018 drought event, which caused a total damage of about EUR 3.3 billion [20] and hit mainly Northern and Central Europe [21,22]. Additionally, dry conditions have strong effects on fire risk [23]. In fact, some meteorological variables are used for the definition of fire danger indices [24–26], which in turn are useful for characterizing or anticipating dangerous conditions for fires [27,28]. Mediterranean countries are particularly affected by forest fires: every year an average of 50,000 fires burn about 4500 km^2 [29]. Recently, the socio-economic transformations of the last 50 years (decline of rural activities, urban development, reforestation programs, investments in fire management, etc.) have significantly changed the incidence of fires which, despite an increase during the 1970s–1980s [30,31], are characterized by an overall decrease [32], as happened in many regions across the world [33,34]. Nevertheless, an increased prevalence of extreme wildfire events (EWEs) has occurred. EWEs are very intense fires that often result in huge burned areas, with significant impacts on human lives and assets [35,36], and related to anthropogenic forcing. Different studies [32,37,38] have highlighted that drought conditions increased the activity of fires in various areas of the Mediterranean basin.

These evidences make it necessary to establish the existing relationships between the occurrence of these natural hazards (floods, landslides and forest fires) and the temporal behaviour of the climate conditions, with particular focus on the applicability of synthetic climate indices that may explain variability and trends of hazard probability. There are very few studies that have linked climate indices with hazard probability. Among these studies, Lung et al. [39] provided an indicator-based impact assessment framework on a European scale. They quantified potential regional changes for the following hazards: heat stress in relation to human health, river flood risk and forest fire risk. Vitolo et al. [40] suggested a methodology to generate layers based on reanalysis data, high resolution and probabilistic medium-range forecasts of two hazard indices, representing fire danger and heat stress.

The aim of this study is to determine the response in the frequency of landslides, floods and forest fires to a set of sectorial climate indices in the frame of the EC-project INDECIS (“Integrated approach for the development across Europe of user-oriented climate indicators for GFCS high-priority sectors: agriculture, disaster risk reduction, energy, health, water and tourism”). Particularly, this study focuses on Calabria, a region of southern Italy located in the centre of the Mediterranean basin, which is considered a hot-spot for climate change [41]. The Calabria region is particularly predisposed to slope instabilities and floods due to both climatic and geomorphologic features [42]. Moreover, the frequent drought events, that often affect Calabria [43,44], also influence particularly wildfire frequency and severity.

2. Materials and Methods

2.1. Study Area

Calabria is an oblong peninsular region of southern Italy, located at the centre of Mediterranean Sea. It has an area of 15,080 km^2, with a 738 km long coastline in front of the Tyrrhenian Sea (on the west side) and the Ionian Sea (on the east side). The mean altitude is 597 m a.s.l. and the maximum is 2267 m a.s.l. Due to the still active tectonic uplift that started in Quaternary, the morphology of the region is rugged and characterized by the presence of the Apennine chain, settled along meridians. Landscape is mainly hilly (49% of the total surface) and mountainous (41%), with flat areas (9%) limited chiefly to the coastal plains, at the mouth of main rivers.

Based on the Köppen-Geiger classification [45], Calabria belongs to the mesotermic climates. Specifically, most of the region presents the Csa type (Mediterranean with dry and hot summers), with the Csb variety (Mediterranean with dry and warm summers) referred to higher elevations in the Apennines.

In general, these Mediterranean climates, characterized by cool and rainy winters and hot and dry summers, makes the regions, such as Calabria, potentially subject to fires during late spring, summer and early autumn, because winter promotes the fuel accumulation and summer triggers the rapid loss of moisture content of the fuel [46]. Forestry extension in Calabria is about 612,000 ha [47], that is about 40% out the whole regional territory and 6% out the total forestry coverage of Italy. In accordance with the European Forest Type [48], forestry in Calabria is mainly composed by "Apennine Corsican mountainous beech forest", "Alpine Scots pine and Black pine forest", "Altimediterranean pine forest", "Chestnut forest", "Pedunculate oak-hornbeam forest", "Sessile oak hornbeam forest", "Downy oak forest" [47]. The majority of these types are classified with a high flammability index, in accordance with the classification of Xanthopoulos et al. [49].

Moreover, for its particular geographical position and its complex orography, Calabria is exposed to a wide variety of meteorological conditions causing high spatial variability of rainfall characteristics. Thus, while the Tyrrhenian sectors and inland areas, exposed to prevailing western currents, present high annual rainfall (with peaks up to 2000 mm/year) caused by orographic effects, the Ionian areas have a lower annual rainfall (with a minimum of 500 mm/year), and are affected by short and intense rains generated by warm-humid southern air masses, with high inter-annual variability. A recent study [42] highlighted an influence of several teleconnection patterns on the rainfall temporal distribution in the region. The Mediterranean Oscillation seems one of the best drivers of precipitation variability over Calabria. Other modes are also relevant, such as the Western Mediterranean Oscillation and the Eastern Atlantic patterns.

The fluvial system is mainly made by ephemeral streams due to the rapid uplift of the territory. These streams are dry during summer, but can cause damaging flash floods [50] during rainy periods, often amplified by concurrent sea storms [51]. Moreover, climatic conditions and tectonic stresses worsened the rocks characteristics, predisposing slopes to instabilities that during rain events cause new landslides or re-mobilized quiescent mass movements [52,53].

2.2. Database

2.2.1. Natural Hazards Dataset

In this study, we use documentary sources to create a catalogue of hazardous events. Documentary sources remain the foundation for the construction of historical records of hazardous events, as they are the only way to obtain information on past damaging events, even if their limitations are widely known in literature [54–56]. Data about the rainfall-triggered geo-hydrological events occurred in Calabria and their damaging effects are included in a catalogue that systematically collects them from different sources of information, including local and national newspapers, web sites, reports from national and regional agencies and public offices, and post-event field surveys [57,58].

Using the mentioned database, we extracted 5022 landslides and 1584 flood occurrences for a 29-year period (1990–2018) in the whole territory of Calabria. In the study period, floods killed 42 people and injured 213. In the same time span, landslides were more frequent but less lethal (6 people) and less injured (141) than floods.

Data of the wildfires on the territory of the Calabria region were obtained from the module Rapid Damage Assessment (RDA) of EFFIS (European Forest Fire Information System [29], implemented in 2003 to map the areas burned during the fire season, analysing the daily MODIS images aboard the TERRA and AQUA satellites (250 m spatial resolution) (accessed on 01 July 2021). Twice a day, the RDA module provides the updated perimeters of burnt areas in Europe for wildfires of at least 30 hectares. Although only a fraction of the total number of fires is mapped, the area burned by fires of this size represents approximately 75–80% of the total area burned in the EU. The burnt areas in the whole territory of Calabria from 2008 to 2018 were therefore deduced from the aforementioned RDA module.

2.2.2. Climate Dataset

We have used daily climatic series already processed in previous works [59,60]. Data of daily rainfall and temperature (minimum and maximum) registered in 93 weather stations (operating since 1916 with different start years) were managed in the past by the "Hydrographic and Mareographic Centre of Catanzaro" and, currently, by the "Arpacal Multi-Risk Functional Centre". The series were checked regarding quality homogeneity [59,60]. The observation periods were 1990–2018 in order to be compared with landslides/floods and 2008–2018 for the relationship with burnt area dataset. For these reasons, the datasets used in previous works have been updated with new data of ARPACAL centre and checked regarding their quality. Regarding missing data, the absence in a station of at least one daily data had the consequence to delete the whole year. However, missing data are not numerous and, consequently, the percentage of useful years for the climate index calculation is higher than 70% in each station. Locations of the weather stations of Calabria are shown in Figure 1; their names and elevations are listed in Table 1.

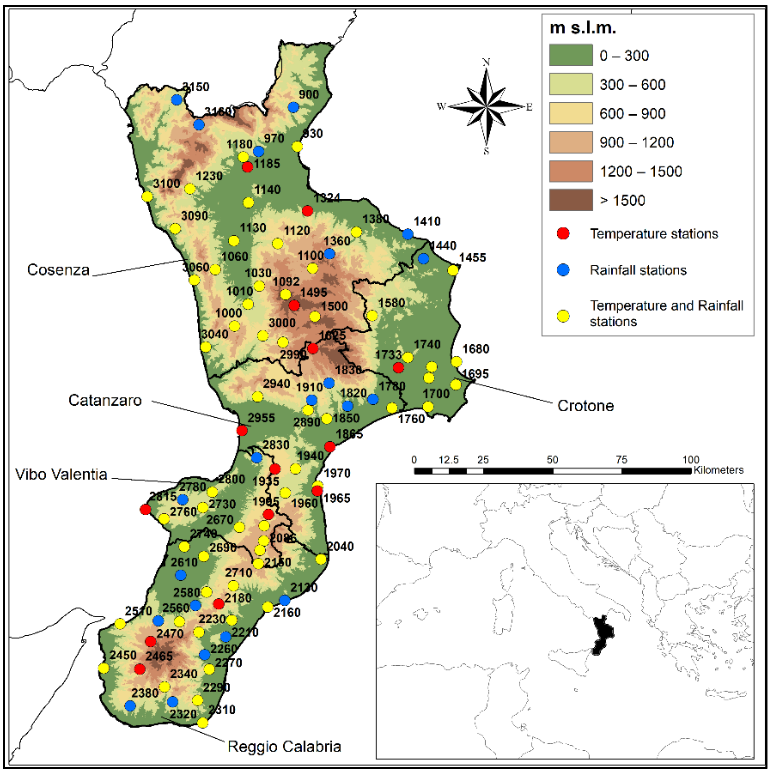


Figure 1. DEM of Calabria with indication of the rainfall and temperature stations.

Table 1. Weather stations used in the study, with indication of ID and elevation (m a.s.l.).

ID	Station Name	Elevation	ID	Station Name	Elevation
900	Albidona	810	2086	Mongiana	921
930	Villapiana Scalo	5	2090	Fabrizia	948
970	Cassano allo Ionio	251	2130	Roccella Ionica	5
1000	Domanico	736	2150	Fabrizia–Cassari	970
1010	Cosenza	242	2160	Gioiosa Ionica	125
1030	San Pietro in Guarano	660	2180	Antonimina–Canolo Nuovo	880
1060	Montalto Uffugo	468	2200	Antonimina	310
1092	Camigliatello–Monte Curcio	1730	2210	Ardore Superiore	250
1100	Cecita	1180	2230	Plati’	300
1120	Acri	790	2260	San Luca	250
1130	Torano Scalo	97	2270	Sant’Agata del Bianco	380
1140	Tarsia	203	2290	Staiti	550
1180	Castrovillari	353	2310	Capo Spartivento	48
1185	Castrovillari–Camerata	82	2320	Bova Superiore	905
1230	San Sosti	404	2340	Roccaforte del Greco	930
1324	Corigliano Calabro	219	2380	Montebello Ionico	470
1360	Longobucco	770	2450	Reggio Calabria	15
1380	Cropalati	367	2465	Cardeto	670
1410	Cariati Marina	10	2470	Gambarie d’Aspromonte	1200
1440	Crucoli	367	2510	Scilla	73
1455	Ciro’ Marina–Punta Alice	10	2540	Santa Cristina d’Aspromonte	510
1495	Botte Donato	1928	2560	Sinopoli	502
1500	Nocelle–Arvo	1315	2580	Molochio	310
1580	Cerenzia	663	2600	Cittanova	407
1670	Cutro	169	2610	Rizziconi	114
1675	Crotone–Papanice	156	2670	Arena	450
1680	Crotone	5	2690	Feroleto della Chiesa	160
1695	Crotone–Salica	162	2710	Mammola–Limina C.C.	800
1700	Isola di Capo Rizzuto–Campolongo	90	2730	Mileto	368
1733	Roccabernarda -Serrarossa	49	2740	Rosarno	61
1740	San Mauro Marchesato	288	2760	Joppolo	185
1760	Botricello	18	2780	Zungri	578
1780	Cropani	347	2800	Vibo Valentia	498
1820	Soveria Simeri	366	2815	Capo Vaticano	30
1825	Taverna–Ciricilla	1270	2830	Filadelfia	550
1830	Albi	710	2890	Tiriolo	690
1850	Catanzaro	334	2940	Nicastro–Bella	400
1865	Borgia–Roccelletta	8	2955	Lamezia Terme-Palazzo	24
1910	Gimigliano	550	2990	Parenti	830
1935	Cenadi–Serralta	1013	3000	Rogliano	650
1940	Palermiti	480	3040	Amantea	54
1960	Chiaravalle Centrale	714	3060	Paola	160
1965	Satriano Marina	10	3090	Cetraro Superiore	416
1970	Soverato Marina	29	3100	Belvedere Marittimo	10
1980	Serra San Bruno	790	3150	Laino Borgo	250
1995	Spadola	714	3160	Campotenese	965
2040	Monasterace–Punta Stilo	70			

2.3. Methods

Climate indices have been recently introduced to overcome the limits existing both in the in situ observations and remotely sensed data regarding their consistency, data quality and accessibility [61]. The Expert Team on Climate Change Detection and Indices (ETCCDI), co-sponsored by the World Meteorological Organisation (WMO) Commission for Climatology (CCl), the World Climate Research Programme (WCRP) and the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), worked for about 20 years (1998–2017) leading also to collect a set of indices representing temperature and precipitation extremes, referring to about 30% of the Earth surface [62–64]. With this approach, the problem of the unavailability of climatic data, free of charge to the scientific community existing in some regions, have been also solved. With HadEX [21] the first global data set introduced by the ETCCDI has been updated. Then, Dunn et al. [65] presented HadEX3, the second update to the data set of gridded land-based indices of temperature and rainfall extremes. With the aim to analyze the effects of climate variability and change on both physical and human environments (e.g., hydrology, water resources, agriculture, etc.), the INDECIS project (www.indecis.eu (accessed on 10 October 2021)) catalogued a series of sector-oriented indices [66].

In this work, aiming the comparison with sectorial indices regarding geo-hydrological risks, thirteen climate indices have been considered. We have chosen the rainfall indices representative to diffuse but not extreme precipitation events, that could influence the triggering of diffuse and deep landslides, given the characteristics of the study area. We have also chosen those climate indices more representative of short and extreme rainfall events that could cause flash floods or shallow and rapid landslides.

For the comparison with landslides and floods, the following climate indices have been selected from a review of the literature [21,62,66,67]:

- R01mm: annual count of days when precipitation was ≥1 mm;
- R03mm: annual count of days when precipitation was ≥3 mm;
- R10mm: annual count of days when precipitation was ≥10 mm;
- R20mm: annual count of days when precipitation was ≥20 mm;
- R50mm: annual count of days when precipitation was ≥50 mm;
- R95TOT: annual total precipitation when daily precipitation ≥95th percentile;
- R95F: fraction of the total annual precipitation, when daily precipitation ≥95th percentile;
- R99TOT: annual total precipitation when daily precipitation ≥99th percentile;
- R99F: fraction of the total annual precipitation, when daily precipitation ≥99th percentile;
- RX1day: maximum annual daily precipitation value;
- RX5day: maximum annual 5-daily precipitation value;
- LWP: maximum number of consecutive “wet days” in a year (“wet day” is a day with a precipitation ≥1 mm);
- RTWD: cumulative annual precipitation on the basis of the daily precipitation ≥1 mm.

The indices listed above have been calculated for each of the 93 weather stations by means of “ClimInd” package within the R platform (https://cran.r-project.org/web/packages/ClimInd/index.html, (accessed on 1 April 2021)). As the geo-hydrological data are available as annual values, the comparisons have been carried out considering for each province and for the whole Calabria region both the yearly average and maximum values of the climate indices evaluated with the data calculated for the stations falling in the territory considered (province or region). For the comparisons, two fitting curve models have been tested: linear and exponential, fixing, for obvious “physical reasons”, an y-value (landslides/floods) equal to zero (or one, in the exponential case) if x (climate index) is zero.

The goodness of fit of the model was measured by means of the coefficient of determination R^2 and the Standard Error (SE) of the model: high values of R^2 and low values of SE together could indicate a good fitting between the two datasets. The estimation of the parameters of the fitting curves have been made by means of the tool of the R-package.

The statistical significance of the parameter estimations was checked through the *p*-value test (s.l. = 5%).

For the comparison with burnt areas, three indices have been used: the Standardized Precipitation Index (SPI), the Standardized Precipitation–Evapotranspiration Index (SPEI) and the Keetch–Byram Index (KBDl). The SPI, widely used in drought monitoring, was developed by McKee et al. [68] to quantify precipitation over multiple time scales. It is considered to be the simplest index, because it only uses monthly precipitation data and can be calculated on various time-scales with different purposes: SPI computed over 1-month, 3 to 6-month, 6 to 12-month and longer time scales is an indicator for meteorological, agricultural, hydrological and economic-social drought, respectively. The calculation of SPI is based on fitting the best probability distribution function to the precipitation dataset, for which McKee et al. [68] proposed the two-parameter Gamma probability density function. Values of SPI higher than 0 imply more than average rainfall (wet conditions); SPI lower than 0 indicates less than average rainfall (drought conditions).

Different from the SPI analysis, the SPEI employs the value of the difference between precipitation and atmospheric evaporative demand [69,70]. Once accumulated reduced precipitation has been transformed to probabilities, these are converted into the standard normal distribution to create the final drought index values. SPEI is widely used to monitor the drought severity under global warming conditions [70,71]. The index refers to multiple time scales too: 1, 3, and 6-month time scales reflect the changes of surface soil moisture; the SPEI of 12-month time scale is related to hydrological changes, reflecting water surplus and deficit on a long-term scale.

Keetch–Byram Index (KBDI) [72] provides an estimate of the cumulative moisture deficit in the deep duff and upper soil layers, and ranges from 0 (saturated soil) to 203.2 mm (extreme drought). KBDI has become the most widely used index worldwide in monitoring and forecasting fires, mainly due to its easy implementation, compared to other indices that normally require more meteorological data as input and complex calculations. The index increases for each day without rain and decreases when it rains, with a variation (daily drought factor) which depends on the daily maximum temperature, on the average annual precipitation and on the value of the same index estimated on the previous day. The calculation must start in time from a "zero point", when it is reasonably certain that the upper soil layers are saturated (i.e., after either the snow melts in spring or a period of abundant rainfall that the authors suggested to be 150–200 mm/week, as fixed in this study). Further explanations on this index can be found in [72] and [73]. In this study, the KBDI was calculated on a daily scale for all the stations of the dataset, thanks to the algorithm present in the ClimIND 0.1–2 package (https://cran.r-project.org/web/packages/ClimInd/index.html, (accessed on 1 April 2021)), appropriately corrected and modified for the treatment of incomplete time series. The average monthly values assumed by the KBDI index were calculated for each station of the dataset. Given the missing data present in each month, in order to obtain consistent monthly time series, only the months with a minimum number of valid KBDI values equal to 20 were taken into account. These data, averaged on a territorial scale (the whole Calabria), were finally compared with those relating to the burnt areas, for the 11-years-time interval (January 2008–December 2018).

For the comparisons of climate indices with burnt areas, three fitting curve models have been tested: linear, quadratic and exponential. As SPI and SPEI can have both negative and positive values, the fitting curve models have been tested separately for the indices data with opposite signs and then a unique R^2 has been estimated. Also in this case, the estimation of the parameters of the fitting curves have been made by means of the tool of the R-package. The statistical significance of the parameter estimations was checked through the *p*-value test (s.l. = 5%).

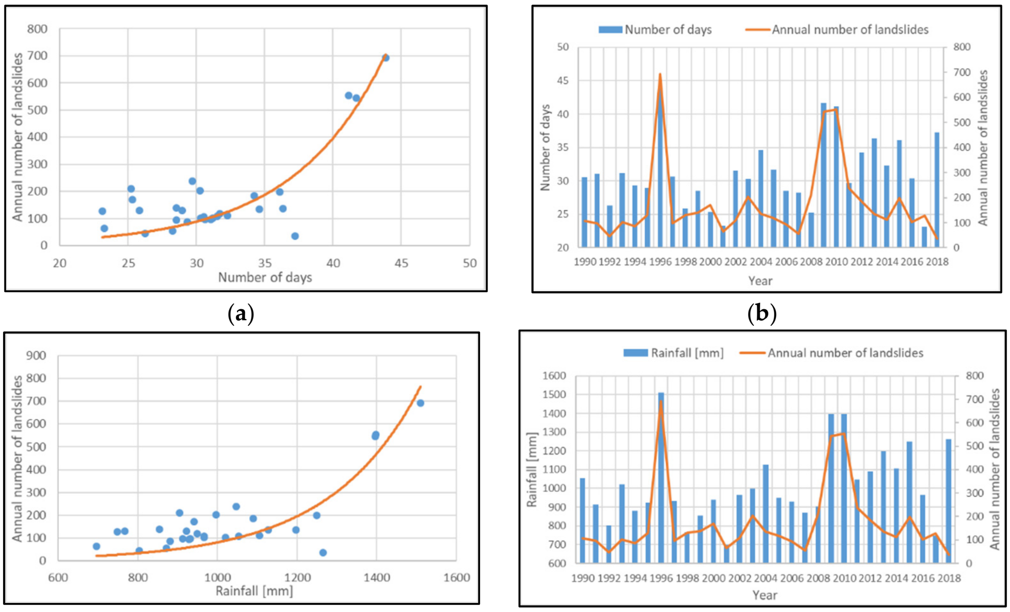
3. Results

3.1. Climate Indices and Mass-Movements

The annual number of landslides has been compared with the selected climate indices. Table 2 shows the expressions of the best fitting models for all the comparisons considering both the average and maximum values for the whole territory of Calabria. The results show that the best comparisons have been obtained with R10mm (average values), RTWD (average and maximum values), R20mm (maximum values): all these fitting models are of exponential type and present values of R^2 higher than 0.68 and SE values lower than 90. As Table 2 shows, for some climate indices the best fitting models are linear with intercept equal to zero. Some of these present high values of R^2 (even higher than 0.75) but also high values of SE (higher than 100): the reason of these divergent outputs is due to the overestimation of R^2 in linear models with zero intercept when R-package is used (i.e., see https://www.riinu.me/2014/08/why-does-linear-model-without-an-intercept-forced-through-the-origin-have-a-higher-r-squared-value-calculated-by-r/ (accessed on 5 August 2021)). Figure 2 shows, for the best two comparisons between climate indices and landslide occurrences, the curves fitting the sample points and the time series of the two datasets. The peaks of the climate indices correspond to the highest annual number of landslides, in particular for the years 1996, 2009 and 2010. This close agreement appears also for almost all the lowest values, particularly for the years 1992, 1998, 2001, 2017. Additionally, close relationships have been found at the province scale. Table 3 shows the best relationships between the annual frequency of landslides and some of the climate indices. R10mm and RTWD are confirmed as the climate indices showing the best matches with the number of landslides for the largest provinces of Calabria (Catanzaro, Cosenza and Reggio Calabria). Conversely, for Crotone and Vibo Valentia, that present the lowest extensions, R01mm and R50mm show the best matches with the annual landslide frequency.

Table 2. The best fitting models between the climate indices (for average and maximum values) and the annual number of landslides occurred in Calabria.

X (Climate Index)	Average or Maximum Values	Correlation Equation (Y = Number of Landslides)	R^2	SE
R01mm	Ave	Y = exp (0.0571·X)	0.5227	107.7
	Max	Y = exp (0.039867·X)	0.5007	110.2
R03mm	Ave	Y = exp (0.077585·X)	0.6194	96.17
	Max	Y = exp (0.0504919·X)	0.5251	107.4
R10mm	Ave	Y = exp (0.149571·X)	0.7412	79.31
	Max	Y = exp (0.085465·X)	0.5938	99.36
R20mm	Ave	Y = exp (0.29148·X)	0.6047	98.01
	Max	Y = exp (0.153742·X)	0.6798	88.21
R50mm	Ave	Y = 72.652·X	0.7591	115.5
	Max	Y = 21.32·X	0.7429	119.3
R95TOT	Ave	Y = exp(0.0116363·X)	0.4345	117.2
	Max	Y = 0.2258·X	0.6892	131.2
R95F	Ave	Y = 6.4044·X	0.6386	141.5
	Max	Y = 3.2616·X	0.5862	151.3
R99TOT	Ave	Y = 1.5829·X	0.7303	122.2
	Max	Y = 0.39027·X	0.6641	136.4
R99F	Ave	Y = 17.868·X	0.6317	142.8
	Max	Y = 5.2515·X	0.6159	145.8
RX1Day	Ave	Y = 2.0164 ·X	0.6365	141.9
	Max	Y = 0.6957·X	0.5957	149.6
RX5Day	Ave	Y = 1.2002·X	0.6439	140.4
	Max	Y = 0.49332·X	0.6490	139.4
LWP	Ave	Y = 25.19·X	0.6073	148.0
	Max	Y = 12.04·X	0.5765	153.1
RTWD	Ave	Y = exp (0.004396·X)	0.7090	84.09
	Max	Y = exp (0.002393·X)	0.6837	87.67



(**a**) (**b**)

(**c**) (**d**)

Figure 2. Two examples of the best comparisons between number of landslides and climate indices for the whole Calabria region, obtained with the average values of R10mm (**a**,**b**) and R10mm (**c**,**d**).

Table 3. The best fitting models between the climate indices (for average or maximum values) and the annual number of landslides occurred in each province of Calabria.

Province	X (Climate Index)	Average or Maximum Values	Correlation Equation (Y = Number of Landslides)	R^2	SE
Catanzaro	R10mm	Max	Y = exp (0.075053·X)	0.4563	22.76
Cosenza	R10mm	Ave	Y = exp (0.117878·X)	0.8436	26.85
Crotone	R01mm	Ave	Y = exp (0.043440·X)	0.1497	19.42
Vibo Valentia	R50mm	Ave	Y = 5.8475·X	0.8002	10.35
Reggio Calabria	RTWD	Max	Y = exp (0.002059·X)	0.5359	27.62

3.2. Floods and Climate Indices

The selected climate indices show a high agreement with the annual frequency of floods in Calabria (Table 4). In the majority of cases, R^2 values are higher than 0.65, anyway remembering the overestimation of R^2 in linear interpolation models with zero-intercept. Considering the lowest values of SE and the highest values of R^2 together, the closest relationships are found with the maximum values of R10mm and R20mm and, secondarily, with the average values of R95TOT, R50mm, RX1Day. In general, there is a very close temporal agreement between the frequency of floods and the values of some of the mentioned indices (Figure 3). Table 5 shows the best relationships between the frequency of floods and the different indices at the province scale. R95TOT and R50mm are confirmed as the climate indices showing the best agreements with flood frequency for the Cosenza, Crotone and Reggio Calabria provinces. For the Catanzaro and Vibo Valentia provinces, R95F and R99F show the best relationships with the annual flood frequency.

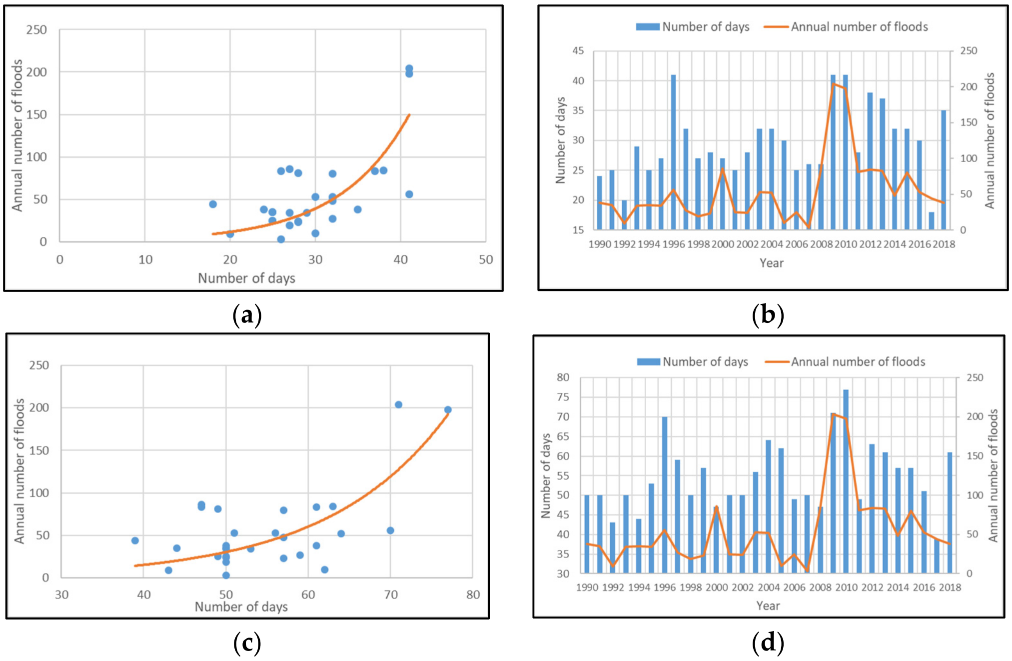


Figure 3. Two examples of the best comparisons between number of floods and climate indices for the whole Calabria region, obtained with the maximum values of R20mm (**a**,**b**) and R10mm (**c**,**d**).

Table 4. The best fitting models between the climate indices (for average and maximum values) and the annual number of floods occurred in Calabria.

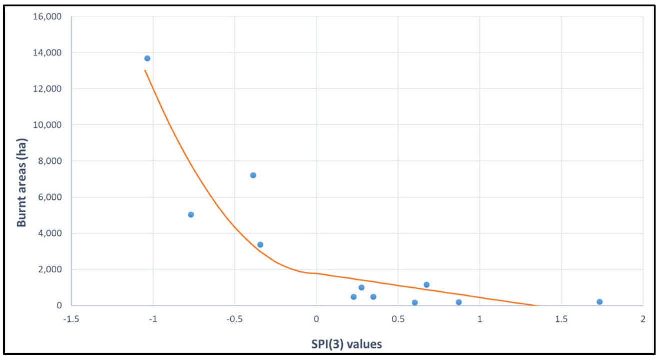
X (Climate Index)	Average or Maximum Values	Correlation Equation (Y = Number of Floods)	R^2	SE
R01mm	Ave	Y = exp (0.044562·X)	0.2861	39.91
	Max	Y = exp (0.030629·X)	0.1086	44.6
R03mm	Ave	Y = exp (0.060293·X)	0.2801	40.08
	Max	Y = exp (0.038725·X)	0.0899	45.06
R10mm	Ave	Y = exp (0.116947·X)	0.3429	38.29
	Max	Y = exp (0.068318·X)	0.5141	32.92
R20mm	Ave	Y = exp (0.227150·X)	0.1236	44.22
	Max	Y = exp (0.122100·X)	0.5145	32.91
R50mm	Ave	Y = 22.585·X	0.7632	35.5
	Max	Y = 6.5998·X	0.7408	37.14
R95TOT	Ave	Y = 0.19032·X	0.7627	35.54
	Max	Y = 0.069233·X	0.6741	41.64
R95F	Ave	Y = 2.0734·X	0.6964	40.20
	Max	Y = 1.049·X	0.6309	44.32
R99TOT	Ave	Y = 0.4976·X	0.7508	36.41
	Max	Y = 0.122·X	0.6748	41.60
R99F	Ave	Y = 5.885·X	0.713	39.08
	Max	Y = 1.6999·X	0.6714	41.81
RX1Day	Ave	Y = exp (0.0403107·X)	0.4098	36.29
	Max	Y = 0.23113·X	0.684	41.01
RX5Day	Ave	Y = 0.38328·X	0.6832	41.06
	Max	Y = 0.15955·X	0.7064	39.53
LWP	Ave	Y = exp (0.53464·X)	0.4087	36.32
	Max	Y = 3.9448·X	0.6439	43.53
RTWD	Ave	Y = exp (0.003439·X)	0.2902	39.80
	Max	Y = exp (0.001870·X)	0.2738	40.25

Table 5. The best fitting models between the climate indices (for average or maximum values) and the annual number of floods occurred in each province of Calabria.

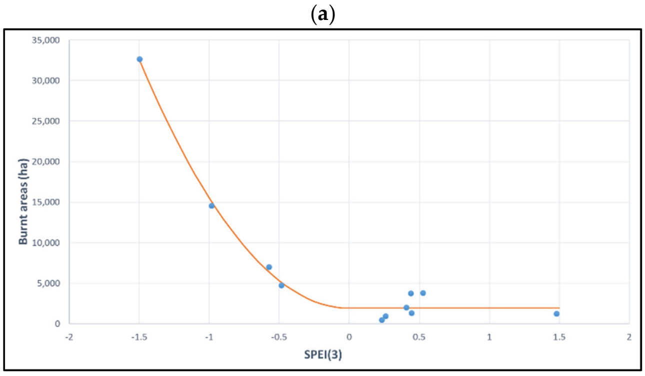
Province	X (Climate Index)	Average or Maximum Values	Correlation Equation (Y = Number of Floods)	R^2	SE
Catanzaro	R95F	Max	Y = exp (0.058378·X)	0.3109	12.94
Cosenza	R95TOT	Max	Y = exp (0.003779·X)	0.8472	6.00
Crotone	R95TOT	Ave	Y = exp (0.0049663·X)	0.5030	4.26
Vibo Valentia	R99F	Ave	Y = exp (0.038725·X)	0.2409	4.53
Reggio Calabria	R50mm	Ave	Y = 6.9124·X	0.8192	9.67

3.3. Wildfires

The comparisons with the burnt areas referred to the whole territory of Calabria have been made considering the three indices SPI, SPEI and KDBI. Table 6 shows the best results obtained comparing climate indices and burnt areas. For SPI and SPEI, the best results have been obtained with the indices on a 3-month scale (SPI(3) and SPEI(3)) and, in particular, corresponding to the month of August (which includes climate data of June, July and August). For KBDI, comparisons reached close results with the values averaged on the year or on smaller intervals. Different scales have been used for the burnt areas: (a) KDBI values have been compared with the burnt area values of the period between April and October, that represents the time-span in which fires usually occur in the study area; (b) for SPI and SPEI the August 3-month climate indices were compared with the burnt areas of August, from June to August and from April to October. Regarding the fitting models, for SPI and SPEI the best results have been reached by means of a quadratic curve for negative values of the climate index and a linear interpolation for positive values (Figure 4). For KBDI the quadratic curve seems to be the best fitting model. Globally, the highest values of R^2 have been obtained with SPEI (mainly for the comparison of index and burnt areas evaluated in the time-span June–July–August) and, then, with KBDI (especially for the comparison of yearly KBDI with the data of burnt areas referred to the "fire season", that is from April to October).

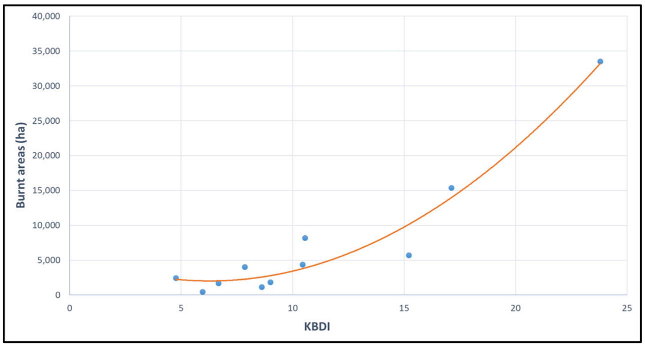


(**a**)



(**b**)

Figure 4. *Cont.*



(**c**)

Figure 4. The best fitting models between burnt areas and climate index: (**a**) SPI(3) in August and A-burnt areas; (**b**) SPEI(3) in August and JJA-burnt areas; (**c**) mean annual KBDI and seasonal (AMJJASO) burnt areas.

Table 6. The best fitting models between the climate indices SPI, SPEI, KBDI and the burnt areas (in hectares) for the whole territory of Calabria.

Index (X)	Time Domain of X (Climate Index)	Time Domain of Burnt Areas (Y)	Interpolation Curve	R^2
SPI (3)	JJA	A	$Y = 1778.7 + 10198.9 \cdot X^2$ for $X < 0$ $Y = 1778.7 - 1332.5 \cdot X$ for $X \geq 0$	0.8486
	JJA	JJA	$Y = 2753.5 + 23774.8 \cdot X^2$ for $X < 0$ $Y = 2753.5 - 803.8 \cdot X$ for $X \geq 0$	0.7837
	JJA	AMJJASO [2]	$Y = 3245.5 + 24366.2 \cdot X^2$ for $X < 0$ $Y = 3245.5 - 848.9 \cdot X$ for $X \geq 0$	0.7948
SPEI (3)	JJA	A	$Y = 1534.7 + 5590.5 \cdot X^2$ for $X < 0$ $Y = 1534.7 - 1322 \cdot X$ for $X \geq 0$	0.9681
	JJA	JJA	$Y = 1907.87 + 13611.69 \cdot X^2$ for $X < 0$ $Y = 1907.87 + 16.83 \cdot X$ for $X \geq 0$	0.9874
	JJA	AMJJASO [2]	$Y = 2447.02 + 13819.6 \cdot X^2$ for $X < 0$ $Y = 2447.02 - 81.62 \cdot X$ for $X \geq 0$	0.9849
KBDI [1]	Year	AMJJASO [2]	$Y = 101.67 \cdot X^2 - 1275.9 \cdot X + 6025.1$	0.9480
	JJASO	AMJJASO [2]	$Y = 21.456 \cdot X^2 - 649.7 \cdot X + 6940.7$	0.9343
	JASO	AMJJASO [2]	$Y = 15.194 \cdot X^2 - 581.63 \cdot X + 7570$	0.9291
	ASO	AMJJASO [2]	$Y = 13.615 \cdot X^2 - 669.75 \cdot X + 10092$	0.9448

[1] KBDI has been averaged on the time domain. [2] the months between April and October represent the period of the year in which fires usually occur.

4. Discussion

The Calabria territory is particularly affected by landslide and flood events having often catastrophic characteristics, with damages and fatalities. Moreover, the region is located in the centre of the Mediterranean basin, known as a hot-spot for climate change. For these reasons, the analysis of the links between the mentioned events and climate characteristics could be very useful.

Generally, climate indices represent a useful tool for analysing trend and climate behaviour and investigating the impact of climate on different sectors and socio-economic activities. The comparisons of these indices with data regarding geo-hydrological events and wildfires, as made in this study, do not represent a method to determine threshold values triggering such events, but could be useful to determine which climatic conditions can predispose a territory to these events. Each event should be compared separately with the registered rainfall aiming to investigate which rainfall characteristic (duration, intensity, etc.) could have been the triggering factor, but this is not among the goals of the present research.

For the study area, results show that landslide occurrences seem to be more linked with climate indices describing not very intense rainfall (R10mm, R20mm, RTWD). Conversely, floods show best matches with climate indices representative of more extreme precipitation (such as R95TOT and R50mm). The obtained results also show best matches of landslides/floods with climate indices on the regional scale, instead of the provincial one. This is due to the number of events used for the comparison, obviously higher for the region than for each province.

Regarding the best fitting models there is a prevalence of the linear one considering both landslides and floods, but the lowest values of the Standard Error (SE) are found with the exponential model. In general, better concordances have been obtained with landslide occurrences than with flood events, that can be due to two factors: (a) landslides are more frequent than floods (consequently, the sampling points for the first ones are more numerous than for the second ones); (b) the characteristics of the rivers in Calabria. In fact, the majority of rivers are called "fiumare" (small rivers) and are highly irregular: they often are very dry but can become raging torrents after short and heavy rainfall events. This is due to the fact that Calabrian rivers rise in rocky gullies and tumble-down steep gradients before reaching gentle valley rivers with pebble beds. In fact, the time of concentration of their basins is very low (only very few hours). The rivers with these characteristics can cause floods and consequent damages. For these reasons, flood occurrences may be mostly influenced by extreme hourly rainfall, but the climate indices applied in this study are calculated by daily data.

Regarding wildfires, the evaluation of the incidence of fires on a given region is a very complex operation because these events often depend on human activities, distribution of vegetation, fire management and extinguishing plans, as well as the ease of fire ignition, which is, in turn, influenced by human presence. Nevertheless, the meteorological factors can modify the moisture content of the fuel [74,75] and thus change the intensity and the extension of fires.

Moreover, it is important to underline that the RDA module database of EFFIS, used for this analysis, is referred to burnt areas with extension greater than 30 hectares (in Europe, these fires are about 75–80% of the total fires) and does not contain differences between natural fires and human-induced fires. However, the good results found with some of the three used indices (especially with SPEI) show the important role of the dry conditions in the extensions of the burnt areas, also from a forecast point of view. It is important to put in evidence that the obtained results are referred to only 11 years and thus cannot be considered with a high statistical significance.

Nevertheless, these results confirm those of Turco et al. [38] who showed that for the whole Mediterranean region the burnt areas have a strong correlation with the SPEI index calculated over the three summer months (June, July and August), and particularly in regions where the vegetation seems to present a lower adaptability to water scarcity conditions. They also revealed that in some areas (northern and eastern Spain and southern Italy) antecedent wet conditions have an influence on fires, as they affect fuel accumulation by increasing (or limiting) the so-called "Mediterranean Scrub".

5. Conclusions

Even though the estimation of the impacts of climate change remains a very complex issue, the analysis of how the climate trends, such as the increase of frequency and severity of extreme weather events, can determine particular tendencies in the occurrence of geo-hydrological events will represent an interesting development of this study. Moreover, the expected increase of droughts and heat waves [76–80] can cause a rise in the burnt areas in a certain way, even regardless of anthropogenic influences, given that drier and hotter conditions lead to greater flammability of the fuel. For these reasons, the results of this work represent a first step of a more detailed analysis that we are going to start and to include in a future work. Moreover, the approach used in this study can be applied to other areas with different physical-geographical features, but it always needs databases with a high degree of completeness and homogeneity, especially for the climatic data.

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