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Statistical Modelling of Extreme Precipitation Indices Supporting Urban Spatial Planning Processes

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Abstract: In this paper, we analyze how statistical modelling of extreme precipitation indices can support urban planners in the analysis and classification of the level of climate sensitivity of the territory and in the subsequent definition of sustainable adaptive planning and design choices. These activities are part of a research project that addresses the issue of climate change from the urban planning perspective to identify solutions to current and future environmental challenges, increasing the climate resilience of infrastructures and communities in urban, rural and coastal areas. These research activities are based on the desire to promote integration between the approaches commonly adopted by urban planners and climate specialists to plan adequate joint risk reduction strategies. As part of this study, the focus will be on the risks produced by the greater frequency and intensity of floods, assessed by the IPCC (Intergovernmental Panel on Climate Change) as one of the key risks for Europe. Specifically, our attention focuses on pluvial flooding, proposing the definition of a statistical modelling of indices related to extreme precipitation and its application to the context of the Calabria Region, in Italy. The indices are recommended by the ETCCDI (Expert Team on Climate Change Detection and Indices) and elaborated starting from official historical data recorded by 146 telemetry active rain gauges, disseminated in the experimentation context.

Key words: Urban areas, climate change, extreme precipitation.

1. Introduction

Floods associated with heavy rainfall, storm surges or alterations in river flows cause negative impacts, posing a threat to society and local ecosystems [1]. Cities are particularly vulnerable to such events due to the concentration of people, buildings, infrastructure and impervious surfaces [2].

Specifically, according to Rosenzweig et al. [3] pluvial flooding occurs when precipitation intensity exceeds the capacity of natural and engineered drainage systems. These phenomena are expected to increase in frequency, severity, and impact through the 21st century due to the combined effects of aforementioned climate change and urbanization.

In fact, the scientific literature [4, 5] recognized that the observed changes in the occurrence and impacts of pluvial flooding have been caused by a combination of different factors.

These include ongoing climate variability, leading to increases in the frequency and intensity of extreme precipitation events, general population growth and high rates of urbanization.

Climate change affects the water cycle [6] by influencing the precipitation patterns. Therefore, planning and design activities of urban drainage in response to the increased risk level in cities are crucial. Many cities are flood-prone, and existing infrastructure may not be resilient enough facing the increased peak flows that may occur in the future [7]. Therefore, planning and design activities of urban drainage in response to the increased risk level in cities are crucial for the adaptation of urban contexts [6].

In particular, climate change adaptation involves actions to adjust to the new climatic conditions by taking appropriate measures [8]. In this regard, many recent studies aim to provide planners with tools that

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support the systematic assessment of a variety of flood adaptation options under a variety of potential urban development and climate scenarios [9-14].

Flood-resilient spatial planning in urban areas involves designing and implementing structural and nonstructural measures [15]. Among these, for example, the research community [16-19] has recently paid increasing attention to NBS (Nature-Based Solutions) in order to limit the evolving risks of urban pluvial flooding in a more environmentally friendly manner [20]. These solutions appear to be of interest because pluvial flooding in urban areas may derive from the limited or temporarily reduced efficiency of surface drainage, which is the specific condition that NBS aim to contain.

In this regard, a recent study [21] underlines that one concept that has spread in some academic communities [22-24] is NCS (Natural Climate Solutions), aimed at adapting existing knowledge and experience, also referred to NBS, to climate action [25]. The same authors outline foundational and operational principles in order to help human society to adopt a culture of adaptive management, in which climate solutions (natural and otherwise) can adapt rapidly and transparently, in concert with their widespread adoption. In fact, planning for adaptation to climate change should strengthen the link between science and society and deal with risks by analyzing the temporal processes of the dynamics that create complexity [26].

These issues are addressed in the research project, which belongs to this paper. The project addresses the issue of climate change from the urban planning perspective to identify solutions to current and future environmental challenges, increasing the climate resilience of infrastructures and communities. These research activities are based on the desire to promote integration between the approaches commonly adopted by urban planners and climate specialists to plan adequate joint risk reduction strategies [27]. To this end, the authors supported the establishment of an interdisciplinary research group through an agreement between the DINCI (Department of Civil Engineering) of the University of Calabria and the ISAC (Institute of Atmospheric and Climate Sciences) of the National Research Council.

Going into the merits of the contents related to the risks produced by the greater frequency and intensity of pluvial floods, the paper is structured as follows. After a summary of the background studies on the research topic, section 2 proposes the definition of a statistical modelling of extreme precipitation indices, based on the indices recommended by the ETCCDI (Expert Team on Climate Change Detection and Indices). Section 3 presents the statistical results related to the Calabria Region (southern Italy). Section 4 discusses the outcomes and proposes the conclusions of the study with reference to the usefulness of the results obtained from the statistical modelling of extreme precipitation indices to support urban spatial planning processes.

2. Material and Methods

Among the various aspects of the changing climate, the study of climate extremes is of particular importance in the literature, as they are often associated with high-impact events that can cause severe damage to both natural systems and human lifestyle [28]. A direct material consequence of climate change is the intensification of extreme precipitation in most regions across the globe [29]. In fact, the risks associated with this phenomenon were recognized by the IPCC (Intergovernmental Panel on Climate Change) as one of the key risks for Europe in its sixth and final climate report of 2022.

Therefore, at the international level, knowledge of trends and patterns of precipitation extremes is vital for infrastructure design, risk assessment, insurance planning and society’s resilience [30]. To this end, from an operation point of view developing quantitative methods for describing the statistics of extreme weather phenomena is essential. In fact, research on climate extremes and indices and their trends is an important topic among researchers who aim to measure and verify climate change in an area of interest [28] and consequently plan appropriate containment strategies.

Specifically, as stated by Hosseinzadehtalaei et al. [31], to study the climate change impact on urban pluvial flooding, outputs from small-scale climate models with high spatio-temporal resolution are needed. The number of these outputs is, however, still limited and not widely available in literature. In order to fill this gap, modelling spatial data based on observations are an important step for the interpretation of data themselves [32].

In particular, the science that deals these issues is the geostatistics, that provides valuable tools for the study of the spatial correlation in data by creating mathematical models [33] for estimating the values of properties (at unsampled places) that vary in space from more or less sparse sample data [34]. In fact, geostatistics can be considered as a collection of numerical techniques that deal with the characterization of spatial attributes, employing primarily random models [34]. In this regard, interpolation tools available in GIS (Geographical Information Systems) are useful and allow the operator to easily perform different kind of activities and to display them graphically in order to show the results in a way intelligible also to non-skilled subjects [35]. Among these tools, the IDW (Inverse Distance Weighting) method assumes that a point having an unknown value is affected more by the control points near it than those that are far away [34]. According to the same authors, in this method the computation of weights is carried out from a linear function of the distance between sets of point data and points to be predicted. Due to its characteristics, it is widely used in various research fields [36-39].

In light of what emerged from the literature study summarized in the previous section, the research activities conducted by the authors are aimed at defining a model for assessing climate sensitivity at the regional scale. Specifically, the definition provided by the IPCC (2022) is adopted. According to it, sensitivity combined with adaptive capacity provides a measure of climate vulnerability. In turn, vulnerability, together with the components of hazard and exposure, defines risk. We consider indices relating to precipitation and temperatures to evaluate climate sensitivity.

Considering this general framework, this work aims to evaluate the spatial distribution of the temporal trends of precipitation extremes, in accordance with the ETCCDI and recommended by the WMO (World Meteorological Organization). In fact, as already recognized by Karl et al. [40], ETCCDI has suggested a broad set of indicators to examine extremes in the climate, which have been extensively employed in various regional and global analyses [28]. The occurrence, duration, and severity of precipitation could be described using these indices [41]. In particular, among these the present study uses the six indices in Table 1.

These indices are used to quantify, even intuitively, the variations of precipitation extremes, which are also very useful for policy makers [42-46]. The aforementioned indices are calculated for rain gauge stations that guarantee the temporal continuity of the data for at least the last 10 years, extending the analysis to the last 30 as much as possible.

Table 1 Extreme precipitation indices defined according to the ECTCCDI.

Indices code	*Name and measurement unit*	*Definition*
Rx1day	Max 1-day precipitation amount (mm)	Annual maximum 1-day precipitation
Rx5day	Max 5-day precipitation amount (mm)	Annual maximum consecutive 5-day precipitation
SDII	Simple daily intensity index (mm/day)	Annual total precipitation divided by the number of wet days (defined as PRCP ≥ 1 mm) in the year
R10	Number of heavy precipitation days (days)	Annual count of days when PRCP ≥ 10 mm
R20	Number of very heavy precipitation days (days)	Annual count of days when PRCP ≥ 20 mm
R95p	Very wet days (mm)	Annual total PRCP > 95th percentile

The research involves the subsequent processing of thematic maps relating to the aforementioned indices, in a GIS environment at a regional scale, through the application of an appropriate interpolation method identified in the aforementioned IDW. In this study, the IDW method is applied to interpolate the spatial data based on the concept of distance weighting, obtaining the interpolated values on a square mesh grid of side 150 m for each of the indices considered and in both duration time intervals 10 and 30 years.

3. Applications

The study area chosen for this research is the Calabria region, in southern Italy (Fig. 1). Affected by rains highly variable in both time and space, Calabrian territory appears adequate to represent the characteristics of rainfall of many geographical areas of the Mediterranean Basin [47]. In addition, Calabria is an interesting case study due to local anthropization phenomena, its geographical position, and some geomorphological peculiarities [48].

This study employed a historical dataset of daily precipitation covering the period from 1993 to 2023. In Italy, these data are collected and monitored by the Regional Agencies for Prevention and Environmental Protection. In Calabria, the Multi-Risk Functional Center of ARPACAL deals with this, having collected at a regional level the legacy of the National Hydrographic and Mareographic Service whose competence was transferred from the State to the Regions in 1998.

The meteorological observation network considered is made up of the 146 stations provided by ARPACAL, represented in Fig. 1. The entire network is made up of 155 rain gauges and the density is approximately 1 station per 100 sq km. Among these, only the stations that have guaranteed the temporal continuity of the series in the last 10 years have been considered, in number equal to 146, extending where possible the analysis of the series to the last 30 years, as anticipated.

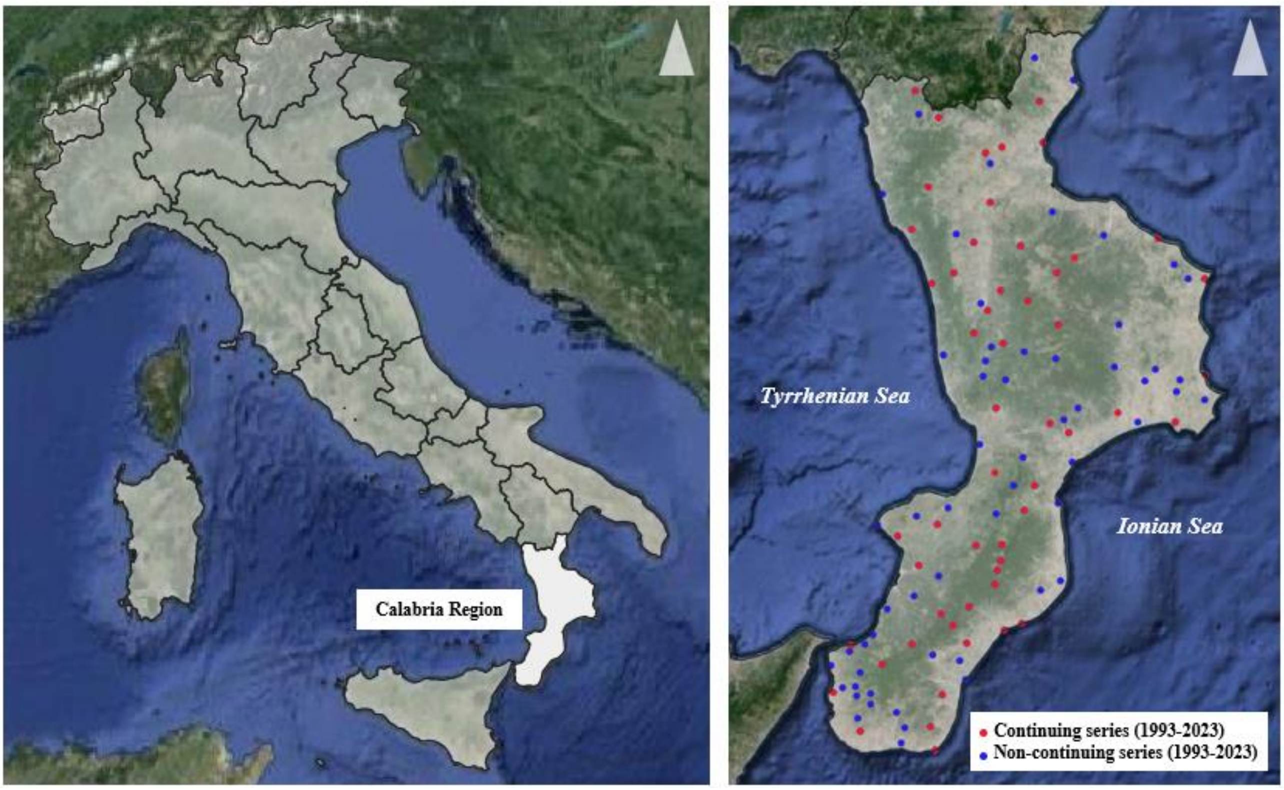

Fig. 1 Network of rain gauges in Calabria Region (Italy).

Table 2 Descriptive statistics of the precipitation extreme indices defined according to the ECTCCDI over 30 years.

Parameter	*Rx1day*	*Rx5day*	*SDII*	*R10*	*R20*	*R95p*
Average	85.9	147.1	11.6	30.7	14.0	614.4
Median	80.5	140.5	11.2	30.5	13.3	580.4
Standard deviation	26.4	44.3	1.9	8.8	5.0	206.0
Range	120.5	198.7	11.2	37.2	23.1	1,110.8
Minimum	41.3	69.8	7.9	15.1	5.6	305.7
Maximum	161.9	268.4	19.1	52.3	28.7	1,416.5

Table 3 Descriptive statistics of the precipitation extreme indices defined according to the ECTCCDI over 10 years.

Parameter	*Rx1day*	*Rx5day*	*SDII*	*R10*	*R20*	*R95p*
Average	89.6	154.8	11.5	30.9	14.0	619.0
Median	84.8	142.9	11.3	30.5	13.4	572.9
Standard deviation	30.3	52.9	1.9	8.9	5.2	219.5
Range	149.8	255.9	8.9	35.8	23.5	1,385.1
Minimum	36.0	69.9	8.1	14.1	5.5	0
Maximum	185.7	325.8	17.0	49.9	29.0	1,385.1

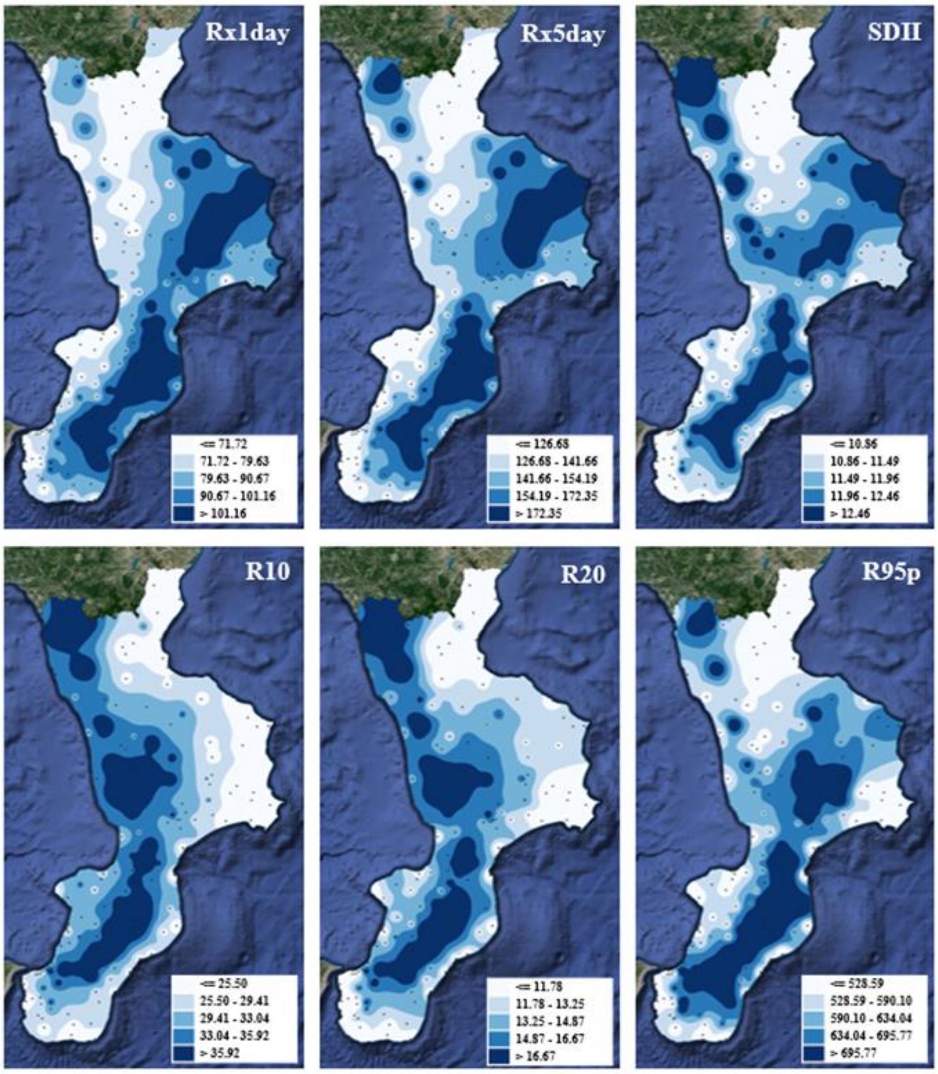

Fig. 2 IDW interpolation map of the precipitation extreme indices defined according to the ECTCCDI over 30 years.

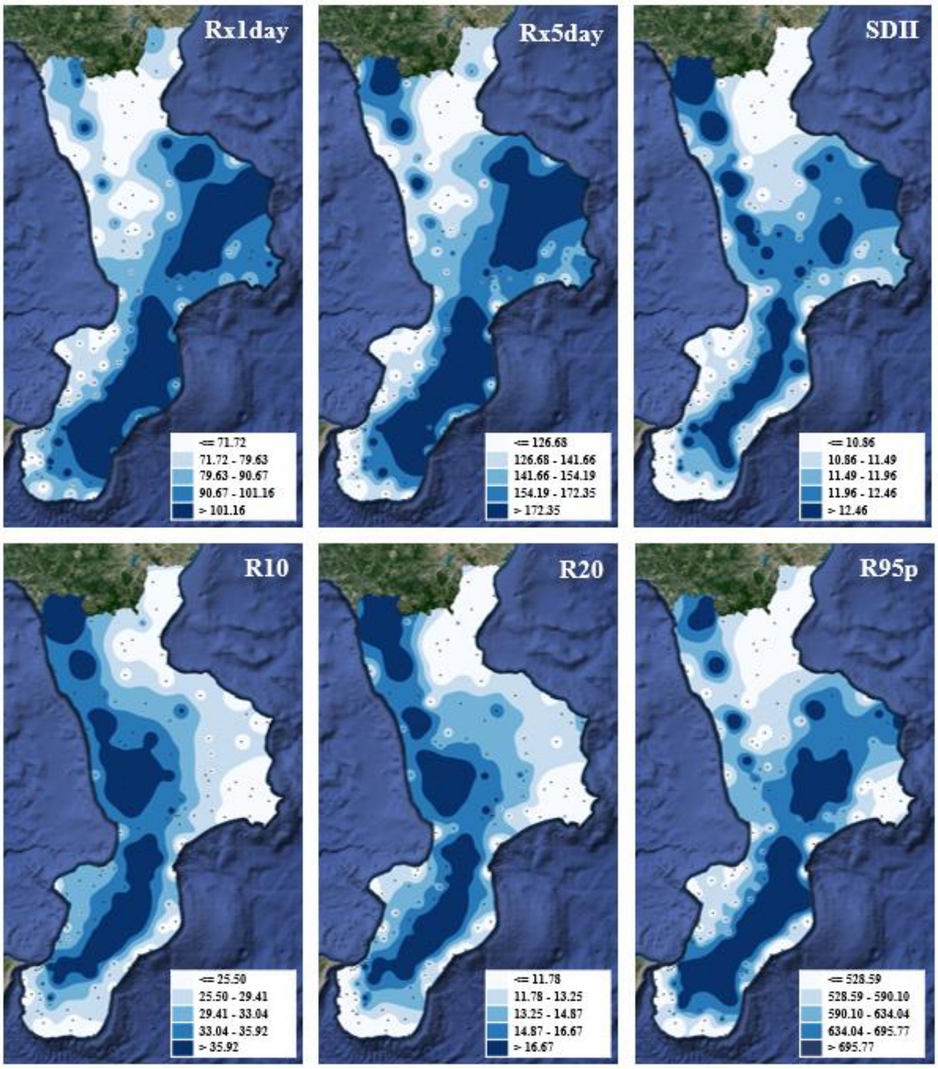

Fig. 3 IDW interpolation map of the precipitation extreme indices defined according to the ECTCCDI over 10 years.

The available data are checked in advance by ARPACAL. After having sampled the indices, whose descriptive statistics are summarized in Tables 2 and 3 for the two-time intervals considered, the IDW maps in Figs. 2 and 3 were developed, which show irregular spatial distributions on the territory, depending on the index considered.

In particular, considering the Rx1day index, the two maps, which respectively represent the average values over 30 years and 10 years, highlight a large area with particularly high index values, which extends from north to south for a large part of the region, markedly in its eastern part. Considering the Rx5day index, the two maps, although less similar to each other than in the case of the first index, confirm the trend of greater extreme precipitation events on the regional Ionian side. The values appear to be increasing on average over the last 10 years with particularly high peaks in areas of the Ionian coast, indicating a tendency towards an increase in extreme rainfall over the most recent years. The SDII index, however, presents a similar mapping in the two time periods.

The maps relating to the R10 and R20 indices show opposite behavior to those relating to the first index, highlighting a large area with higher values on the western side of the region, close to the Tyrrhenian Sea. This apparent contradiction is not surprising, and is in agreement with previous studies conducted on Calabria and related to rainfall extremes [49, 50], confirming that although precipitation events are more frequent on the western side of the region (greater number of rainy days), these events are more intense (greater accumulations) on its eastern side.

Finally, with reference to the last R95p index, which expresses the quantity of precipitation on very rainy days, the two maps are similar to each other, confirming the band most affected by the phenomenon on the central-Ionian side, as in the case of the first index.

4. Discussion and Conclusion

Spatial planners allude to resilience, meaning the capacity of the territorial system to cope with changes, variously understood, that affect particularly vulnerable sites. Resilient urban systems absorb the stress induced by climate variability, adapt and reorganize themselves to make themselves less vulnerable to the effects of the climate. However, recognizing that the trend of extreme climatic events is only partially known and predictable, it appears necessary to analyze the characteristics and extent of the impacts caused, identify the areas at greatest risk, investigate where and how the phenomena are repeated most frequently in order to intervene with ad hoc policies and strategies for adapting places according to sustainable development objectives.

Risk can occur if, in a certain place and at a certain time, a vulnerable receptor exposed to a source of danger suffers the consequences triggered by the danger. Therefore, the concept of resilience is linked, inversely, to that of vulnerability which, in the climatic sense, is a function of sensitivity and local adaptation capacity. In particular, sensitivity represents the degree to which the territory is influenced by the variability of climate, measurable quantitatively on the basis of the numerical processing of climate data, observed or simulated, including, for example, precipitation and temperatures. Adaptive capacity, on the other hand, represents, from a qualitative point of view, the ability of the entire territorial system, including institutions, the population and all competent bodies, to respond and adapt to potential climate risks, as well as to take advantage of any opportunities related to the change.

In light of these assumptions, as part of this contribution, a statistical modelling of extreme indices has been defined which is useful for quantifying and consequently mapping the precipitation extremes which represent one of the elements characterizing climate sensitivity.

In this regard, the results presented refer to the entire Calabrian regional context which, located in the central part of the Mediterranean area, is one of the hottest regions in Italy. The regional territory presents peculiar microclimatic characteristics. Meteorological phenomena are strongly linked to geographical position, geomorphological characteristics, complex topography and particular physiographic characteristics that generate a wide variety of microclimates. In particular, the Mediterranean climate is typical of coastal areas with notable temperature and rainfall variations between seasons, especially compared to inland territories.

The results obtained represent a tool to support planners in the analysis and classification of the territory’s level of climate risk. Important operational conclusions can be drawn from the research results. Among these, the main one is the physical and data-based identification of priority areas of intervention in order to scientifically guide design choices.

From a general point of view, this research confirmed how the Mediterranean area represents a climate change hotspot, but also the importance of an in-depth analysis of high-resolution rainfall data, in order to better classify the main systems of precipitation associated with extreme events for study areas to be defined, for example, at municipal level.

Starting from the considerations set out above, the research activities connected to this research project start from the evaluation of the climate sensitivity affecting the macro-regional territory which will be achieved by adopting a similar statistical modelling of indices also for the purpose of analyzing extreme temperatures. In this regard, the next developments of the research consist in the analysis of the temperature series and in the final processing of the sensitivity map at the regional scale.

Subsequently, as anticipated, it is planned to deepen a focus on a local context identified in the Municipality of Lamezia Terme (Province of Catanzaro), where the Institute of Atmospheric and Climate Sciences of the National Research Council is based and the relevant monitoring station is present. For the local context, it is planned to consider, in addition to those already analyzed, also the data recorded by this station and to develop a better spatial resolution local sensitivity map.

Subsequently, the activities will evolve, for the pilot case, together with the assessment of local adaptive capacity, the definition of a climate action plan, also involving the involvement of local communities to allow us to understand which are the most suitable planning solutions adaptive cities at the local level.

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