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ORIGINAL PAPER

Extreme weather risks for tourism in the European Union

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Abstract

With mounting evidence of extreme weather events, it is increasingly important to understand the risks that thunderstorms, extreme precipitation, and wildfires pose to tourism. This study investigates the past occurrence of these phenomena in Europe, analyses recent trends, and evaluates them in relation to the dependency on tourism. The Tourism Exposure Index is developed to assess these risks, comprising two sub-indices: the Hazard Index and the Tourism Dependency Index. Results reveal a spatial concentration of regions with high/very-high tourism exposure, particularly in southern Europe and around the Mediterranean Sea. These findings contribute to a better understanding of the spatial distribution of weather extremes with highly disruptive potential. It is concluded that at-risk regions should develop weather hazard adaptation plans for tourism.

Keywords Adaptation · Climate change · Destinations · Vulnerability · Weather extremes · Natural hazards

1 Introduction

This paper builds on several premises established in previous research: First, tourist transport and tourism destinations are exposed to various hazards, including those related to hydrometeorological phenomena (Dubois et al. 2016; Gómez 2005; Gössling et al. 2023; Rosselló et al. 2020). Second, these hazards are being altered in the context of climate change, with an overall trend towards more frequent and intense events (Baird et al. 2024; IPCC et al. 2021). Third, tourism is a sector characterized by pronounced spatial disparities in terms of visitor volumes, economic importance, and development trends, among other

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factors (Almeida et al. 2021; Bohlin et al. 2020; Drakakis 2024; Shi et al. 2019; Arent et al., 2014). Against this background, the present study aims to map regional differences in the impacts of various risks associated with extreme hydrometeorological phenomena as observed in the past.

Conducting this kind of research presents two fundamental challenges: how to account for the influence of climate change and which hydrometeorological phenomena to consider. Regarding climate change, previous tourism studies have typically approached this issue in two main ways. One common approach involves using global projections based on scenarios of temperature change to define maximum warming thresholds that should not be exceeded to avoid catastrophic outcomes (IPCC 2021). However, when these projections are applied to model future tourism flows, the results are often fraught with high uncertainty (Gössling & Hall, 2016). For instance, a common theme in the literature is the anticipated decrease in summer tourism in the Mediterranean due to the risk of extreme heat, with subsequent shifts in tourism demand to other regions (Amelung and Viner 2006; Prettenthaler et al. 2021). Given the many uncertainties and complexities involved, such studies have a low level of confidence (Kovats et al. 2014; Scott et al. 2012).

Another approach to accounting for changes in climate and their impact on tourism is to extend the trends observed in recent decades (Rosselló and Santana-Gallego 2014; Töglhofer et al. 2011; Yu et al., 2009). It is important to note that past changes in climate variables do not necessarily indicate that future developments will follow the same patterns. However, the approach provides a more concrete and quantifiable indicator, particularly at the local and regional levels. This approach also enables the comparison of diverse datasets—such as social, economic, and tourism data from recent years—with climatological datasets, whether observational or derived from global models.

Regarding the selection of hazards considered in this study, summer tourism in Europe serves as a useful example. Several studies have projected a decline in tourism numbers due to heat waves, with a corresponding increase in tourism in cooler areas such as the Alps and Northern Europe. However, these studies often overlook other factors, such as precipitation, which may be more significant for tourists (Steiger et al. 2022). Additionally, there is an expectation that climate change-related hazards will increase in destinations likely to receive tourists who are avoiding the Mediterranean (Pröbstl-Haider et al. 2021).

Furthermore, the idea that there is an ideal general temperate for tourism– one of the most cited definitions in this sense is Mieczkowski's (1985) Tourism Climate Index (TCI) that determined a daytime maximum temperature of 20–27 °C as preferred by tourists– has been questioned, as acceptable temperature thresholds vary depending on the tourism activity. Traditional summer tourism activities in seaside resorts, for instance, are particularly adapted to very high temperatures (Prettenthaler and Neger 2023). In winter tourism destinations, while certain weather conditions can pose hazards affecting tourism transport (Gössling et al. 2023), sub-zero temperatures are essential for key winter tourism activities (Steiger et al. 2022).

To develop a more systematic understanding of weather conditions, several studies have developed indices. Beach tourism in particular has seen the construction of various indices, starting with a modified version of the Tourism Climate Index (TCI; Morgan et al. 2000), the Climate Index for Tourism (CIT; de Freitas et al. 2008); the Mean Historical Climate for Tourism (MHC) index (Méndez-Lázaro et al. 2014), and the Holiday Climate Index for beach tourism (HCI: Beach) (Rutty et al. 2020. The latter two both focus on Caribbean destinations. Besides temperature, Mieczkowski already considered rainfall, hours of sunshine, and wind speed. Some of the newer indices also included aspects such as relative humidity and, related to this, thermal sensation, as well as the aesthetic appeal of sky conditions. Meanwhile, indices for other tourism activities have been proposed, for instance, the Holiday Climate Index for urban tourism (HCI: Urban) (Scott et al. 2016), the Camping Climate Index (CCI) (Ma et al. 2020), and the Ski Climate Index (SCI) (Demiroglu et al. 2021).

These newer indices are highly valuable for tourism management purposes, as they provide concrete results on an area's suitability for a specific type of tourism demand. However, they cannot be used for comparing year-round effects on a larger scale in regions offering diverse tourism activities. To use these specific indicators, one would need detailed information on the distribution of specific tourism segments; however, such data are usually not available in official tourism statistics.

To avoid complexities related to the interpretation of results, the present study focuses on three kinds of risk that affect tourism negatively and have brought about considerable damage in the past. These risks - thunderstorms, extreme precipitation, and fire weather - have also become more prominent, increasing in occurrences and impacts over the recent decades. Hoeppe (2016) and Tazarek et al. (2021) document an increasing trend of convective storms and their general impacts. Thunderstorms mainly cause local disturbances due to wind gusts, local flooding, mudflows, and hail, with documented damages to tourism facilities (Bai 2016; Kifworo et al. 2023; Olefs et al. 2021) and are particularly relevant to tourism demand (Bernardi et al. 2025). Steiger et al. (2016) also suggest thunderstorms are less acceptable to mountain summer tourists than days with continuous rain. However, when precipitation reaches extreme levels– a phenomenon that has significantly intensified in Europe (Sun et al. 2021)– its effects on tourism can also be severe in the short and longer term, including the destruction of tourism infrastructure and a deteriorating destination image (Baird et al. 2024; Rosselló et al. 2020). The disruptive character of such events has been evident in many recent events, from flooding in Northern Italy to Valencia, Spain. However, there is arguably also much evidence that even extreme events do not necessarily deter tourism for more extended periods. Gómez-Martín et al. (2014), Hübner and Gössling (2012), Otrachshenko and Nunes (2022), Zeng et al. (2023) found that extreme heat, rain, or fires experiences only had a limited effect on decisions to (not) return.

Similarly to the previous hazards, fire weather in Europe has also shown a continuous increase during the last decades (Hetzer et al. 2024; Jolly et al., 2015). Low-intensity fires are part of the natural processes of some ecosystems and thus can contribute to the maintenance of landscapes attractive for tourism. However, the alterations of these natural regimes and the occurrence of extreme wildfire events– generally related to severe drought– are always detrimental to tourism destinations. Damages have been reported to increase, including the direct impacts of fire on tourism sites as well as the adverse impact of fire smoke that spreads over larger areas (Neger et al., 2024); Otrachshenko and Nunes 2022; Thapa et al., 2023).

To understand and compare the importance of these hazards in different regions, it is necessary to define and measure "exposure" in relation to the significance of tourism in regional economies (Neger et al., 2024; Scott et al. 2019). This study builds on previous research that has developed indices combining variables from different fields that need to be considered together to understand potential impacts. Examples of such applications in tourism include the vulnerability of beach tourism (Perch-Nielsen 2010), the global vulnerability of tourism to climate change (Scott et al. 2019), and the current exposure of tourism to fire in Europe (Neger et al., 2024). This research further expands on earlier studies by developing indices for three relevant hydrometeorological phenomena: thunderstorms, extreme precipitation, and fires. Including other hazards (heatwaves or coastal flooding) would provide an even more comprehensive overview. The spatial unit of analysis is the European Union, the world's leading region in terms of international tourism arrivals (UNWTO, 2024), with available data that is comparable across countries and regions. Results are visualized on maps to illustrate and interpret regional vulnerability disparities.

2 Materials and methods

2.1 Description of the datasets

The research considers two kinds of data: socioeconomic data for tourism and climate data for hazards. Socioeconomic data are derived from the Statistical Office of the European Union (Eurostat) (https://ec.europa.eu/eurostat/data/database), which is provided at the NUTS (Nomenclature of Territorial Units for Statistics) level 2 (NUTS2), that is, at the second highest subnational level, with different labels in the member states of the European Union, such as states, (planning) regions, or provinces. In the 'Eurostat' v.4.0 R package (Lahti et al. 2017), the following variables are available for download: nights spent at tourist accommodation establishments by NUTS 2 regions (tour_occ_nin2), national accounts aggregates by industry, up to NACE (statistical classification of economic activities in the European Community) A*64 (nama_10_a64), nights spent at tourist accommodation establishments (tour_occ_ninat), and gross domestic product (GDP) at current market prices by NUTS 2 regions (nama_10r_2gdp). The period selected for the analysis covers the calendar years 2011 to 2020, and an arithmetic mean was used to reduce the bias of the annual variation.

The primary source for climate data was the ERA5 dataset (Hersbach et al. 2020), the fifth generation of the reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) with global coverage. This dataset is available every 60 min in a grid with a spatial resolution of 0.25° x 0.25°. The reanalysis data is available in single and pressure levels (Hersbach et al. 2023) from 1940 to the present. The variables considered relevant for the present research in this dataset were Convective Available Potential Energy (CAPE) (in J kg-1), Total Precipitation (TP) (in m), and Convective Precipitation (CP) (in m) from 1980 to 2020, every 60 min, in a spatial domain that covers the European Union: 8°W to 40°E and 30°N to 75°N.

Another source of this research is the Fire Weather Index (FWI), part of the fire danger indices' historical data from the Copernicus Emergency Management Service (Copernicus Climate Change Service 2019; Vitolo et al. 2020). This dataset is derived from the ERA5 reanalysis dataset and is available daily in a regular grid of 0.25° x 0.25° from 1979 to 2022. The FWI combines the Initial Spread Index and the Build-up Index, which rate potential fire intensity and spreading. The Initial Spread Index is focused on daily weather information regarding moisture and the effect of wind, whereas the Build-Up Index rates the availability of dry fuel based on meteorological data (especially precipitation and temperature) during the preceding months up to the previous day (Abatzoglou et al. 2018). The values of the

FWI (dimensionless) are categorized as representing the following risks: very low danger FWI < 5.2, low danger FWI > 5.2 and < 11.2, moderate danger FWI > 11.2 and < 21.3 and high danger FWI > 21.3 and 38.0, very high danger FWI > 38.0 and < 50, and extreme danger: FWI > 50. This research uses the daily values of the FWI for the period 1980 to 2020 in the spatial domain previously mentioned.

2.2 Data processing

The Tourism Exposure Index (TEI) consist of two subindices, the Hazard Index (HI) and the Tourism Dependency Index (TDI) (Figs. 1 and 2). The multiplication of these two subindices results in the TEI (Eq. 1):

$$TEI = HI \times TDI \tag{1}$$

2.2.1 The hazard index

The HI has three components to cover thunderstorms, precipitation and fire, including the Thunderstorm Hazard Index (THI), the Extreme Precipitation Hazard Index (EHI), and the Fire Hazard Index (FHI). It is essential to mention that two subcomponents are developed for each hazard, including the long-term mean and observed changes over the last decades, to incorporate the impact of climate change. The first component (C1) is the annual mean number of days or hours (depending on the hazard) for which a particular parameter exceeds a threshold value defining the event. In contrast, the second component (C2) is the decadal trend of the annual number of days or hours (depending on the hazard) during which the selected threshold value was exceeded. The computation of the trends uses the Mann-Kend-

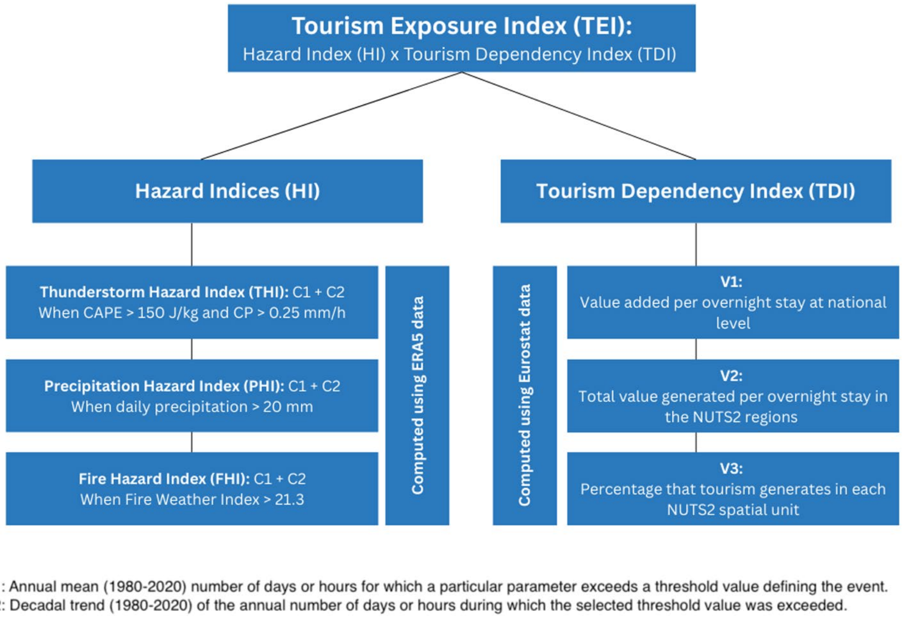

Fig. 1 Summary of the methodology to determine the Tourism Exposure Index

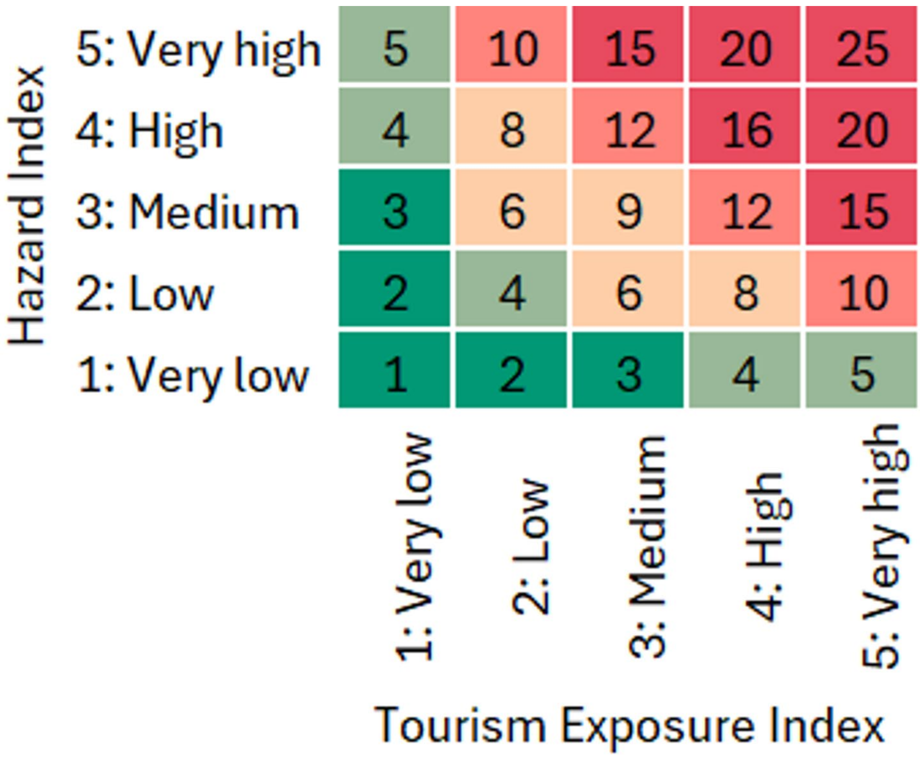

Fig. 2 Combined matrix of the Hazard Indices and the Tourism Dependency Index

all non-parametric test (Wang et al. 2020). Then, both components are integrated, as shown in Eq. 2:

$$HI = C1 + C2 \tag{2}$$

In the case of the THI, calculating the mean number of hours per year (1980–2020) with thunderstorm conditions follows the approach proposed by Taszarek et al. (2021a, b). This approach considers a convective available potential energy (CAPE) greater than 150 J kg-1 and convective precipitation greater than 0.25 mm h-1 (C1). The selection of this covariable, along with the specified threshold values, represents a typical thunderstorm setting characterized by an unstable environment (indicated by CAPE) and precipitation from vertically developed clouds (measured by CP).This was the basis to compute the decadal trend (1980–2020) in the mean number of hours per year with thunderstorm conditions (C2). Both components were normalized using the max-min approach (i.e., values ranging from 0 to 1), and Eq. 2 was applied. The resulting values (in a regular grid of 0.25° x 0.25°) were used to calculate the maximum value in each spatial unit using the 'raster' package (Hijmans 2018) in R. Finally, the values were categorized using the natural breaks (Jenks) classification method (Jenks 1967; Osaragi 2019), and five hazard levels were defined: [1] Very Low, [2] Low, [3] Medium, [4] High, and [5] Very High.

For the EHI, the first step was the computation of the total daily accumulated precipitation using the TP variable (with a timestep of 60 min) contained in the ERA5 reanalysis data. Second, the very heavy precipitation days index (eca_r20mm) defined by the European Climate Assessment project (Schulzweida and Quast 2015) was applied. In addition to being a widely used indicator, the choice of 20 mm/day exceeds the percentiles defined as very wet (90th) and extremely wet days (95th) for this region, as identified in a recent study (Berényi et al. 2023).This index considers a daily precipitation sum exceeding 20 mm; hence, calculations express the annual number of very heavy precipitation days (C1) for the period 1980 to 2020, and like in the previous case, the decadal trend (1980 to 2020) for the same parameter (C2). Both components were normalized (0–1), Eq. 2 was applied, and the maximum value was assigned to each NUTS2 spatial unit. Then, based on the Jenks classification method, the resulting values were categorized into five levels [1–5].

Finally, for the FHI, the mean number of days was calculated for the period 1980 to 2020, in which the FWI exceeded the 23.1 value (i.e., High danger) (C1). The threshold was chosen based on the predefined values established by the Canadian Forest Fire Danger Rating System, the creators of the index. “High Danger” corresponds to the fourth level out of six in these predefined categories. The decadal trend (1980 to 2020) of the same parameter was also computed for the same period (C2). Both components were normalized (0–1), and like in the previous cases, Eq. 2 was applied, and the maximum value was assigned to each NUTS2 spatial unit. Finally, five hazard levels were defined using the Jenks classification method.

2.2.2 The tourism dependency index

The Tourism Dependency Index (TDI) (Neger et al. 2024) considers tourism intensity and the importance of tourism in the regional economy. The parameters that are included are overnight stays (available at the NUTS2 level) and tourism revenues (at the national level). It is important to note that this approach entails the limitation of not accounting for subnational disparities in tourism revenue. However, they are the most specific data at the lowest spatial level that could be retrieved for a study with a European-wide scope. Regarding the validity of this approach, it is important to note that the index developed by Neger et al. had been inspired by the previous work of Peeters et al. (2018), which used the same parameters, together with a thorough examination of destinations experiencing over-tourism. The TDI values in this study slightly differ from those presented in Neger et al. (2024) due to the consideration of a different period (2011–2020). The methodology is shown in Eqs. 3–5. First, the value added per overnight stay was calculated at the national level as a proxy for tourism revenues per NUTS2 spatial unit (Eq. 3):

$$v1 = nama\_10\_a64 \div tour\_occ\_nin2 \tag{3}$$

The resulting value was multiplied per the tour_occ_nin2 variable to estimate the total value generated per overnight stay in the NUTS2 regions (Eq. 4):

$$v2 = v1 \times tour\_occ\_nin2 \tag{4}$$

Finally, the v2 is divided into the nama_10r_2gdp variable to approximate the percentage that tourism generates in each NUTS2 spatial unit. The resulting values are categorized into five tourism dependency levels: [1] Very Low, [2] Low, [3] Medium, [4] High, and [5] Very High (Fig. 4), to be compared with the hazard indices previously explained (Eq. 5):

$$v3 = v2 \div nama\_10r\_2gdp \tag{5}$$

In the final step, Eq. 1 was applied by replacing the HI parameter for the THI, PHI, and FHI. Five exposure levels for each hazard were also defined (Fig. 5) using a 2-Dimensional matrix approach (Neger et al., 2024; Frigerio et al., 2016) (Fig. 1). As a limitation, the indices do not allow for seasonal integration, i.e., to consider the risk of extreme weather events occurring at times when visitation is highest. No weights were used in the index, in line with related publications (Cutter et al., 2012; Koks et al. 2015; Wu et al. 2002).

2.2.3 Data limitations

Despite the advantages of reanalysis datasets such as ERA5 over in situ observations — including higher spatial and temporal resolution (which is particularly useful at regional and continental scales) and the wide range of derived parameters — these datasets also have some limitations. For instance, several studies have found that ERA5 generally underestimates precipitation (e.g., Lavers et al. 2022; Bandhauer et al., 2022). A similar underestimation has been observed for convective parameters related to the representation of severe thunderstorm environments (Taszarek et al. 2021a, b). These biases are likely due to fine-scale processes that cannot be fully resolved by the numerical models used in such reanalyses. Therefore, results should be interpreted as approximations of the distribution of extreme weather events.

A second important limitation is the lack of tourism data with higher temporal resolution—for example, seasonal data, which would allow for a more fine-grained evaluation of impacts. Tourist flows are often concentrated in specific months depending on the type of activity. Without monthly tourist arrival data and corresponding weather data, it is not possible to account for these seasonal effects or their implications for tourism systems—for example, by exploring seasonal impacts on Mediterranean coastal tourism, mountain tourism in the Alps, or urban tourism. Consequently, the findings in this paper highlight only the spatial convergence of tourism and weather extremes without addressing their temporal dimension.

3 Results

Figure 3 shows findings for thunderstorms, extreme precipitation, and fire proxies for all of geographical Europe, given that these are continuous data which are later adjusted to a medium value per NUTS2 region for the European Union. Regarding thunderstorms (Fig. 3a), a concentration is visible in Northern Italy along the southern boundaries of the Alps (up to around 500 h per year) and along the Dinaric Alps in Southeastern Europe. Generally, almost all of Italy, besides its Southernmost part and the Mediterranean islands, is an

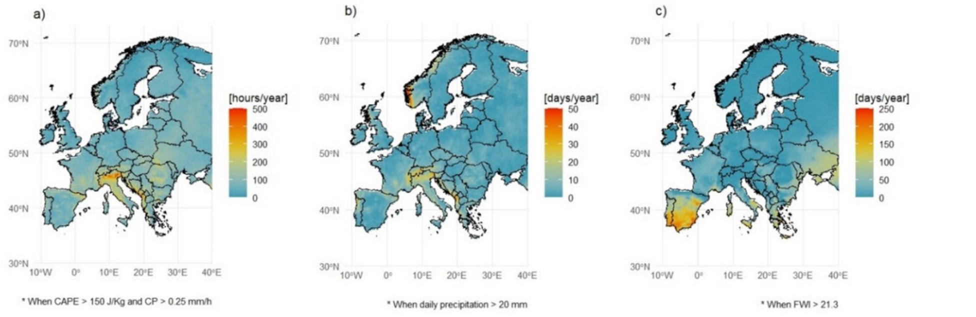

Fig. 3 Spatial distribution of the (**a**) annual mean number of hours with thunderstorms, (**b**) the annual mean number of days with extreme precipitation, and (**c**) the annual mean number of days with fire weather, all computed using the ERA5 reanalysis dataset (1980–2020)

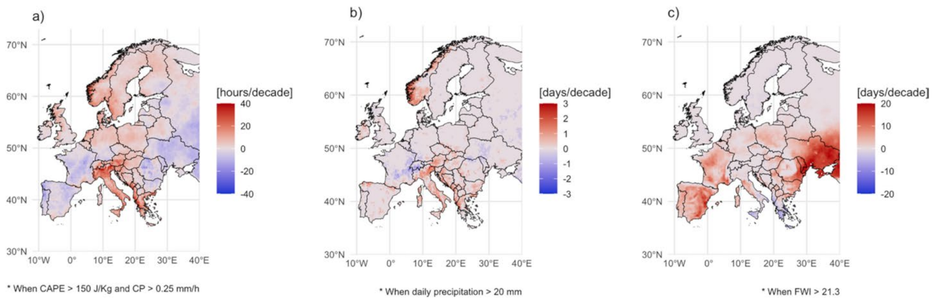

Fig. 4 Spatial distribution of the (**a**) decadal trend of the number of hours with thunderstorms, (**b**) the decadal trend of days with extreme precipitation, and (**c**) the decadal trend of days with fire weather, all computed using the ERA5 reanalysis dataset (1980–2020)

area of high thunderstorm risk. Another area with relatively high values is found along the Pyrenees and in the Southwestern area of the Norwegian fjords.

Regarding extreme precipitation (Fig. 3b), the Norwegian fjords are the area with the highest values in all of Europe, with more than 50 days per year with extreme precipitation potential, followed by the Southern part of the Dinaric Alps between Montenegro and Albania. Other areas with relatively high values include the remainder of the Dinaric Alps, most of the Alps except the Eastern Alps in Austria, most of the Italian Peninsula, the Massif Central in France, the Pyrenees, Western Scotland, and, with exceptionally high values, the northern coastal area of Portugal.

The highest values of fire weather (Fig. 3c) are found along the Southernmost parts of Europe, especially the Iberian Peninsula (Spain and Portugal), with a high proportion of areas with an average of around 200 to 250 days per year with fire weather potential. Other high-risk areas are concentrated along the southern limits of the European Union, from Italy to Greece, including several Mediterranean islands, with values between 100 and 150 days. The northernmost areas with relatively high fire risk are the Provence in France and several areas along the Black Sea in Bulgaria, Romania, and Ukraine.

Figure 4 gives an overview of the computed decadal trends of the three hazards considered in this study (the Supplementary Material contains a detailed list of the values per

NUTS2 region shown in Figs. 4 and 5). The data shows an overall trend for values to increase, i.e. for weather patterns to become more common, in the areas that already show high values. However, there are exceptions where this observation does not apply. Regarding thunderstorms (Fig. 4a), the most notable increase is reported for Northern Italy, Montenegro, Albania and the Western mainland areas of Greece (plus around 40 h per decade), along with the Southwestern Norwegian fjords. Other areas with a relatively high increase are the rest of Italy, Austria, Slovenia, the Netherlands, Denmark, and parts of Scotland, Sweden and Norway. The areas with the most remarkable decrease within the European Union are located in France, Spain, Portugal, and Romania.

The map regarding the decadal trends in precipitation data (Fig. 4b) shows a similar picture, with the highest increases of up to three days per decade along most parts of the Norwegian coast and the countries along the Adriatic Sea as well as Austria. Other areas with surging values are found in some Mediterranean islands such as Corsica and Sardinia and, contrary to the thunderstorm data, in the Iberian Peninsula. Areas with the most notable decreases are found in Switzerland and the central southern parts of France.

The decadal trends in fire weather (Fig. 4c) are very different from the other two variables, with increases in almost the entire study area. The highest increases affect Ukraine (around 20 days per decade), but considerable values (ranging from plus 12 to plus 16 days per decade) also show for the Iberian Peninsula, France, Romania, and Moldova. The only areas with a slight negative trend are found in Southern Italy, Albania, and Central and Southern Greece. This represents an interesting development, as these places are characterized by significant fire risk in Fig. 1c.

The indices in Fig. 5 integrate the overall exposure to the three kinds of hazards and the decadal trends for the NUTS2 regions, excluding several of the areas identified in the previous maps that showed exceptionally high values, such as southern Norway for thunderstorms and extreme precipitation, and the Ukraine for fire weather. Within the European Union, a very high hazard index regarding thunderstorms (Fig. 4a) is found in most of northern Italy, along the Croatian coast and in northwest Greece. Almost all the rest of Italy and Greece, northeastern Spain, parts of Southern France and Southeastern Germany, most of Austria and the entire country of Slovenia face high exposure. On the contrary, the largest areas with very low exposure regarding thunderstorms comprise the whole of Portugal, Ireland, and Estonia, together with central Spain, northern France, parts of Germany, and northern Sweden.

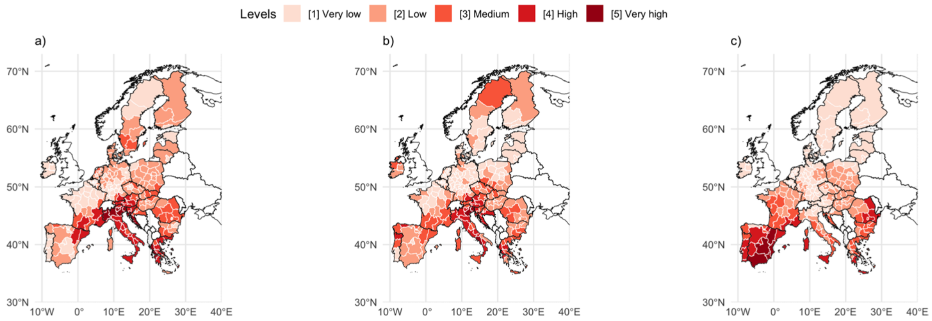

Fig. 5 Spatial distribution (by NUTS2) of the (**a**) Thunderstorm Hazard Index, the (**b**) Extreme Precipitation Hazard Index, and the (**c**) Fire Hazard Index

In terms of extreme precipitation (Fig. 5b), very high values are again concentrated in northern Italy, together with high values in most of the rest of Italy, as well as in parts of Austria, Greece, Slovenia, and Croatia and a single region of Spain and of Germany. In contrast to thunderstorm exposure, northern Portugal is also highly affected, with high and medium values, while regions categorized as 'medium' are also found in Ireland and northern Sweden. The very low exposure areas are southern Portugal, northern France, Belgium, the Netherlands, most of Germany, northern Poland, southern Sweden and Finland, and the entire Baltic states.

The very high values of the Fire Hazard Index (Fig. 5c) are all found in southern Spain, with most of the rest of the country being highly exposed. Other regions with high exposure are found in most of Portugal, southern France, Sardinia and Sicily in Italy, as well as several regions in southern Greece and eastern Romania. Almost all of northern Europe shows very low exposure. The southernmost low exposure regions are found in northern Italy, Slovenia and central Croatia.

Regarding the spatial pattern of the tourism dependency index (Fig. 6), it is crucial to bear in mind that results are influenced by the importance of tourism within the regional economy. This is why several areas with very high absolute tourism numbers, such as Île de France (Paris) or Lazio (Rome), have very low risks due to their diversified overall economy, in contrast to many rural areas where the economy depends almost entirely on tourism. This especially applies to several of the Greek islands and the Algarve in Southern Portugal with very high dependencies, and, to a lesser degree, to the Balearic Islands in Spain, South Tyrol in Italy and Crete in Greece with high dependencies. Corsica in France, Tyrol and Salzburg in Austria, Trento and Valle d'Aosta in Italy, Zeeland in the Netherlands, Adriatic Croatia, and the northern Aegean islands in Greece reveal medium dependencies. Low dependency areas are scattered among the rest of western and southern Europe, mostly in coastal areas, while most of the European Union's NUTS2 areas show a very low dependency.

The previous results were combined in the Tourism Exposure Index; the final values are shown on a map in Fig. 7 and in a country-wide comparison in Fig. 8. Combining the previous results in the Tourism Exposure Index for thunderstorms (Fig. 7a and d), five regions stand out with very high levels: South Tyrol, Trento, and Valle d'Aosta in Italy, the Ionian and South Aegean islands in Greece, as well as Adriatic Croatia. Other areas with high values are mostly adjacent or relatively close to the very high-risk areas: Veneto and Friuli-Venezia Giulia in Italy, Tyrol and Salzburg in western Austria, and Epirus in Greece. In

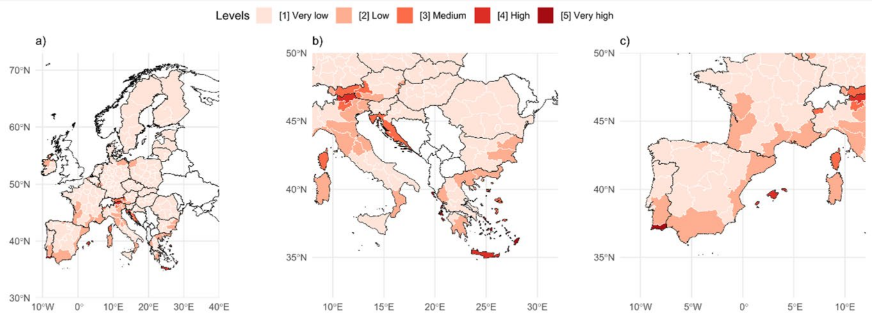

Fig. 6 Spatial distribution (by NUTS2) of the Tourism Dependency Index in (**a**) the European Union and (**b**-**c**) two different subregions

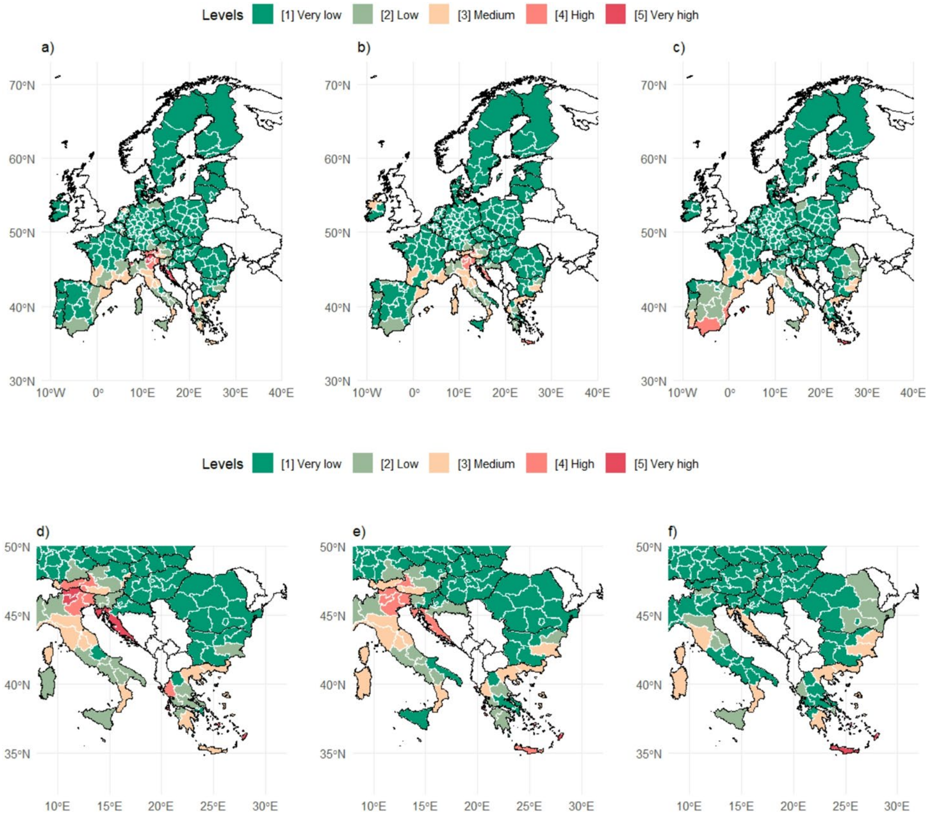

Fig. 7 Spatial distribution (by NUTS2) of the Tourism Exposure Indices for thunderstorms (**a** & **d**), extreme precipitation (**b** & **e**), and fires (**c** & **f**) in a changing climate

Austria, Italy and Greece, there are other regions with medium exposure, along with France, Spain, and Portugal.

The spatial distribution for tourism exposure regarding extreme precipitation (Fig. 7b and e) is concentrated within the same larger area from the Central Alps southwards to the Mediterranean. However, there are significant differences when looking at the regional data in detail. In this case, the Greek Ionian and South Aegean islands are the only ones facing a very high risk. The high-risk category comprises Crete in Greece, Adriatic Croatia, Salzburg in Austria, South Tyrol, Trento, Veneto and Friuli-Venezia Giulia in Italy. Again, Austria, Italy, and Greece include further medium exposure regions. Other countries with regions that show medium exposure values regarding extreme precipitation and tourism are Bulgaria, France, Ireland, and Spain.

The higher values of tourism exposure to fire (Fig. 7c and f) are concentrated within three countries in the south of Europe: Spain (very high in the Balearic Islands and high in Andalusia and in the Valencian Community), Greece (very high in Crete and the South Aegean), and Portugal (very high in the Algarve). The three countries also contain further regions with medium exposure, together with regions in Bulgaria, Croatia, France, and Italy.

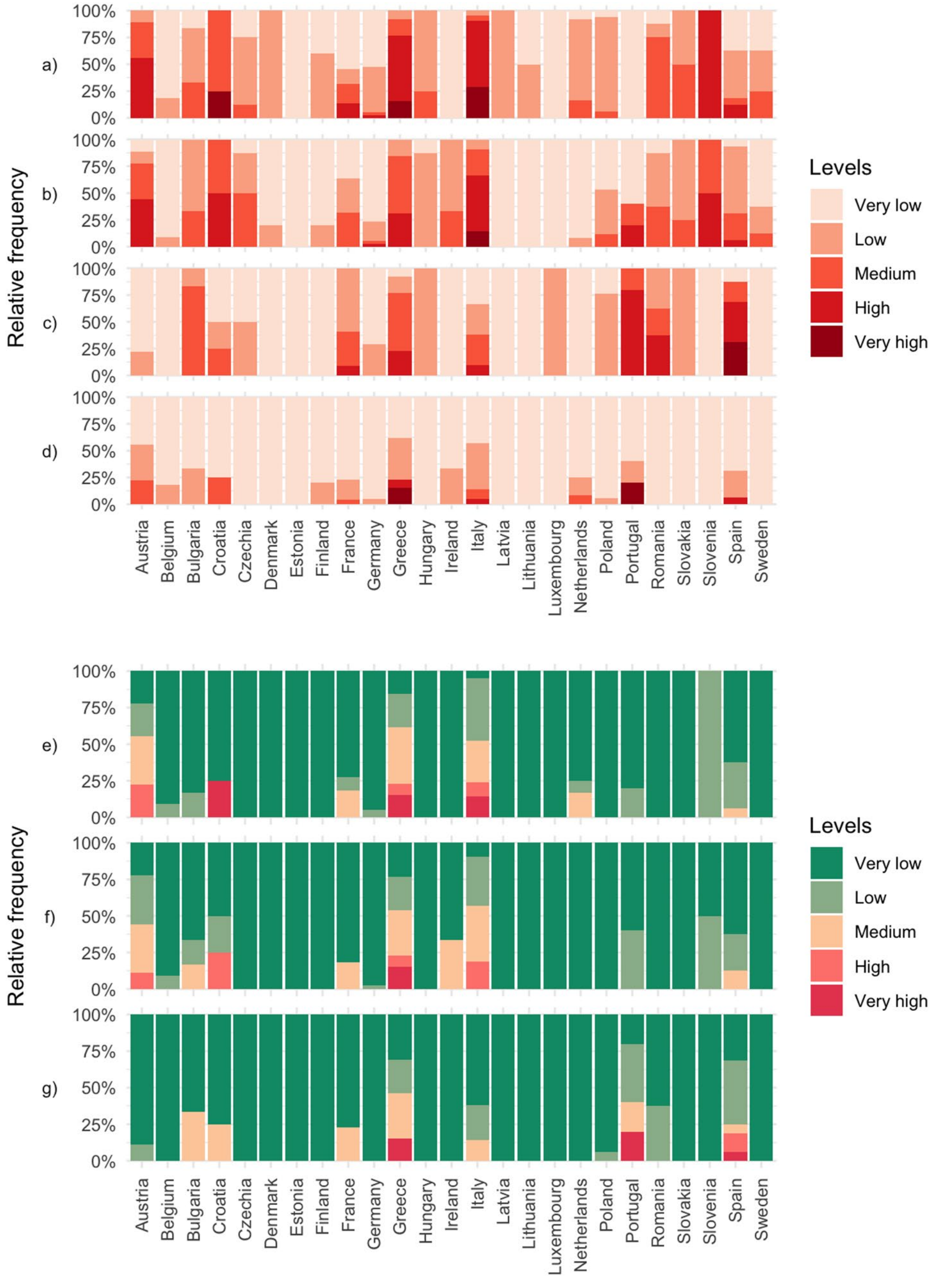

Fig. 8 Relative frequency of spatial units (NUTS2) by country, computed for each index: **a**) Thunderstorm Hazard Index (THI), **b**) Extreme Precipitation Hazard Index (PHI), **c**) Fire Hazard Index (FHI), **d**) Tourism Dependency Index (TDI), **e**) Tourism Exposure Index (THI) for Thunderstorm, **f**) Tourism Exposure Index (THI) to Extreme Precipitation, and **g**) Tourism Exposure Index (THI) to Fire

In summary, there is an apparent spatial concentration of regions with high or very high tourism exposure towards the southern parts of Europe, around the Mediterranean Sea. Several regions stand out for being exposed to different kinds of analysed hazards. The single most critical area is the NUTS2 region in the South Aegean in Greece, with a very high tourism exposure index in all three domains: thunderstorms, extreme precipitation, and fire. The Ionian Islands in Greece also have very high exposure towards extreme precipitation and thunderstorms. Still, their exposure to fire under a changing climate was determined to be low, considering the negative trend in fire weather over the recent decades. Other areas where different kinds of relatively high exposure coexist are Adriatic Croatia (very high for thunderstorms, high for extreme precipitation, and medium for fire) and Crete in Greece (medium for thunderstorms, high for extreme precipitation, and very high for fire). In other regions, only one of three phenomena has relevance: Andalusia in southern Spain, for example, has a high exposure to wildfires but a low exposure to thunderstorms or heavy precipitation.

4 Discussion

This research identifies the regions in the European Union facing the greatest risks from extreme weather hazards, as here identified for thunderstorms, extreme precipitation, and fires, while also being dependent on tourism. While findings mirror much publicized recent events, such as wildfires ravaging the island of Rhodes (The Guardian 2023), the Tourism Exposure Index is the first attempt to provide a more systematic assessment for an entire continent. The results cannot be used to predict future impact hotspots, but they suggest that regions facing individual or multiple hazards would benefit from developing tourism adaptation plans that also consider other economic sectors affected by hydrometeorological phenomena. Similar studies for other world regions are warranted in light of record-breaking extreme weather phenomena observed all around the globe (World Meteorological Organization 2023).

While this research enhances our understanding of the current distribution and significance of three hydrometeorological phenomena affecting tourism in Europe, it only marginally advances our understanding of overall tourism vulnerability. So far, research on the implications of changes in tourism climates has mainly focused on gradual changes in weather parameters, particularly temperature, considering future conditions up to the end of the century (Amelung et al. 2007; Hein et al. 2009; Rutty and Scott 2010). However, it is becoming evident that extreme weather events are significantly more relevant in the immediate future, as they are far more disruptive and unpredictable when and where they occur. Thus, studying hydrometeorological phenomena is increasingly important for planning and adaptation.

Findings as presented in this paper help identify regions where individual or multiple weather extremes have been concentrated or where trends indicate an increasing number of such events. Based on this, destinations can assess their vulnerabilities and develop management strategies. For example, Neger et al. (2024) presented a wildfire management framework for exposed destinations, highlighting the importance of resilient infrastructure, early warning systems, risk management plans tailored to local conditions, and the economic diversification of tourism-dependent at-risk destinations. Similar frameworks should be developed to address thunderstorms and extreme precipitation events where these have been identified as potential risks.

It is equally important to better understand tourist responses to weather risks (Gössling et al. 2012; Scott and Gössling 2022). As this research illustrates, hydrometeorological phenomena should be distinguished from longer-term gradual changes in destination climates. Extreme events can be expected to have more immediate implications for travel decisions and future destination choices, even though empirical studies indicate considerable resilience on the side of tourists to the experience of extreme events (Hübner and Gössling 2012; Gössling et al. 2016; Zanni and Ryley 2015).

This serves as a reminder that tourism arises from complex motivations, ranging from novelty-seeking and relaxation to self-development and romance (Pearce and Lee 2005). Expectations of specific weather conditions can be relevant to destination choices, but they are rarely the sole reason for underlying decisions. For example, a significant share of international tourism is focused on visiting friends and relatives, health or religion (27%), while business travellers (13%) are directed to specific locations irrespective of weather. Tourism with the main purpose of leisure and recreation accounts for 56% of all travel (UNWTO 2019). Weather expectations are primarily relevant for these tourists, while weather-related disruptions can potentially affect all forms of tourism. Despite these complexities, analysts continue to use temperature to project future tourism demand. For example, a recent publication by the European Union concludes that:

"[…] under a 4°C scenario, significant changes are projected in tourism demand. The projected overall impact on European tourism demand is expected to be positive, with a projected rise of 1.58% for the highest warming scenario […]." (Matei et al. 2023: 29).

Conclusions such as these impress high accuracy in predictions, to the second decimal (1.58%), even though they must be considered highly unreliable, lacking robustness. Not only do such studies ignore broader socio-economic implications of a 4 °C world for tourism, in which socio-economic instability will negatively affect tourism demand and destination stability (Scott et al. 2019); they also disregard complexities of decision-making processes that are influenced by personal experiences, the media, available vacation days, the timing of vacation leave, and the relevance of non-weather travel motives. This study highlights the disruptive potential of extreme weather events, which may come to affect future travel demand and transport system viability in significant ways in key destinations, adding another element of uncertainty that will weigh into tourist demand responses and decision-making. This does not mean that projections and particularly the development of future scenarios are without application in advising tourism management decisions. However, they should be combined with data on observed climate variations and socio-economic data on tourism, such as in the TEI, as well as a consideration of the tourism types practiced in each destination and further variables influencing tourist travel. While an approach of this kind will likely be unfeasible at the international level due to lack of data availability, it would be interesting to explore national and regional applications, possibly with the development of a new index derived from the combination of existing indices as shown in a present example.

Key insights from this study include the vulnerability of specific regions to extreme weather phenomena, which have become more frequent and intense over time. In regions affected by such weather extremes, disruptions can pose significantly greater challenges for tourism than concerns over longer-term gradual changes in weather patterns. Consequently, destination managers and regional planners should focus on preparing for disruptive events rather than solely addressing gradual changes. The implications of these developments for tourism may include impacts on reservations (timing), insurance (trip interruption or cancellation), as well as travel motivation (feasibility of activities) and decision-making (choice of destination and repeat visitation).

The European Union is currently a unique region where such tourism risk assessments can be conducted, although extending these methods to other major tourism regions worldwide is highly recommended. To support this, countries are encouraged to enhance their statistical databases, while the European Union should aim to provide more detailed temporal and spatial data. For instance, seasonal assessments, rather than annual ones, require precise information on when revenue is generated, ideally made available for much smaller geographic units.

5 Conclusions

This study provides a comprehensive assessment of tourism exposure to hydrometeorological hazards in Europe, focusing on thunderstorms, extreme precipitation, and fire weather. By developing the Tourism Exposure Index (TEI), which combines the Hazard Index (HI) (in a changing climate) and the Tourism Dependency Index (TDI), the research identifies regions with the highest tourism exposure, notably in southern Europe and around the Mediterranean Sea. The South Aegean and Ionian Islands in Greece emerge as the most vulnerable areas, highlighting the pressing need for targeted adaptation strategies.

The findings emphasize the spatial disparities in tourism exposure, with southern regions facing greater risks due to their climatic conditions and economic reliance on tourism. The increased frequency and intensity of extreme weather events underscore the urgency for at-risk destinations to implement adaptation plans that address both immediate and long-term impacts on tourism infrastructure and visitor safety.

The TEI serves as a critical tool for regional planners and policymakers, providing a data-driven basis for developing effective climate adaptation frameworks tailored to local needs. Future research should expand on these findings by incorporating seasonal variations in tourism demand as well as tourist motivations to further enhance the understanding of how climate change will shape tourism dynamics across Europe.

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