CSS/Italy 2025
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Centro Polifunzionale Studenti Università "Aldo Moro" (ex Palazzo Poste)
Bari (Italy), September 15-17, 2025

A statistical study of precipitation data in Sicily: looking for signatures of climate change

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INFN Istituto Nazionale di Fisica Nucleare

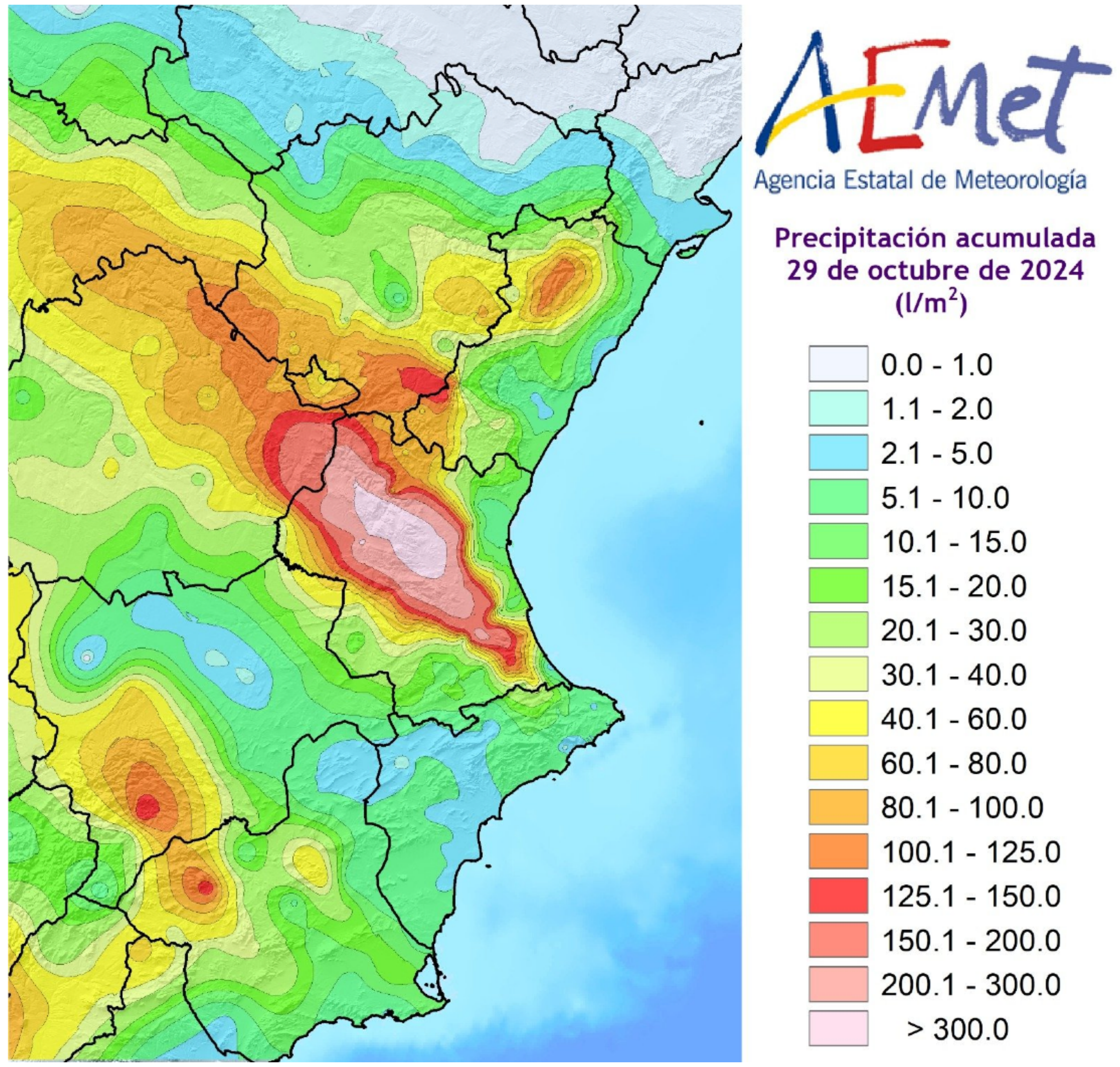
COMPLEXITY SCIENCE HUB VIENNA

Plan of the talk

- Introduction and motivation
- Precipitation dataset
- Empirical analysis
- Statistical analysis
- Conclusions

In Valencia (Spain) all of a sudden...last October (29/10/2024)

In 8 hours the rain of 1 year



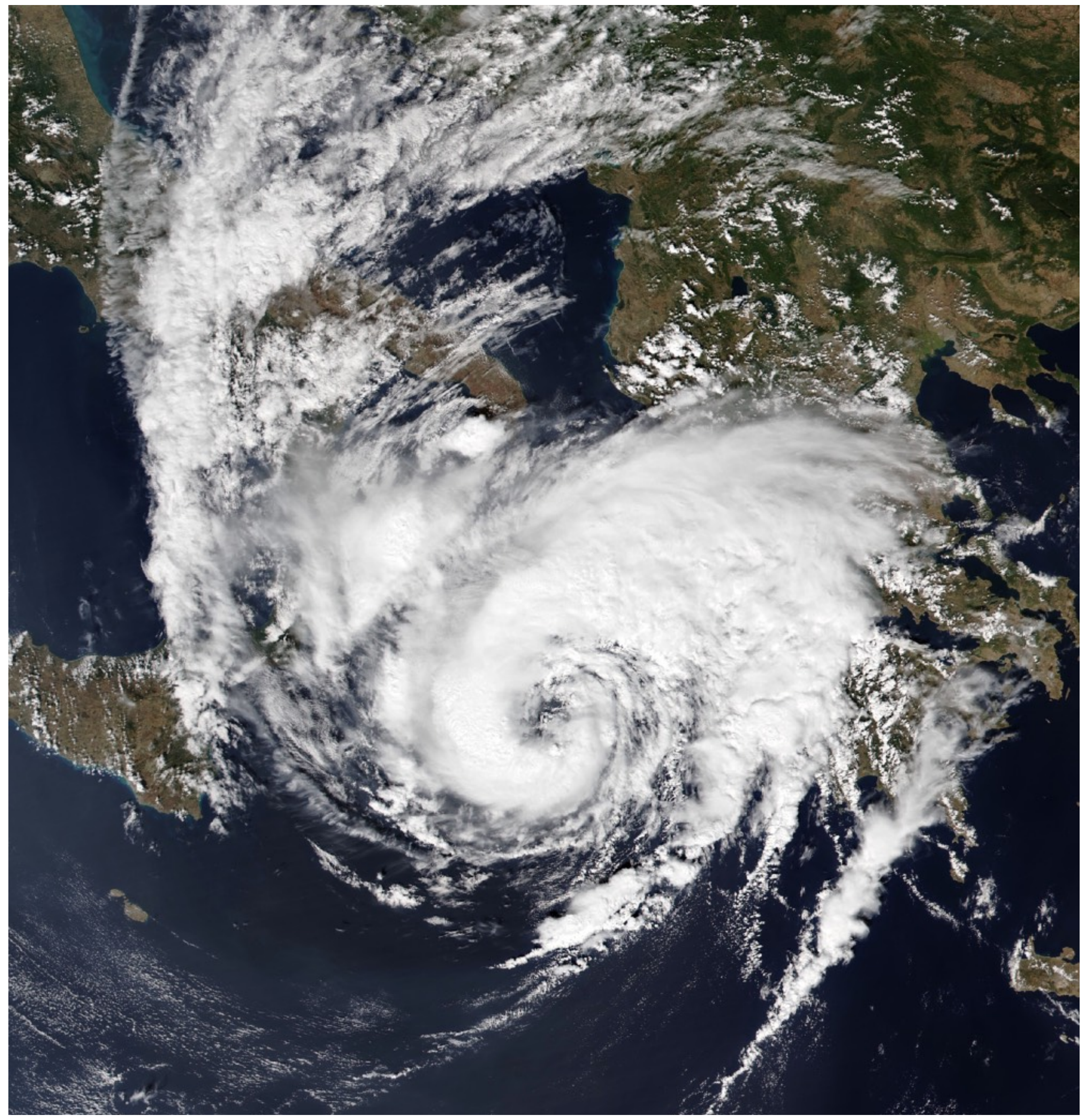
In Sicily, close to Catania, all of a sudden...a couple of weeks after Valencia water bomb and flood...

we had more amount of rain than in Valencia, 500 mm of water in 12 hours, after many months without any rain

...but not only water bombs and floods !

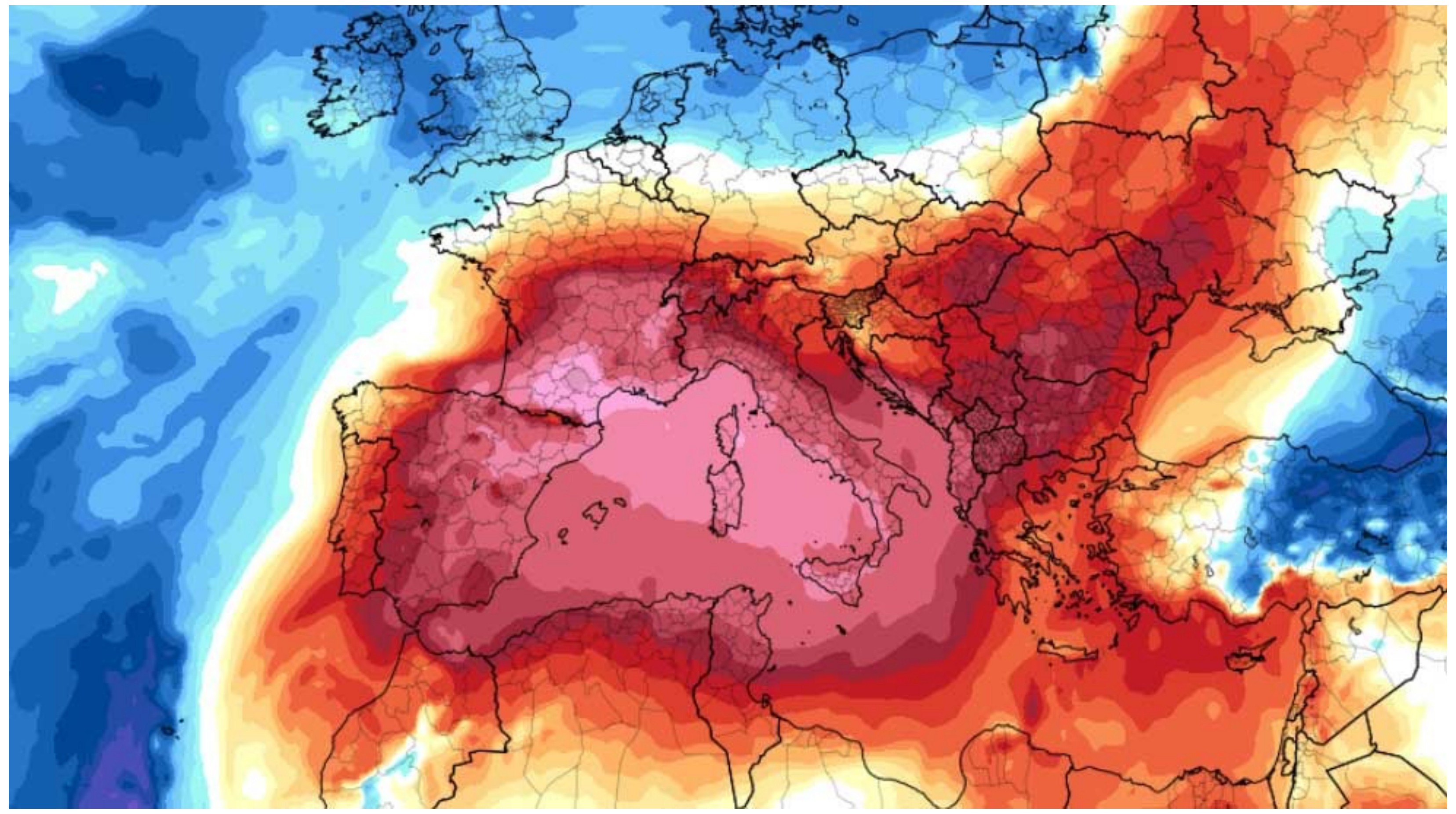
We are living in a period of wild changes facing an increase occurrence of extreme events

Droughts



Mediterranean hurricanes or Medicanes

Big forest fires



Heatwaves

Extreme events have become more and more frequent with a devastating impact on our daily life !

MOTIVATION

It is then important to investigate and characterise in a quantitative way

datasets of climatic variables like time series of temperature, pressure, rainfall, etc.

in order to see tendencies and possible precursor or emerging signals of climate change

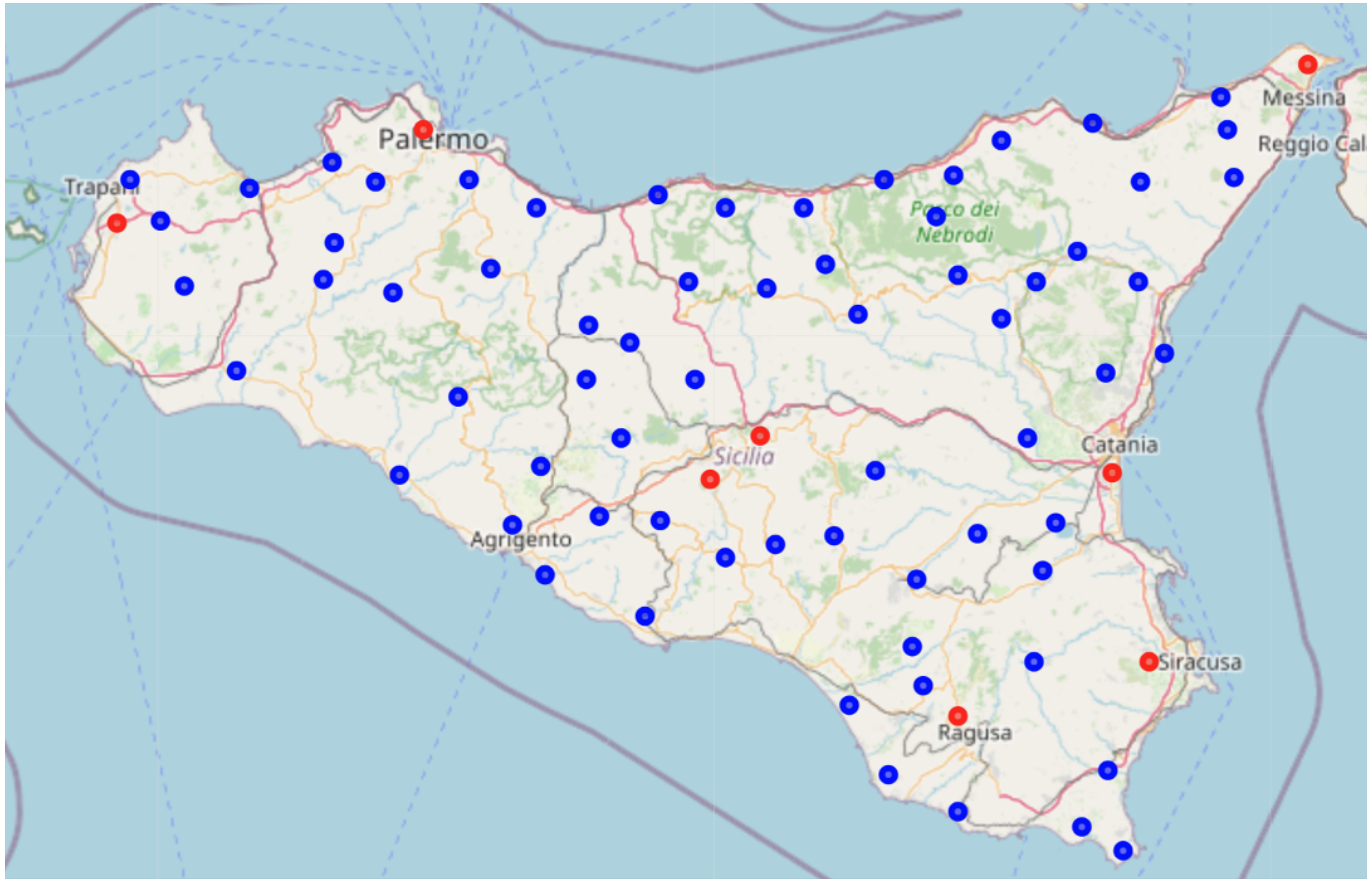
and find sustainable new strategies to moderate the impact of these extreme events

Sicily island is at the center of the Mediterranean sea

Sicily is just in the middle of the Mediterranean sea and thus has a privileged position to investigate possible signs of climate change in this area

We studied precipitation data recorded in Sicily in the last two decades

Our Precipitation Dataset of Sicily



Data provided by the

Sicilian

Agrometereological

Informative System

www.sias.regione.sicilia.it

Hourly-based time series in the period

01/01/2002 - 31/07/2023

for 75 rain gauge stations

Our first paper reports on an empirical analysis of this dataset

we considered seasonal periods of three months for the last two decades

Eur. Phys. J. B (2024)97:154
https://doi.org/10.1140/epjb/s10051-024-00792-3

THE EUROPEAN PHYSICAL JOURNAL B

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Regular Article - Statistical and Nonlinear Physics

Empirical analysis of hourly rainfall data in Sicily from 2002 to 2023

Vera Pecorino[1,a], T. Di Matteo[2,6], Matteo Milazzo[1], Luigi Pasotti[3], Alessandro Pluchino[1,4], and Andrea Rapisarda[1,4,5]

The instrument to measure rainfall, the rain gauge, is very simple

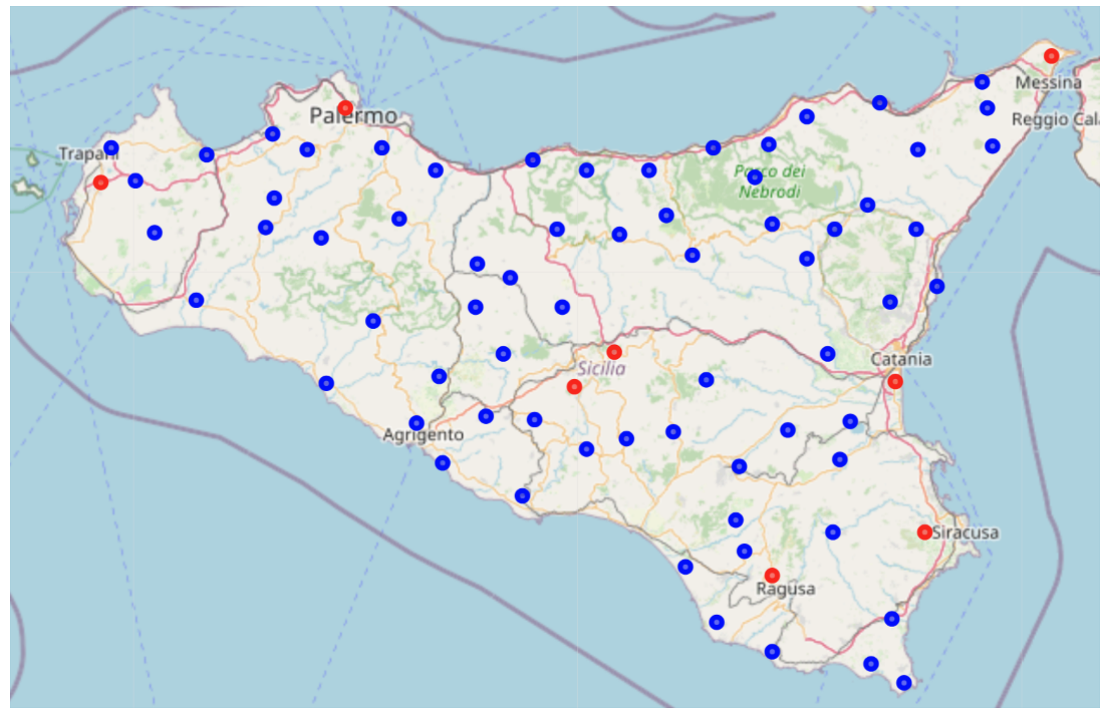
1 mm of rain = 1 L of rain per m^2

Rainfall volumes

Rainfall volume

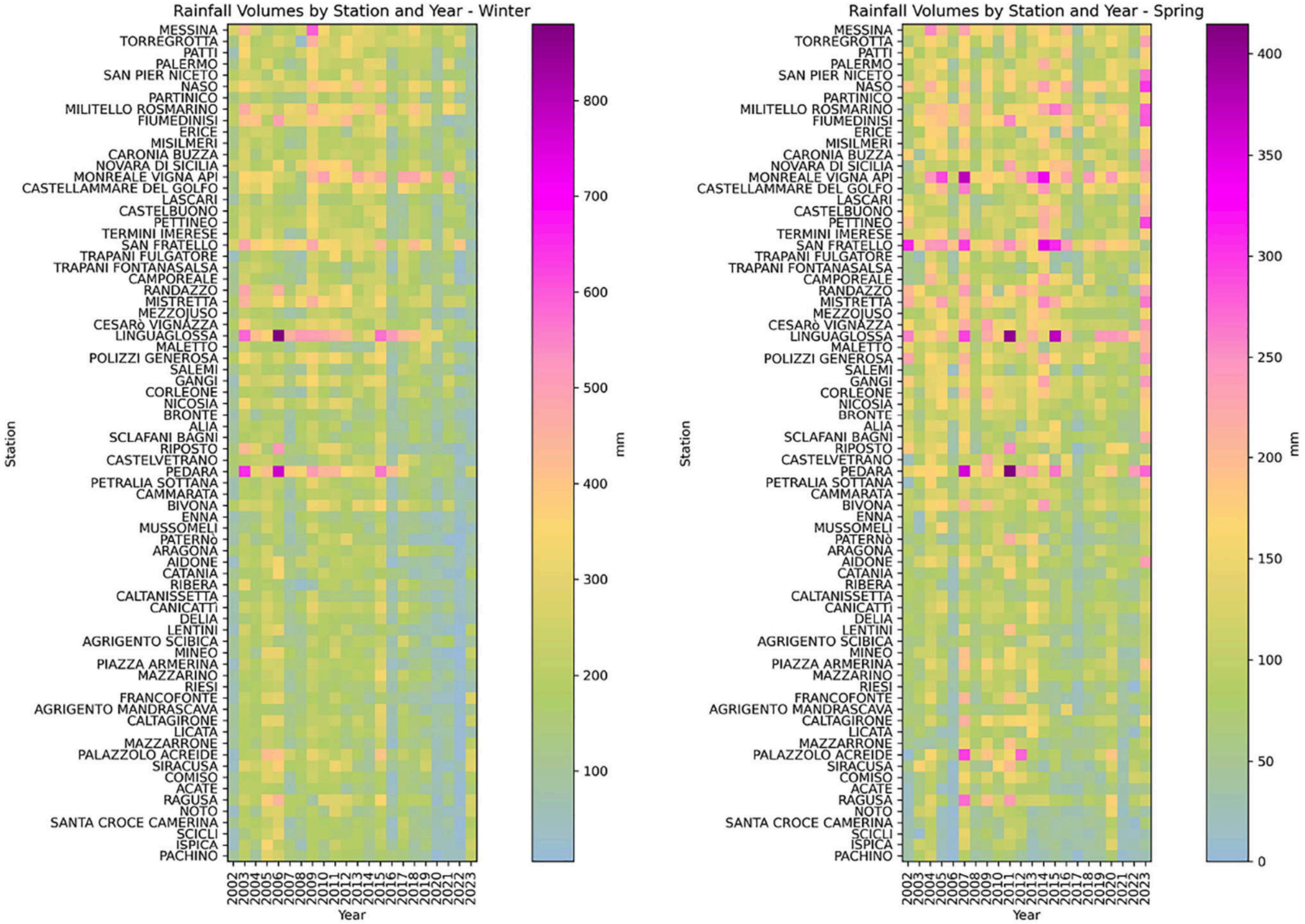
is

the sum of the hourly records of rain over the 3 months of the season for each station



winter

spring



North

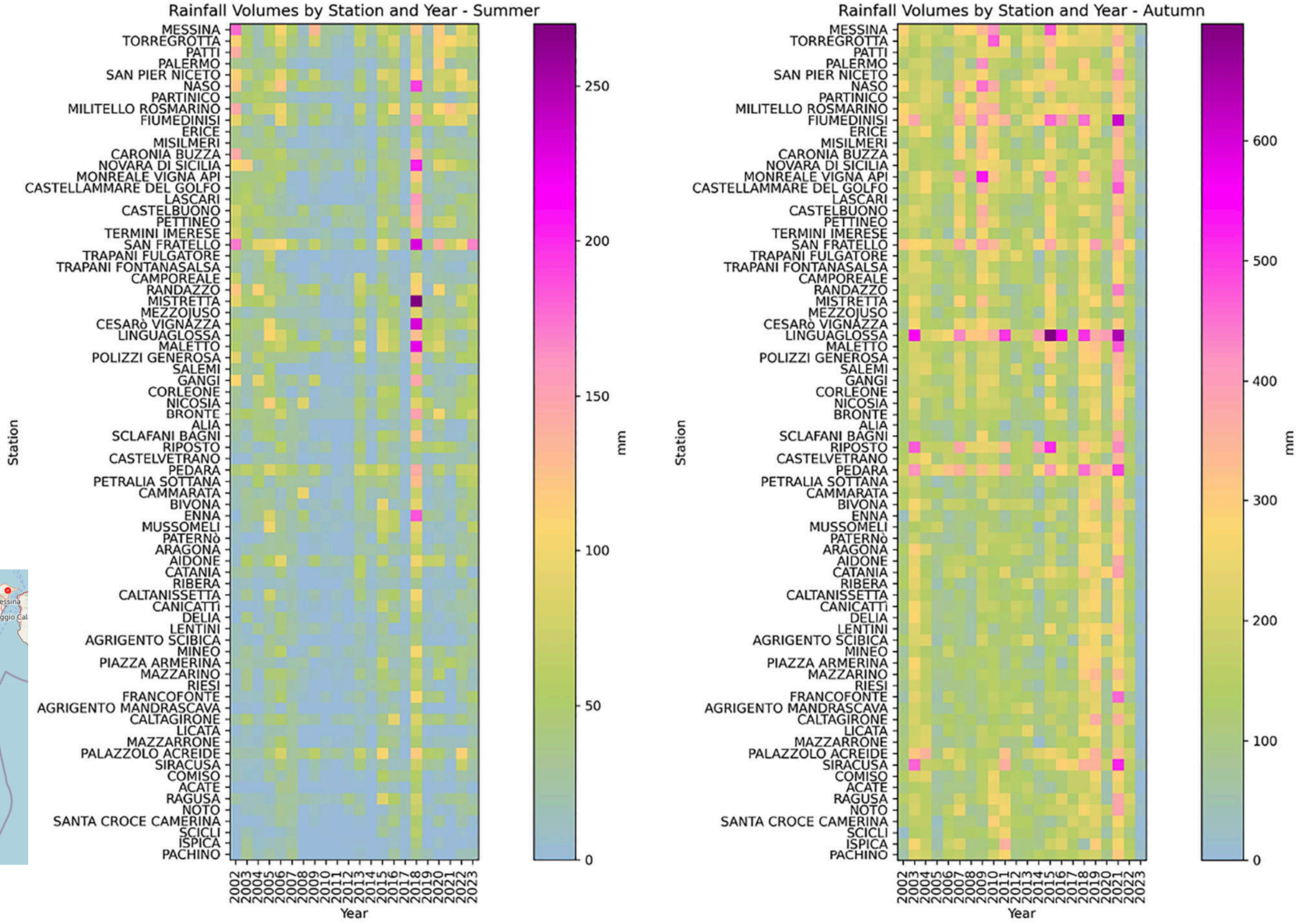
South

Fig. 3 2D grid of seasonal precipitation volumes: gauge stations are on y-axis and years on x-axis. Colors are referred to the magnitude of the parameter. Stations are ordered following the direction North (Messina)–South (Pachino). Colorbars map the color-numerical magnitude relation. Upper (lower) limit represents the seasonal maximum (minimum) amount recorded across all stations and years. From left to right: winter, spring

Rainfall volumes

summer

autumn



North

South

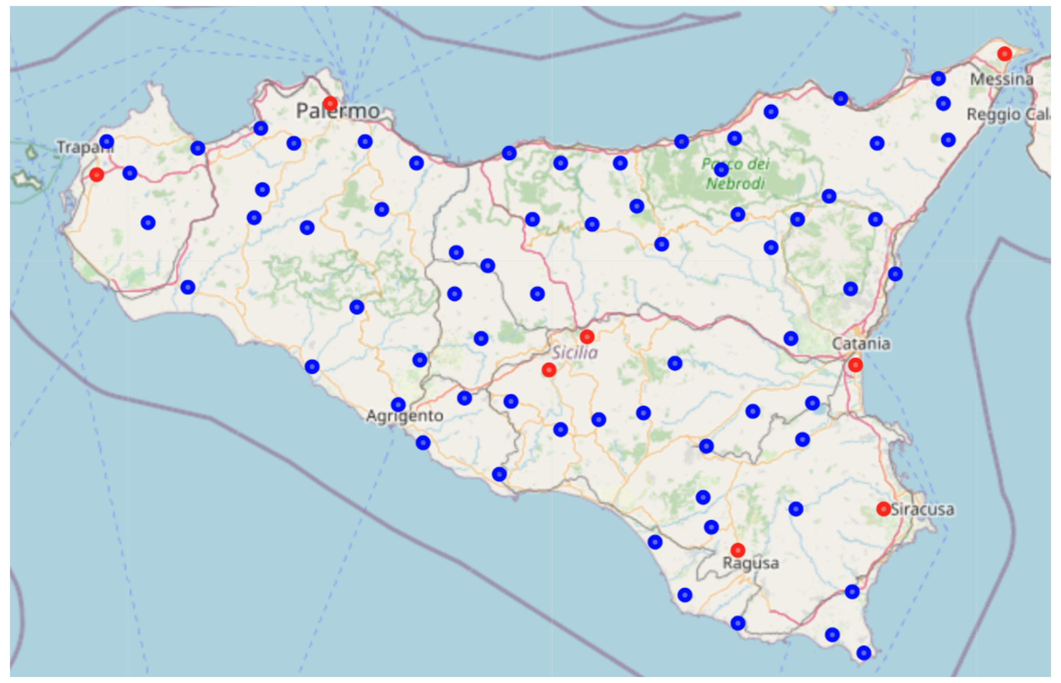
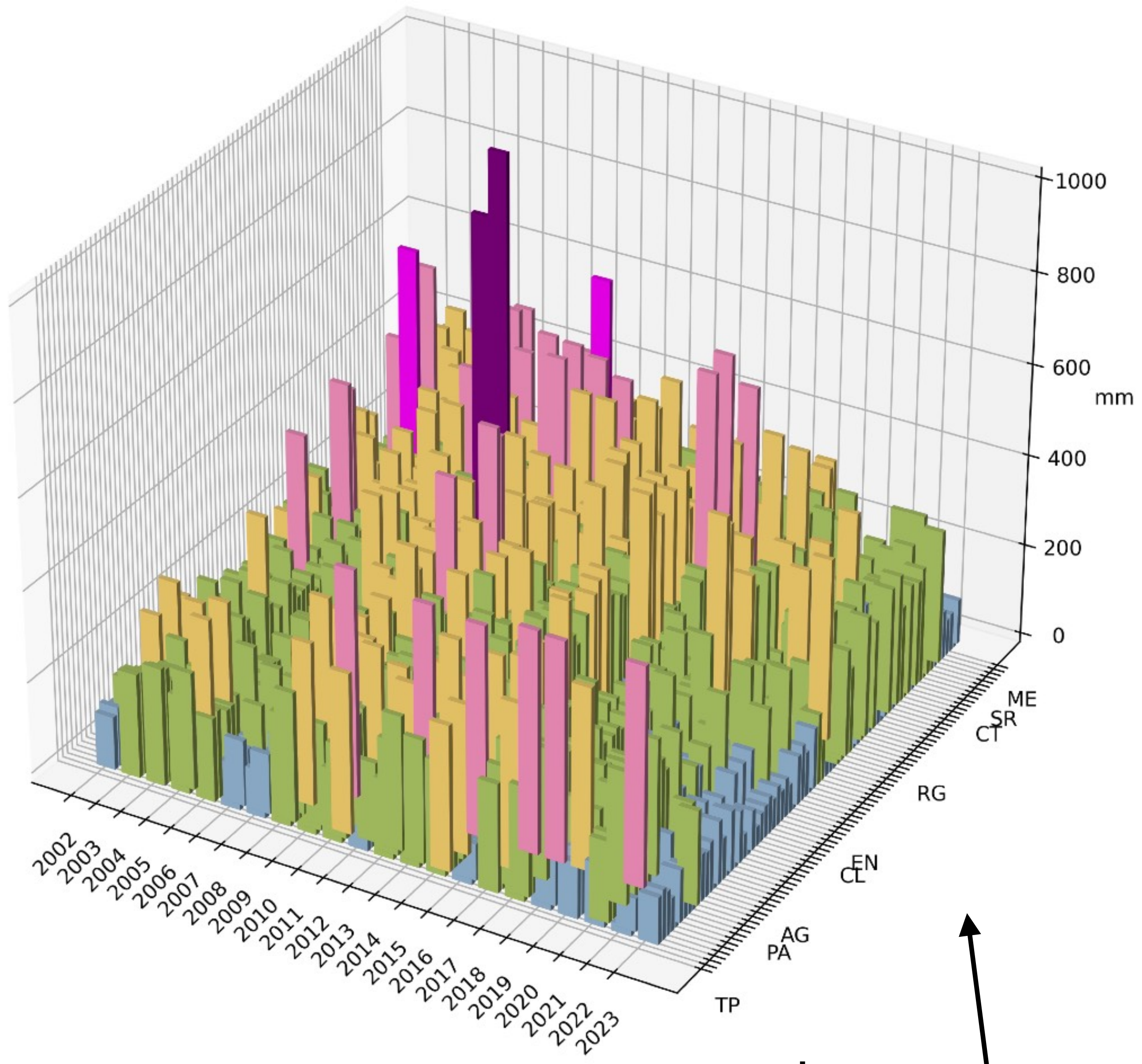


Fig. 4 2D grid of seasonal precipitation volumes: gauge stations are on y-axis and years on x-axis. Colors are referred to the magnitude of the parameter. Stations are ordered following the direction North (Messina)–South (Pachino). Colorbars map the color-numerical magnitude relation. Upper (lower) limit represents the seasonal maximum (minimum) amount recorded across all stations and years. From left to right: summer, autumn

Rainfall volumes comparison

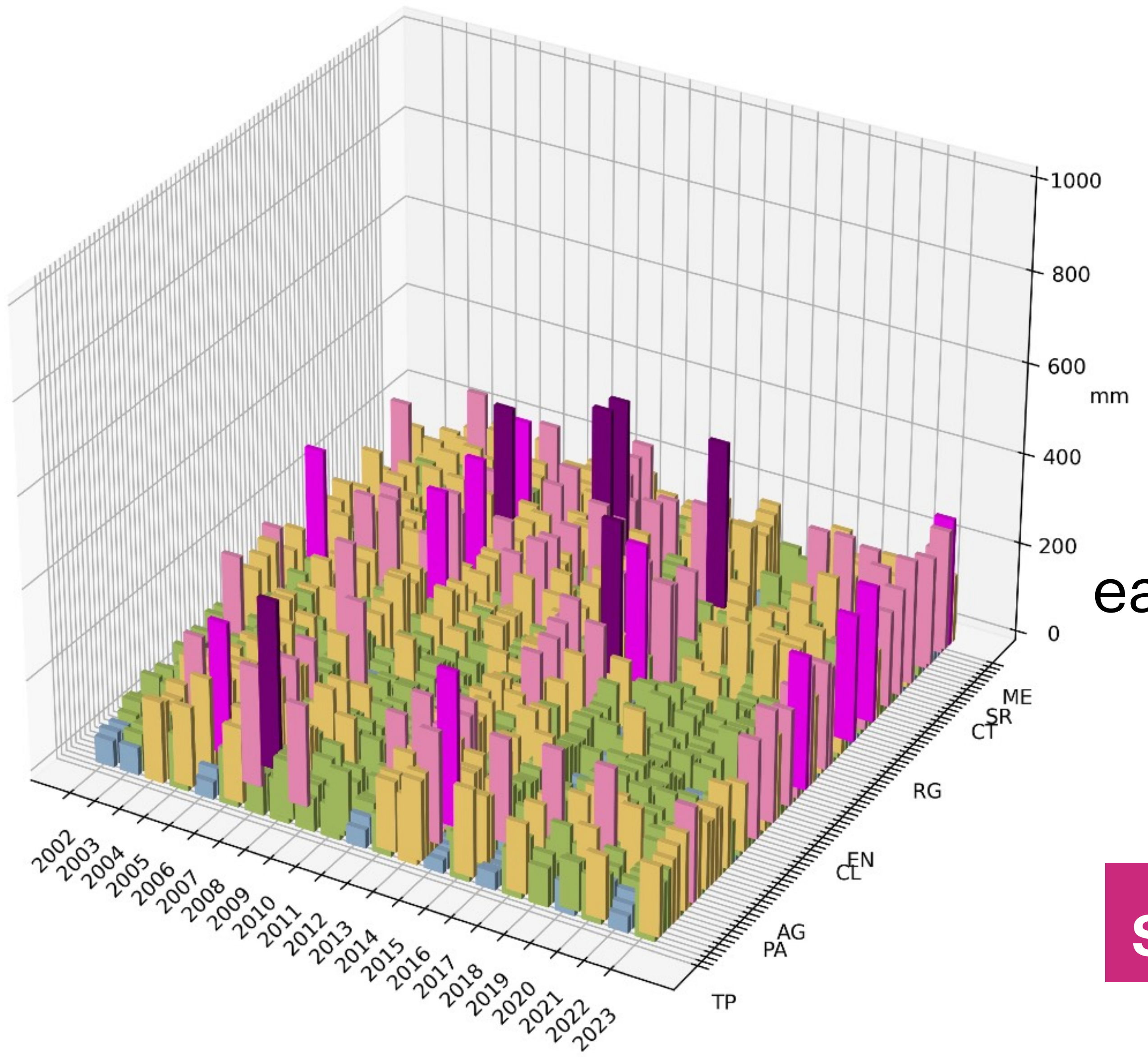
winter



east

west

spring

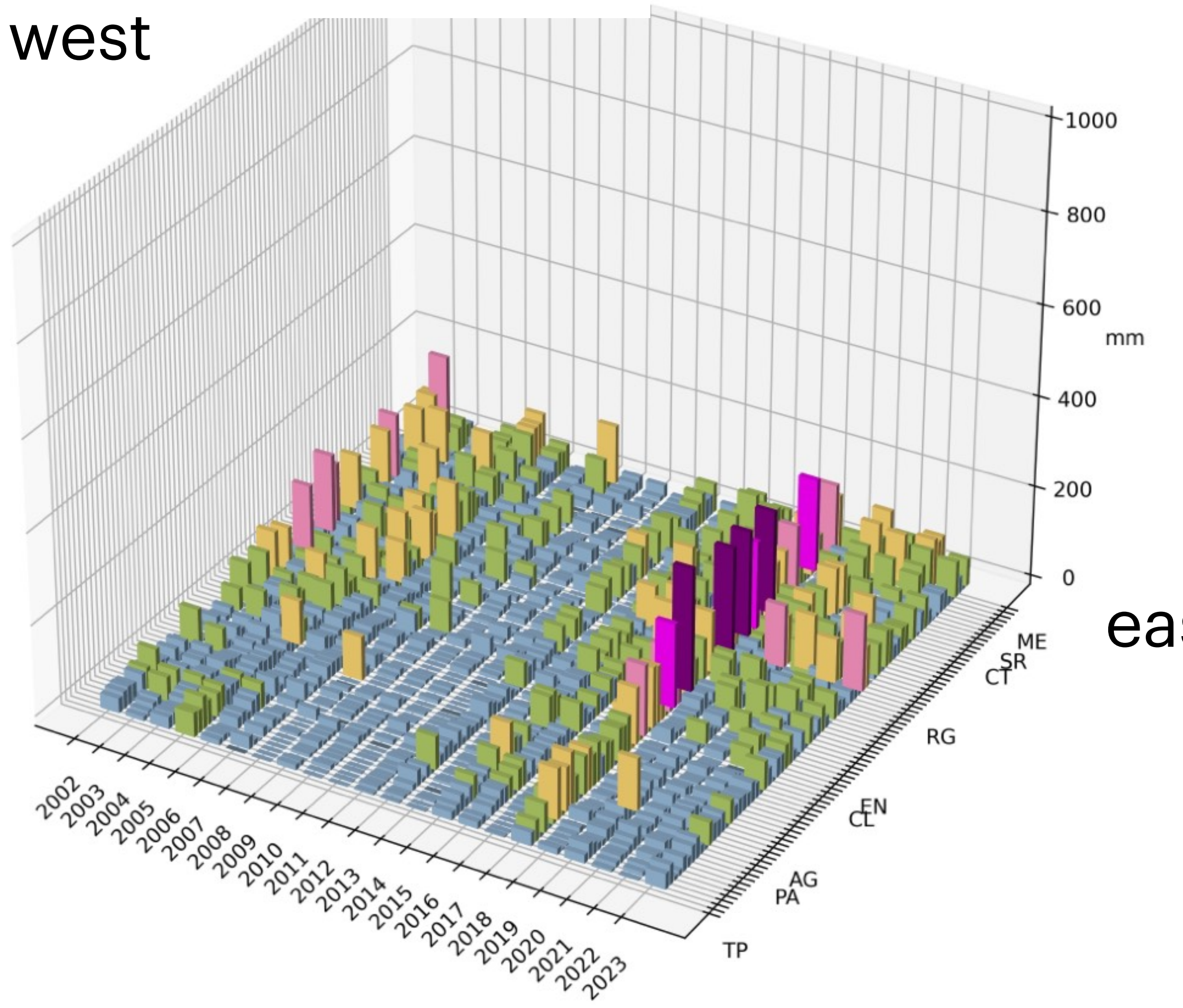


east

west

Eastern part of Sicily has been more affected by higher precipitations volumes especially in the last years and in autumn

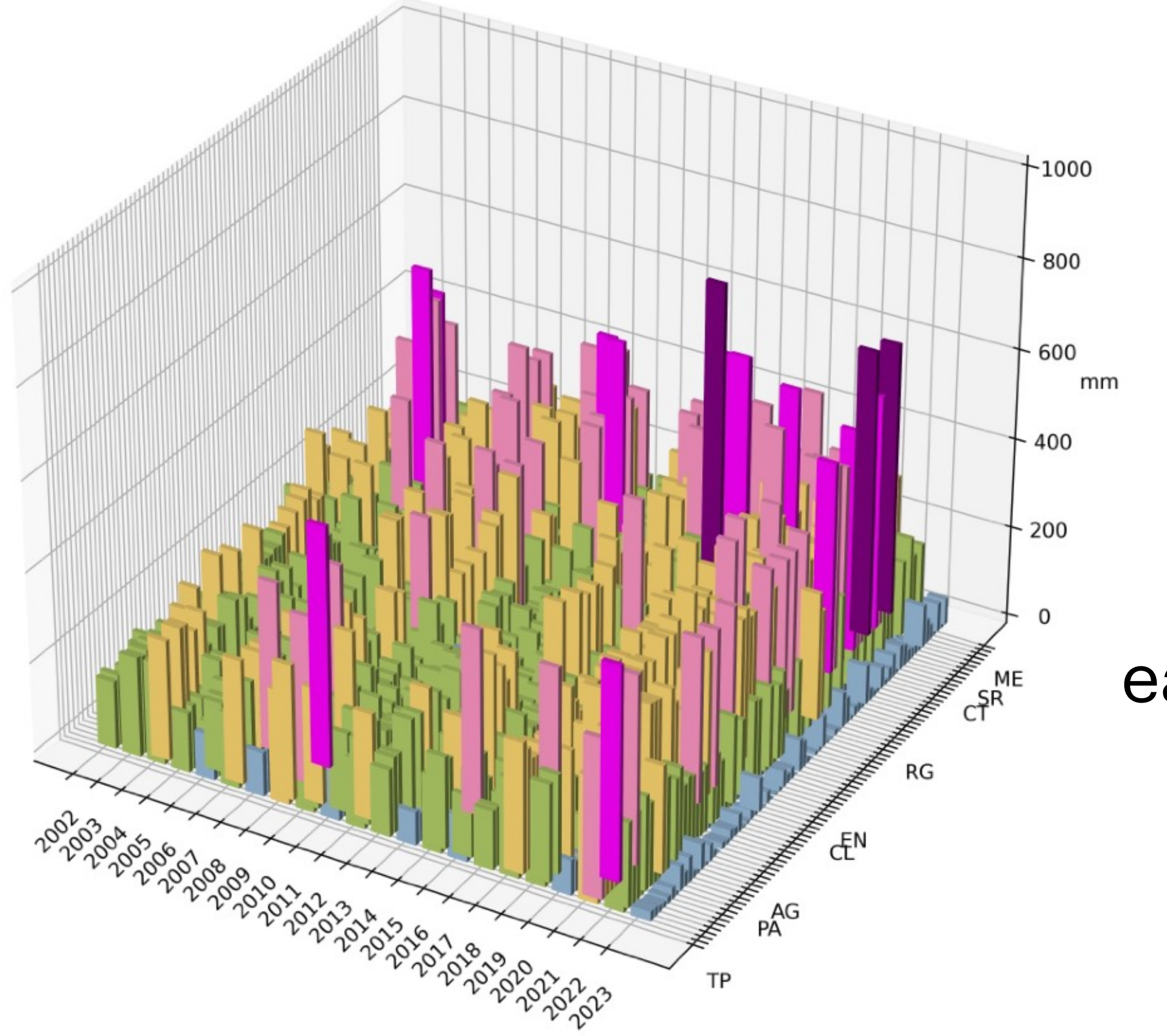
summer



east

west

autumn



east

west

In winter precipitation volumes are decreasing along the years

Rainfall events

A rainfall event is the episode of consecutive wet hours

Each rainfall event can be characterized by two quantities:
duration (min) and depth (mm)

The duration is the length of consecutive wet hours

The rainfall depth is the sum of precipitation for the corresponding event duration

winter

spring

North

South

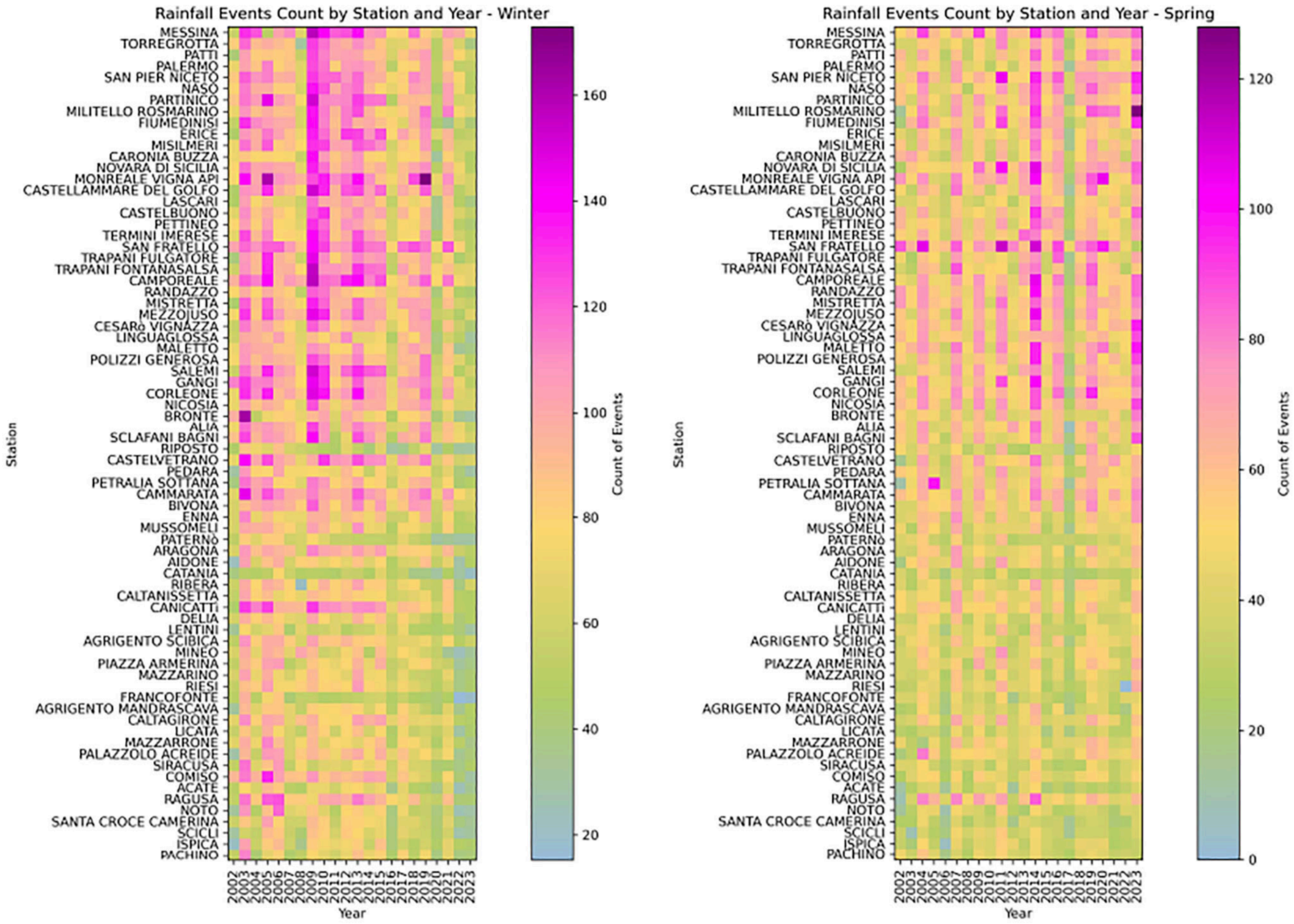


Fig. 5 2D grid of seasonal count of rainfall events: gauge stations are on y-axis and years on x-axis. Colors are referred to the magnitude of the parameter. Stations are ordered following the direction North (Messina)–South (Pachino). Colorbars map the color-numerical magnitude relation. Upper (lower) limit represents the seasonal maximum (minimum) amount recorded across all stations and years. From left to right: winter, spring

Rainfall events

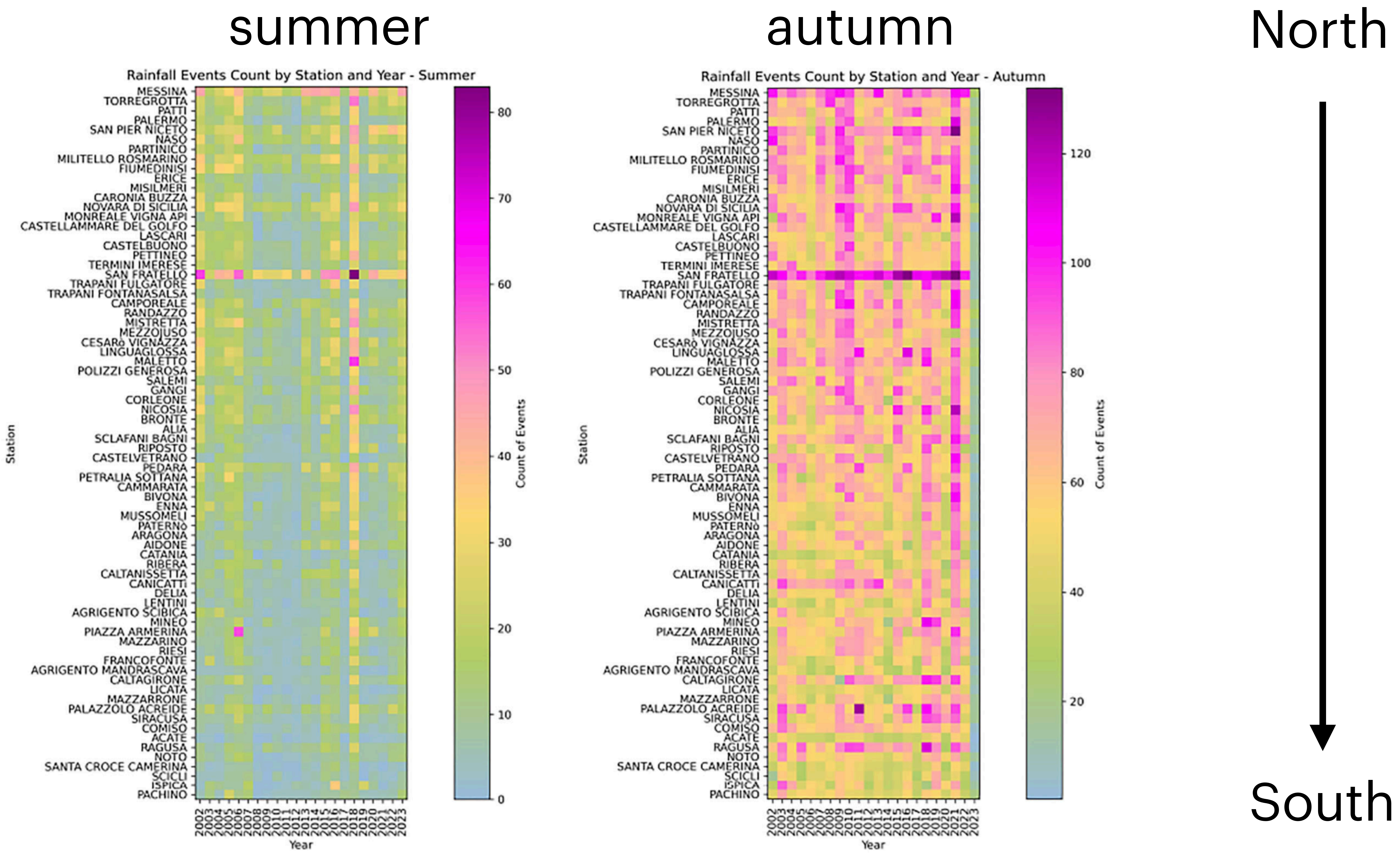


Fig. 6 2D grid of seasonal count of rainfall events: gauge stations are on y-axis and years on x-axis. Colors are referred to the magnitude of the parameter. Stations are ordered following the direction North (Messina)–South (Pachino). Colorbars map the color-numerical magnitude relation. Upper (lower) limit represents the seasonal maximum (minimum) amount recorded across all stations and years. From left to right: summer, autumn

Different categories of events

In order to differentiate the rainfall events with respect to their intensity, one can classify each rainfall event with percentile thresholds, as proposed by the World Climate Research Program and the World Meteorological Organization.

So one can identify six intensity classes hourly-based as shown in the table below

	Intensity class	***[mm/h]***	***percentile***
NOT EXTREME	Weak	1-2	<50
	Moderate	2-6	50-90
	Heavy	6-10	90-97.5
EXTREME	Very heavy	10-18	97.5-99.8
	Shower	18-25	99.8-99.9
	Torrential	>25	>99.9

where the event is classified according to the maximum of the precipitation value recorded during the event

Comparison among the two decades

$$S = \frac{(\text{Variable})_{2013-2023}}{(\text{Variable})_{2002-2012}}$$

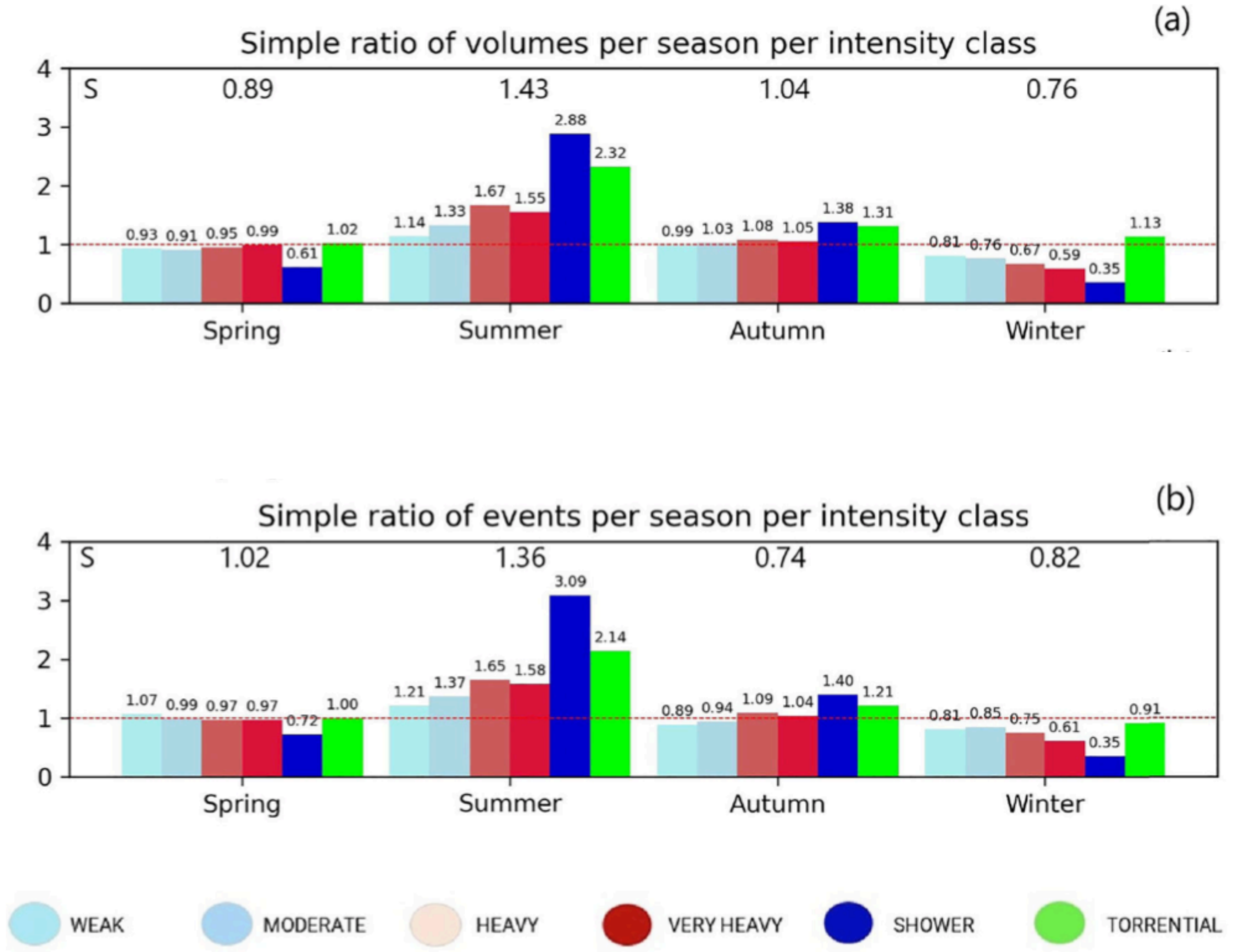


Fig. 7 Simple ratio bar charts. Colors correspond to precipitation intensity classes. Above each chart is reported the seasonal not categorical simple ratio. On the y-axis we show the simple ratio, on the x-axis the seasons

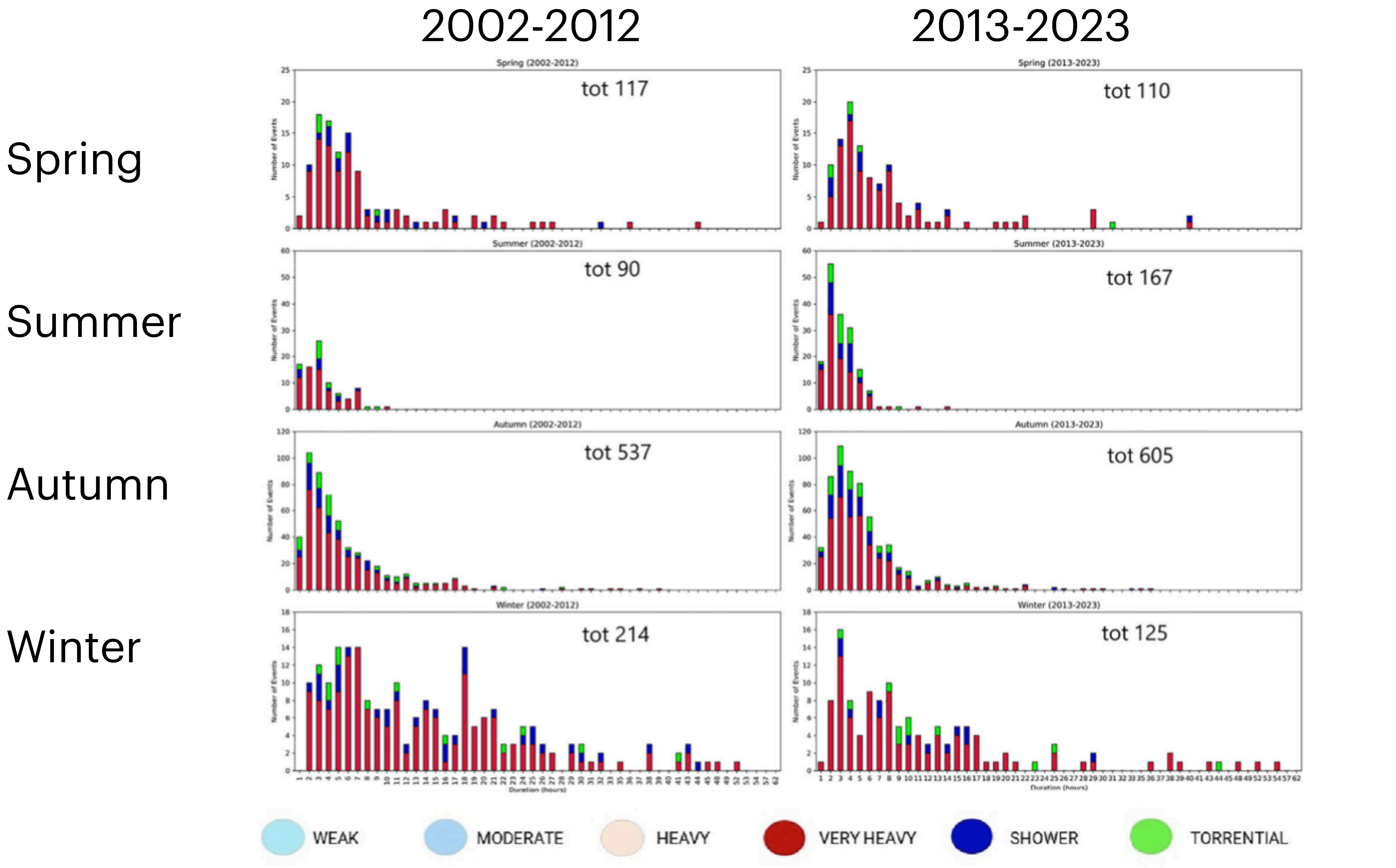


Fig. 8 Seasonal histograms: on the y-axis is reported the number of events, on the x-axis the duration. Colors corresponds to intensity classes. Each plot reports the seasonal total number of events. Seasons from top to bottom: spring–summer–autumn–winter. Left column 2002–2012. Right column 2013–2023

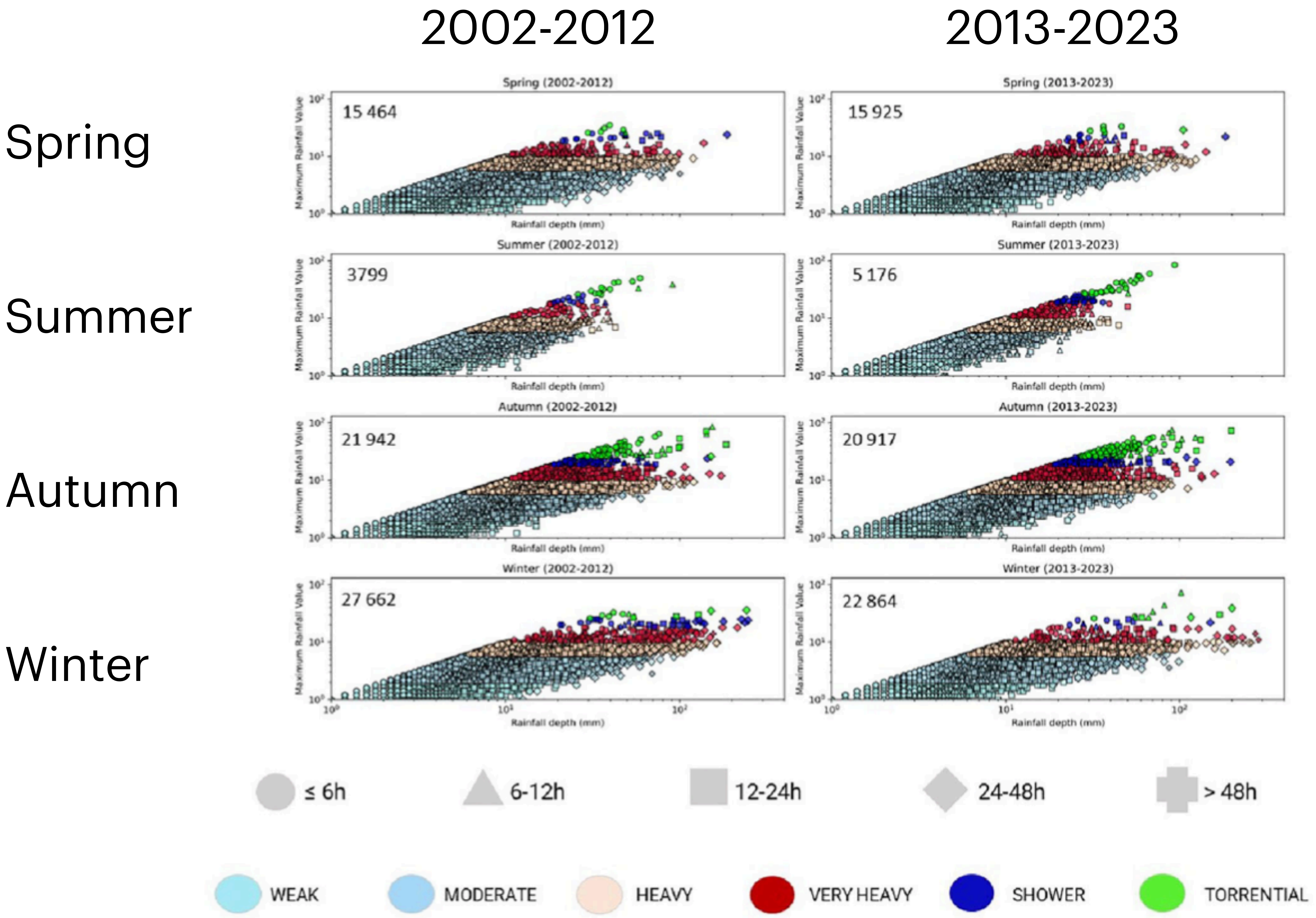


Fig. 9 Seasonal scatter plots of maximum hourly record (mm/h) on y versus rainfall depth (mm) on x. Colors correspond to precipitation intensity classes whereas shapes to different duration ranges. Seasons from top to bottom: spring–summer–autumn–winter. Left column period 2002–2012. Right column period 2013–2023

Summary of the empirical analysis

clear signals of change along the last two decades

- Rainfall volume data indicate higher precipitation volumes in the eastern part of Sicily
- Precipitation volumes increase in autumn and decrease in winter seasons
- There is an increase of the number of extreme events during summer and autumn seasons
- winter seasons are showing less extreme events and are becoming more similar to spring seasons
- dry periods are becoming longer and affect large areas of Sicily especially in the west part

Recently this paper was chosen for the EPJ B Highlight page

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EPJ B Highlight - Characterising shifts in Sicily's seasonal rainfall

Published on 19 November 2024

Mapping hourly rainfall on Sicily

Over the past decade, rainfall patterns on Sicily have shifted from a 4- to a 2-season cycle, reflecting similar shifts taking place worldwide.

Around the world, man-made climate change is increasing both the frequency and severity of extreme weather events. Seasonal patterns in rainfall are an especially important indicator of these changes: while a lack of rain can lead to more severe droughts, an excess can trigger catastrophic events such as landslides and flash flooding. To better understand the impact of these risks, it is vital for researchers to characterise these changes in as much detail as possible.

Through new research published in *EPJ B*, researchers led by Vera Pecorino at the University of Catania, Italy, present a highly detailed analysis of recent changes in seasonal rainfall on the Italian island of Sicily. Their results confirm that over the past decade, the island's rainfall patterns underwent a profound shift from a 4- to a 2-season cycle.

The team hopes that their work could help researchers to better understand the shifts in climate currently taking place across the globe, and to develop more feasible strategies for managing climate-related risks.

Within Europe, the Mediterranean is more affected by changes in seasonal rainfall than any other region. In the past decade, Sicily has experienced especially unusual trends in seasonal rainfall.

To study these trends, Pecorino's team analysed hourly measurements of Sicily's rainfall, taken since the beginning of the century: providing a more extensive dataset than any previous study. Their analysis of the data clearly showed that between 2013 and 2023, Sicily's seasonal rainfall cycle underwent a fundamental shift.

During summer and autumn, rainfall significantly increased, with little variation between the two seasons. In contrast, rainfall decreased during the winter and spring – again with little variation between both seasons.

According to Pecorino's team, these changes signal a clear shift from a 4- to a 2-season cycle – more similar to the rainfall patterns found in tropical regions. In turn, this shift closely coincided with an uptick in the frequency and severity of droughts and flash flooding: a trend which is already repeating in many regions across the globe.

Pecorino, V., Matteo, T.D., Milazzo, M. et al. Empirical analysis of hourly rainfall data in Sicily from 2002 to 2023. *Eur. Phys. J. B* **97**:154 (2024). https://doi.org/10.1140/epjb/s10051-024-00792-3

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"Thank you for the very fruitful and efficient collaboration. It has been a pleasure!!"

Paul van Loosdrecht, Guest Editor Topical issue: Excitonic Processes in Condensed Matter, Nanostructured and Molecular Materials, 2013

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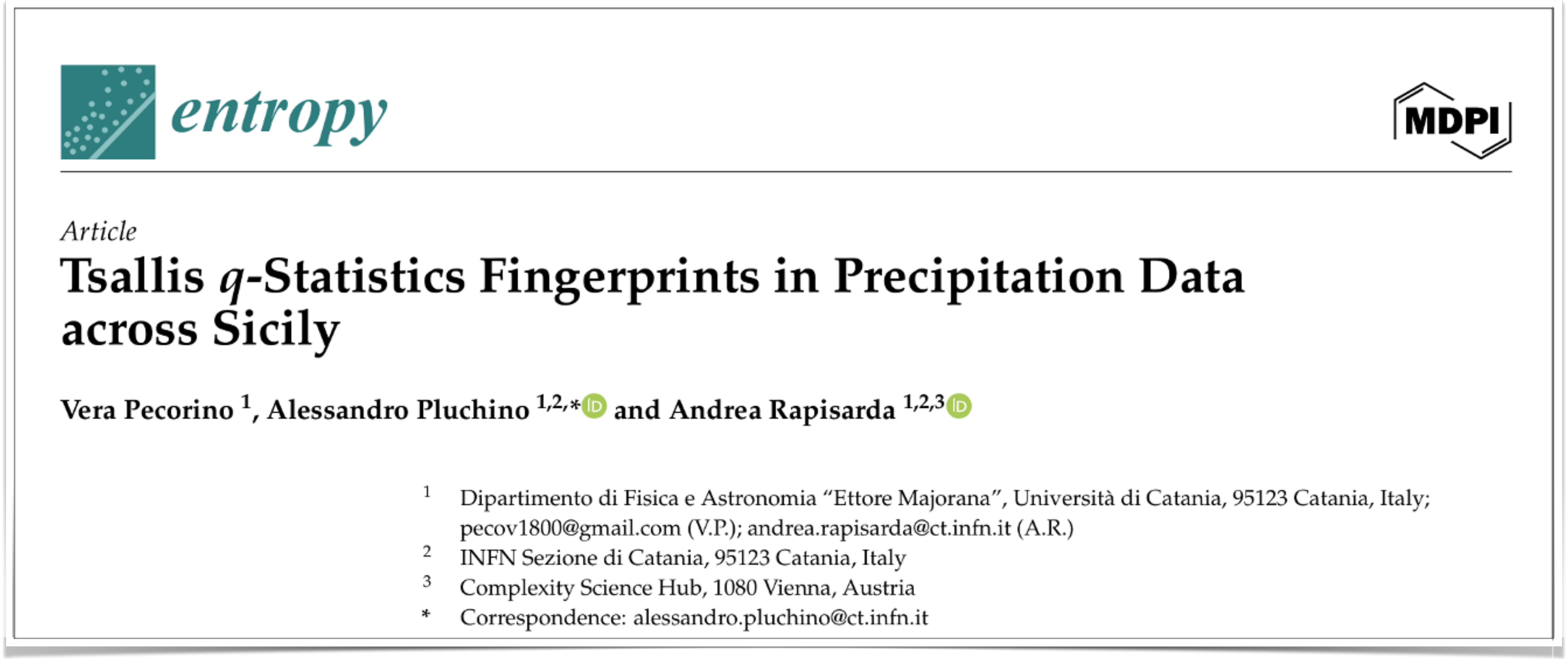
Statisical analysis


entropy

MDPI

Article

Tsallis *q*-Statistics Fingerprints in Precipitation Data across Sicily

Vera Pecorino [1], Alessandro Pluchino [1,2,*] and Andrea Rapisarda [1,2,3]

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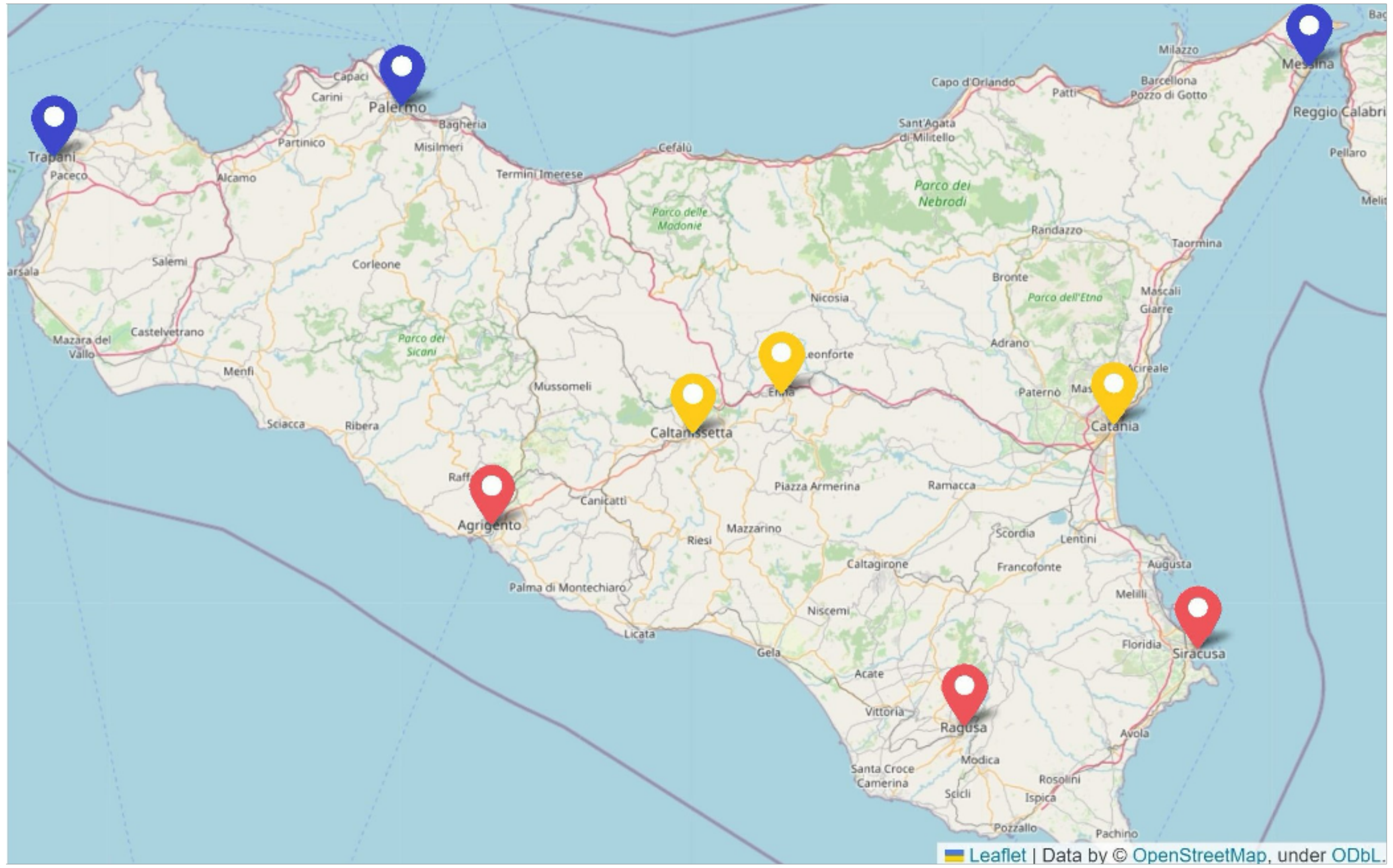
Entropy **2024**, *26*, 623. https://doi.org/10.3390/e26080623

Study of the rainfall time series only for the 9 major cities of Sicily

but data collected every 10 minutes



We performed a statistical analysis for

→ Event duration [*time*]

→ Event depth [mm]

→ Event max [mm×*event*]

comparing the first decade 2002-2012

with the second decade 2013-2023

Depth Power laws

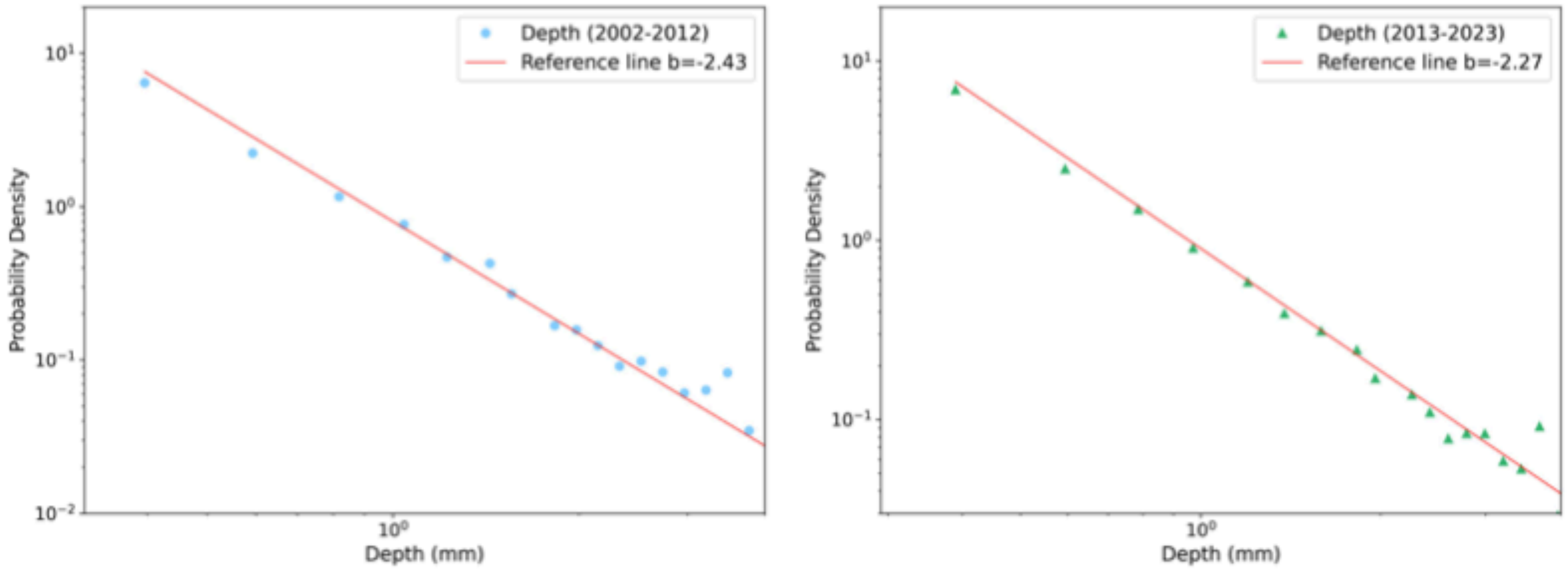


Figure 2. Probability density function of autumn rainfall depth in log–log scale and its fits with a power law (red line) for the two decades considered: 2002–2012 (**left** panel) and 2013–2023 (**right** panel). The slopes of the fits are also reported, see text for more details.

Max per event power laws

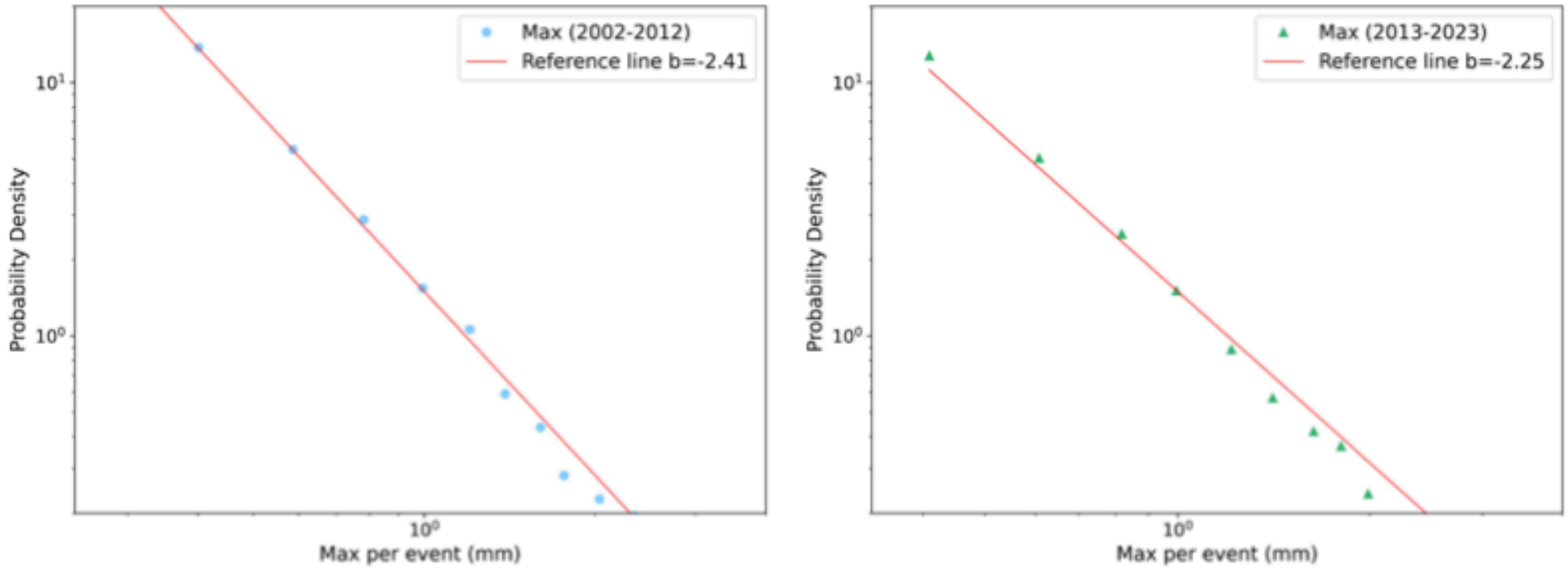


Figure 3. Probability density function of autumn max per event in log–log scale and the fit with a power law (red line) for the two decades considered: 2002–2012 (**left** panel) and 2013–2023 (**right** panel). The slopes of the fits are also reported, see text for more details.

Event duration power laws

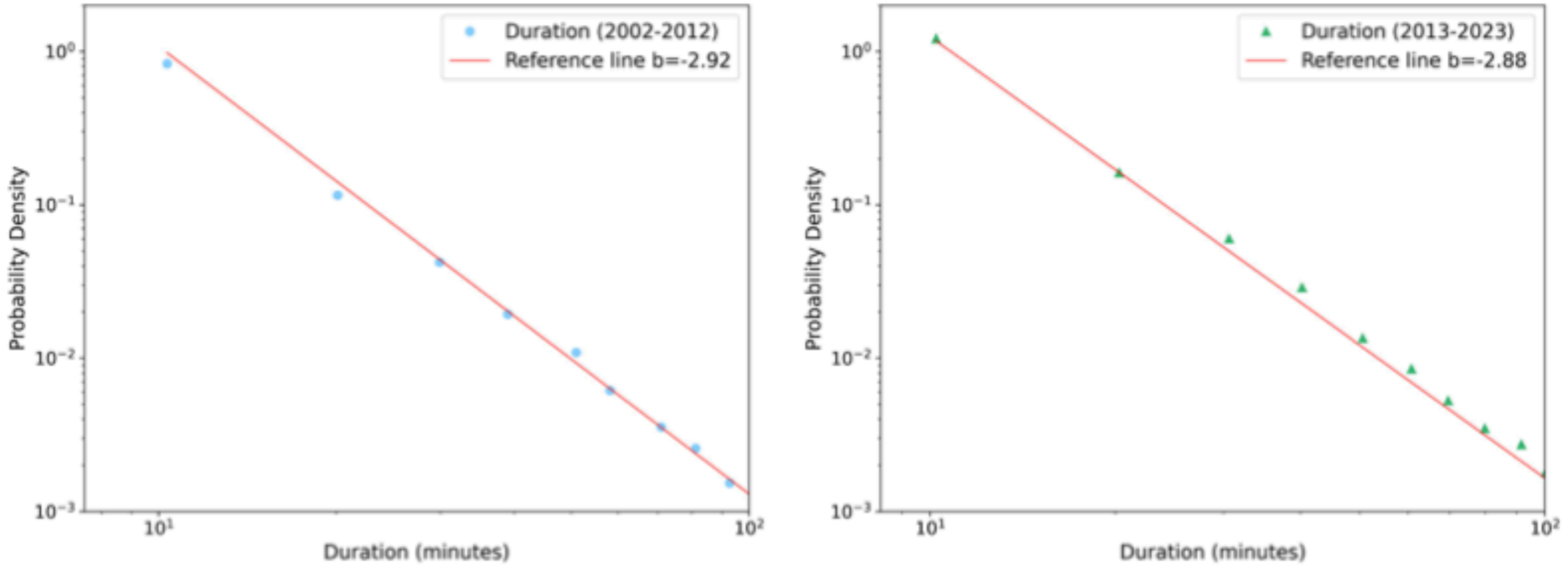


Figure 4. Probability density function of autumn rainfall event duration in log–log scale and its fits with a power law (red line) for the two decades considered: 2002–2012 (**left** panel) and 2013–2023 (**right** panel). The slopes of the fits are also reported, see text for more details.

Comparison of the power law slopes

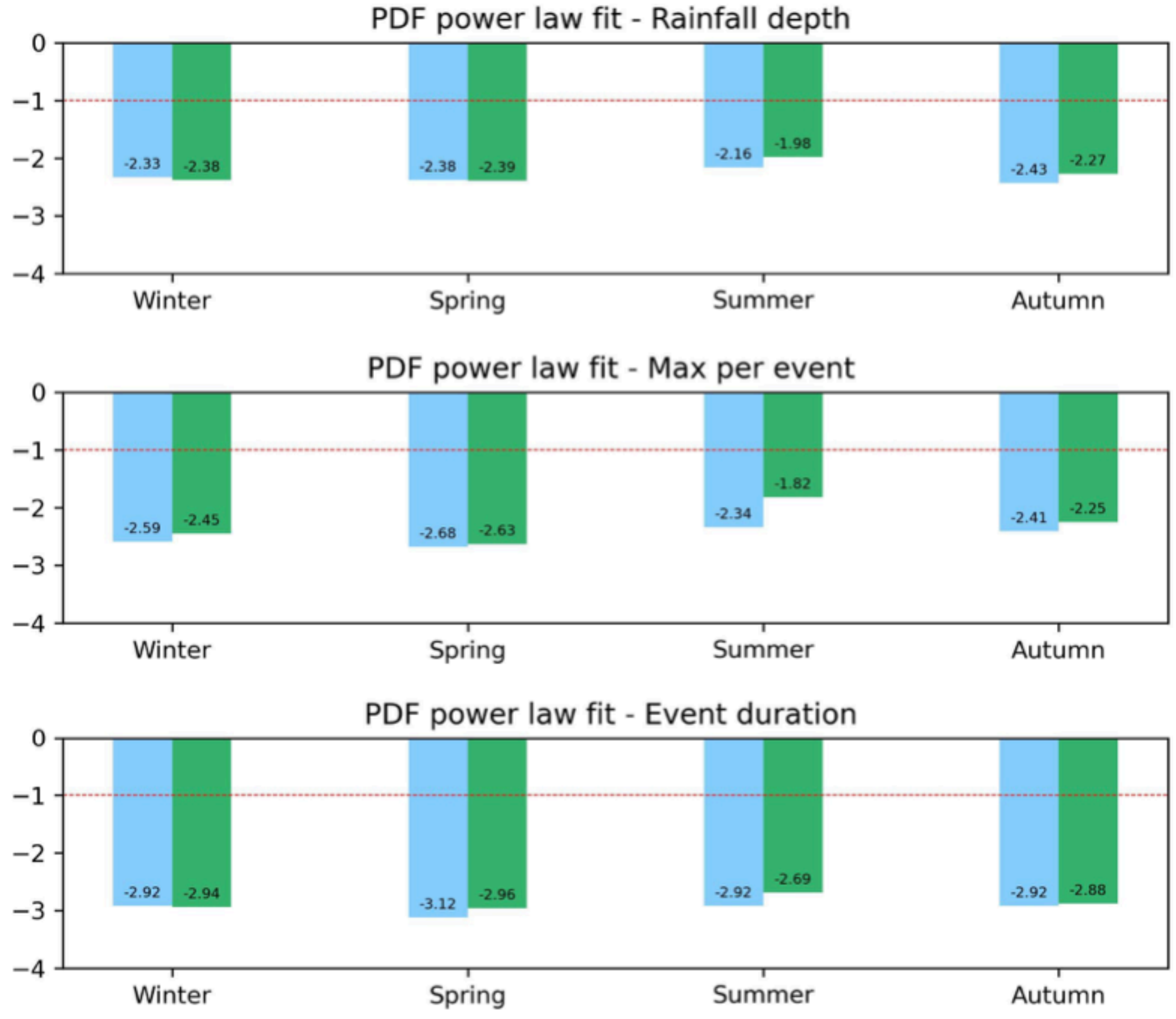


Figure 5. We report the values of the slopes of the power-law fits for the events' rainfall depth (**top** panel), maximum record (**central** panel), and duration (**bottom** panel). The different colors refer to the two decades studied: blue for the period 2002–2012 and green for the period 2013–2023. Differences between the two decades can be appreciated, in particular for summer. An horizontal red dotted line has been added as reference for the eye. See text for more details.

2002-2012

2013-2023

In general the slopes of the second decade tend to diminish indicating an increase of extreme events

Decumulative pdf of depth

2002-2012 2013-2023

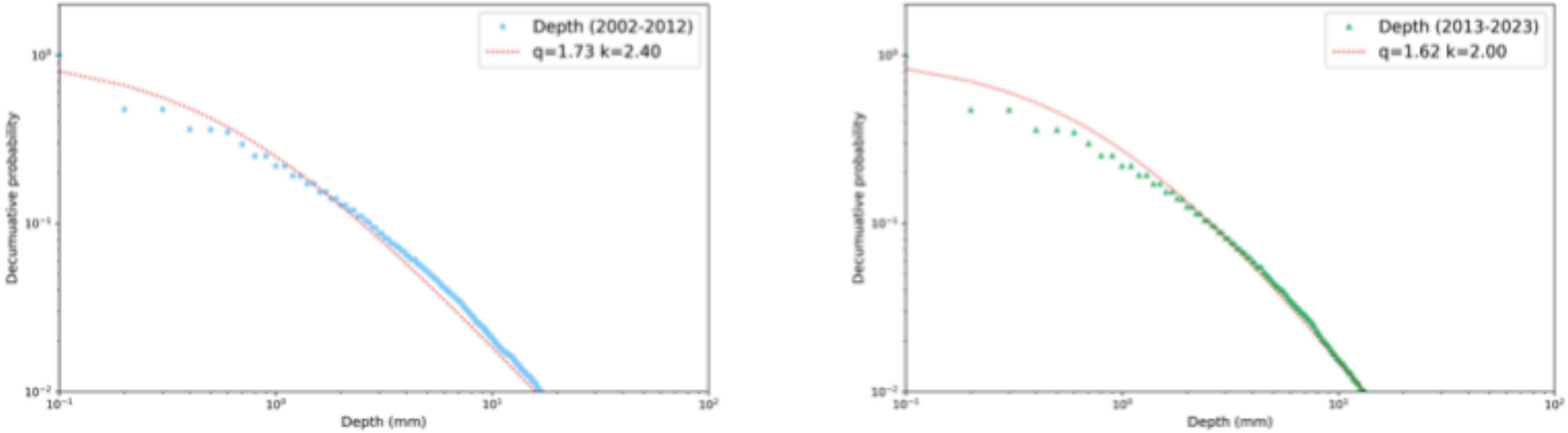


Figure 6. Decumulative probability distributions in log–log scale of winter rainfall depth per event and their *q*-exponential fits. Comparison between decades: 2002–2012 (**left** panel) and 2013–2023 (**right** panel).

$$e_q(x) = [1 + (1-q)kx]^{\frac{1}{1-q}},$$

Decumulative pdf of max per event

2002-2012 | 2013-2023

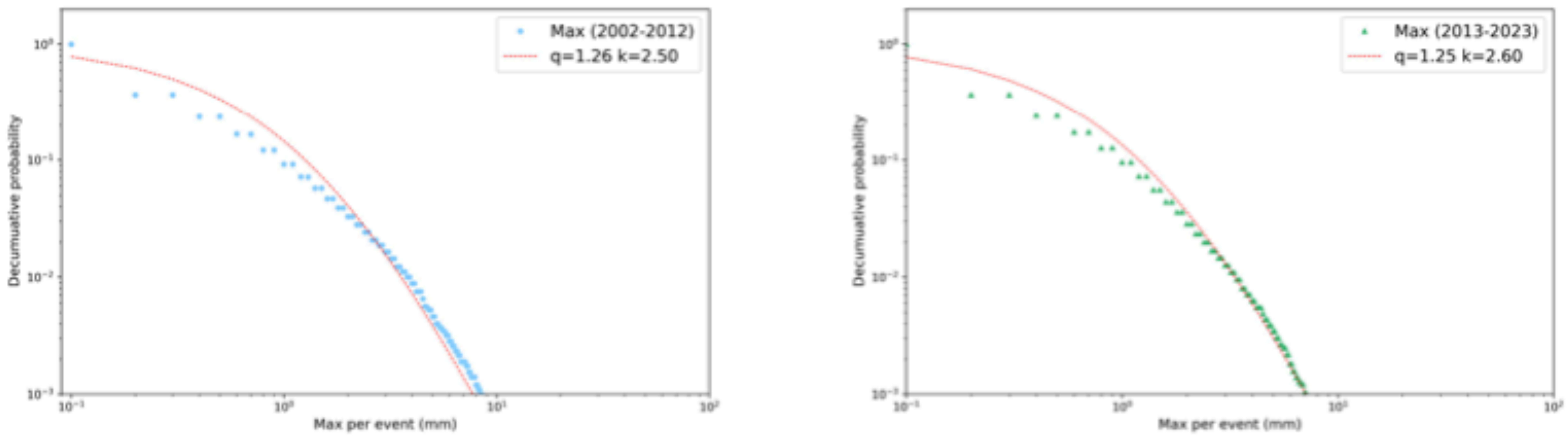


Figure 7. Decumulative probability distributions in log–log scale of winter maximum per event and their *q*-exponential fits. Comparison between decades: 2002–2012 (**left** panel) and 2013–2023 (**right** panel).

Decumulative pdf of event duration

2002-2012

2013-2023

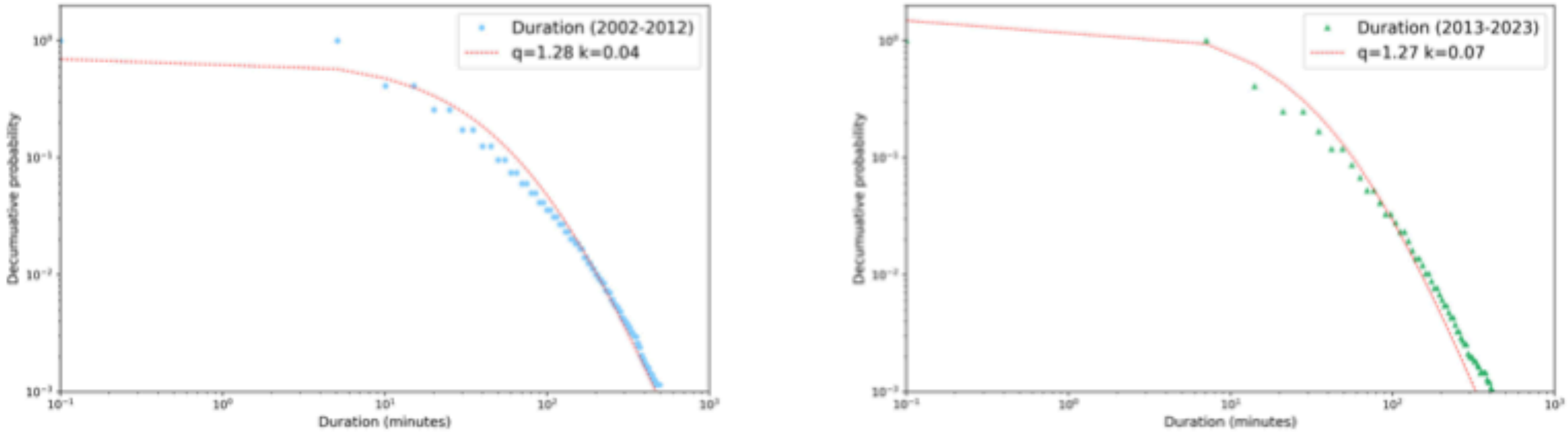
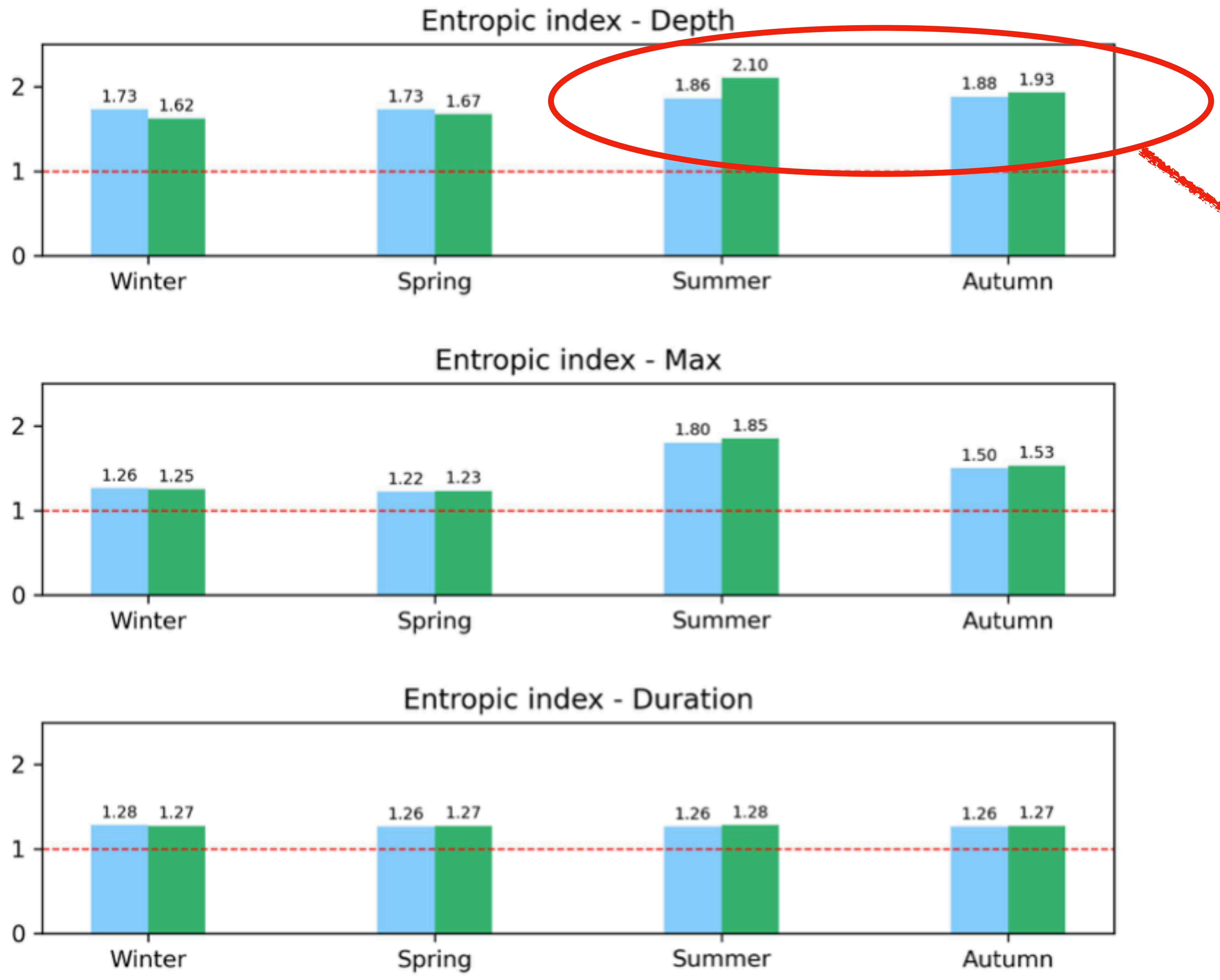


Figure 8. Decumulative probability distributions in log–log scale of winter event duration and their *q*-exponential fits. Comparison between decades: 2002–2012 (**left** panel) and 2013–2023 (**right** panel).

Comparison of the q -values

2002-2012

2013-2023



Major changes of the entropic index q

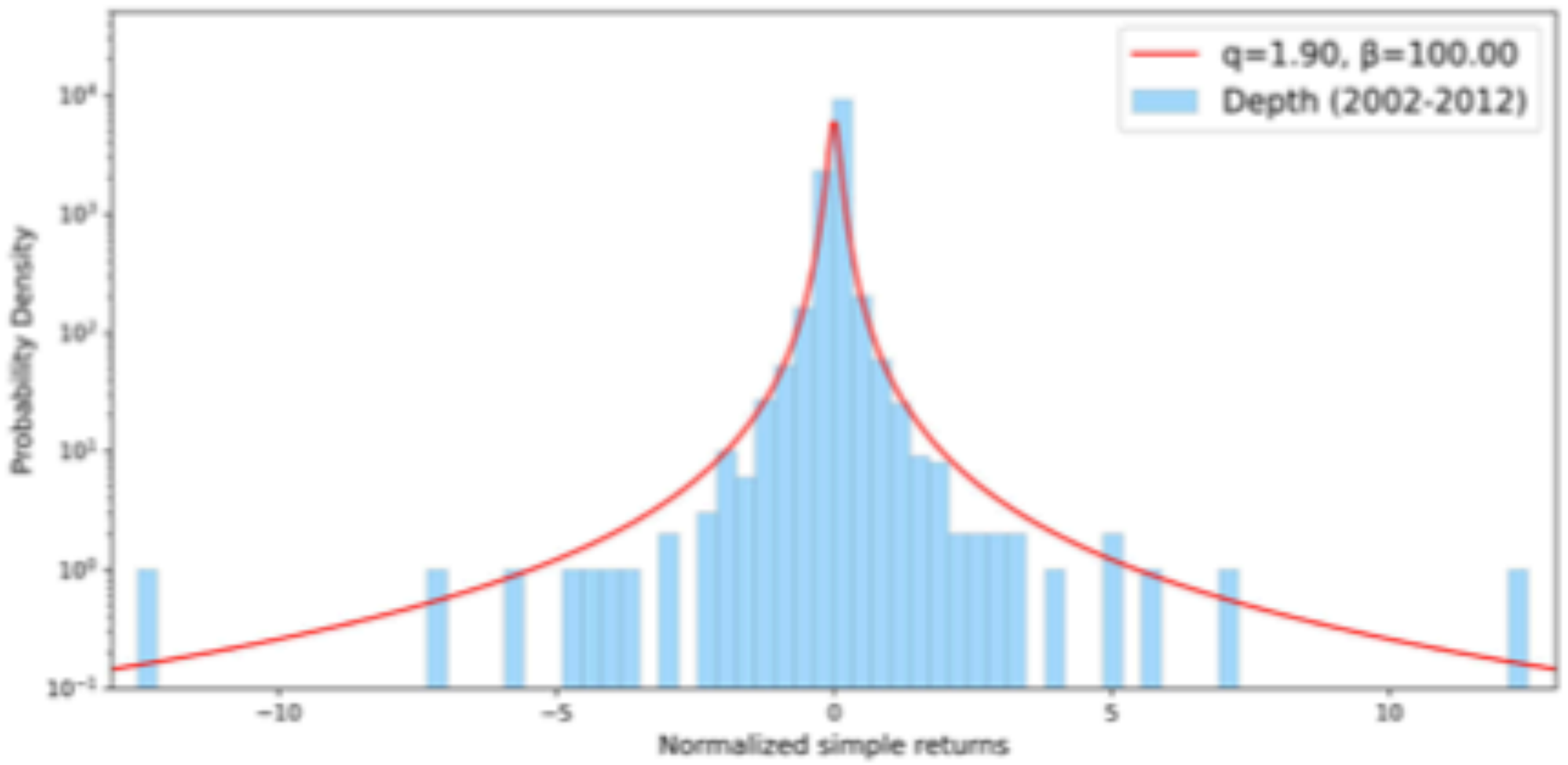
Figure 9. Seasonal bar chart of the entropic index q calculated for the rainfall depth, maximum intensity per event, and duration decumulative distributions. Comparison between decades: 2002–2012 (blue) and 2013–2023 (green). A red dotted line as be added as reference for $q = 1$. See text for more details.

Returns pdf for rainfall depth

$$R = \frac{[(x_{n+1} - x_n) - x_{mean}]}{\sigma_{std.dev}}$$

2002-2012

2013-2023



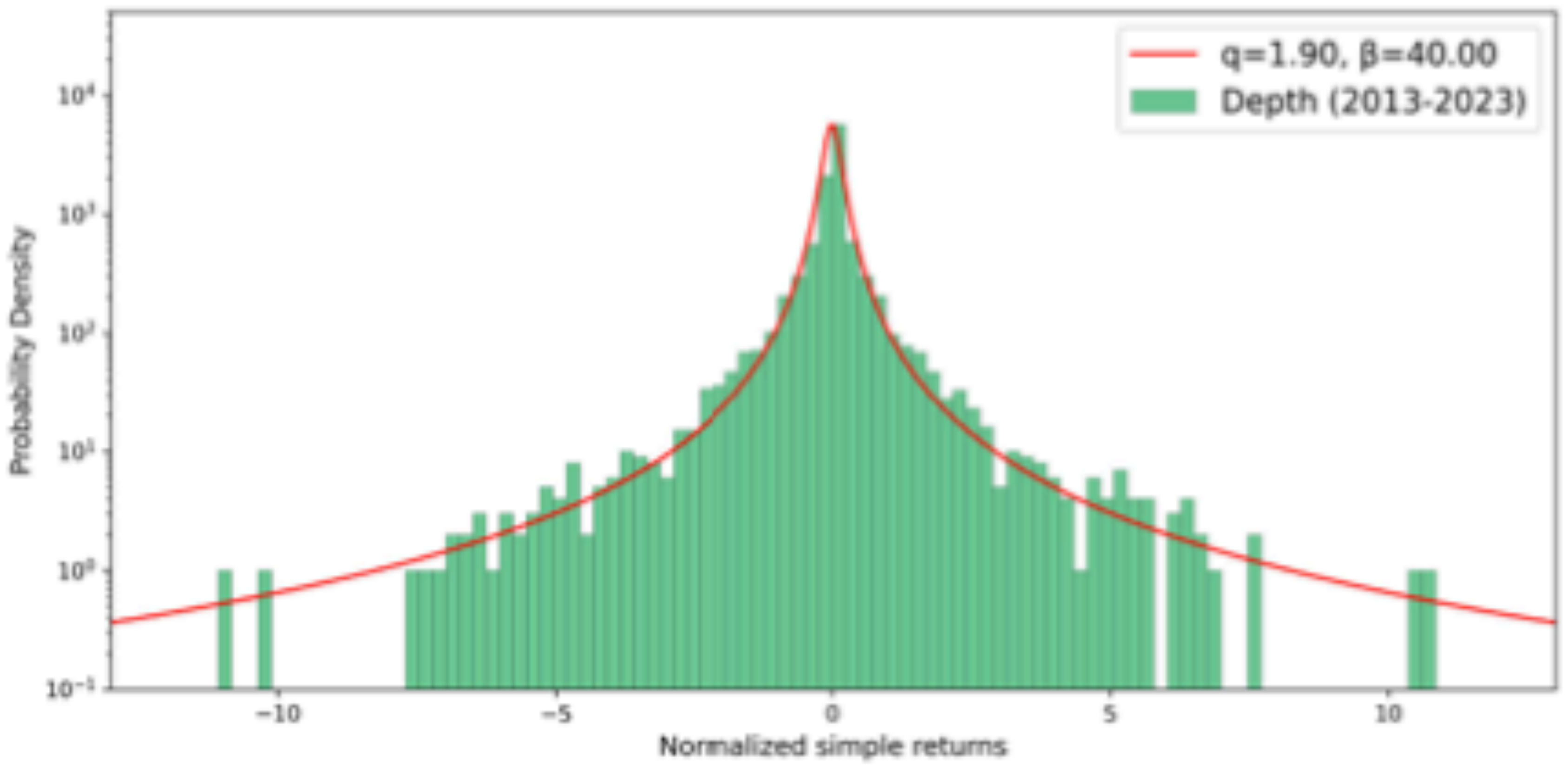


Figure 10. Simple returns in log–lin scale: data and q-Gaussian fits of spring events' rainfall depth. The comparison between the two considered decades, i.e., 2002–2012 (**left** panel) and 2013–2023 (**right** panel), does not show any relevant differences in the entropic index q.

$$G_q(x) = A\left[1 - (1-q)\beta x^2\right]^{\frac{1}{1-q}},$$

Returns pdf for rainfall event duration

$$R = \frac{[(x_{n+1} - x_n) - x_{mean}]}{\sigma_{std.dev}}.$$

2002-2012 2013-2023

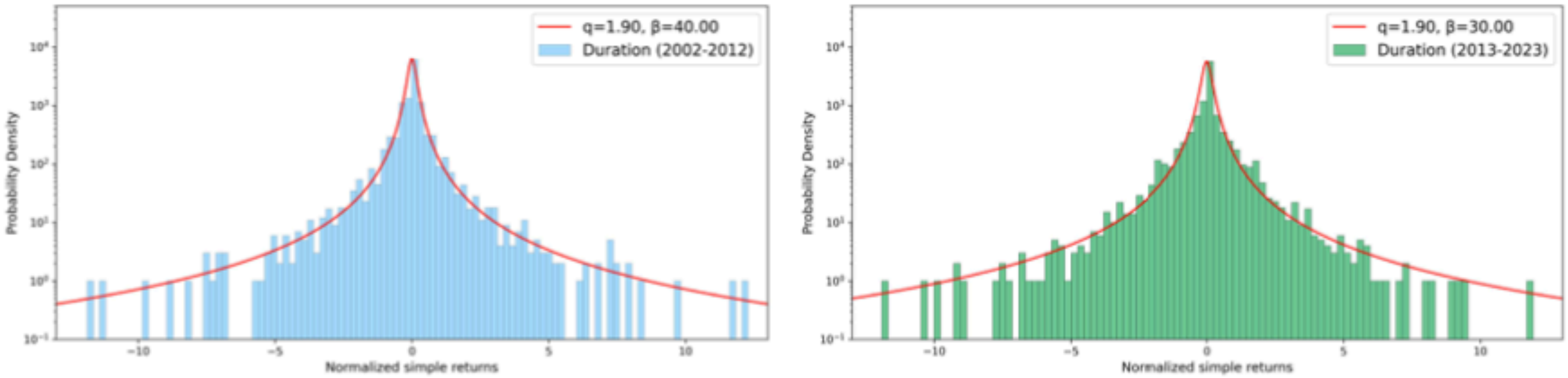


Figure 12. Simple returns in log–lin scale: data and q-Gaussian fits of spring rainfall event duration. In the **left** panel we report the 2002–2012 decade, while the **right** panel shows the 2013–2023 decade. See text for more details.

$$G_q(x) = A\left[1 - (1-q)\beta x^2\right]^{\frac{1}{1-q}},$$

Returns pdf for rainfall for max per event

$$R = \frac{[(x_{n+1} - x_n) - x_{mean}]}{\sigma_{std.dev}}.$$

2002-2012 2013-2023

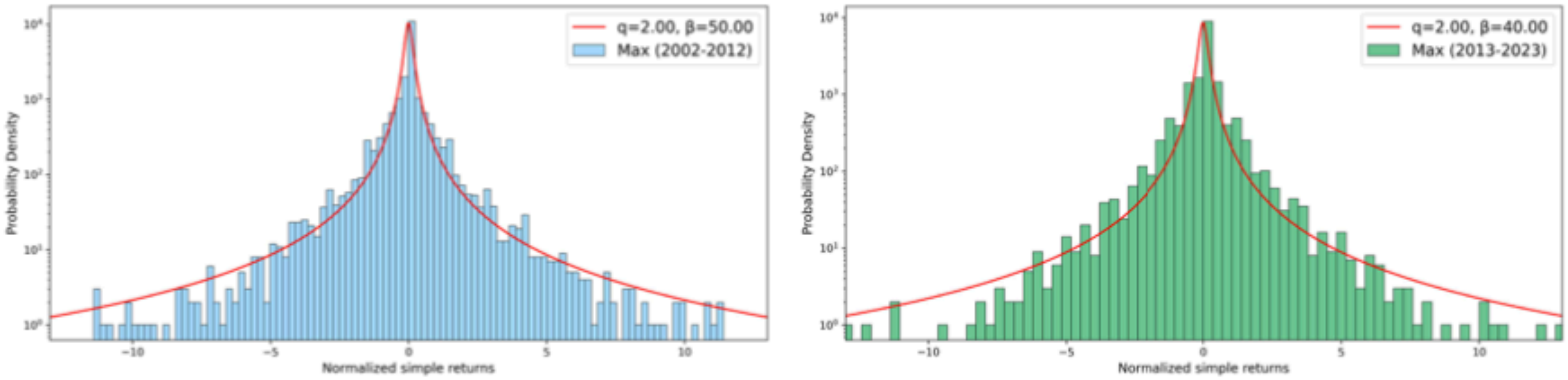


Figure 11. Simple returns in log–lin scale: data and q-Gaussian fits of winter maximum per event. In the **left** panel, we report the 2002–2012 decade, while the **right** panel shows the 2013–2023 decade. See text for more details.

$$G_q(x) = A\left[1 - (1-q)\beta x^2\right]^{\frac{1}{1-q}},$$

Comparison of the q-values

2002-2012

2013-2023

Change of the entropic index q

Figure 13. Bar chart of entropic index q for rainfall depth (**top** panel), maximum intensity recorded per event (**central** panel), and event duration (**bottom** panel) are reported for decade (2002–2012 in green and 2013–2023 in blue) and season. A red dotted line as be added as reference for $q = 1$. See text for more details.

Summary of the results for the statistical analysis

- In general **rainfall data show a clear complex behavior** with power laws whose slope changes with time from the first to the second decade

- Most evident changes for the summer seasons with a decrease of the slope for rainfall depth, maximum per event and event duration

- Decumulative pdfs can be very well reproduced by q-exponential curves, indicating long-range correlations: also in this case changes in the entropic index with time are observed for summer seasons going from the first to the second decade

- Returns shows non-Gaussian behavior which can be very well reproduced by q-Gaussians. In this case changes in the entropic index over decades are observed for return durations for summer and autumn seasons, indicating and increase of extreme events

A recent paper on the same dataset for Granger Causality

frontiers | Frontiers in Physics

TYPE Original Research
PUBLISHED 05 February 2025
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Multiscale Granger dependencies in the precipitation network of the island of Sicily

Vera Pecorino[1], Alessandro Pluchino[1,2], Andrea Rapisarda[1,2,3]* and Kateřina Hlaváčková-Schindler[4]

[1]Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Catania, Italy, [2]INFN Sezione di Catania, INFN, Catania, Italy, [3]Complexity Science Hub Vienna, CSH, Vienna, Austria, [4]Faculty of Computer Science, University of Vienna, Vienna, Austria

. In this study, we investigate the Granger causal (GC) dependencies in the network of precipitation measurement sites of Sicily at different timescales (every 10 min, 1 h, 6 h, 12 h, and 24 h). We study, across seasons and years, different parameters that characterize the GC dependencies: the total in/out-degree of nodes, the total in/out strength of nodes, the total number of links in the network, the number of eastward/westward links, the strength of eastward/westward links, and the maximum strength of links. We then investigate GC statistic intensities, focusing on the temporal evolution of maximum values over multiple timescales.

Granger causality networks reveal scale-invariant dependencies, with stronger and sparser connections at timescales that extend beyond 6 h, with a notable westward flow of predictive information. These patterns, which are consistent across seasons, suggest localized perturbation fronts, with stronger links indicating a more significant influence on westward predictions. This study highlights shifts in Sicily's water cycle that call for adaptive management strategies in the face of the increasing frequency of extreme events.

Granger Causality

In the context of linear regression [32–34], any target series Y can be considered the weighted sum of its past states plus an error term. Then, it is possible to make a second model by also summing the past states of a source variable. The former, Equation 1, is referred to as a “reduced model”, and the latter, Equation 2, as a “full model”.

$$Y_t = \sum_{m=1}^{p} a_m Y_{t-m} + \epsilon_t \tag{1}$$

$$Y_t = \sum_{m=1}^{p} a_m Y_{t-m} + \sum_{m=1}^{q} b_m X_{t-m} + \epsilon_t \tag{2}$$

Equation 1 represents a univariate autoregressive process in which Y_t depends solely on its own past values up to p lags. The coefficients a_m measure the influence of the past values. Equation 2 extends the autoregressive model by including the past values of another time series, X_t (up to q lags). The coefficients b_m capture the influence of X_t on Y_t. If the coefficients b_m are statistically significant, this suggests that X_t Granger causes Y_t.

In both equations, ϵ_t accounts for the unexplained variability. Since in this study X and Y are two different rain gauge time series, in the full model, the future states of the target rain gauge Y are predicted by its own past states p and the previous states of the source X. In the reduced model, only the target is taken into account. The GC strength, defined as the logarithmic ratio between the variance of the error term of the reduced model and that of the full model, quantifies the soundness of the regressions and tests whether the full model improves the predictability of the target time series. Therefore, the existence of a link means that the past source contains information about the future of the target. The stronger the connection, the higher the predictability of the target; in other words, the influence of the source on the future of the target.

Example of Granger causality network

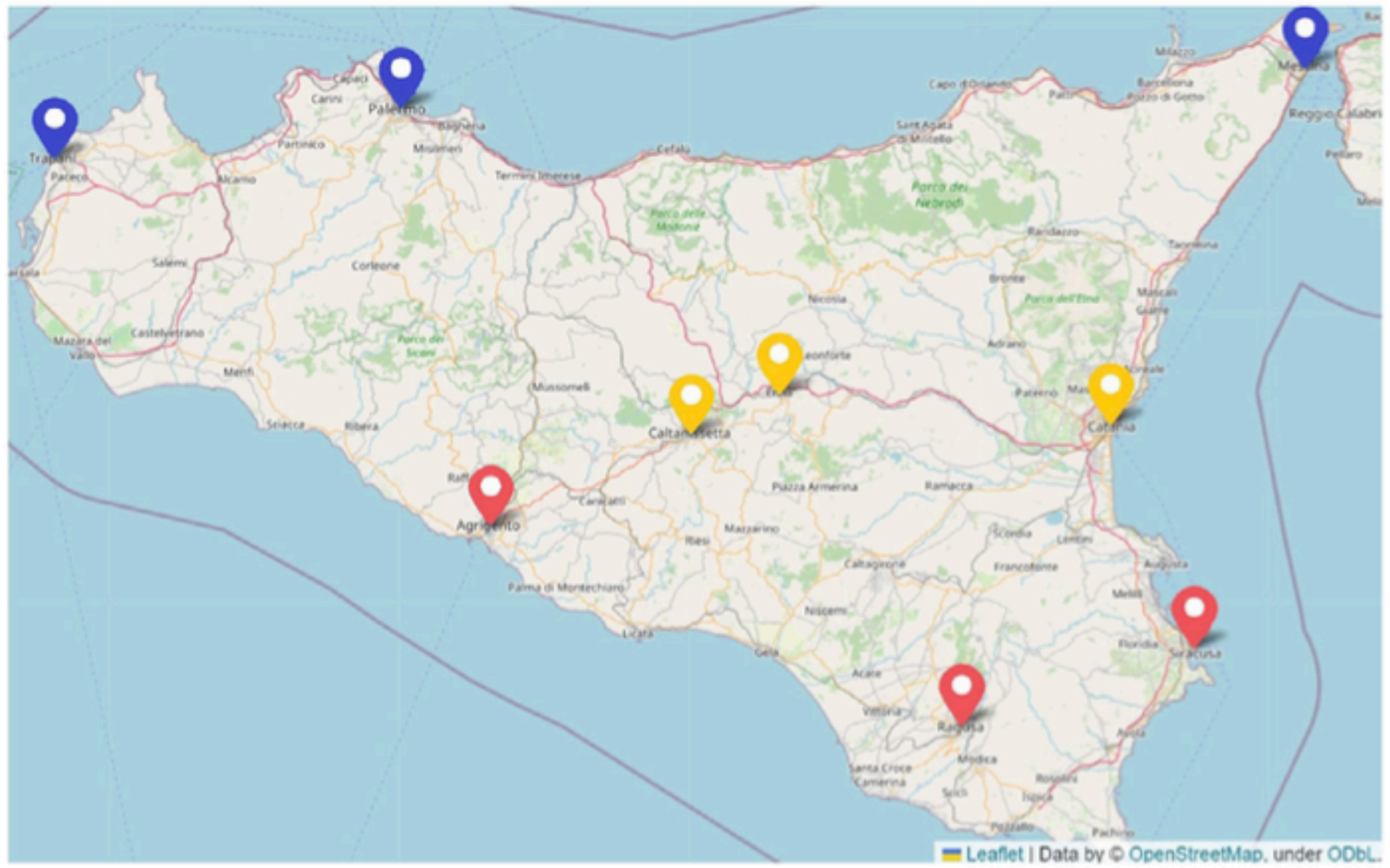

FIGURE 1
Selected subset of the SIAS network represented by nine rain gauges located in the main cities of Sicily, Italy.

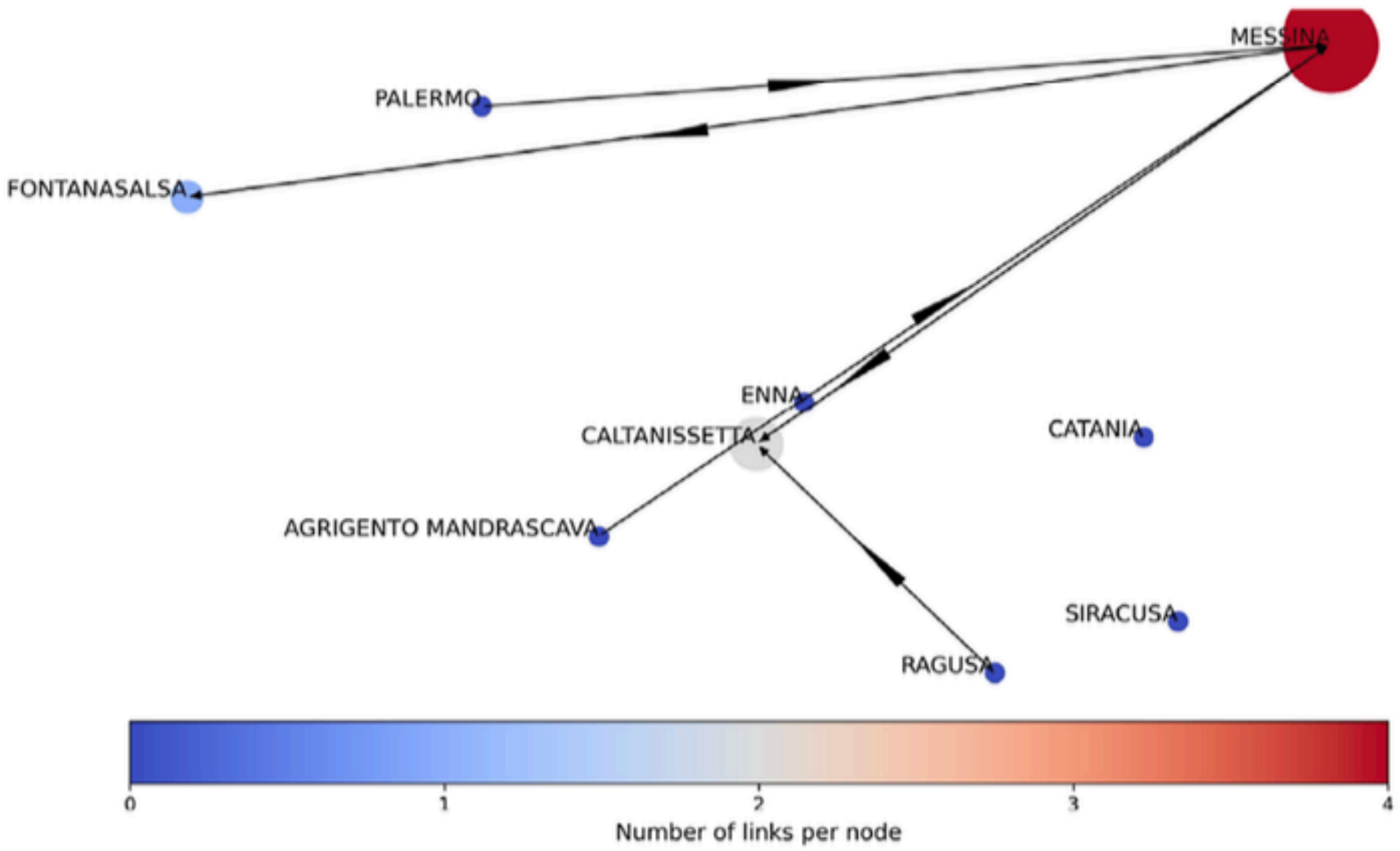

FIGURE 2
Example of a 24 h timescale Granger network for the winter of 2002. The color of the nodes (from blue to red) is proportional to their total degree (the total number of node links), and their size shows the strength of the GC statistics (the sum of the strengths of the node's links). The position of the nodes in the graph approximately corresponds to the geographical positions of the sites. Directed edges are reported as thin black arrows.

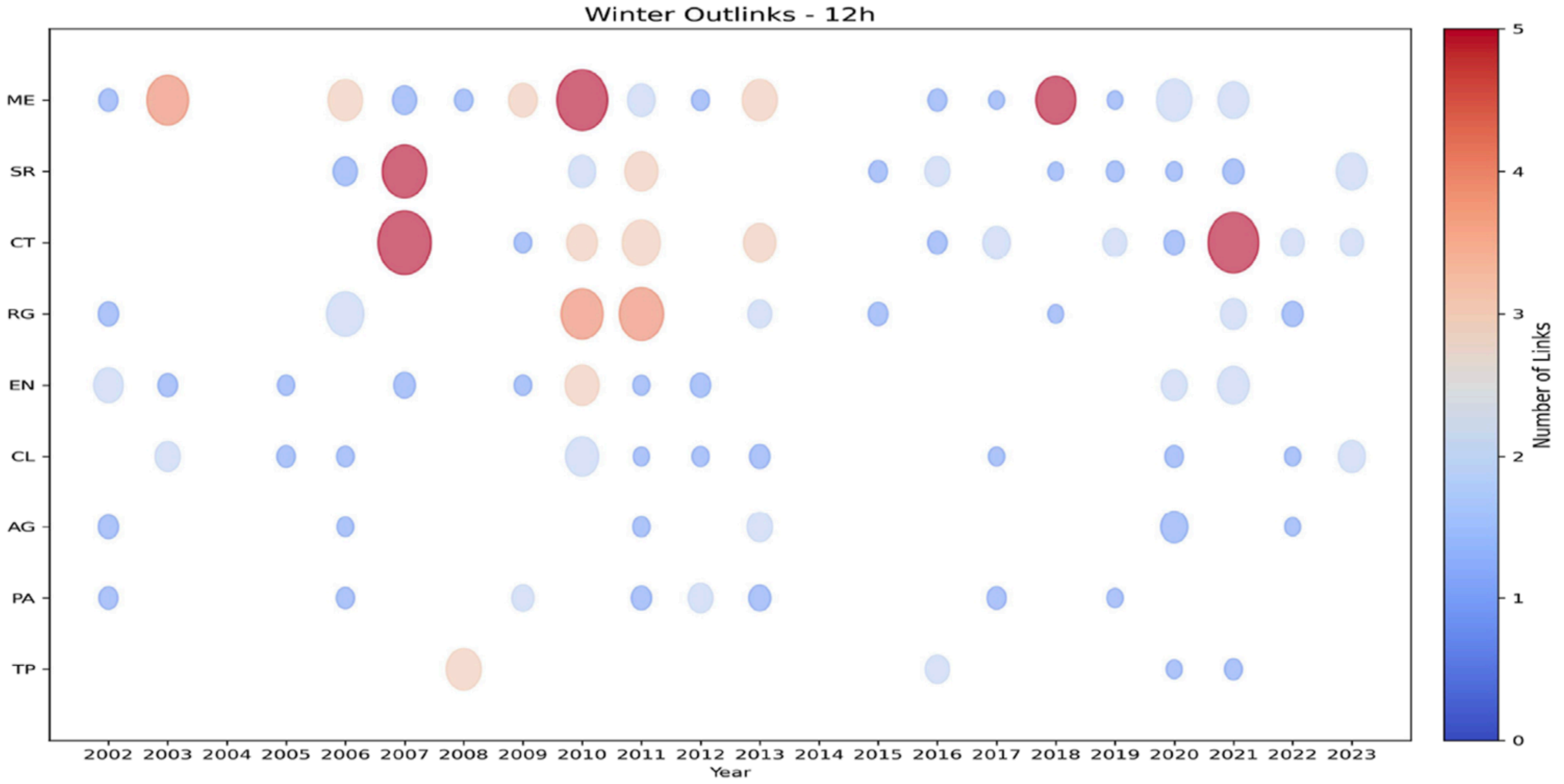

FIGURE 3
2D grid of winter out-link networks at the 12 h timescale. Years are placed on the x-axis, and the nine rain gauges ordered east (ME) to west (TP) are plotted on the y-axis, so that each vertical line represents a single network in a single year. The color of the nodes (from blue to red) is proportional to their out-degree (i.e., the total number of out-links), and their size shows the strength of the GC statistics (i.e., the sum of the strengths of the out-links).

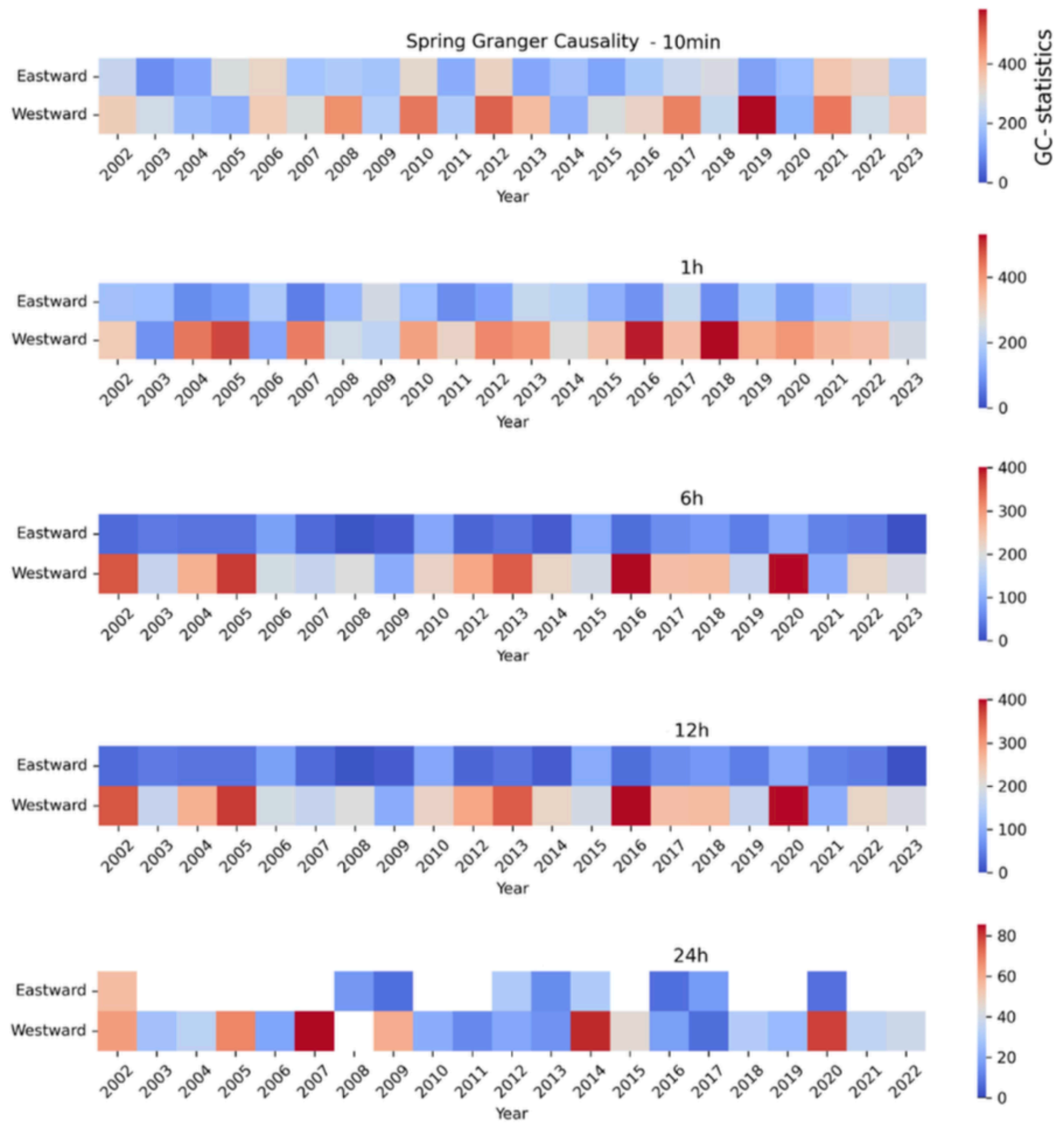

FIGURE 7
Matrices 2 *x* 22 per season for each timescale. The two rows represent the sum of the weight of eastward and westward links across the networks. The columns refer to individual years. The cool–warm color map is normalized across years and directions for each season and timescale. From top to bottom: 10 min, 1 h, 6 h, 12 h, and 24 h.

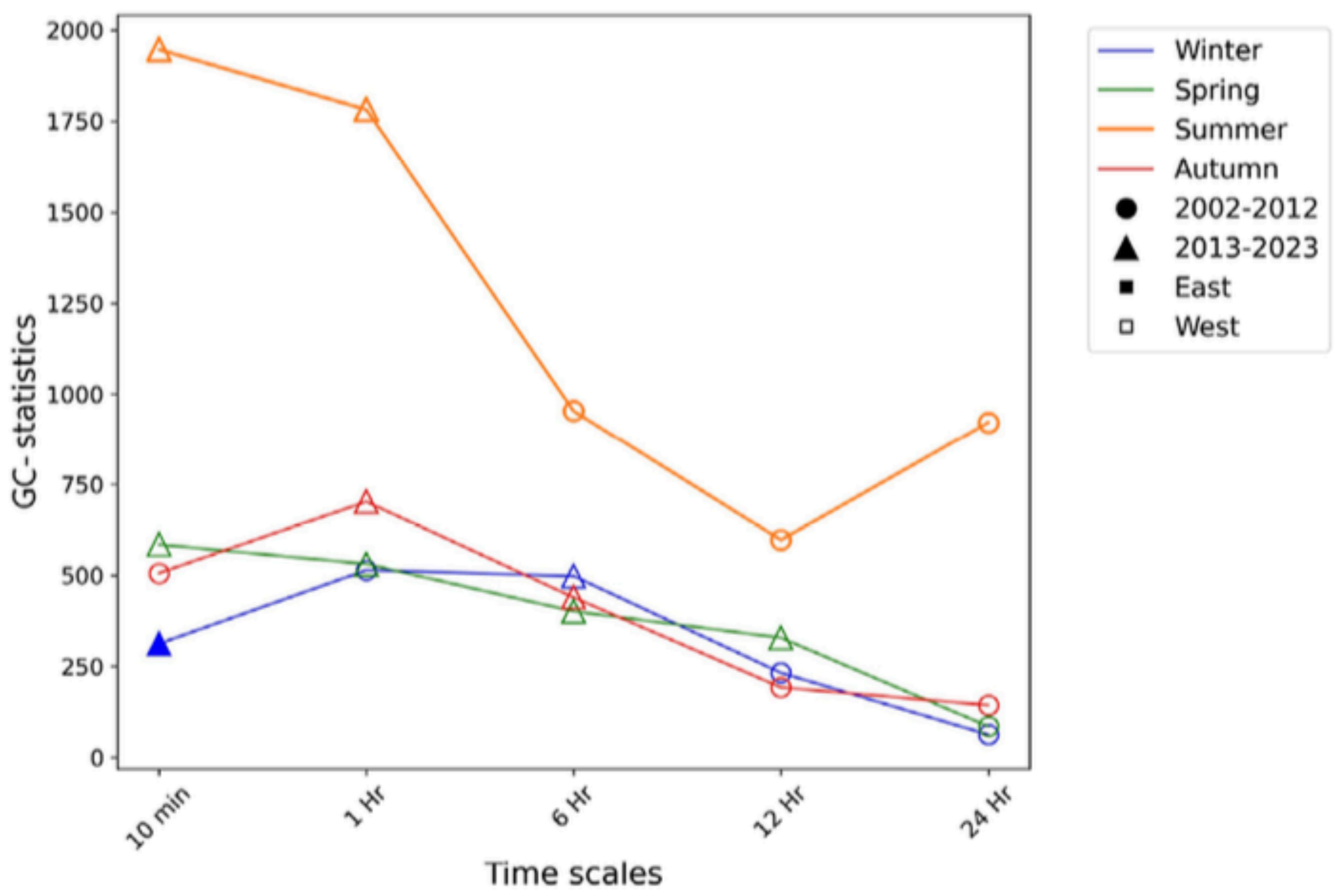

FIGURE 8
Behavior of the maximum GC statistic intensity computed across all seasons and timescales: on the *y*-axis is reported the intensity of the GC statistics, on the *x*-axis are shown multiple timescales. Blue, green, yellow, and red stand respectively for winter, spring, summer, and autumn. Circular markers refer to the 2002–2012 interval; triangular markers are related to the 2013–2023 period. Filled markers represent eastward records; unfilled markers indicate westward ones.

A study in preparation on dry spells

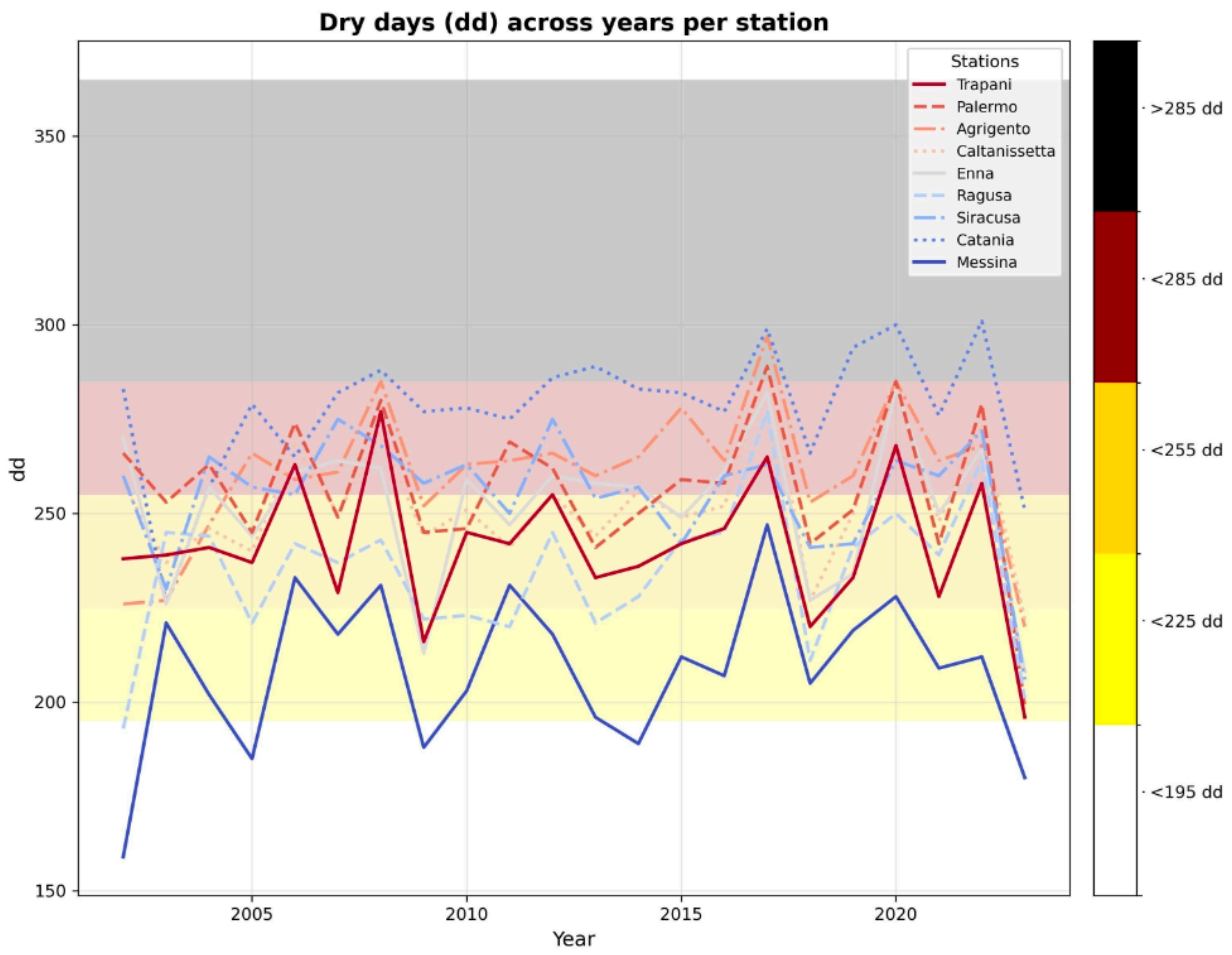

Figure 3. Dry days across years per station: on the y axis are displayed the number of dry days (dd) versus years on the x axis. The cities are shown through diverse solid lines: western stations are red (Trapani, Palermo and Agrigento), midland is gray (Enna, Caltanissetta) and eastern stations are blue (Ragusa, Siracusa, Catania, Messina). Colored shaded areas on the plane are referred to different severity of drought, as reported of the colorbar on the right side.

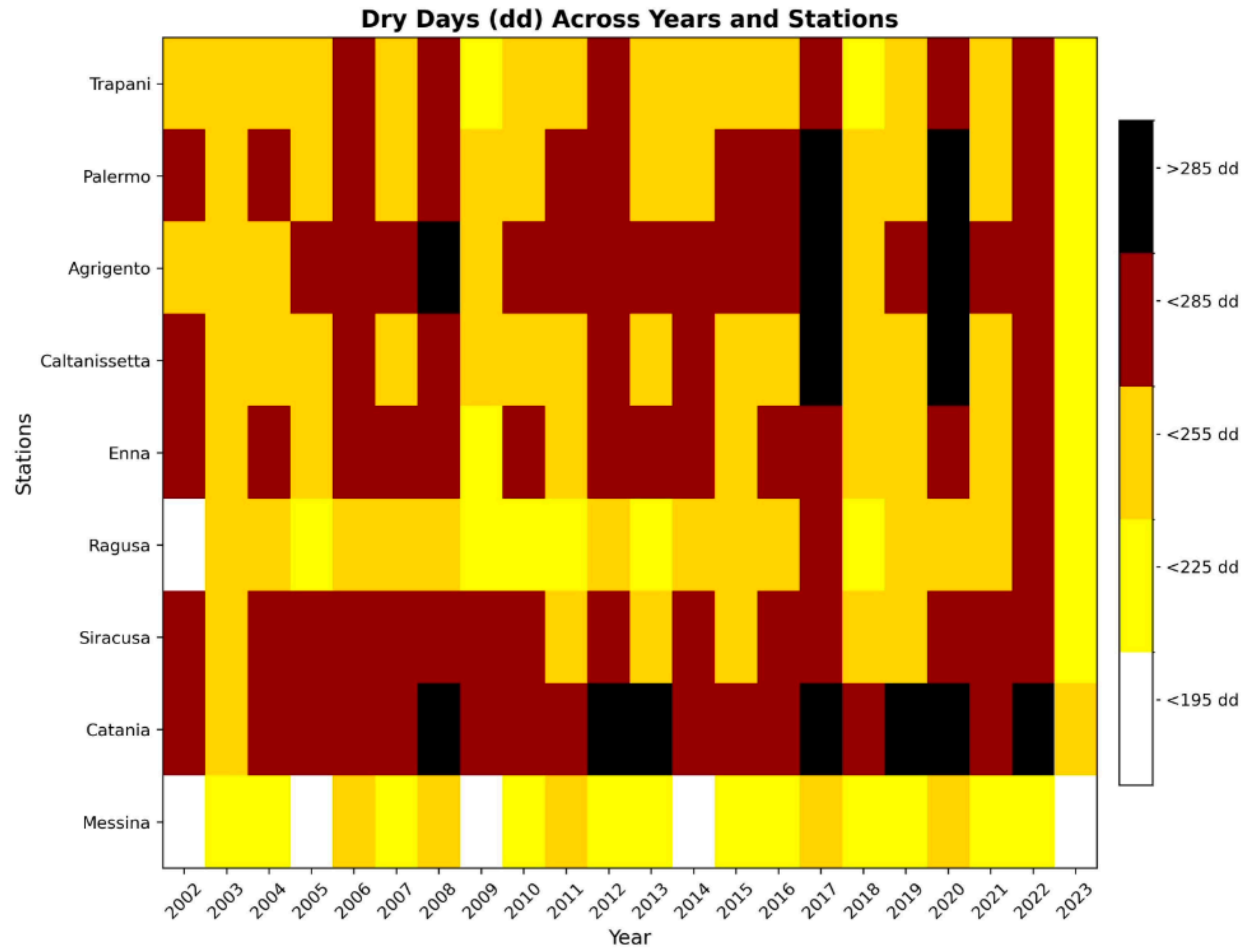

Figure 4. 2D grid of dry days across years per station: gauge stations are on y axis and years on x axis. Colors are referred to the number of dry days during the year. Stations are ordered following the direction West (Trapani) - East (Messina). The cell's colors are referred to different severity of drought, as reported of the colorbar on the right side.

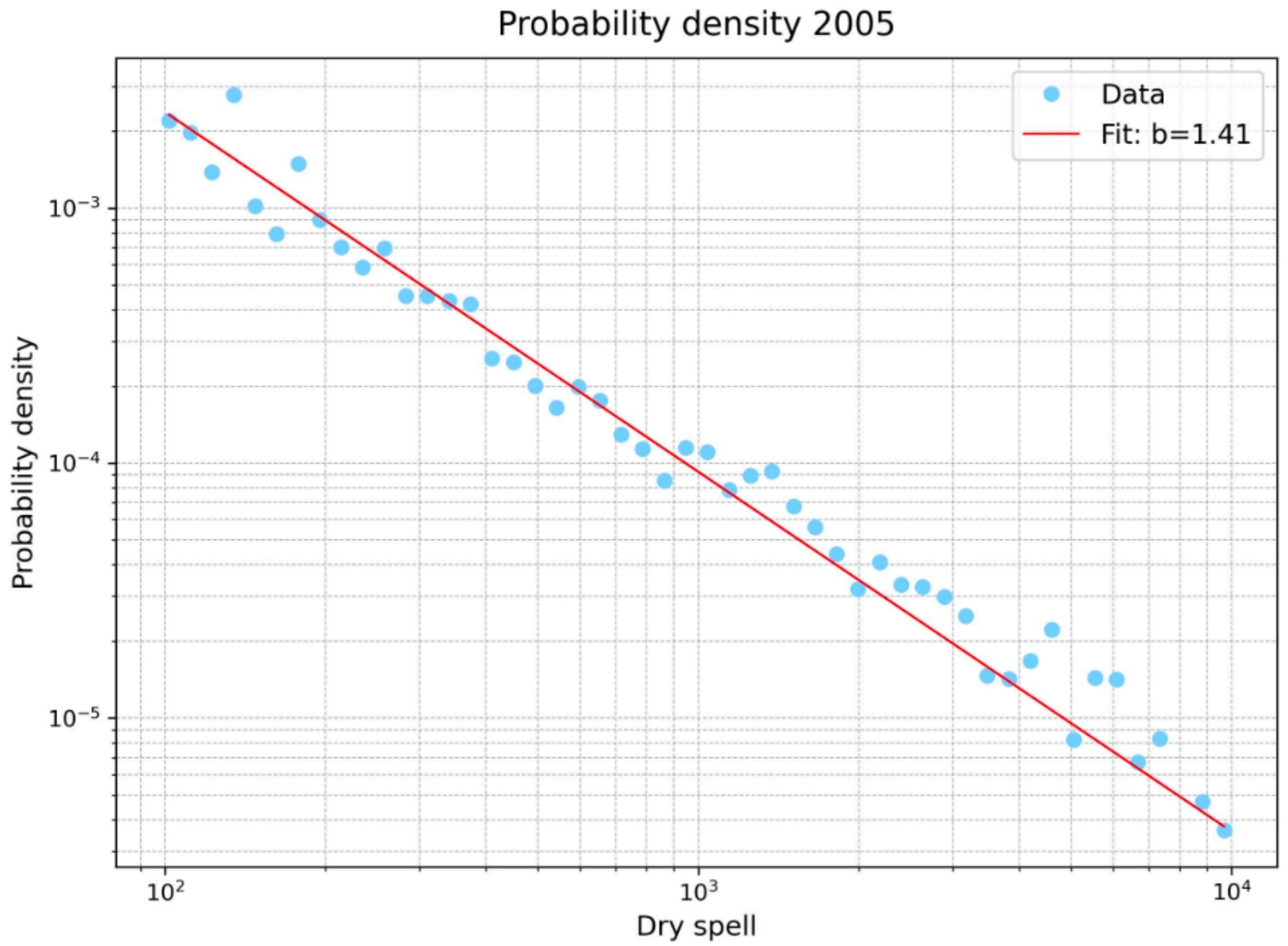

Figure 5. Probability density function of 2005 dry spell in log-log scale and its fits with a power law (red line).

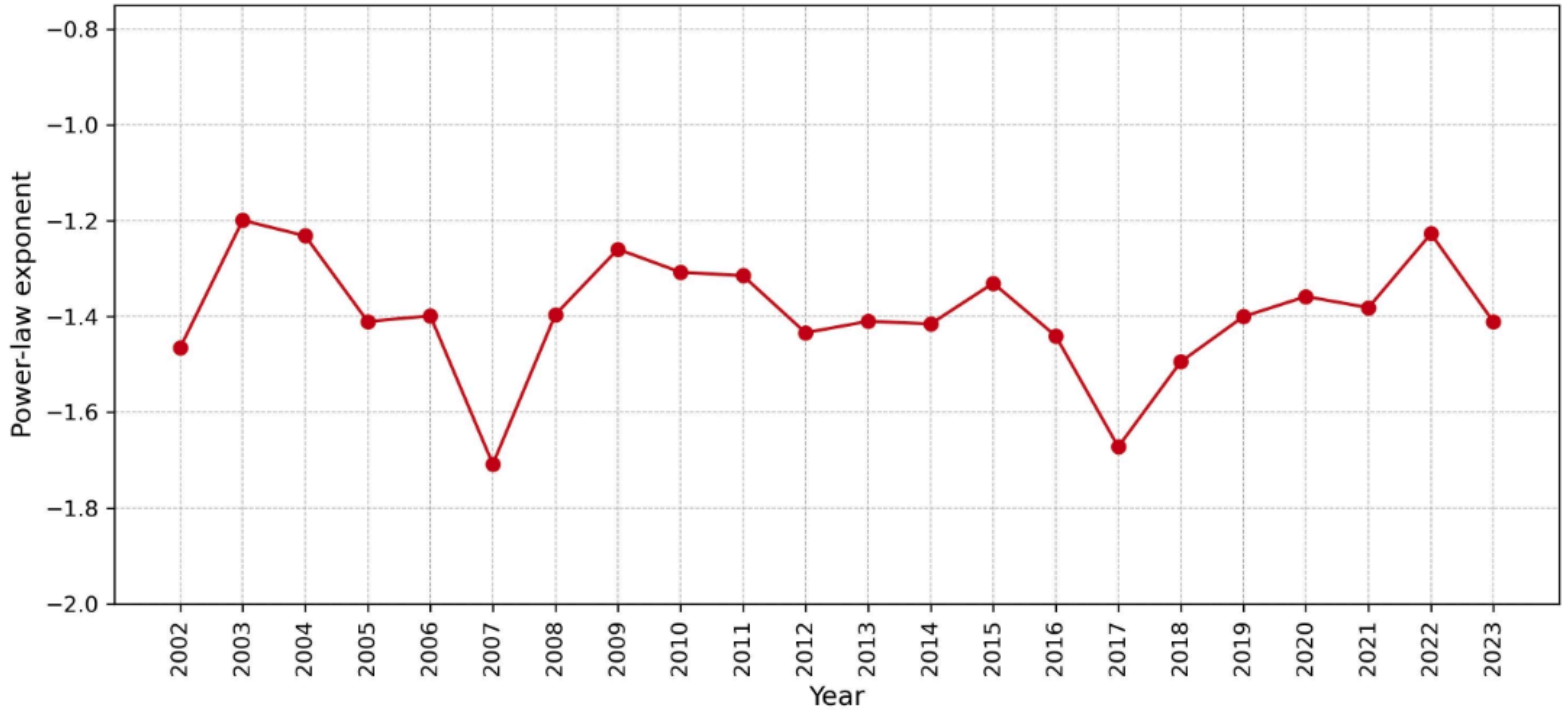

Figure 6. Comparison among slopes of power-law fits for spell time across years.

Finally...remember that...

It could be worse...it could be raining!

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