Orographic effect on extreme precipitation statistics peaks at hourly time scales

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Abstract

Orographic impact on extreme sub-daily precipitation is critical for risk management but remains insufficiently understood due to complicated atmosphere-orography interactions and large uncertainties. We investigate the problem adopting a framework able to reduce uncertainties and isolate the systematic interaction of Mediterranean cyclones with a regular orographic barrier. The average decrease with elevation reported for hourly extremes is found enhanced at sub-hourly durations. Tail heaviness of 10-minute intensities is negligibly affected by orography, suggesting self-similarity of the distributions at the convective scale. Orography decreases the tail heaviness at longer durations, with a maximum impact around hourly scales. These observations are explained by an orographically-induced redistribution of precipitation towards stratiform-like processes, and by the succession of convective cores in multi-hour extremes. Our results imply a breaking of scale-invariance at sub-hourly durations, with important implications for natural hazards management in mountainous areas.

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Key Points:

- Orography negligibly affects tail heaviness of 10-minute intensity and decreases it for longer durations with a minimum around 1 hour
- The "reverse orographic effect" previously observed for hourly extremes is found to be more marked at sub-hourly durations
- Breaking of scale-invariance at sub-hourly durations in mountainous areas bares important implications for risk management

Abstract

Orographic impact on extreme sub-daily precipitation is critical for risk management but remains insufficiently understood due to complicated atmosphere-orography interactions and large uncertainties. We investigate the problem adopting a framework able to reduce uncertainties and isolate the systematic interaction of Mediterranean cyclones with a regular orographic barrier. The average decrease with elevation reported for hourly extremes is found enhanced at sub-hourly durations. Tail heaviness of 10-minute intensities is negligibly affected by orography, suggesting self-similarity of the distributions at the convective scale. Orography decreases the tail heaviness at longer durations, with a maximum impact around hourly scales. These observations are explained by an orographically-induced redistribution of precipitation towards stratiform-like processes, and by the succession of convective cores in multi-hour extremes. Our results imply a breaking of scale-invariance at sub-hourly durations, with important implications for natural hazards management in mountainous areas.

Plain Language Summary

Preparedness to natural hazards in mountainous areas strongly relies on the knowledge of extreme rainfall probability. The presence of mountains influences the motion of air masses, thereby modifying the storms characteristics. Here, we use a novel approach to quantify the impact of mountains on the probability of occurrence of extreme rainfall of short duration. We find that mountains tend to decrease the mean annual maximum intensities at sub-hourly scales and tend to decrease the extremely high intensities, such as the events occurring on average once in 100 years. The second effect is however non-monotonic, in that it grows between 10 minute and 1 hour and diminishes between 1and 6 hours. This means that sub-hourly extremes could be higher than what we can estimate from hourly data, and implies that statistical methods typically adopted for risk assessment may systematically underestimate the risk of short-duration extremes.

1 Introduction

In mountainous regions, preparedness to precipitation driven natural hazards such as flash floods and debris flows, strongly relies on the quantitative knowledge of extreme precipitation of short duration (Borga et al., 2014). In particular, rare yearly exceedance probabilities are crucial for risk assessment and management (Chow et al., 1988). This information is traditionally derived from observations using statistical methods based on the sampled extremes and are thus subject to large stochastic and sampling uncertainties that reduce our ability to understand the underlying processes and predict the local responses to climate change (Fatichi et al., 2016). The methods typically adopted to decrease these uncertainties entail the pooling of information from multiple sources; either spatially, from homogeneous regions, and/or temporally, by assuming scale-invariance of extreme precipitation across durations (Buishand, 1991; Burlando and Rosso, 1996). Drawback of these methods is the need for assumptions that may mask inter-station and inter-duration effects (Furcolo et al., 2016).

Orography physically bounds the atmospheric air motion inducing ascent of air parcels, generating atmospheric waves and, therefore, affecting the precipitation processes (Bonacina, 1945; Roe, 2005). The impact of orography on long-duration precipitation (i.e., daily or multi-day) is quite well understood, with an increase of the yield along the windward slope due to the lifting of air masses, and a decrease in the lee side slopes because of air descent and drying; overall, a typically positive net impact is reported, the so-called “orographic enhancement”. Conversely, the picture for sub-daily extremes is less clear (Haiden et al., 1992; Nykaken and Harris, 2003; Rossi et al., 2020). Among the research efforts on the orographic effect on extreme short-duration precipitation, only few studies focused on the right-tail statistics and yearly exceedance probabilities. Investigations based on hourly rain gauges reported that short-duration annual maxima at higher elevations were characterized by lighter-tails, and highlighted the presence of a “reverse orographic effect”, that is the mean annual maxima for hourly durations was found to decrease with elevation, opposing the orographic enhancement of longer duration amounts (Allamano et al., 2009; Avanzi et al., 2015). However, possible varying effects on the right-tail characteristics across durations could not be thoroughly examined due to the scale-invariance assumptions adopted, and no information could be derived for sub-hourly durations due to the lack of sufficiently long data records. Further, the presence of multiple types of precipitating systems, which may interact differently with orography, and of multiple directions of advection, complicates these analyses (Picard and Mass, 2017; Marra et al., 2019).

The objective of this study is to improve our understanding of the orographic impact on the statistics of short duration extreme precipitation. Specifically, we quantify the impact of orography on the right-tail statistics of sub-daily and sub-hourly precipitation, and investigate the underlying statistical mechanisms. To do so, we adopt an analytical framework in which effects related to the contribution of multiple precipitating systems and advection directions are removed by isolating unique atmosphere-orography interaction conditions, and stochastic uncertainties inherent in the observation of extremes are reduced without requiring scaling/homogeneity assumptions. In this manner we are able to perform right-tail statistical analyses directly on sub-hourly records using relatively few years of data.

2 Methodology

Novel approaches permit to quantify the yearly probability of exceedance of extremes by explicitly considering that they are finite independent samples of a stochastic process of interest, the so-called ordinary events (Marani and Ignaccolo, 2015). Under the assumption that the cumulative distribution function of the ordinary events $F(\cdot)$ is known, it is possible to quantify yearly non-exceedance probabilities ζ of extreme intensities x as: $\zeta(x) \simeq F(x)^n$, where n is the average yearly number of ordinary events (Marra et al., 2019). This approach allows considering multiple types of ordinary events contributing to the generation of extremes, such as events associated to different atmospheric circulations or precipitation processes. In this case, the yearly non-exceedance probabilities can be written as: $\zeta(x) \simeq \prod_{i=1}^{S}[F_i(x)]^{n_i}$, where $F_i(\cdot)$ is the cumulative distribution function of the *i-th* of S types of ordinary events, and n_i is the corresponding average yearly number (Marra et al., 2019; Miniussi et al., 2020).

While daily precipitation ordinary events are well described by Weibull distributions (Marani and Ignaccolo, 2015; Zorzetto et al., 2016), sub-daily intensities follow more general distributions that are, however, Weibull right-tail equivalent (Papalexiou, 2018; Papalexiou et al., 2018; Marra et al., 2020). It is thus possible to describe a portion of their distribution which includes extremes using a two-parameter distribution in the form $F(x;\lambda,\kappa) = 1 - \mathrm{e}^{-\left(\frac{x}{\lambda}\right)^{\kappa}}$, where x is the precipitation intensity of interest, and λ and κ are the scale and shape parameters, respectively. The shape parameter, in particular, determines the tail heaviness, with heavier tails for smaller shapes and vice versa. The tail of the extreme value distribution $\zeta(x)$ is then modulated by number of yearly events, with decreasing heaviness at increasing number of yearly events, and vice versa. When defined consistently across durations, the ordinary events share some of the statistical properties of annual maxima (Marra et al., 2020) but, since much larger in number, the stochastic uncertainty in the analysis of their tails is reduced. In this way, reliable estimates of intensities characterized extremely low yearly exceedance probability can be obtained from short records (Zorzetto et al., 2016; Marra et al., 2018).

Here, we focus on the right-tail statistics of ordinary events which interact with orography in a prescribed, systematic way. We examine a region of the southeastern Mediterranean, characterized by Mediterranean climate (cold wet winter, warm dry summer), in which a regular physiographic structure parallels the shoreline (Fig. 1): coastal plains, lowland hills raising to a moderate mountain range (<1000 m a.s.l.), and a deep rift valley including the lowest point on Earth (currently ~430 m below the sea level), the Dead Sea. East of the mountains, the steep orography towards the rift causes a rain shadow desert with a sharp gradient to semi-arid and arid climate (Kushnir et al., 2017). Mediterranean cyclones account for 75-90% of the precipitation amount in the area and move inland along westerly tracks roughly perpendicular to the orographic barrier (Alpert et al., 1990; Armon et al., 2019). The rest of precipitation is associated to systems typically extending from the south and interacting with orography in an irregular way (de Vries et al., 2013; Armon et al., 2018). Almost all the precipitation caused by Mediterranean cyclones is associated to low-level clouds; low-level flows pass the warm waters of the Mediterranean, lowering the static stability of air parcels, triggering convection, and causing precipitation to reach the ground in liquid phase with only sporadic snowfall. Previous studies tested the use of ordinary events for precipitation frequency analyses in this region, demonstrating the robustness of the assumptions and the ability of the framework to reproduce extremes from relatively short records (Marra et al., 2019; Marra et al., 2020).

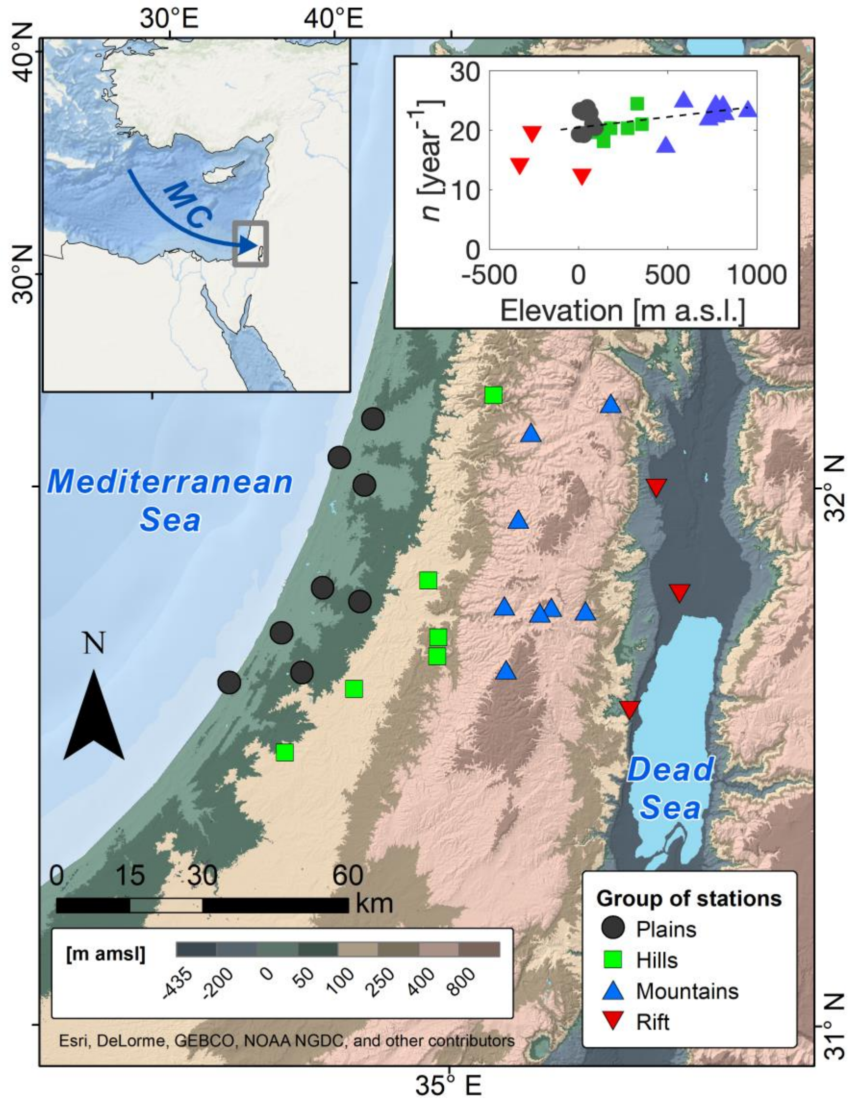

Figure 1. Map of the study region detailing orography, typical direction of advection of Mediterranean cyclones (MC) in the area, and location of the rain gauges used in the study. The inset shows the average yearly number of ordinary events as a function of elevation; the slope derived from the uphill stations (rift stations are excluded) is superimposed and statistically significant (p-value 0.04).

Precipitation data are collected for 25 quality-controlled automatic tipping bucket rain gauges in a latitudinal strip across the region (~31.5–32.2°N). The instruments have a resolution of 0.1 mm per tip and automatically record data every 10 minutes. Data are organized by hydrologic years (September 1 to August 31) and years with more than 10% missing data are discarded. The records span 9-26 years (17.0 ± 4.7 yr). To aid the analyses, the stations are organized into four groups according to the local physiography (Fig. 1): plains (west of the mountains, elevation $z < 100$ m a.s.l.), hills ($100 < z \leq 400$ m a.s.l.), mountains ($z > 400$ m a.s.l.), rift (east of the mountains, $z < 50$ m a.s.l.).

Following previous studies in similar climates (Restrepo-Posada and Eagleson, 1982; Marra et al., 2020), independent storms are defined as consecutive wet ($\geq$ 0.1 mm/10 min) time intervals separated by 6-hour dry hiatuses; short (< 30 min) storms are removed to avoid noise due to individual tips of the rain gauge. Storms associated to Mediterranean cyclones are isolated according to a semi-objective synoptic classification (Alpert et al., 2004), as detailed in Table S1; as the classification is daily, the time in which each storm ends is used. Ordinary events are computed as the maximum intensities observed within each storm using moving windows of durations between 10 minutes and 6 hours (10, 20, 30 min, 1, 2, 3, 6 hours) (Marra et al., 2020). The ordinary events' right-tail is defined as the Weibull-identically-distributed portion of the events; in our region this was identified as the largest 25% of the ordinary events (Marra et al., 2019; Marra et al, 2020). The scale and shape parameters of the Weibull distributions describing the ordinary events are computed left-censoring the remaining portion of the data, that is without considering the intensities but retaining the weight in probability, and using a least squares regression in Weibull-transformed coordinates (Marani & Ignaccolo, 2015). The number of events per year is computed as the arithmetic mean of the yearly number of ordinary events. Despite the relatively short records, given the number of yearly ordinary events (Fig. 1), the two parameters describing their right tails are estimated using between ~40 and over 150 data points, with clear advantages in estimation accuracy over traditional extreme value methods in which one/few events per year are used and three parameters are sought.

The impact of terrain elevation on the parameters and number of yearly events is examined using the non-parametric Sen's slope estimator and the slope significance (0.05 significance level) is tested using the Mann-Kendall test (Haan, 2002). No serial correlation in the data is expected. The stations downwind of orography are affected by a different orographic effect, and are too few and sparse to represent the steep gradient on lee side of the mountain range. Rift stations are thus shown in the figures for a qualitative description of the downwind effect, but are not used for these statistical analyses.

3 Results and Discussion

The events occurrence frequency is weakly (3.6 events km^{-1}) but significantly (p-value 0.04) affected by orography (Fig. 1), with some of the variance possibly explained by latitude (Armon et al., 2019). On the lee side of the mountain range, the descent of dry air induced by orography drastically decreases the yearly numbers. The shape parameter of the ordinary events right-tail distribution (Fig. 2 a-d) decreases with duration in the plains and, less markedly, in the hills, indicating heavier-tailed distributions at longer durations. This confirms what found in Marra et al. (2020) in a coastal region at slightly higher latitude. Conversely, a non-monotonic behavior of the shape is observed in the mountains, with increasing shape parameter, hence lighter tails, at longer durations, and a maximum around durations of 1 hour. In the downwind rift the shape smoothly increases with duration, indicating heavier-tails at shorter durations. Estimating annual maxima from 10-minute data in the region yields 11% and 6% underestimation for 10- and 20-minute durations, respectively (Marra and Morin, 2015). This underestimation does not depend on the intensity, and is thus expected to affect the scale parameter only, with no systematic impact on the shape parameter. Additionally, as based on ordinary events our results for short durations are expected to be less affected by saturation of the tipping bucket devices at high intensities with respect to results based on traditional analyses of extremes.

The non-monotonic dependence of the tail with duration observed in the mountains and, to some extent, in the rift implies a violation of the scale-invariance, assumption often adopted in the analysis of extremes, at sub-hourly durations. This is highlighted in Fig. 2 e-h, where the relative deviations of the scale parameter from the power-law relations computed for durations exceeding 1 hour, are shown (see also Fig. S2); this is the time interval in which the power-law behavior generally holds more robustly (Burlando and Rosso, 1996; Ceresetti et al., 2010), and in which the systematic underestimations due to the use of 10-minute blocks are negligible. Interestingly, these deviations concern all sub-hourly durations and pertain regions in which, on average, the 10-minute peak intensities are lower, so that they cannot be explained by measurement effects related to the saturation of the tipping bucket rain gauge at high intensities.

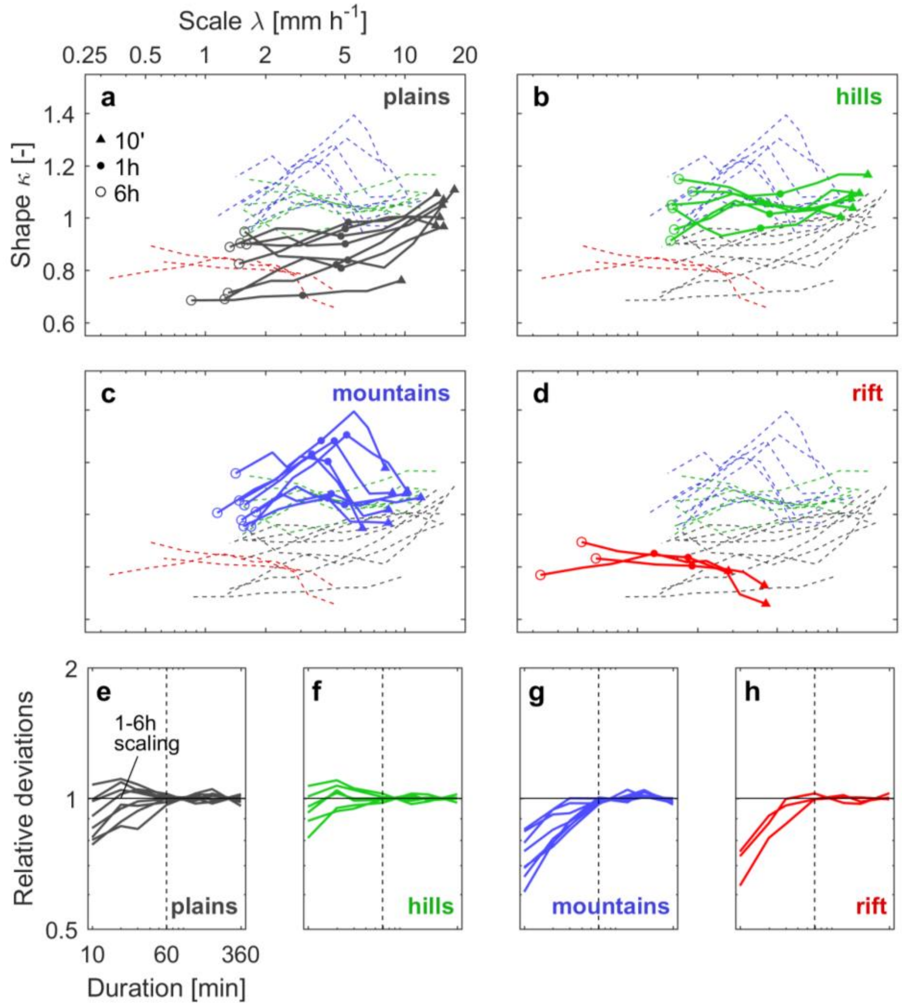

Figure 2. (a-d) Parameters of the distributions describing the right tail of the ordinary events over the four regions for durations of 10, 20, 30 minutes, 1, 2, 3, 6 hours; durations of 10 minutes, 1 hour and 6 hours are marked with triangles, dots and circles, respectively. Parameters of the other regions are dashed in the background to aid visual comparison. (e-h) Relative deviations of the scale parameters from the scale-duration power-law relations computed for 1-6 hours time interval.

The case of non-systematic atmosphere-orography interaction (that is, all the non-Mediterranean-cyclone events) is shown as a control case in the supplementary Figure S1; here, plains, hills and mountains all share similar parameters and behaviors, with lighter-tailed distributions at shorter durations. This shows that isolating systematic interactions is crucial to understand the mechanisms behind the orographic impact on precipitation right-tail characteristics, and confirms that what shown in Fig. 2 is an effect related to the interaction of westerlies induced by Mediterranean cyclones with the local terrain.

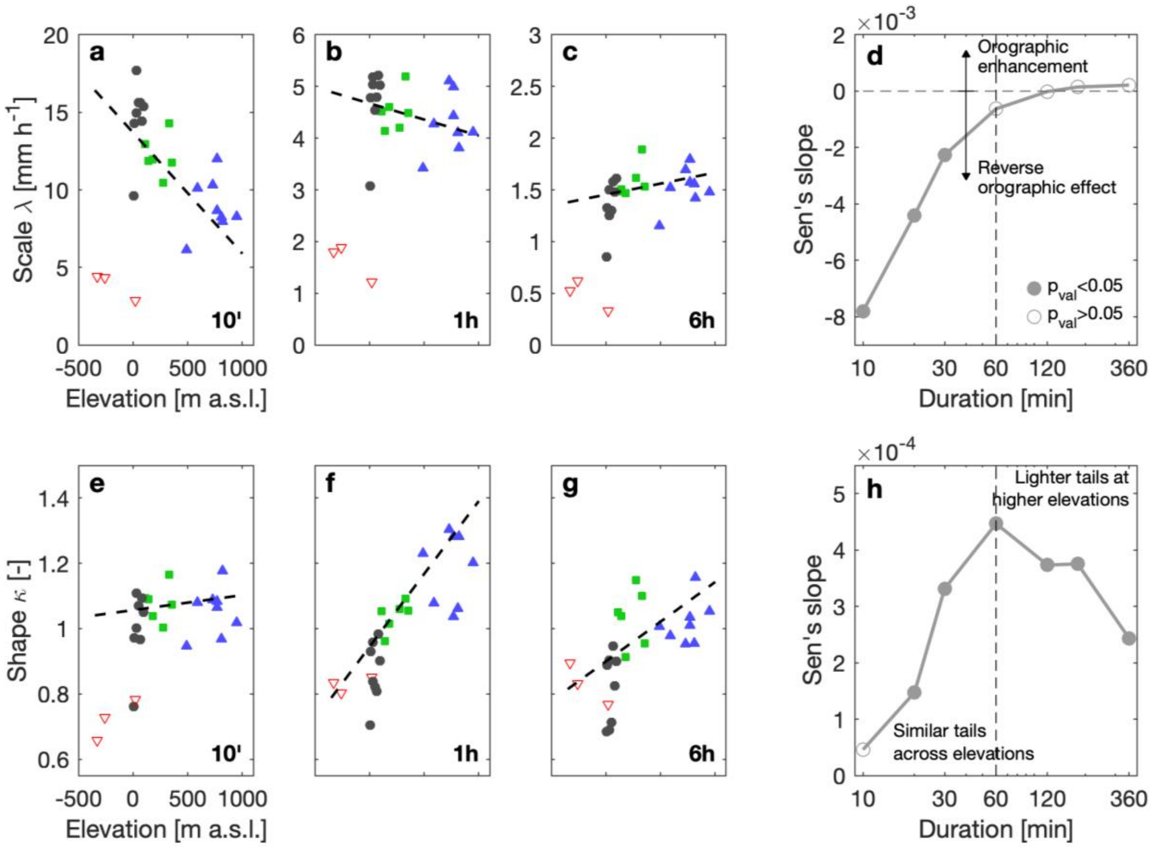

Figure 3. (a-c) Scale parameters of the Weibull distributions describing the ordinary events right-tail for durations of 10 minutes, 1 hour and 6 hours as a function of elevation; approximations of the relations between scale parameter and elevation for the uphill stations (rift stations are excluded) are shown as dashed lines. (d) Sen's slope of the scale-elevation relations as a function of duration; statistically significant slopes are shown as full dots. (e-g) Shape parameters of the Weibull distributions describing the ordinary events right-tail for durations of 10 minutes, 1 hour and 6 hours as a function of elevation; approximations of the relations between shape parameter and elevation for the uphill stations (rift stations are excluded) are shown as dashed lines. (h) Sen's slope of the shape-elevation relations as a function of duration; statistically significant slopes are shown as full dots.

The relation between terrain elevation and scale and shape parameters describing the right-tail of ordinary events is shown in Fig. 3, for durations of 10 minutes, 1 hour and 6 hours. The slope of the relations between scale parameter and elevation for the uphill stations changes sign between durations of 1 and 2 hours, with statistically significant negative slopes for sub-hourly durations. Non-statistically-significant slopes are reported for hourly (negative slope) and multi-hour (positive slope) intensities. This indicates that sub-hourly ordinary events are typically larger at lower elevations, and become weaker with increasing elevation: it is the “reverse orographic effect” reported by Allamano et al. (2009) and Avanzi et al. (2015) for hourly durations. Our results prove this is not an artifact introduced by the use of hourly data to estimate hourly extremes, and suggest that the effect is enhanced and more significant at shorter durations.

Notwithstanding, the shape parameter shows a peculiar behavior with elevation, with opposing trends for sub-hourly and multi-hour durations. No significant dependence on elevation can be identified at 10-minute duration, while longer durations present statistically significant positive slopes, implying lighter tails at higher elevation. More specifically, the slopes increase between 10 minutes and 1 hour and decreases for durations between 1 and 6 hours. This means that for increasing durations up to 1 hour, higher elevations are characterized by increasingly lighter-tailed distributions. For multi-hour durations the effect diminishes and the dependence on elevation becomes less marked, even if still significant.

These observations imply that the tail heaviness of very-short-duration (10 minutes) processes is not strongly impacted by orography, suggesting a degree of self-similarity in the distributions of convective-scale processes. Conversely, orography plays a prominent role in the way the instantaneous intensities aggregate in time, which impacts the tail heaviness in a non-monotonic way. The effect is related to the way orography affects the temporal organization of extremes. Extreme short-duration intensities are decreased by elevation and the temporal structure of the precipitation time series is smoothed (Fig. 4). This confirms previous observations on the characteristics of convective precipitation in the area (Peleg and Morin, 2012), and is likely related to a redistribution of precipitation towards stratiform-like processes surrounding the convective cores induced by the orographic lifting of air masses (Houze et al., 2001; Bongioannini Cerlini et al., 2005). The temporal autocorrelation structure and the fraction of wet time intervals observed around the intensity peaks support this observation (Fig. S3). At very short time scales, extremes essentially consist in convective cores. As duration increases, the surrounding stratiform-like processes start contributing, and then, further increasing duration, possible sequences of convective cores (e.g., Roe, 2005). For multi-hour durations, this causes the well-known “orographic enhancement” while hourly time scales are probably long enough to include the stratiform-like processes but not enough to include the sequences convective cores (Peleg and Morin, 2012).

Orography is expected to affect various aspects of extreme precipitation differently, depending on height, slope and lateral extent of the topographic barrier, wind speed, atmospheric stability, relative humidity, and moisture fluxes, etc. (Roe, 2005). Our results are based on the unique circumstances we isolated, and the characteristic hourly time scale we report is likely related to the typical convective processes originated by Mediterranean cyclones in the region. However, these systems consist in westerly winds blowing almost perpendicularly to the mountain range (Fig. 1), low-level clouds fed by abundant moisture flux, and low-level advection from the sea. The breadth of this study is thus expected to be wider, as it represents more general cases in which low-level moisture and clouds are forced upwards by mountain barriers generating heavy rainfall along their track. For instance, similar conditions are present during atmospheric rivers at the eastern boundaries of oceanic basins (e.g., Dacre et al., 2015), extra-tropical cyclones at the eastern Atlantic Ocean or the Mediterranean (Toreti et al., 2016) and other regions of the world. Our findings suggest that, in these conditions, sub-hourly precipitation intensities in mountainous regions may be characterized by heavier tails than hourly intensities, and that the heaviness of such tails cannot be adequately quantified using scale-invariant methods. This bares important implications for risk management in mountainous areas and for the design of protection infrastructures against natural hazards related to short-duration extremes, such as debris flows and flash floods.

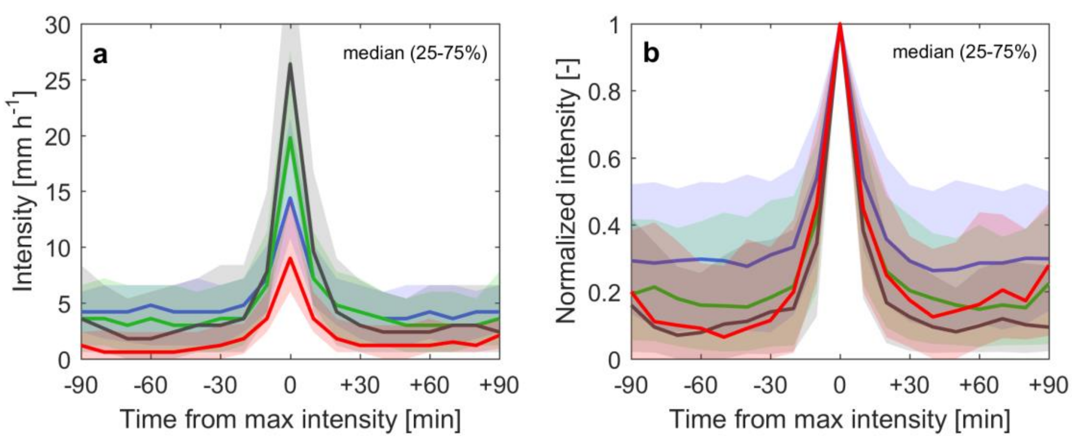

Figure 4. Temporal structure of extreme events. (a) Time series (median and 50% interval) of the ordinary events centered around the moment in which the maximum 10-min intensity is recorded; colors

refer to the physiographic region as in Fig. 1. (b) Same as in panel a, but with intensities normalized over the event maximum value.

4 Conclusions

We quantified the impact of orography on the right-tail statistics of sub-daily and sub-hourly precipitation exploiting a novel framework for the analysis of extremes based on multiple types of ordinary events. In this way, we could reduce the stochastic uncertainties without requiring scaling/homogeneity assumptions, and remove possible effects related to the contribution of different precipitating system and advection directions. We focused on the case of Mediterranean cyclones in the southeastern Mediterranean, where unique atmosphere-orography interaction conditions are observed.

Our findings confirm the presence of a “reverse orographic effect”, previously observed for hourly intensities, and suggest it could be further enhanced at shorter durations. The tail heaviness at very short durations (10 minutes) seems unaffected by orography, suggesting a degree of self-similarity in the distributions of convective-scale processes. Conversely, orography tends to decrease the tail heaviness at longer durations, with a maximum around hourly scales; in mountainous regions a non-monotonic response is observed, with decreasing tail heaviness between 10 minute and 1 hour and increasing between 1 and 6 hours. This is likely related to a smoothing of the events structure, possibly caused by the redistribution of precipitation towards stratiform-like processes: while hourly time intervals likely include individual convective cores and the related stratiform-like portion, multi-hour intervals may include sequences of convective and stratiform-like elements, which aggregate and cause the well-known orographic enhancement.

Our findings place previous observations limited to hourly durations into a wider context, and add crucial knowledge for risk management in mountainous regions. In fact, the breaking of scale-invariance observed around hourly durations implies a systematic underestimation of the tail heaviness for sub-hourly intensities by the often-adopted scale-invariant methods. This has important implications for the management of natural hazards typical of mountainous regions, such as flash floods and debris flows. As based on the analysis of Mediterranean cyclones with typical advection directions roughly perpendicular to the mountain range, our results are quantitatively relevant for this specific study case, but are expected to represent more general cases in which low-level moisture is forced by mountain barriers along the storm track, such as extra-tropical cyclones and atmospheric rivers at the eastern boundaries of their oceanic basins. Analysis of different regions and types of precipitating systems, and investigations based on convection-permitting numerical models could improve the understanding of the physical mechanisms behind the observations, and could provide improved information on short-duration extremes related to multiple underlying processes. The used approach can be extended to other study cases and can be used to investigate non-stationary conditions and climate change impacts on extreme precipitation under orographic forcing.

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Supporting Information to:

Orographic effect on extreme precipitation statistics peaks at hourly time scales

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Table S1: Synoptic systems in the semi-automatic classification by Alpert at al. (2004) and corresponding use in this study, as follows: (1) Mediterranean cyclones, (2) other types of system, (3) labelled as Mediterranean cyclones if occurring up to two days after a Mediterranean cyclones wet day.

Code	*Alpert et al. (2004)*	*Class*
1	Red Sea Trough with the Eastern axis	2
2	Red Sea Trough with the Western axis	2
3	Red Sea Trough with the Central axis	2
4	Persian Trough (Weak)	3
5	Persian Trough (Medium)	3
6	Persian Trough (Deep)	3
7	High to the East	3
8	High to the West	3
9	High to the North	3
10	High over Israel (Central)	3
11	Low to the East (Deep)	1
12	Cyprus Low to the South (Deep)	1
13	Cyprus Low to the South (Shallow)	1
14	Cyprus Low to the North (Deep)	1
15	Cyprus Low to the North (Shallow)	1
16	cold Low to the West	1
17	Low to the East (Shallow)	1
18	Sharav Low to the West	2
19	Sharav Low over Israel (Central)	2

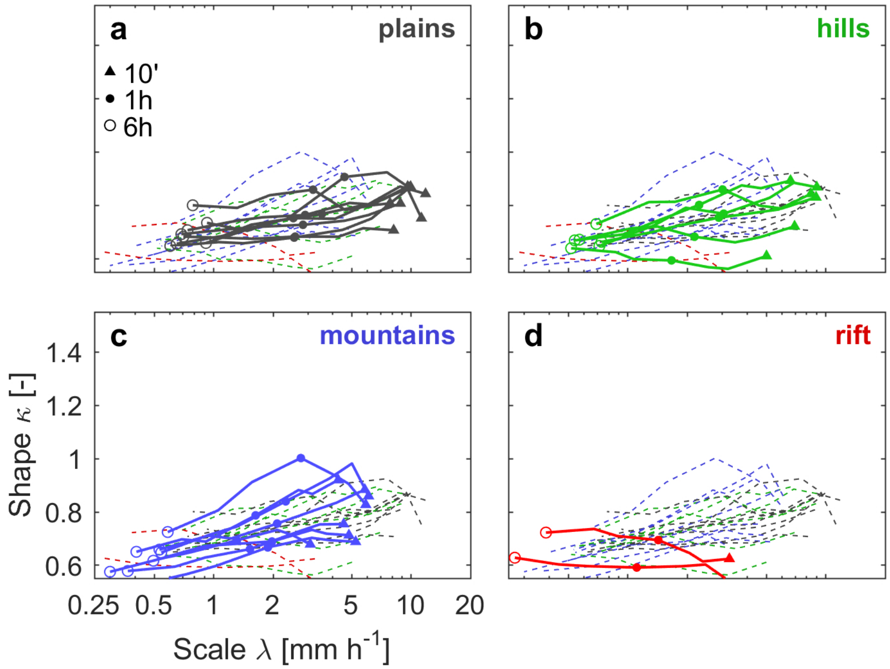

Figure S1. Same as Figure 2 (a-d), but computed using all the precipitation events which are not associated to Mediterranean cyclones. Served as control case since the interaction of these events with orography is less systematic (wind directions can be non-perpendicular to the mountains, and clouds are not restricted to low levels; e.g., Alpert et al., 2004; Armon et al., 2019). Indeed, the orographic impact (panel c in Figure 1) on the shape of hourly intensities is less marked and all the groups but the rift show a mild decrease of the shape with duration.

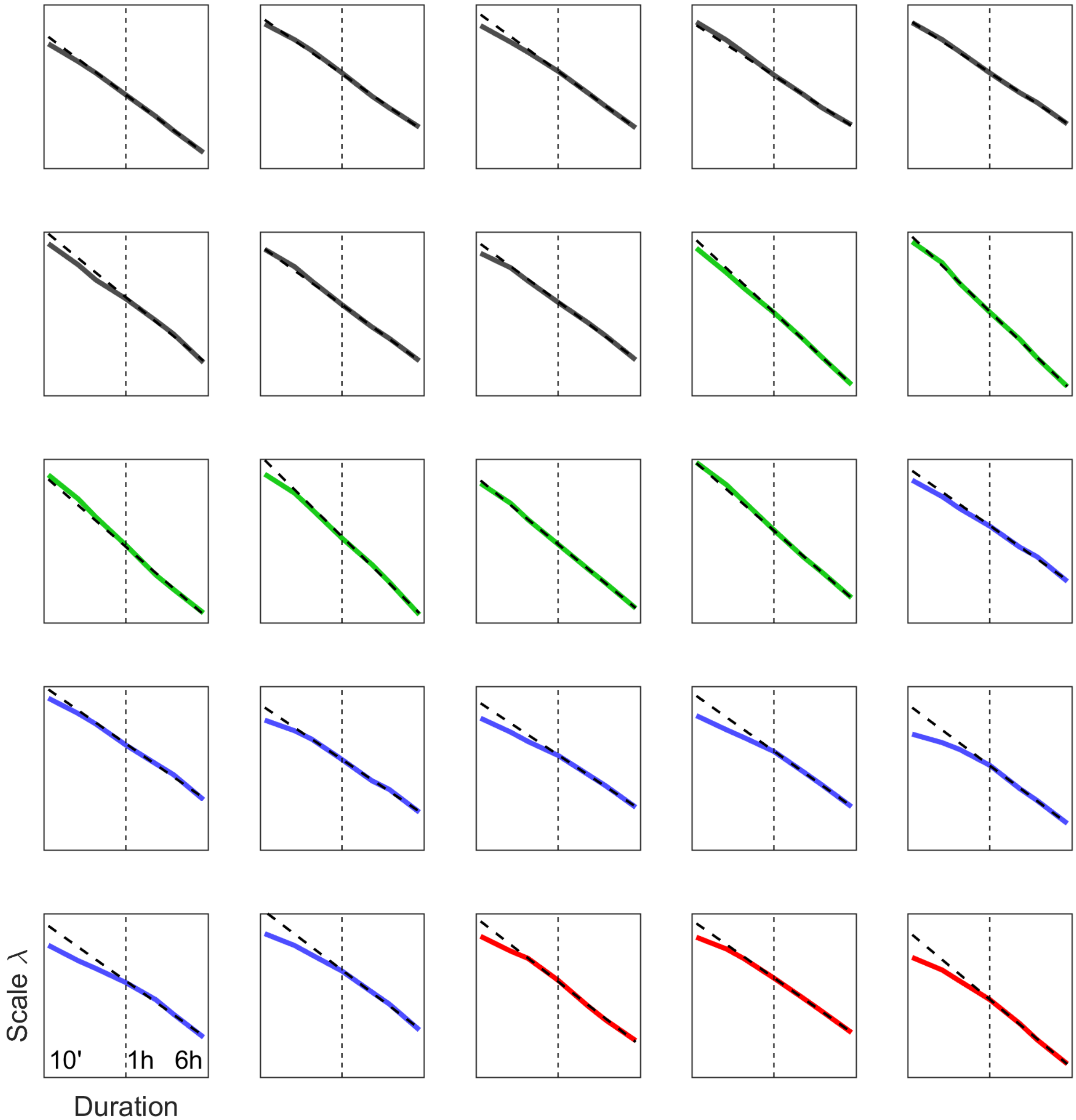

Figure S2. Scale parameters (90% confidence interval region) of the ordinary events as a function of duration at each station colored according to the physiographic region as in Fig. 1. Note that the y-axes differ between regions and that both x and y axes are log-transformed. Power law (simple scaling) relations computed for durations above 1 hour are shown as dashed black lines. The power law scaling holds for all duration at most stations; however, following the non-monotonous behavior of the shape reported in Fig. 2 and Fig. 3, a break for sub-hourly durations is observed in the most orography-affected regions.

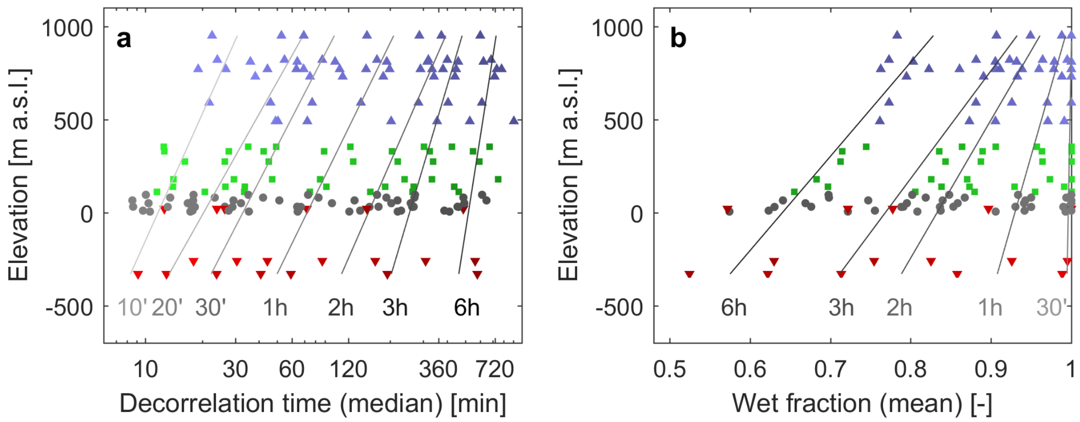

Figure S3. (a) Median decorrelation time of the ordinary events (x-axis) as a function of elevation (y-axis); darker shading refers to longer durations, colors refer to the physiographic region as in Fig. 1. The autocorrelation function A of coarse resolution timeseries obtained aggregating the original 10-min timeseries to blocks of the duration of interest is computed for each ordinary event of each station and for each duration of interest. The decorrelation time is quantified estimating the scale parameter b of the fitting three-parameter exponential in the form: $A(t) = a \cdot e^{-\left(\frac{t}{b}\right)^c}$ (Marra and Morin, 2018). (b) Mean wet fraction for the right-tail ordinary events (x-axis) as a function of elevation (y-axis). The wet fraction is computed as the fraction of non-zero 10-min time intervals observed within each ordinary event

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