

Supplement

S1 Methodological sensitivity and validation

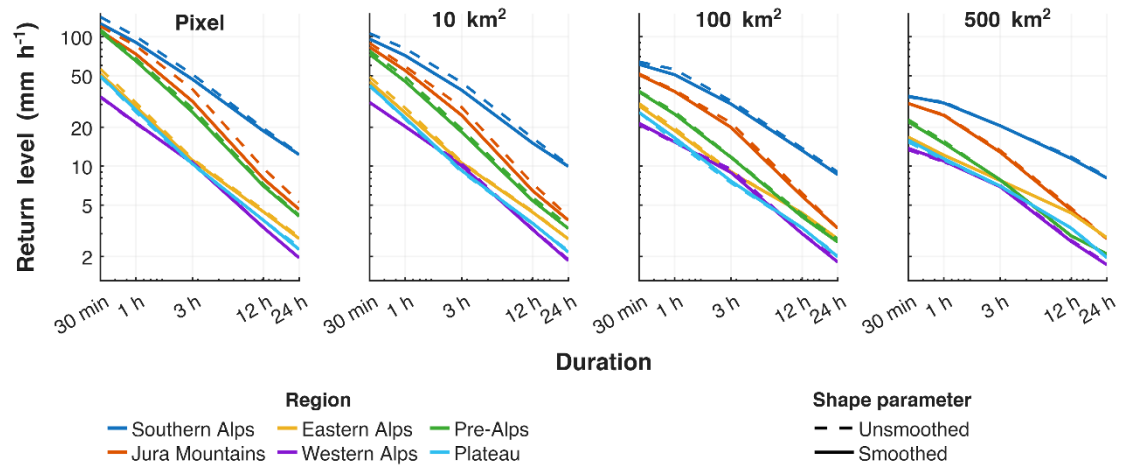


Figure S1. Comparison of 20-year IDAF curves estimated using smoothed and unsmoothed Weibull shape parameters. Analysis-site locations are shown in Fig. 1.

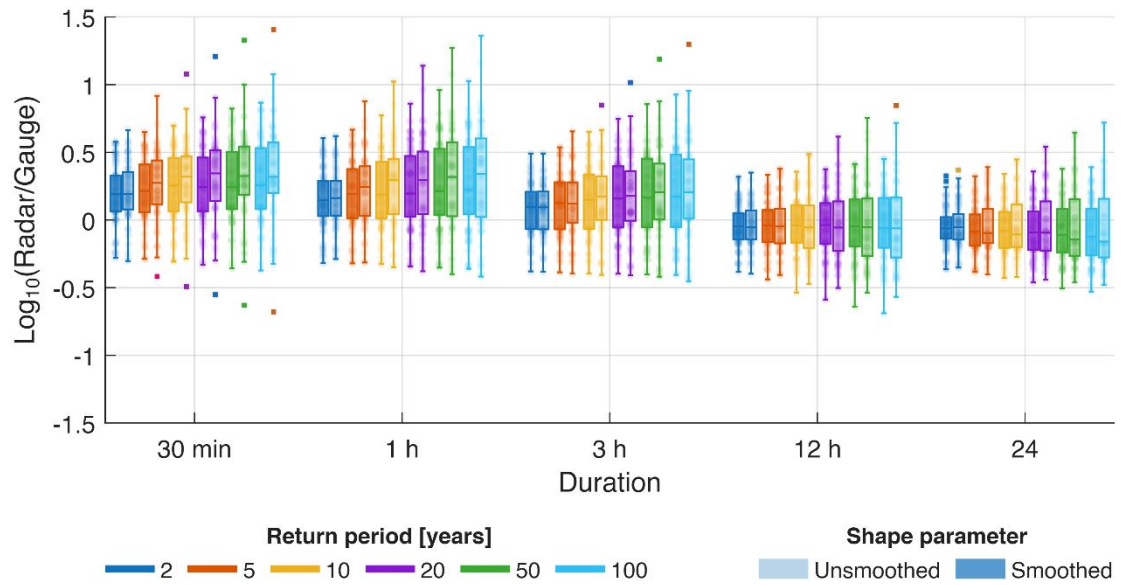


Figure S2. Bias between radar- (1 km^2 pixel scale) and gauge-derived return levels, expressed as $\text{Log}_{10}\left(\frac{\text{Radar}}{\text{Gauge}}\right)$, for estimates obtained using smoothed and unsmoothed Weibull shape parameters.

S2 Additional IDAF results and parameter fields

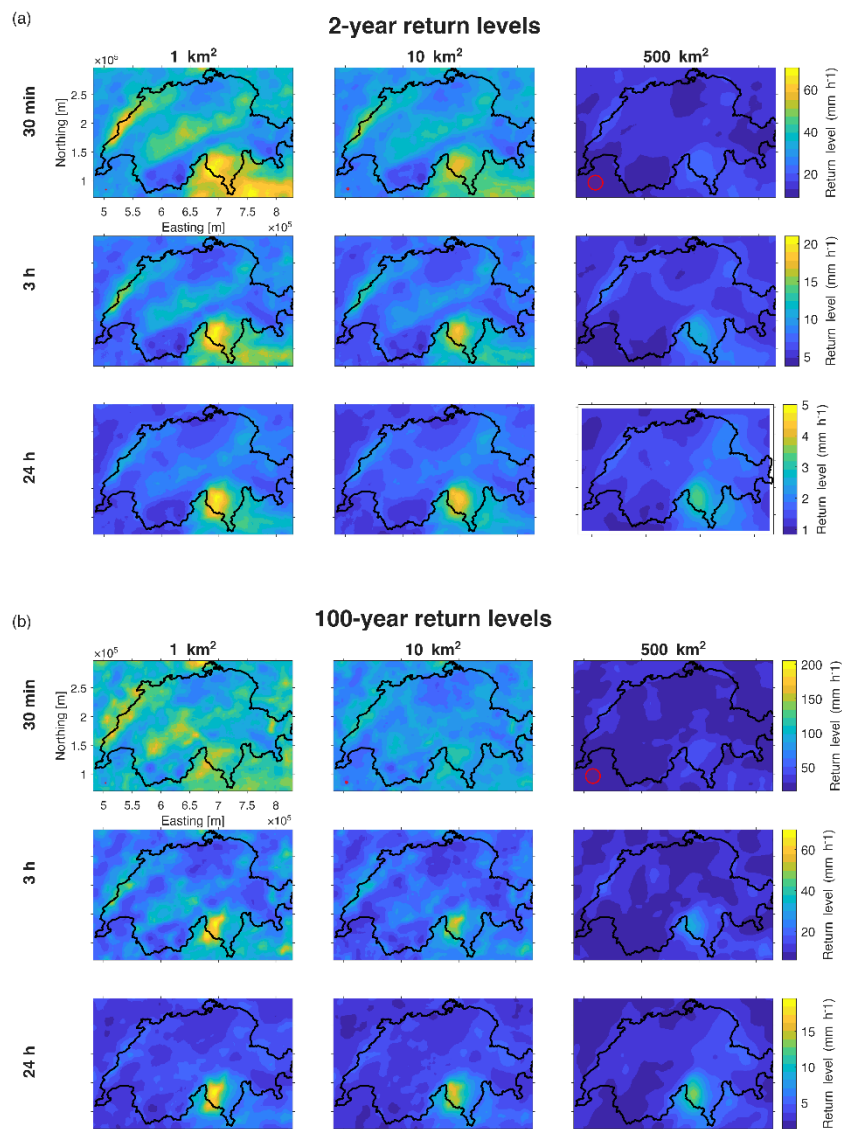


Figure S3. Spatial distribution of rainfall return levels for varying areas and durations for (a) 2- and (b) 100-year return periods. Red circles (top row) illustrate the equivalent spatial extent of each areal scale.

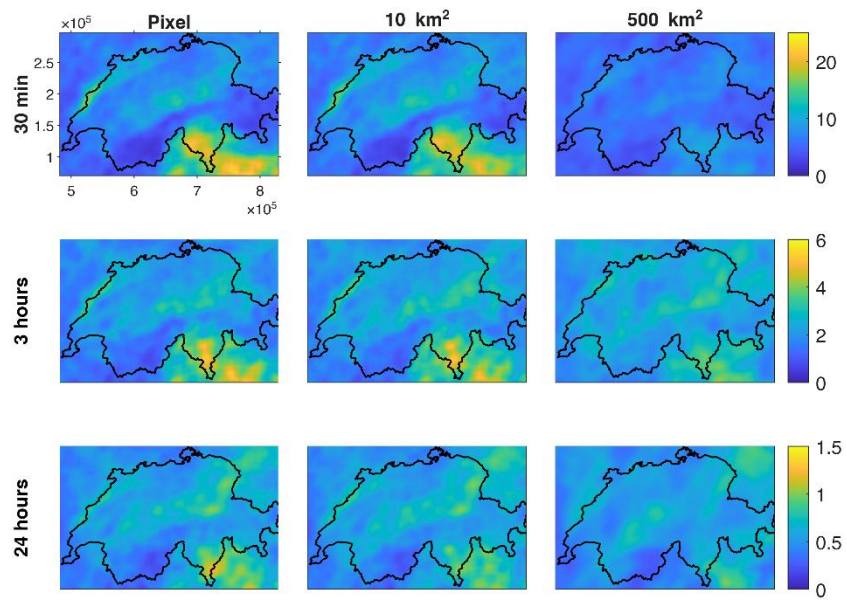


Figure S4. Spatial distribution of the fitted Weibull scale parameter across different areas and durations.

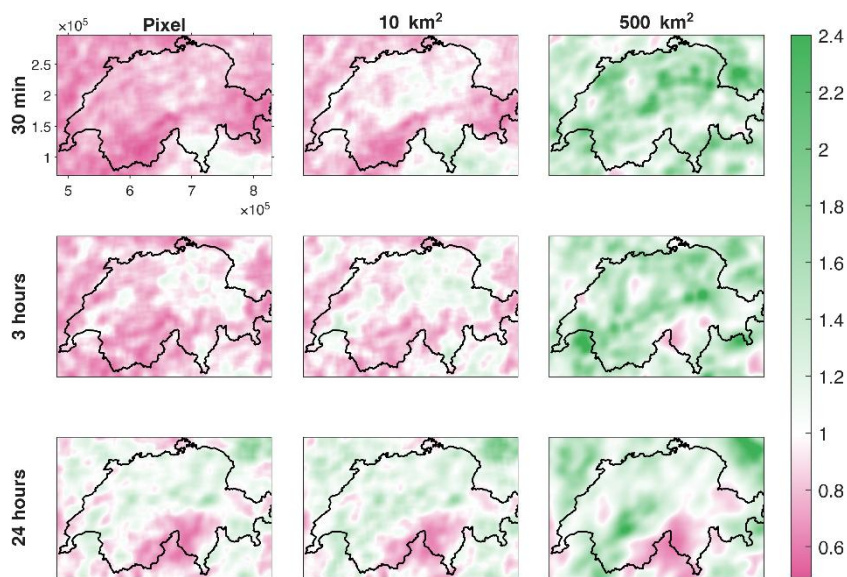


Figure S5. Spatial distribution of the fitted Weibull shape parameter across different areas and durations.

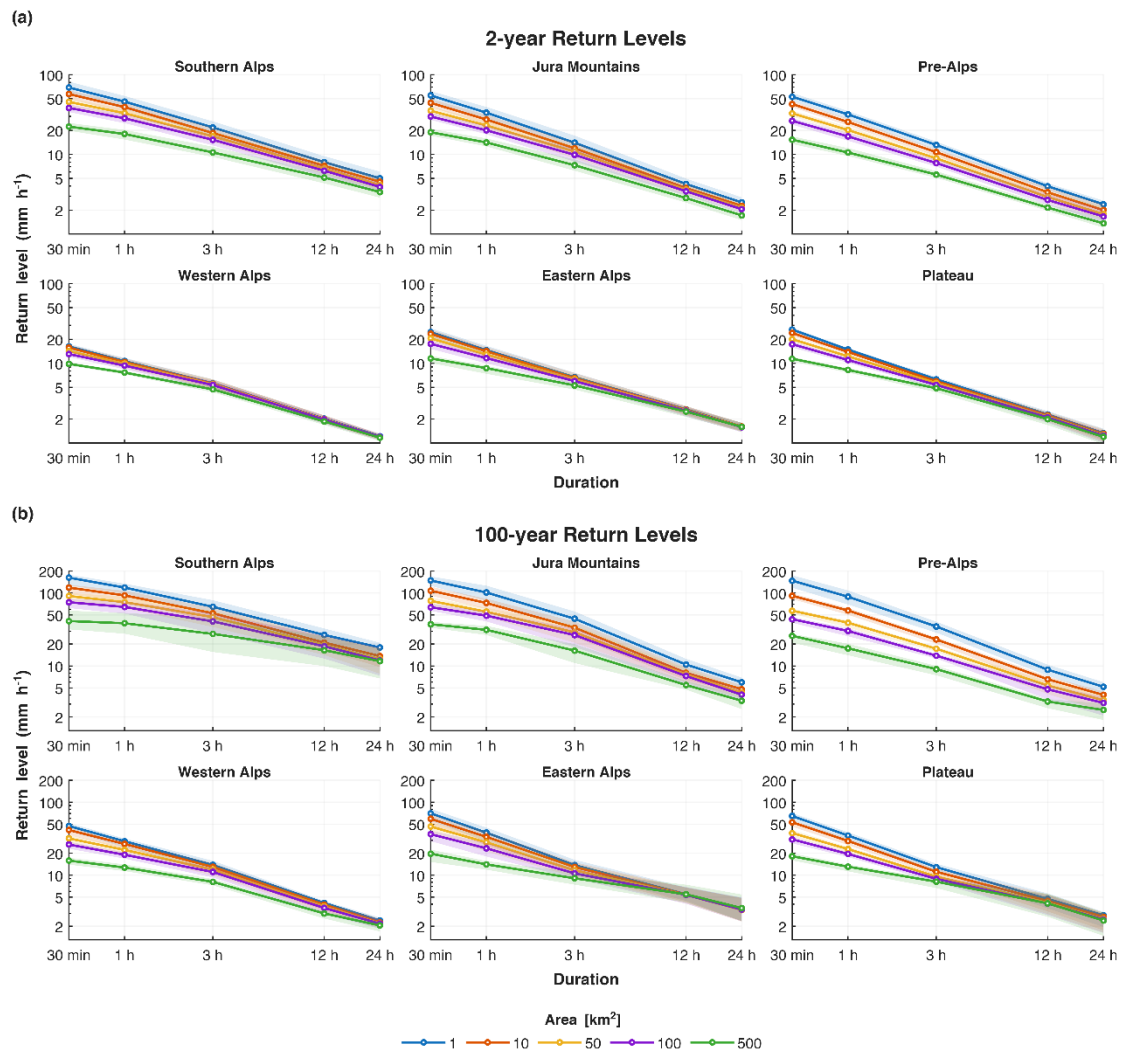


Figure S6. IDAF curves estimated for (a) 2-year and (b) 100-year return periods. Shaded areas represent the 90% confidence interval from 100 bootstrap samples. The locations of the analysis sites are displayed in Fig. 1.

S3 Location and Orographic Controls on the Spatiotemporal Dependence of Extreme Rainfall

Orographic precipitation arises from complex, non-linear interactions between flow dynamics, thermodynamics, and terrain (Benoit et al., 2024). While elevation is often associated with enhanced precipitation, short-duration (sub-daily) extremes have been demonstrated to decrease with elevation, resulting in the so-called 'reverse orographic effect' for rainfall extremes (Allamano et al., 2009; Avanzi et al., 2015; Formetta et al., 2022; Marra et al., 2021; Rosin et al., 2024). In the Swiss Alps, Benoit et al. (2024) found that the traditional positive linear relationship between elevation and mean daily precipitation holds in only 15% of cases, and that the sign, magnitude, and linearity of the influence of elevation on mean daily precipitation varies significantly in space and time. Similarly, Formetta et al. (2022) identified two distinct regimes in the Italian Alps: reverse orographic scaling at hourly and sub-hourly durations, and orographic enhancement emerging only at durations above 8 hours. Note however that these findings were not limited to summer precipitation, but emerged from analyses spanning all seasons.

To examine the dependency of Swiss rainfall on location and topography across spatial and temporal scales, we analyse four transects across Switzerland (Fig. S7): two north–south transects (eastings 580 km and 705 km) and two west–east transects (northings 220 km and 160 km). The locations were selected to capture key orographic and geographic features. Transects are computed as 10 km-wide spatial averages to reduce pixel-scale noise. Return levels are normalised over the maximum value along each transect, allowing direct comparison across spatiotemporal scales. Corresponding transects for the shape parameter are presented in Fig. S8.

Transect 1 (western north-south) exhibits strong sensitivity to both spatial and temporal aggregation, closely linked to orographic structures. For 1-h duration and small areas ($\leq 100 \text{ km}^2$), distinct maxima align with the Jura mountains ($\sim 230 \text{ km}$) and Western Alps/Pre-Alps ($\sim 140 \text{ km}$). However, as the aggregation area increases to 500 km^2 , the dominant maximum shifts toward the northern Jura mountains and the enhancement over the Western Alps disappears. At the 24-h duration, rainfall maxima over the Jura persist, whereas the rainfall peaks over the Western Alps decrease. Notably, for large areas only, an additional maximum emerges over the Plateau, consistent with long-duration synoptic precipitation. The inner Alps ($\sim 110 \text{ km}$) remain low across all temporal and areal scales. These patterns are observed for all the calculated return periods.

Transect 2 (eastern north-south) is much less affected by temporal or areal scaling. A broad intense maximum over the high elevation Southern Alps ($\sim 130 \text{ km}$) persists for all spatiotemporal scales, while persistent minima are observed over the Eastern Alps ($\sim 180 \text{ km}$) and Plateau (~ 230 and $\sim 270 \text{ km}$). Increasing aggregation area or duration primarily attenuates small-scale local variability without altering the overall spatial pattern of extremes. This behaviour is consistent with the strong orographic forcing associated with moist southerly flow against the main mountain barrier in the Ticino region.

Transect T3 (northern west–east) exhibits a sharp 1 h rainfall peak over the Jura mountains at $\sim 540 \text{ km}$ for all areas, and at $\sim 560 \text{ km}$ for areas under 500 km^2 . At 24 h duration, this maximum is strong only for small ($1\text{--}10 \text{ km}^2$) areas, while a broad, coherent region of high intensity appears around the Pre-Alps and Eastern Alps ($730\text{--}760 \text{ km}$) for all area scales, indicating orographic forcing on the north-Alpine barrier.

Transect T4 (southern west–east) shows multiple 1 h local maxima occur over orographic features across the Western Jura, Pre-Alps and Eastern Alps for areas under 500 km^2 , while 24 h extremes collapse into a single, broad maximum over the Southern Alps, largely independent of area. Return level minima are present across the central Plateau ($\sim 540\text{--}660 \text{ km}$) and Eastern Alps (770 km).

Overall, the transect analysis demonstrated that the influence of topography on extreme rainfall in Switzerland is inherently scale-dependent and cannot be described by a single, monotonic elevation–precipitation relationship. Small-area, short-duration extremes generally track local orographic enhancement, while larger areas and longer durations exhibit weaker and less direct correlations with

topography. Locations that exhibit relatively high intensities at short durations and small areas may become comparatively unremarkable at longer durations or larger spatial supports, and vice versa. This

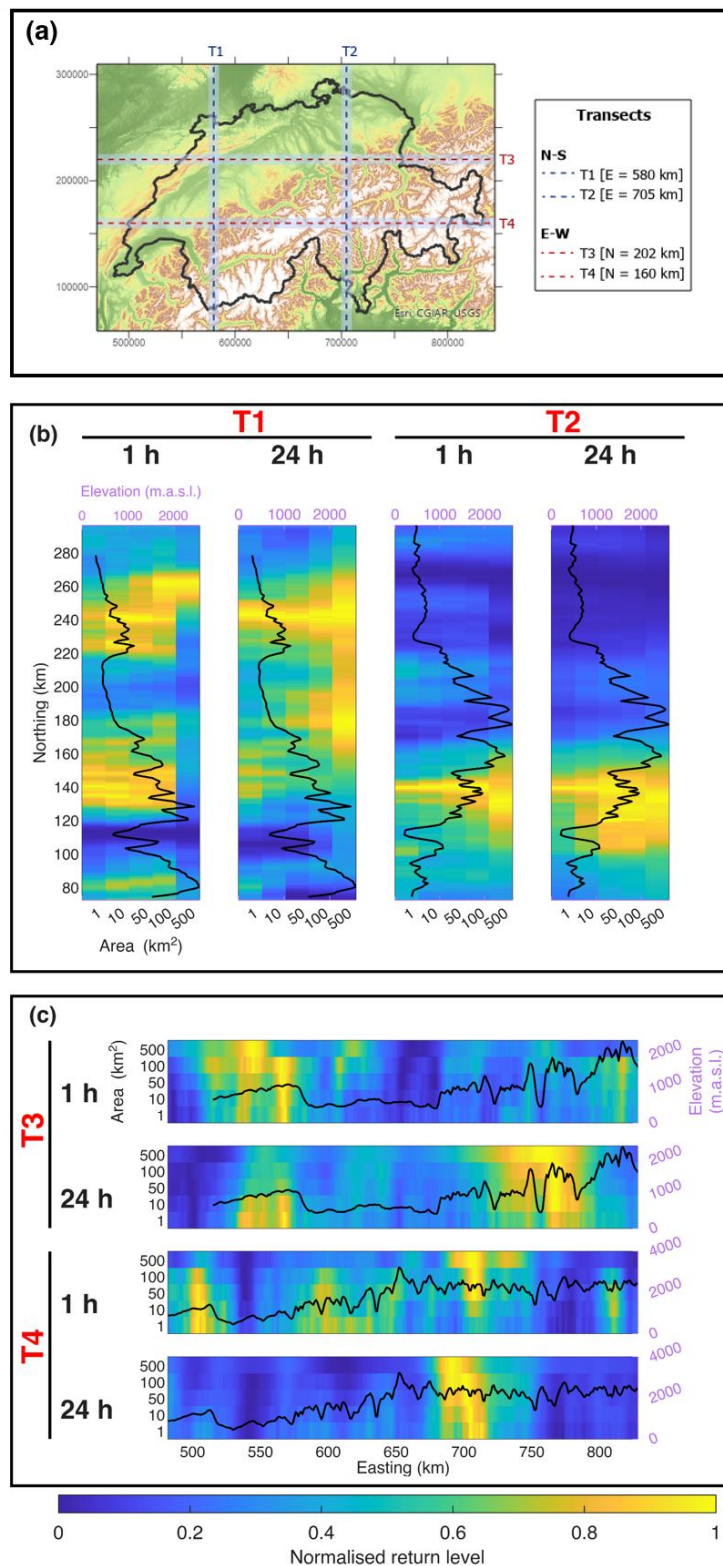


Figure S7. Normalised 20-year return levels as a function of area along four transects for 1 and 24 h durations. (a) Study area showing the locations of two north–south transects at eastings of 580 km (T1) and 705 km (T2), and two east–west transects at northings of 220 km (T3) and 160 km (T4). (b) Normalised return levels along the north–south transects. (c) Same as (b), but for the east–west transects. Solid lines denote the corresponding orographic profiles.

underscores the necessity of assessing rainfall severity across multiple spatial and temporal scales, rather than relying on a single duration-area combination, to fully characterise hydrological risk in complex terrain.

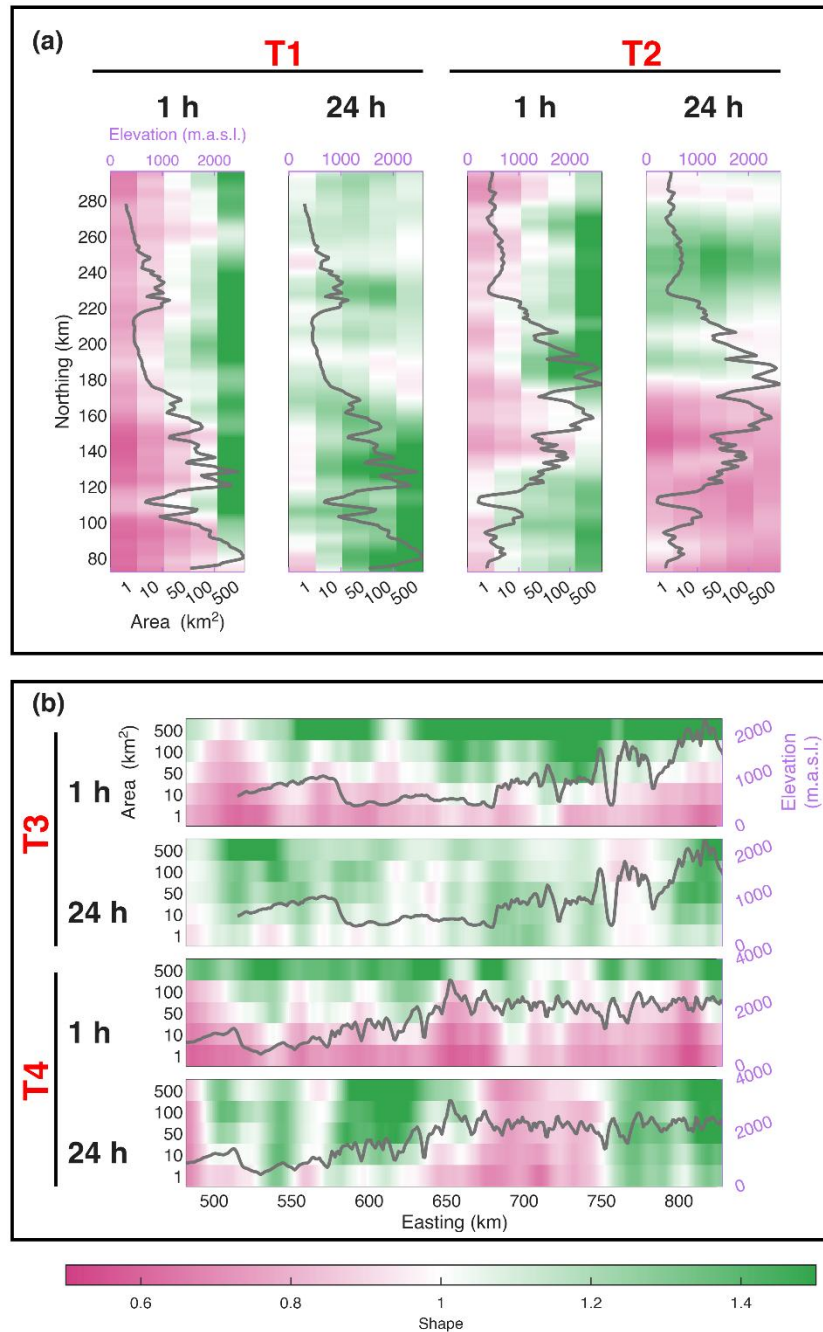


Figure S8. Weibull shape parameter along the transects shown in Fig. S7 for 1 h and 24 h durations. (a) North-south transects (T1 – T2). (b) East-west transects (T3 – T4). Solid lines indicate the corresponding orographic profiles.