Supplementary Materials

The rise of the rare and severe, an unsupervised dynamical fingerprint of heatwaves and extreme events of precipitation over Italy from 1991 to 2020

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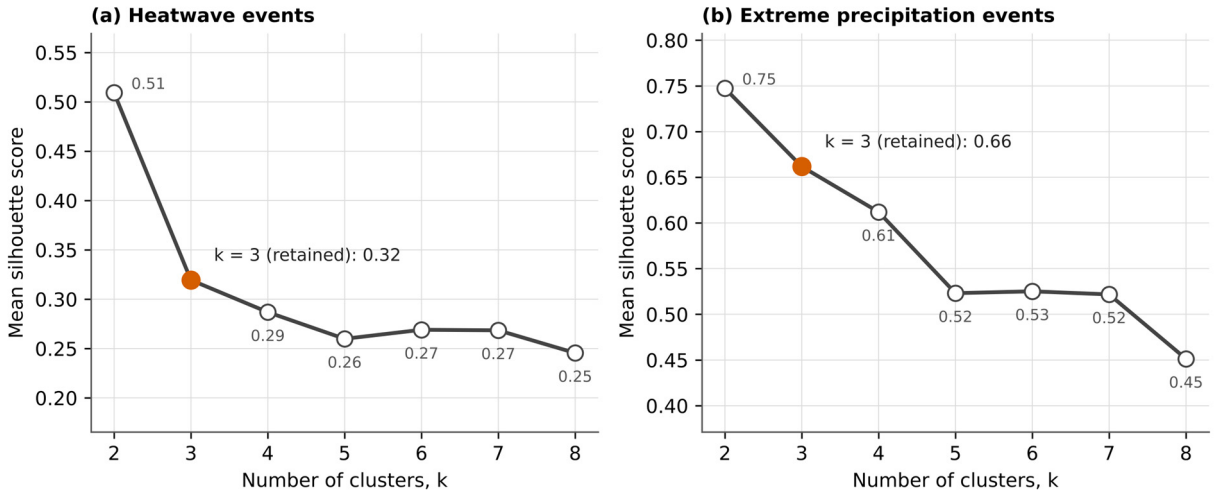

Figure S1. Mean silhouette score as a function of the number of clusters k for (a) heatwave events (n = 1767) and (b) extreme precipitation events (n = 10,925). For precipitation, scores were computed on a random subsample of 4000 events; for the retained three-cluster solution, the score computed on the full catalogue is 0.66. The highlighted point marks the retained solution (k = 3). For both hazards the score is highest for k = 2, a partition that separates shorter and smaller events from longer and larger ones and merges the rarest, most persistent and most extensive events with part of an intermediate group (Section 2.4 of the main text).

Table S1. Sensitivity of the trend results to the number of clusters

Annual-frequency trends (Mann–Kendall test and Sen's slope, 1991–2020) for the classes obtained with k = 2, 3 and 4. Within each k, classes are ordered by increasing mean peak area; for k = 3, they correspond to the archetypes discussed in the main text. Values in bold indicate statistically significant trends ($p < 0.05$).

(a) Heatwave events

k	Class (by mean peak area)	Events	Mean duration (days)	Mean peak area (km²)	Kendall's τ	p value	Sen's slope (events per decade)
2	Class 1	1473	4.1	66 674	0.13	0.317	2.3
2	Class 2	294	12.7	643 327	**0.58**	**< 0.0001**	**2.8**
3	Brief localised spikes	994	3.6	30 266	0.16	0.211	2.2
3	Regional multi-day heatwaves	590	5.5	188 994	0.07	0.615	0.4
3	Persistent nationwide heatwaves	183	15.5	796 490	**0.69**	**< 0.0001**	**2.5**
4	Class 1	907	3.6	27 248	0.23	0.083	2.9
4	Class 2	552	4.7	123 281	-0.12	0.380	-0.8
4	Class 3	237	9.8	523 757	**0.35**	**0.0092**	**1.6**
4	Class 4	71	20.9	992 293	**0.59**	**< 0.0001**	**1.5**

(b) Extreme precipitation events

k	Class (by mean peak area)	Events	Mean duration (days)	Mean peak area (km²)	Kendall's τ	p value	Sen's slope (events per decade)
2	Class 1	10033	1.2	8 556	**0.27**	**0.038**	**17.1**
2	Class 2	892	3.2	91 349	0.13	0.316	1.2
3	Local bursts	9284	1.1	6 672	0.24	0.066	16.0
3	Persistent quasi-stationary systems	1417	2.4	47 195	0.18	0.169	2.8
3	Organised propagating systems	224	4.1	171 890	**0.43**	**0.0017**	**1.4**
4	Class 1	8786	1.1	5 745	**0.26**	**0.045**	**15.8**
4	Class 2	1598	1.9	40 203	0.07	0.617	1.3
4	Class 3	350	3.5	48 431	0.17	0.201	1.0
4	Class 4	191	4.0	186 652	**0.32**	**0.017**	**1.3**

Table S2. Sensitivity of the classification to the computation of peak area

Archetypes and annual-frequency trends obtained with the approximate peak area used in the main text (largest daily number of member cells multiplied by the area of a single grid cell at a reference latitude) and with the exact peak area of Equation (6) (sum of the latitude-dependent areas of the member cells). With the exact areas, 28 of the 1767 heatwave events (1.6%) and 22 of the 10,925 precipitation events (0.2%) change archetype. Values in bold indicate statistically significant trends ($p < 0.05$).

(a) Heatwave events

Peak area computation	Archetype	Events	Mean peak area (km²)	Kendall's τ	p value	Sen's slope (events per decade)
Approximate (main text)	Brief localised spikes	994	30 266	0.16	0.211	2.2
	Regional multi-day heatwaves	590	188 994	0.07	0.615	0.4
	Persistent nationwide heatwaves	183	796 490	**0.69**	**< 0.0001**	**2.5**
Exact (Equation (6))	Brief localised spikes	1006	32 710	0.16	0.230	2.0
	Regional multi-day heatwaves	594	211 106	0.08	0.541	0.5
	Persistent nationwide heatwaves	167	815 370	**0.60**	**< 0.0001**	**2.4**

(b) Extreme precipitation events

Peak area computation	Archetype	Events	Mean peak area (km²)	Kendall's τ	p value	Sen's slope (events per decade)
Approximate (main text)	Local bursts	9284	6 672	0.24	0.066	16.0
	Persistent quasi-stationary systems	1417	47 195	0.18	0.169	2.8
	Organised propagating systems	224	171 890	**0.43**	**0.0017**	**1.4**
Exact (Equation (6))	Local bursts	9269	7 158	0.24	0.066	15.8
	Persistent quasi-stationary systems	1425	49 348	0.17	0.186	2.8

Peak area computation	Archetype	Events	Mean peak area (km^2)	Kendall's τ	p value	Sen's slope (events per decade)
	Organised propagating systems	231	176 323	**0.39**	**0.0043**	**1.4**