Supplementary results

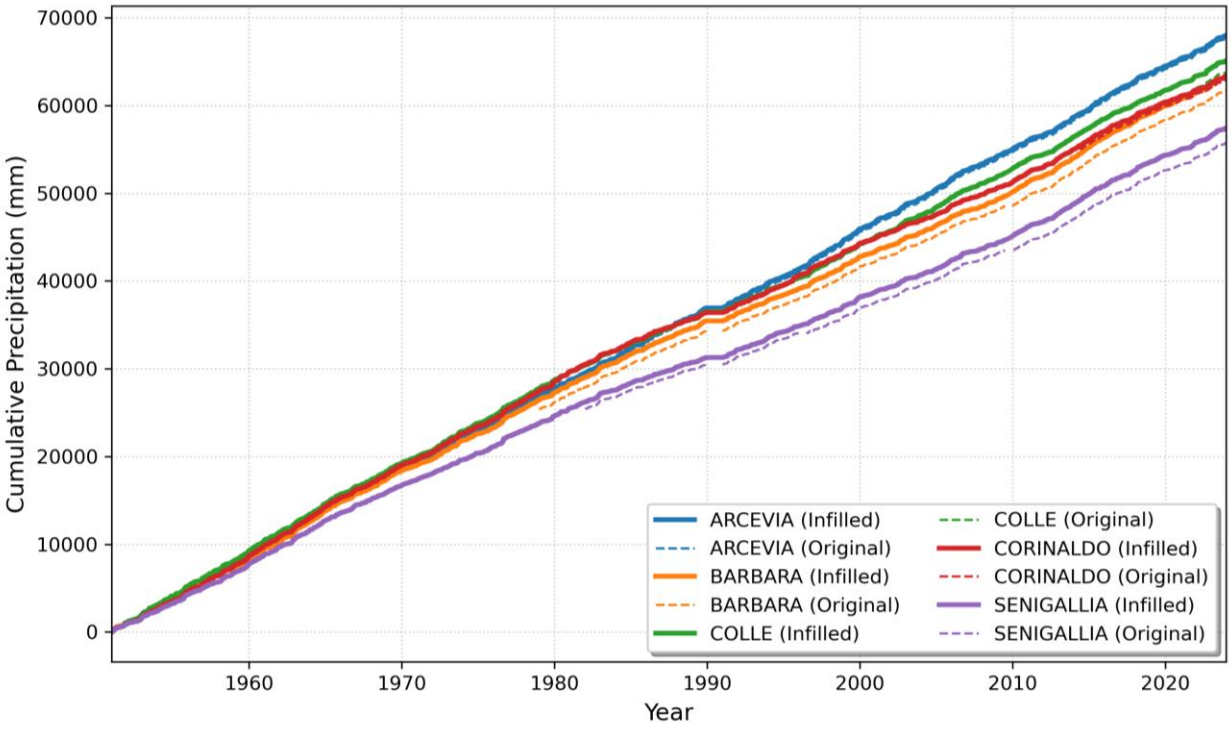
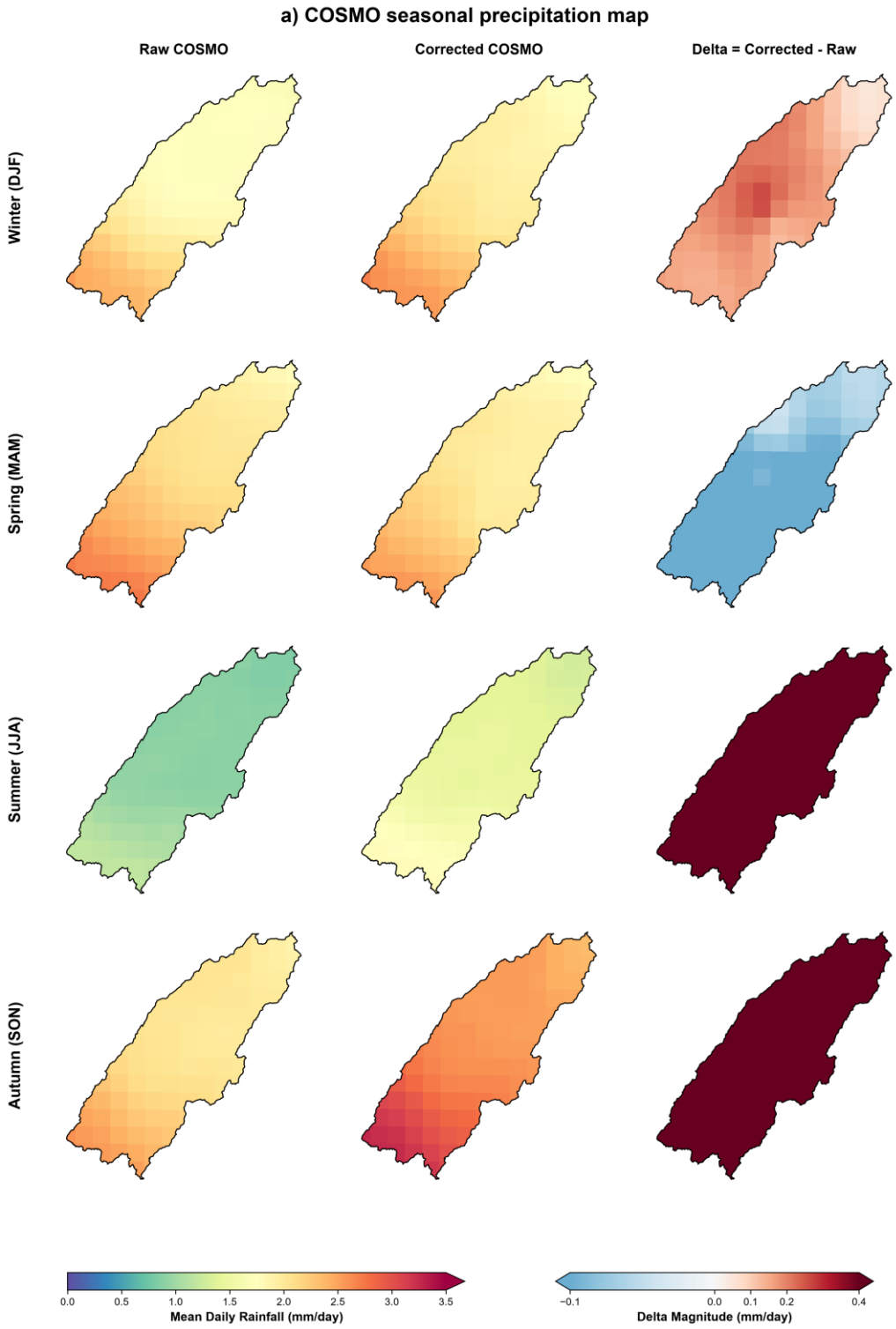


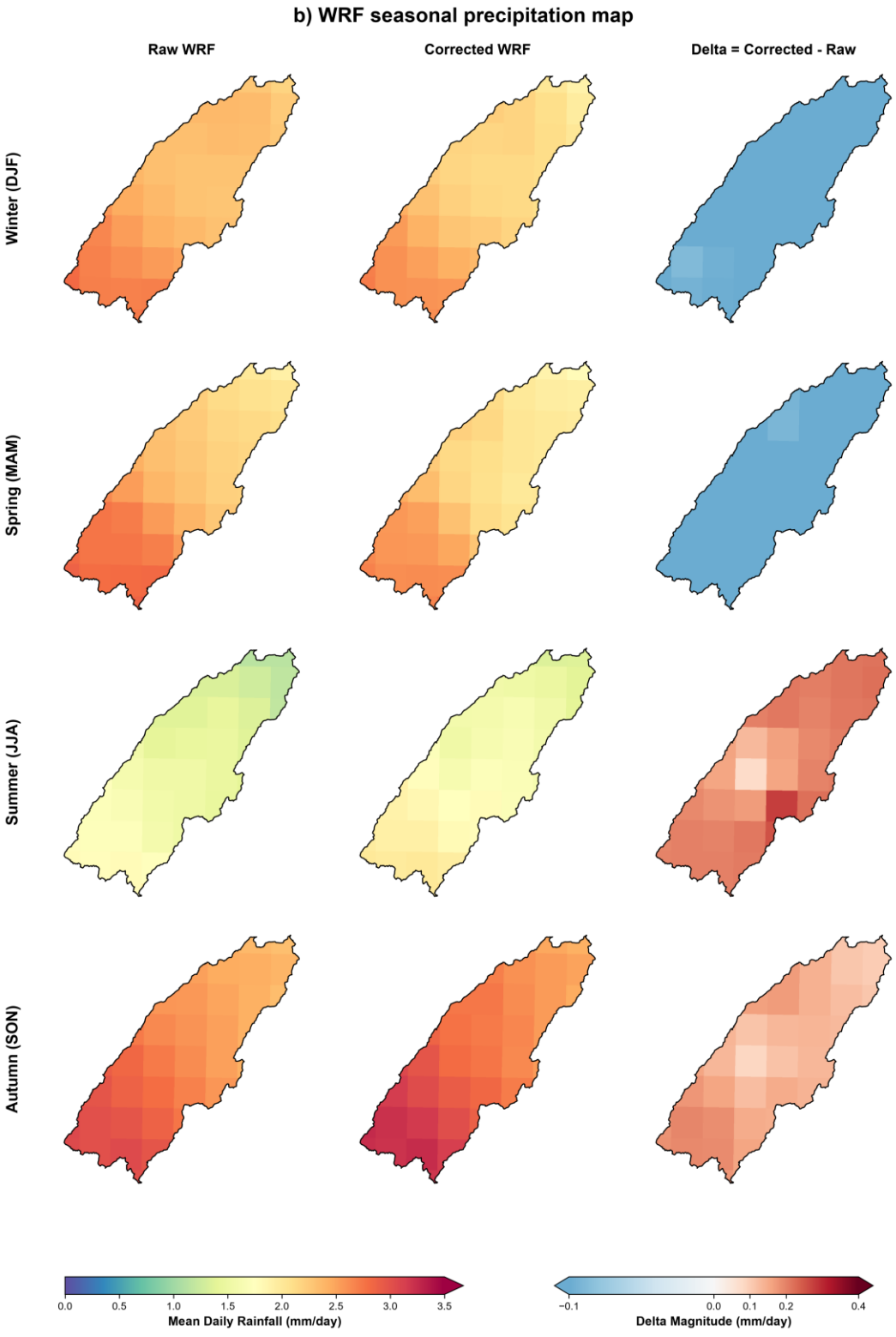
Figure S1: The raw-versus-infilling cumulative of multi-station observed long-term data validation (1951-2023), excluding 1990-year data due to manual-to-automated instrumentation in 1990 causing a complete data loss across all stations except Arcevia. It shows the consistency of long-term rainfall records at specific stations by computing the cumulative precipitation of entire periods to identify the gradients of the data results (raw data and missed data infilled) in the gauging stations, such as Arcevia, Barbara, Colle, Corinaldo, and Senigallia.

Table S1: Synthetic out-of-sample cross-validation metrics for the Localized Multiple Linear Regression data imputation framework (1951–2023). Synthetic gap stress tests across the five catchment weather stations (Arcevia, Barbara, Colle, Corinaldo, and Senigallia). Donor stations were dynamically selected for each target gauge based on a strict cross-correlation baseline ($r > 0.6$). Evaluated metrics include: **(1)** Wet/Dry Critical Success Index (CSI) for occurrence accuracy at daily thresholds >1.0 mm; **(2)** Upper-Tail Percentile Recovery for 95th and 99th daily precipitation intensities alongside their relative percentage bias %; and **(3)** Annual Daily Maximum (Rx1day) Mean Absolute Error (MAE, mm).

Station	**3 Selected Donors**	**Wet/Dry CSI**	**RAW P_{95} (mm)**	**Filled P_{95} (mm)**	**P_{95} Bias (%)**	**RAW P_{99} (mm)**	**Filled P_{99} (mm)**	**P_{99} Bias (%)**	**Rx1day MAE (mm)**
ARCEVIA	Colle, Barbara, Corinaldo	0.775	32.7	27.09	-17.17%	50.8	45.36	-10.71%	7.43
BARBARA	Colle, Arcevia, Corinaldo	0.768	30.86	26.42	-14.37%	46.92	39.57	-15.66%	6.15
COLLE	Barbara, Arcevia, Corinaldo	0.784	29.6	23.76	-19.73%	45.94	39.71	-13.56%	6.72
CORINALDO	Barbara, Senigallia, Colle	0.734	33.95	29.36	-13.51%	55.48	44.83	-19.19%	7.25
SENIGALLIA	Corinaldo, Barbara, Colle	0.705	29.92	20.72	-30.76%	59.17	42.99	-27.34%	12.75

Figure S2: Seasonal precipitation maps of mean daily rainfall during the historical period (1979/81–2008) for the raw and corrected COSMO **(a)** and WRF **(b)** models, as well as the change between corrected and raw maps over the Misa River basin (third column).




b) WRF seasonal precipitation map
Raw WRF
Corrected WRF
Delta = Corrected - Raw
Winter (DJF)
Spring (MAM)
Summer (JJA)
Autumn (SON)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Mean Daily Rainfall (mm/day)
−0.1
0.0
0.1
0.2
0.4
Delta Magnitude (mm/day)

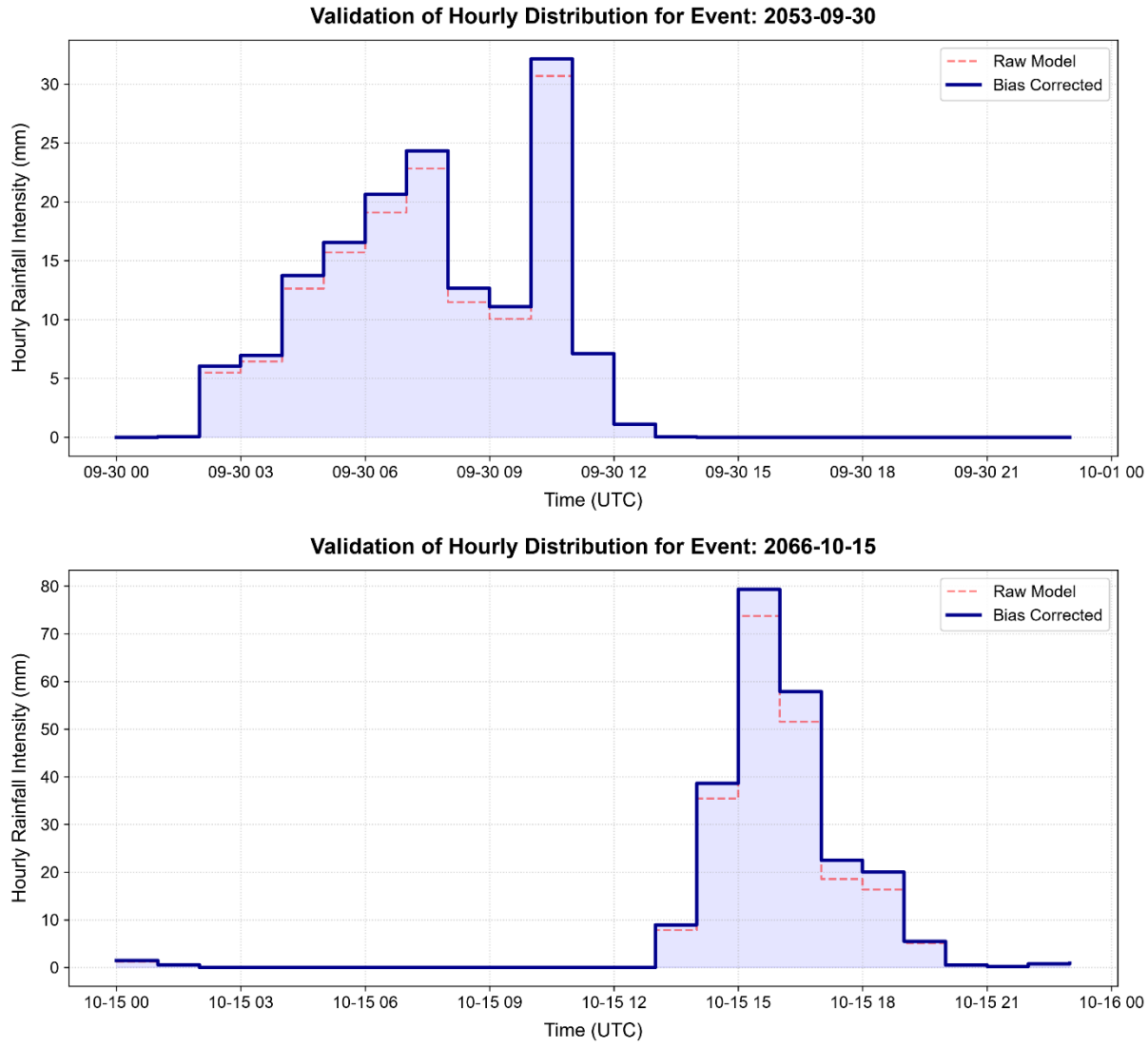


Figure S3. Confirmation of the temporal distribution of model data after daily QDM bias correction for a specific extreme event over a 24-hour period. Model hourly output data were aggregated to a daily time and bias-corrected, then disaggregated back to the original hourly model grid. It verifies the mass conservation and the sequence preservation by plotting the hourly distribution of the bias-corrected model data for a certain selected extreme 24-hour event against the original hourly model data

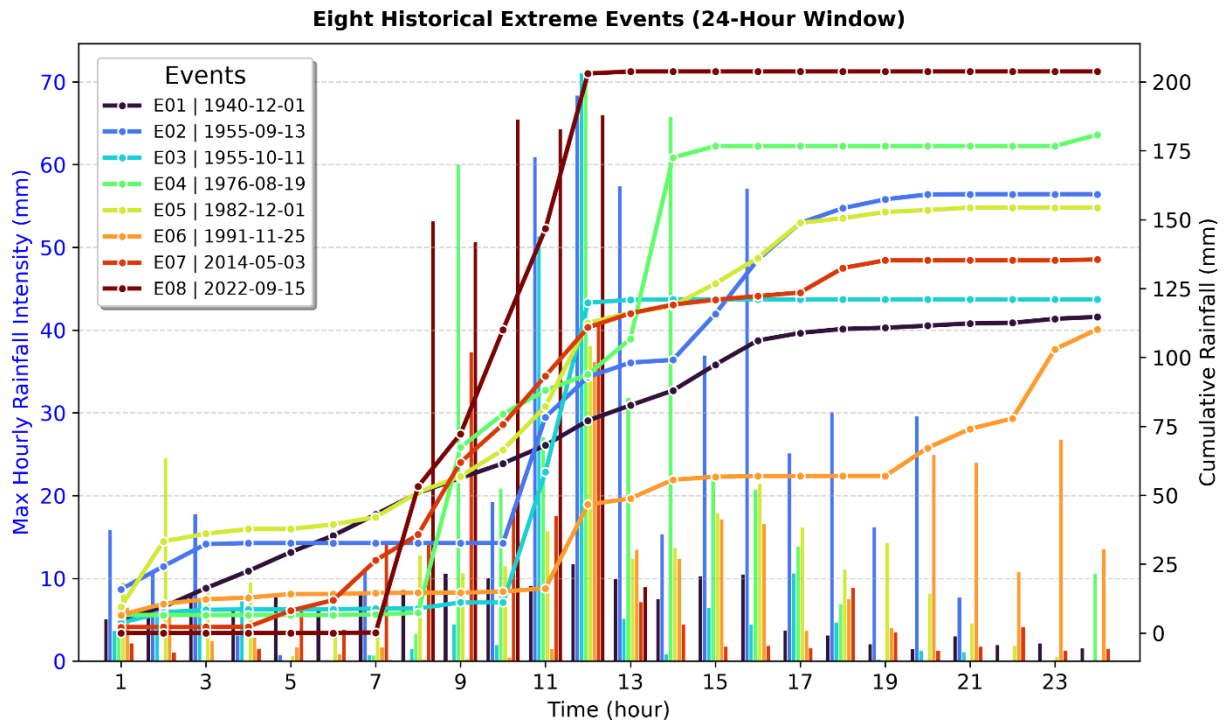


Figure S4. The historical extreme events of temporal distribution of 24-hour periods. The selected top eight extreme events, such as 01 Dec 1940, 13 Sept 1955, 11 Oct 1955, 19 Aug 1976, 01 Dec 1982, 25 Nov 1991, 03 May 2014, and 15 Sept 2022, cause flooding in the Misa River basin and are hindcasted by the WRF model and reconstruct hourly rainfall distribution.

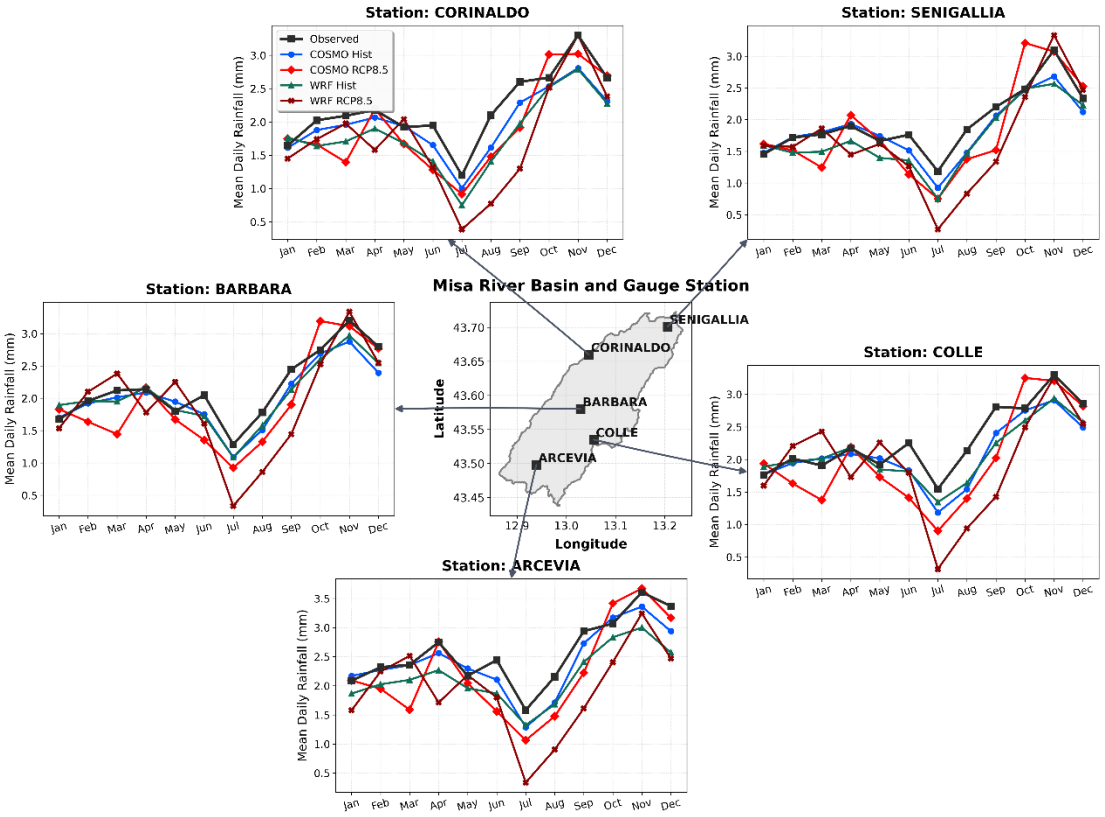


Figure S5. Nearest grid-to-station point (<4 km buffer) of seasonal climatology of mean daily rainfall comparison under the historical observed and model periods (1979/81–2008) and future projection period (2039–2068): Observed (black line); COSMO model results of the blue line (historical) and light red line (RCP8.5); and the WRF model results of the green line (historical) and dark red line (RCP8.5). The central map/boundary of the Misa River basin and its weather stations, such as Arcevia, Barbara, Colle, Corinaldo, and Senigallia stations.

Table S2. Basin average statistical summary of historical observed, historical raw model and corrected model values

Summary Statistics	Observed	Raw COSMO	Corr. COSMO	Raw WRF	Corr. WRF
Mean (mm d^{-1})	2.23	1.81	2.07	2.25	1.98
Std dev (mm d^{-1})	5.70	4.73	5.59	6.59	5.76
Wet day freq. (%)	40.40	37.65	37.04	38.21	36.03
P90 wet days (mm)	14.48	12.81	15.49	15.93	14.98
P99 wet days (mm)	40.24	32.15	37.60	46.92	41.13
Max (mm d^{-1})	70.64	60.64	68.44	98.67	86.61

Table S3. Comparison of extreme rainfall percentiles (90th, 95th, 99th) values between observed data and WRF and COSMO model simulations of raw versus bias-corrected using a <4 km buffer surrounding each gauging station.

		WRF			COSMO		
Station	**Dataset**	**90th**	**95th**	**99th**	**90th**	**95th**	**99th**
ARCEVIA	Obs.	8.24	15.3	33.46	8.38	15.66	34.15
	Raw	7.33	14.6	37.19	6.85	12.74	28.17
	Corr.	7.19	14.72	33.90	7.45	15.31	33.48
BARBARA	Obs.	6.74	13.03	29.51	6.67	13.12	29.46
	Raw	6.27	13.94	35.36	5.23	10.32	23.27
	Corr.	6.23	12.81	31.36	6.12	13.12	28.84
COLLE	Obs.	6.87	13.70	30.86	6.77	13.63	30.78
	Raw	6.64	13.30	34.07	5.81	10.98	25.17
	Corr.	6.87	13.65	31.92	6.68	12.95	30.54
CORINALDO	Obs.	6.77	12.94	29.96	6.65	12.74	29.54
	Raw	6.07	12.85	32.29	5.25	10.43	23.81
	Corr.	5.99	12.58	30.68	5.91	12.39	29.41
SENIGALLIA	Obs.	5.81	11.32	28.21	5.80	11.2	27.38
	Raw	5.57	11.37	31.80	4.96	9.66	21.29
	Corr.	5.76	11.26	30.44	5.39	11.01	27.38

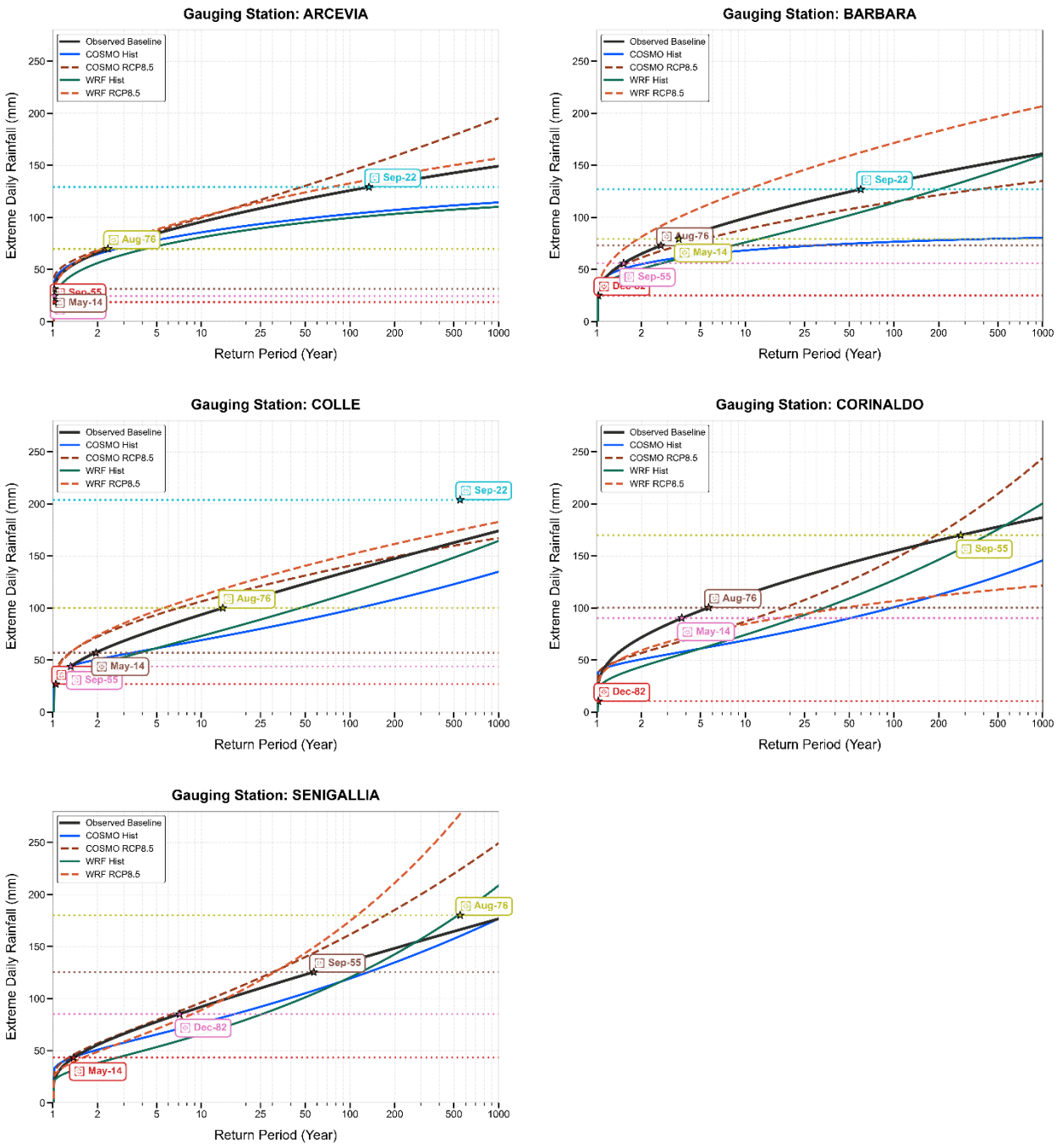


Figure S6. Daily extreme rainfall and its return periods at each gauging point of the nearest model grids with a less than 4 km buffer for the historical observed (1951-2023), historical model (1979/81-2008), and future (2039-2068) data: The extreme rainfall return periods' fit lines graph of the COSMO historical model (blue line), WRF historical model (green line), COSMO RCP 8.5 (dark broken red line), WRF RCP 8.5 (light broken red line), and historical observed extremes (horizontal broken lines) in each station level.

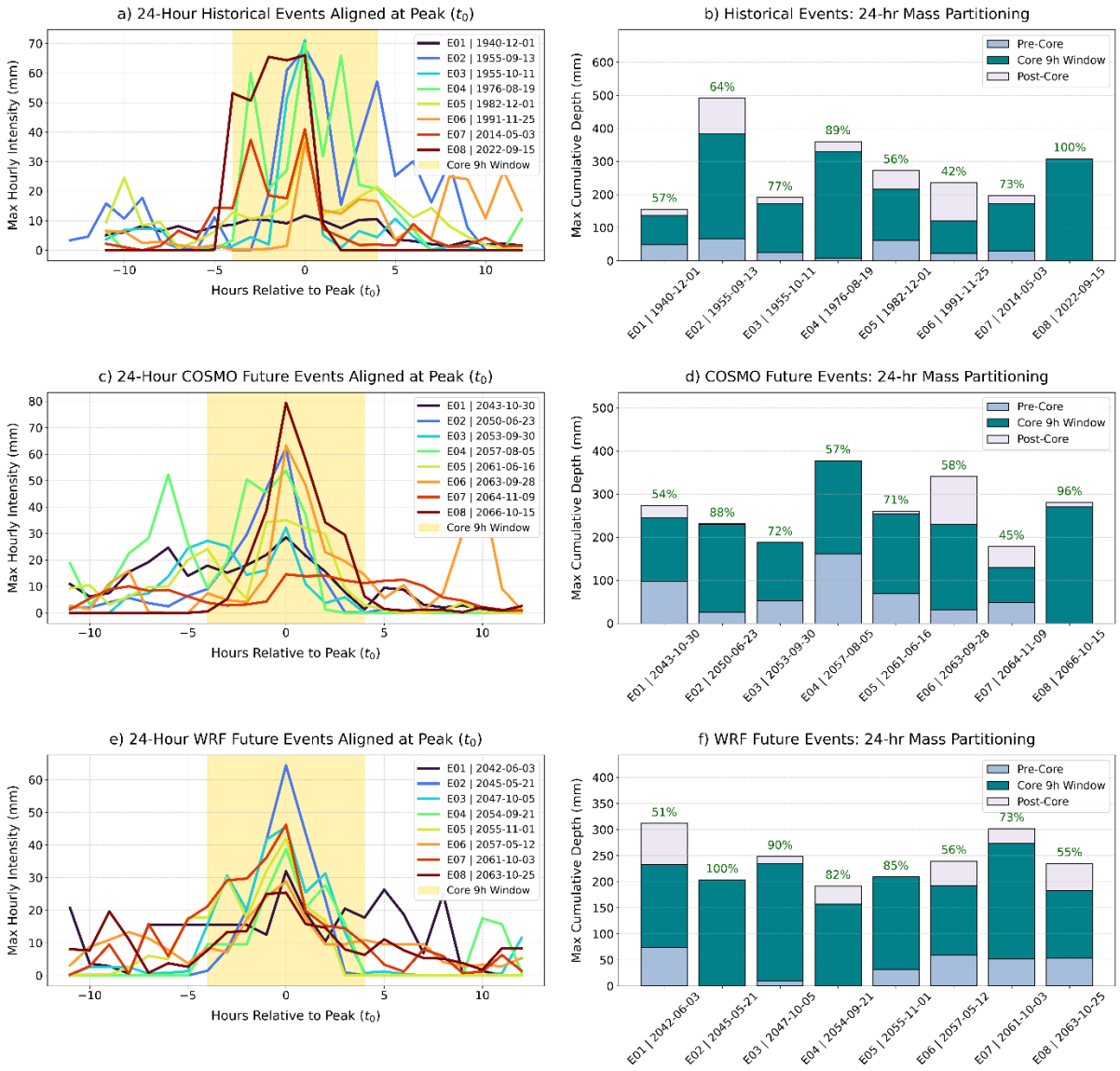


Figure S7: Sensitivity analysis of historical and future temporal concentration of rainfall within the selected 9-hour window relative to the full 24-hour period. Mass partitioning of total 24-hour rainfall depth is divided into pre-core (t < -4 h), core 9-hour window (t = ±4 h, relative to peak intensity (to)), and post-core (t > +4 h) stages. Panels **(a)**, **(c)**, and **(e)** show maximum intensity and concentration time; panels **(b)**, **(d)**, and **(f)** show the cumulative maximum depth amount and its sensitivity to the selected 9-hour core window relative to the remaining pre-core and post-core periods of the historical and future periods of each extreme. The percentages show the amount of cumulative rainfall depth captured in the core 9-hour window of each extreme event from a 24-hour total in panels **(b)**, **(d)**, and **(f)**.