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Extreme heat and mortality in the state of Rio de Janeiro in November 2023: attribution to climate change and ENSO

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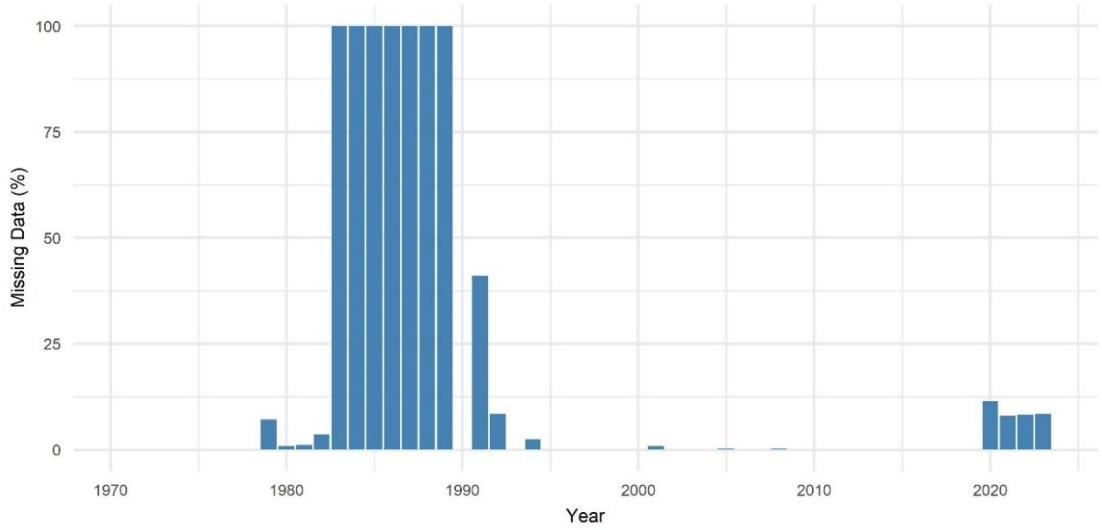

Figure S1. Percentage of missing maximum temperature data by year in Itaperuna station for the 1971-2023 period.

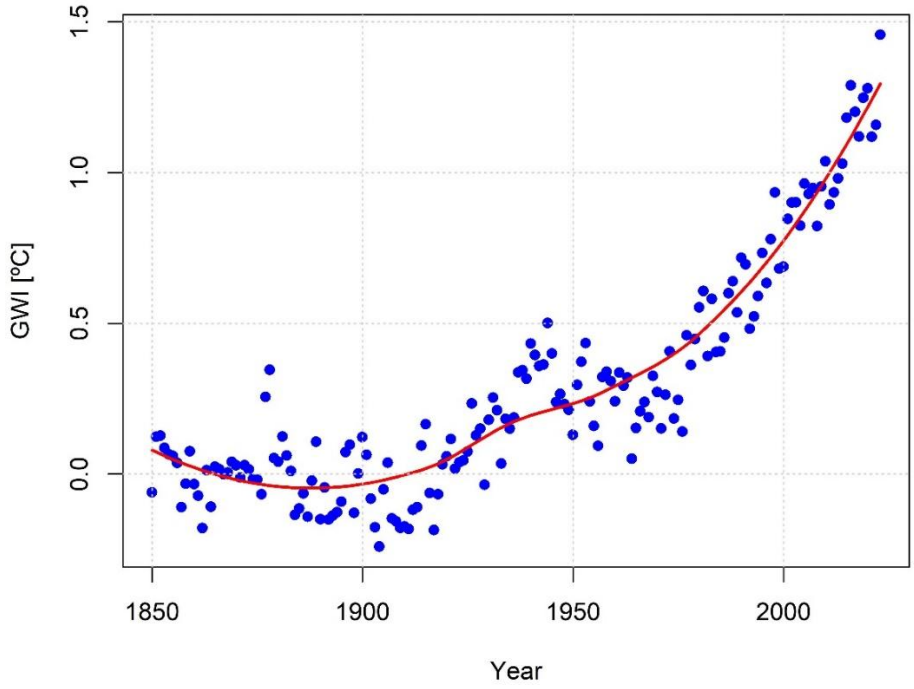

Figure S2. Global Warming Index (red line, in °C) based on the global mean temperature anomalies (with respect to 1850-1900) observed for each year (dots).

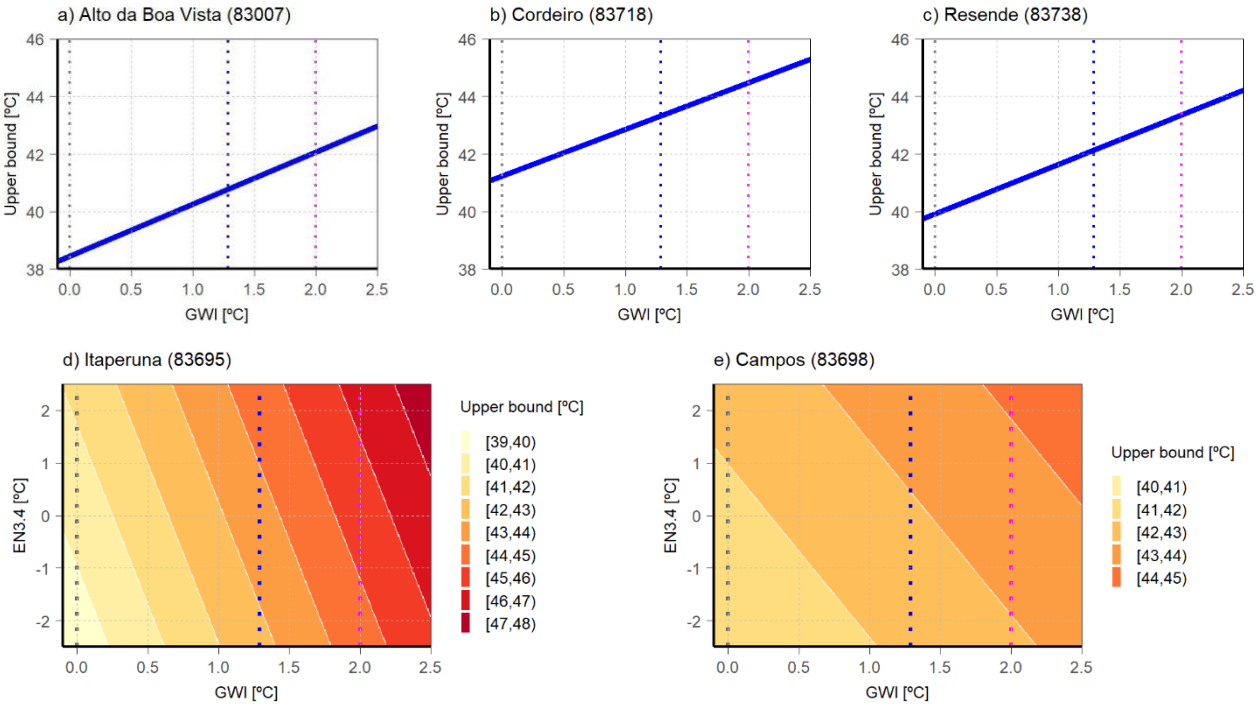

Figure S3: Upper bound of extreme temperatures obtained for the nonstationary GEV distribution with negative shape parameter [°C]. This upper bound depends linearly on the covariates GWI and EN3.4.

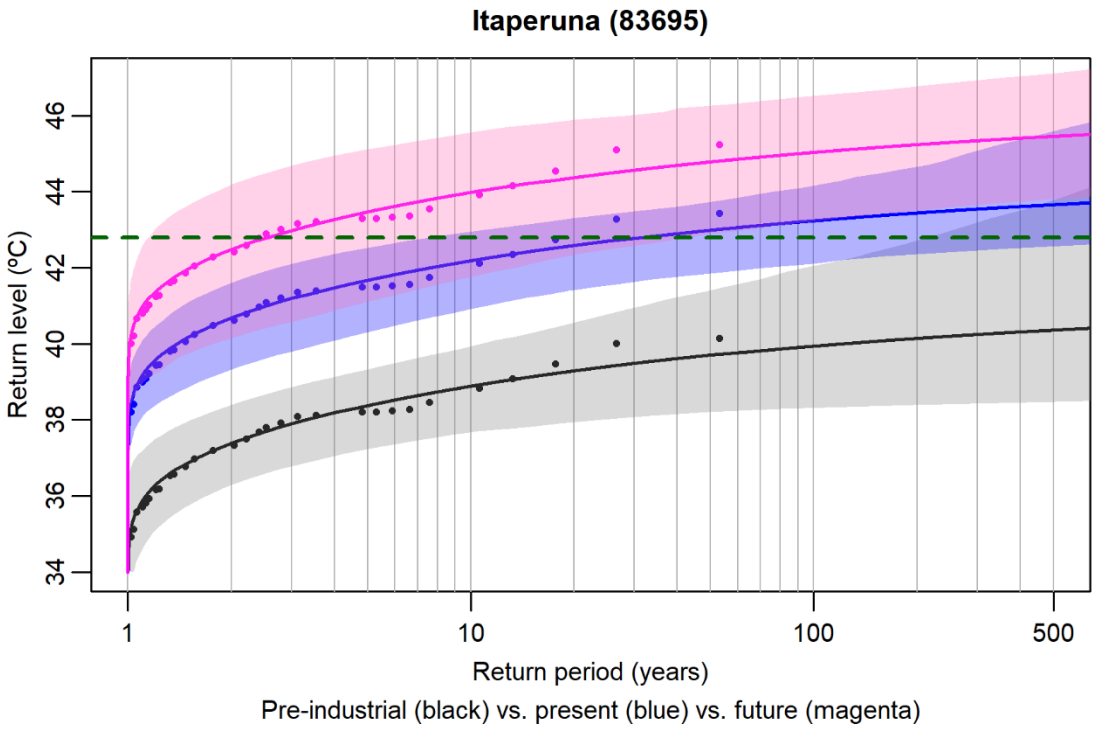

Figure S4. Frequency-magnitude TXx at Itaperuna station for 2023-like El Niño conditions and pre-industrial (black line, GWI = 0.00°C), present (blue line, GWI = 1.29°C) and future (magenta line, GWI = 2.00°C) climates according to a non-stationary GEV (M_{3_multi}). The corresponding 90% confidence intervals are shown in shading. Observed extreme temperature values are plotted as points and shown three times—shifted to represent pre-industrial, present-day (2023), and future climates—by subtracting or adding the product of the global warming index (GWI) and the estimated GWI coefficient from the non-stationary GEV model's location parameter.. Horizontal dashed line denotes the magnitude of the observed event (2023 TXx, Table 1).

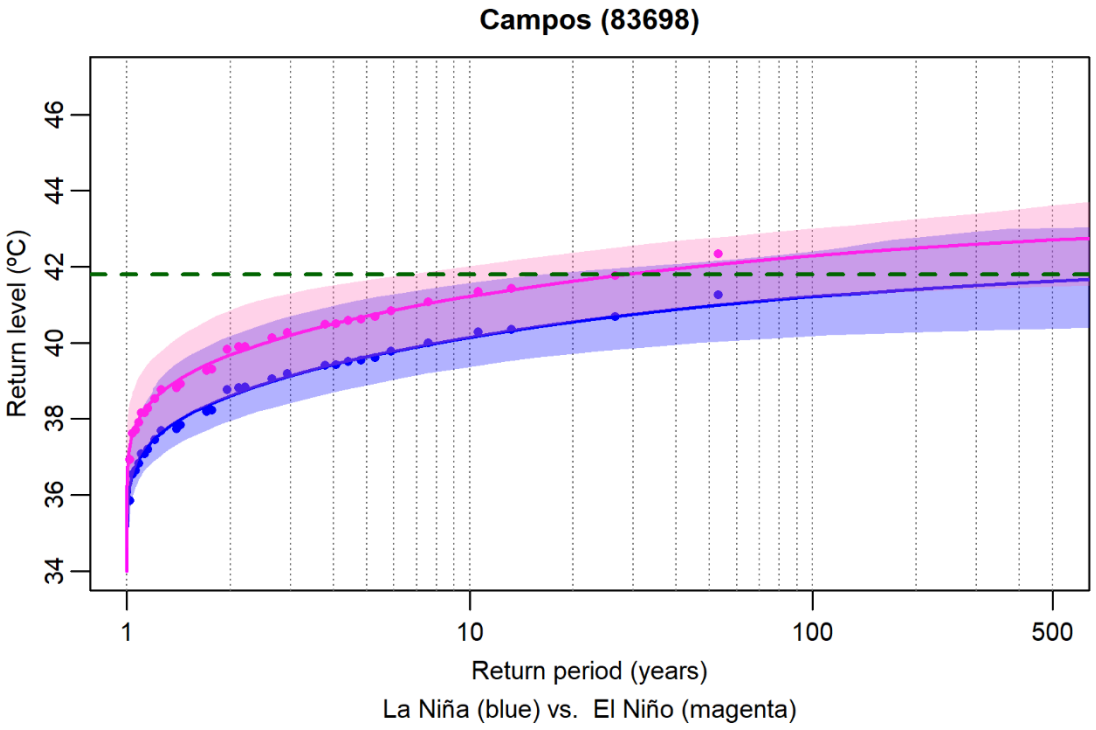

Figure S5. Frequency-magnitude curve of TXx at Campos station for present-day climate (GWI = 1.29°C) and strong La Niña (EN3.4 = -2°C) and strong El Niño (EN3.4 = 2°C) conditions according to a non-stationary GEV (M_{3_multi}). The corresponding 90% confidence intervals are shown in shading. Observed extreme temperature values are plotted as points and shown two times—shifted to represent El Niño and La Niña—by subtracting or adding the product of the EN3.4 index and the estimated EN3.4 coefficient from the non-stationary GEV model's location parameter.. Horizontal dashed line denotes the magnitude of the observed event (2023 TXx, Table 1).

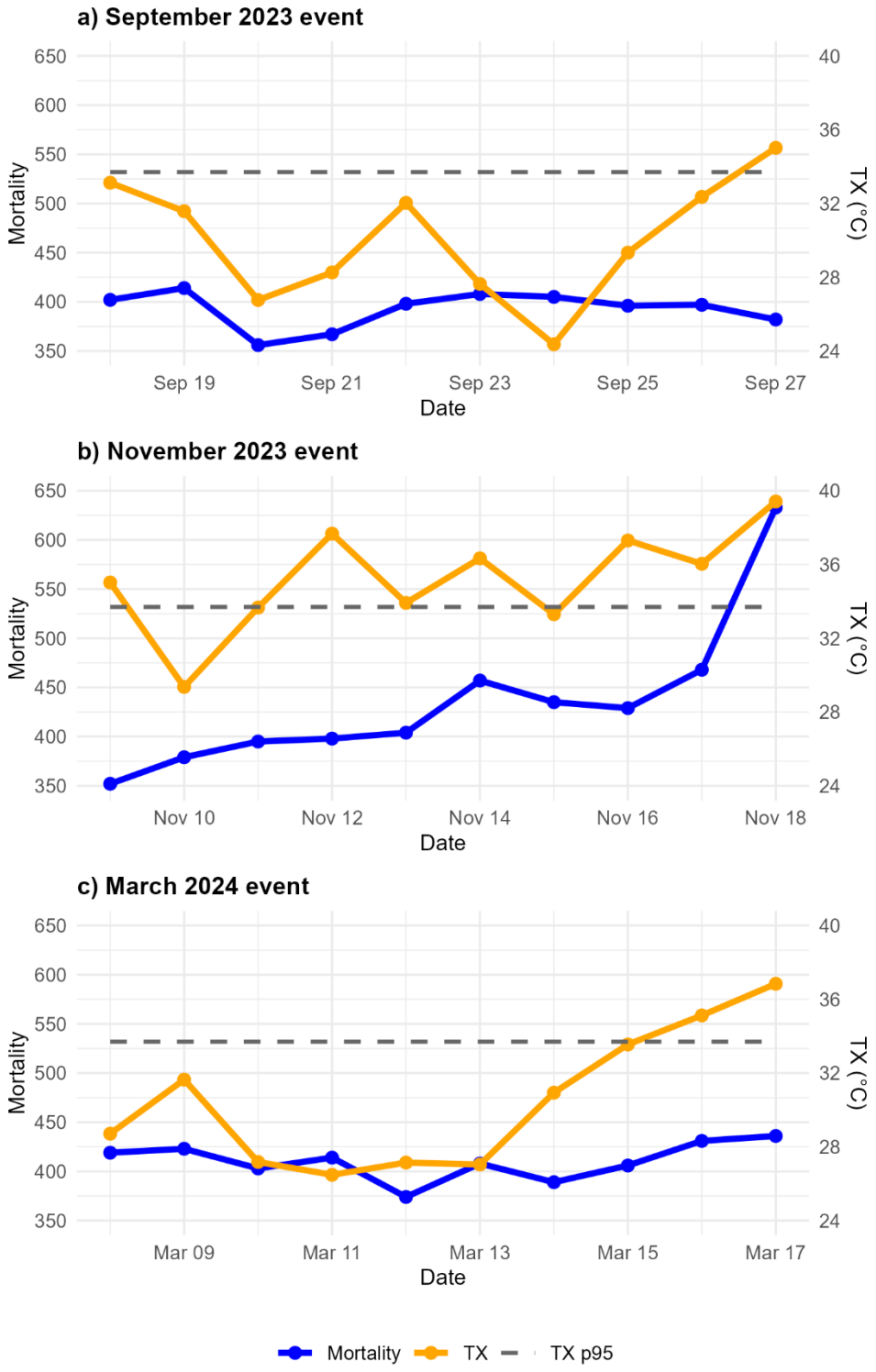

Figure S6. Evolution of mortality and maximum temperature (TX) during 10 days prior to the peak of the extreme events of September 2023, November 2023 and March 2024.

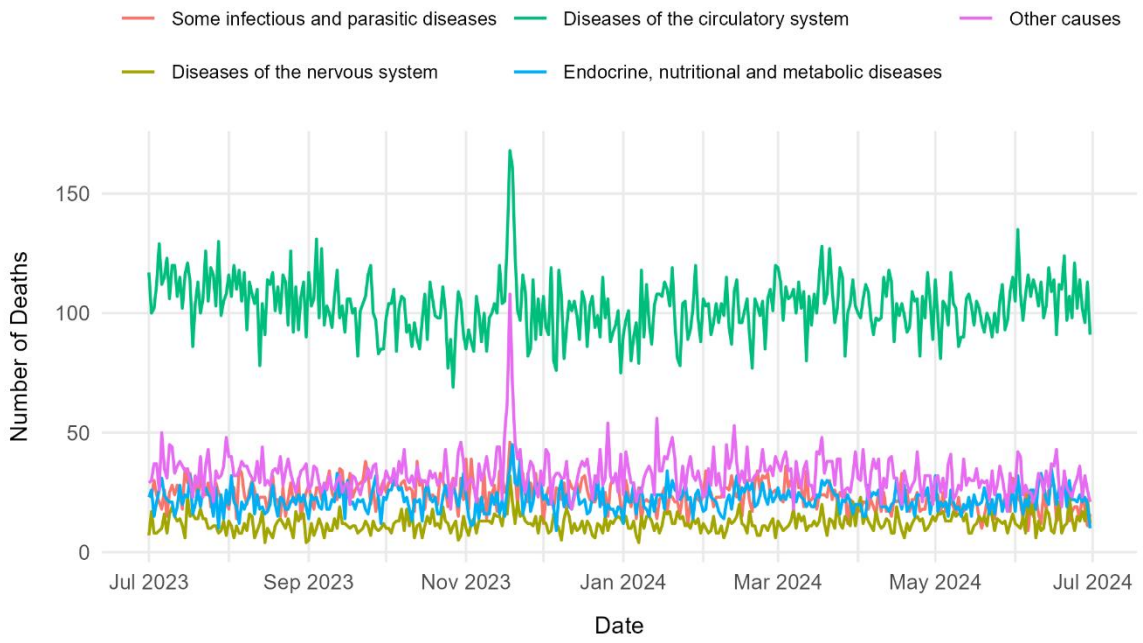

Fig. S7: Daily evolution of deaths by causality in the Rio de Janeiro State during 2023/24. Only those causes that presented a maximum on November 18, 2023 are shown.

ID	Station	Latitude	Longitude	Altitude [m.a.s.l]	Population according to the last census 2022 (*)	Initial Date [YYYY-MM-DD]	Final Date [YYYY-MM-DD]	Missing Data (1971-2024) [%]	Missing Data (2023-09-01-2024-03-20) [%]
83007	Alto da Boa Vista	-22.97	-43.28	347.1	6,211,223	1966-05-31	2024-03-20	7.56	0.00
83695	Itaperuna	-21.20	-41.91	123.6	101,041	1961-01-01	2024-03-20	15.00	10.40
83698	Campos	-21.74	-41.33	11.2	483,540	1961-01-01	2024-03-20	4.77	0.00
83718	Cordeiro	-22.02	-42.36	505.9	20,783	1971-07-15	2024-03-20	6,37	14.85
83738	Resende	-22.45	-44.44	439.9	129,612	1961-01-01	2024-03-20	8.00	0.00

Table S1. Metadata of the weather stations used in this work. (*) The census data can be consulted on the website of the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística, https://censo2022.ibge.gov.br/panorama/?utm_source=ibge&utm_medium=home&utm_campaign=portal).

Sensitivity		Relative Risk		
		Pre-industrial	Present	Future
Lag	7	1.30 (CI 1.27-1.34)	1.45 (CI 1.37-1.52)	1.53 (CI 1.44-1.64)
	10	1.33 (CI 1.29-1.38)	1.49 (CI 1.40-1.58)	1.59 (CI 1.47-1.72)
	14	1.32 (CI 1.27-1.38)	1.49 (CI 1.38-1.60)	1.59 (CI 1.44-1.75)
	21	1.28 (CI 1.21-1.35)	1.40 (CI 1.27-1.56)	1.48 (CI 1.30-1.69)
crossbasis degrees of freedom of exposure	3	1.30 (CI 1.28-1.33)	1.44 (CI 1.40-1.49)	1.53 (CI 1.47-1.59)
	5	1.30 (CI 1.27-1.34)	1.45 (CI 1.37-1.52)	1.53 (CI 1.44-1.64)
	7	1.30 (CI 1.25-1.35)	1.43 (CI 1.33-1.54)	1.52 (CI 1.38-1.66)
crossbasis lag degrees of freedom	2	1.30 (CI 1.27-1.34)	1.44 (CI 1.37-1.52)	1.53 (CI 1.43-1.63)
	4	1.30 (CI 1.27-1.34)	1.45 (CI 1.37-1.52)	1.53 (CI 1.44-1.64)
	6	1.30 (CI 1.27-1.34)	1.45 (CI 1.37-1.52)	1.53 (CI 1.44-1.64)
degrees of freedom of time per year	4	1.33 (CI 1.30-1.37)	1.50 (CI 1.43-1.58)	1.61 (CI 1.51-1.71)
	8	1.30 (CI 1.27-1.34)	1.45 (CI 1.37-1.52)	1.53 (CI 1.44-1.64)
	12	1.30 (CI 1.26-1.34)	1.45 (CI 1.37-1.53)	1.54 (CI 1.43-1.64)

Table S2. Sensitivity analysis of relative risk to varying the specifications of the models used to represent the relationship between heat and mortality.

	M_{0_S}	M_{1_gwi}	$M_{2\_en3.4}$	M_{3_multi}
Alto da Boa Vista (83007)				
M_{1_gwi}	Yes	x	Yes	No
$M_{2\_en3.4}$	No	No	x	No
M_{3_multi}	Yes	No	Yes	x
Itaperuna (83695)				
M_{1_gwi}	Yes	x	Yes	No
$M_{2\_en3.4}$	Yes	No	x	No
M_{3_multi}	Yes	Yes	Yes	x
Campos (83698)				
M_{1_gwi}	No	x	No	No
$M_{2\_en3.4}$	No	No	x	No
M_{3_multi}	Yes	No	No	x
Cordeiro (83718)				
M_{1_gwi}	Yes	x	Yes	No
$M_{2\_en3.4}$	No	No	X	No
M_{3_multi}	Yes	No	Yes	x
Resende (83738)				
M_{1_gwi}	Yes	x	Yes	No
$M_{2\_en3.4}$	No	No	X	No
M_{3_multi}	Yes	No	Yes	x

Table S3. Likelihood ratio test results at 5% significance level for each weather station. Cells indicate whether the models displayed in the rows are significantly better than those in the columns.

	Criterion	M_{0_S}	M_{1_gwi}	$M_{2\_en3.4}$	M_{2_oni}	$M_{2\_soi\_monthly}$	$M_{2\_soi\_season}$	$M_{3\_multi\_en3.4}$	$M_{3\_multi\_oni}$	$M_{3\_multi\_soi\_monthly}$	$M_{3\_multi\_soi\_season}$
Alto da Boa Vista (83007)	AIC	182.91	175.72	182.70	183.50	184.65	184.34	175.69 *	176.07	176.44	176.23
	BIC	188.82	183.60 *	190.59	191.38	192.53	192.22	185.55	185.92	186.29	186.08
Itaperuna (83695)	AIC	188.25	177.74	186.19	186.88	187.60	187.83	173.40	172.59 *	173.26	173.75
	BIC	194.16	185.62	194.07	194.76	195.48	195.15	183.25	182.44 *	183.11	183.60
Campos (83698)	AIC	177.53	178.09	176.54	176.79	178.29	178.75	176.48	176.44 *	178.26	178.72
	BIC	183.44 *	185.97	184.42	184.67	186.17	186.63	186.33	186.30	188.11	188.57
Cordeiro (83718)	AIC	182.47	178.01	183.12	183.39	184.37	184.04	177.91	177.84 *	178.91	178.03
	BIC	188.38	185.89 *	191.01	191.27	192.26	191.92	187.76	187.69	188.76	187.88
Resende (83738)	AIC	176.24	169.89 *	177.94	178.02	177.85	178.06	171.70	171.60	171.87	171.89
	BIC	182.15	177.77 *	185.82	185.90	185.74	185.94	181.55	181.45	181.72	181.74

Table S4: Sensitivity of the GEV fit to the ENSO index used.

ID	Station	Model	Probability under present climate [%]	Probability under future climate [%]	Probability ratio (Future w.r.t present)
83007	Alto da Boa Vista	M_{1_gwi}	3.29 (CI 0.02 — 9.04)	26.04 (CI 2.53 — 70.42)	7.94 (CI 4.08 — 99.60)
83695	Itaperuna	M_{3_multi}	3.17 (CI 0.02 — 13.18)	39.06 (CI 2.34 — 86.96)	12.32 (CI 2.32 — 130.12)
83698	Campos	M_{3_multi}	3.54 (CI 0.00 — 15.08)	10.76 (CI 0.11 —73.53)	3.04 (CI 0.77 — 45.37)
83718	Cordeiro	M_{1_gwi}	5.18 (CI 1.28 — 12.74)	20.00 (CI 3.61 — 6.94)	3.86 (CI 1.67 — 7.78)
83738	Resende	M_{1_gwi}	4.27 (CI 0.00 — 9.78)	23.26 (CI 3.61 — 74.63)	5.45 (CI > 2.56)

Table S5: Changes in the likelihood of extreme temperatures. Probability of occurrence of the observed TXx in 2023 in the present climate; the future climate; and rate of change of probability between future and present climate. The best GEV models are used for the estimation. For the multi-covariate model (M_{3_multi}) and all climate conditions (GWI values), we consider an EN3.4 index equal to that observed in 2023 (EN3.4 = 2.02°C).

ID	Station	Correlation between TXx and TSA	P-value
83007	Alto da Boa Vista	-0.11	0.43
83695	Itaperuna	0.07	0.62
83698	Campos	0.20	0.15
83718	Cordeiro	0.04	0.77
83738	Resende	0.26	0.06

Table S6. Spearman correlation between the hottest day of the year (TXx) and Tropical South Atlantic (TSA) Sea Surface Temperature index, after filtering the linear trends of both series.

Station	**Variable**	**Missing Data [%]**
Alto da Boa Vista	Daily mean relative humidity	88.20
	Daily minimum relative humidity	87.11
Itaperuna	Daily mean relative humidity	22.72
	Daily minimum relative humidity	22.02
Campos	Daily mean relative humidity	30.00
	Daily minimum relative humidity	25.33
Cordeiro	Daily mean relative humidity	46.73
	Daily minimum relative humidity	31.86
Resende	Daily mean relative humidity	33.02
	Daily minimum relative humidity	27.19

Table S7: Percentage of missing data in relative humidity variables for the five stations studied in the INMET dataset.