Supplementary Material for

Extreme heat and mortality in the State of Rio de Janeiro in the 2023/24 season: attribution to climate change and ENSO

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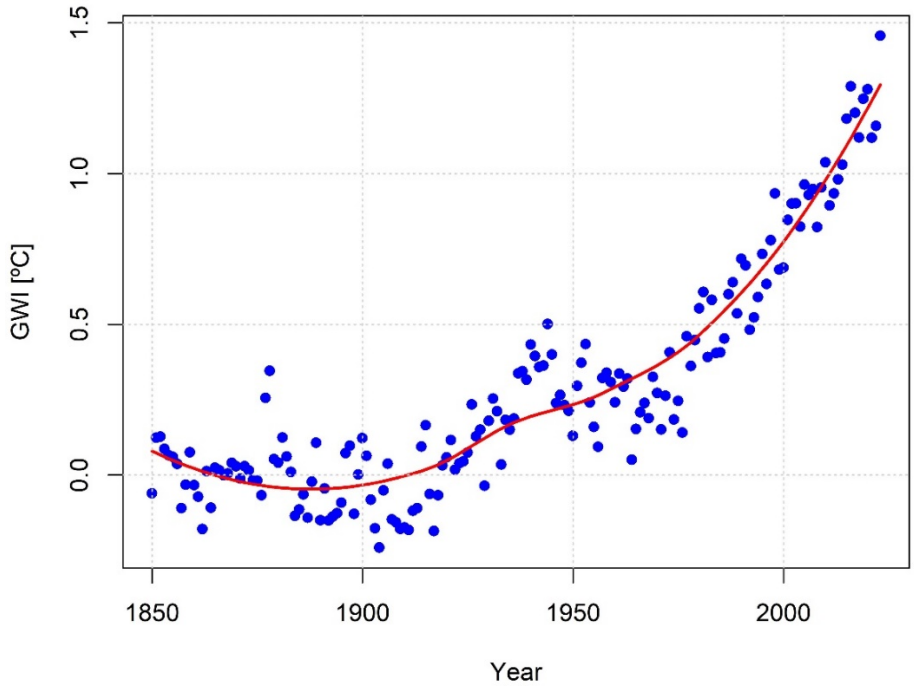

Figure S1. Global Warming Index (red line, in °C) based on the global mean temperature anomalies (with respect to 1850-1900) observed for each year (dots).

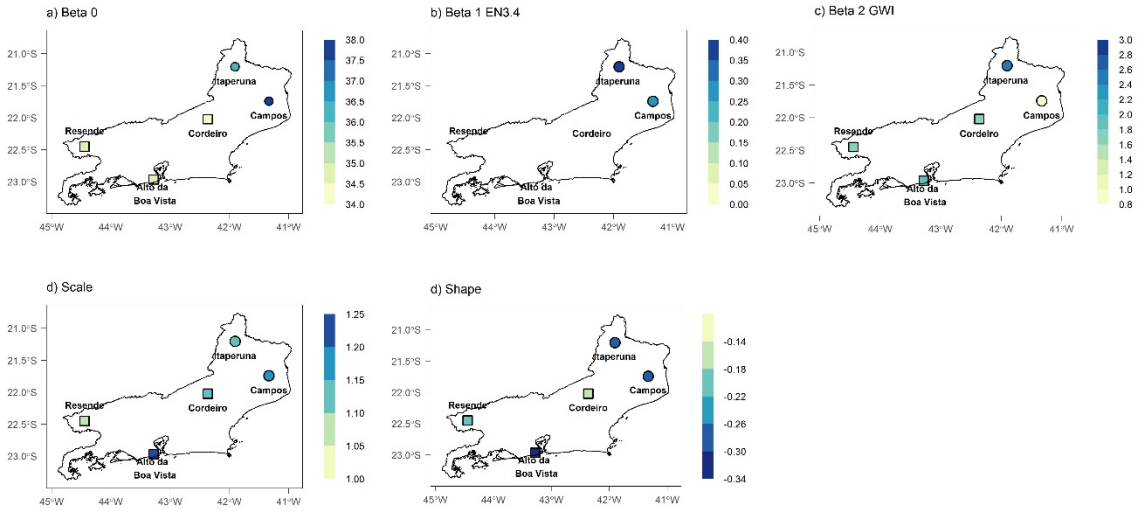

Figure S2. GEV parameters for the best model, M_{1_gwi} (square) and M_{3_multi} (circle): a) Intercept of the linear regression in Eq. 2; b) coefficient associated with EN3.4 index in the linear regression of Eq. 2; c) coefficient associated with GWI in the linear regression of Eq. 2; d) scale parameter of the GEV; e) shape parameter of the GEV.

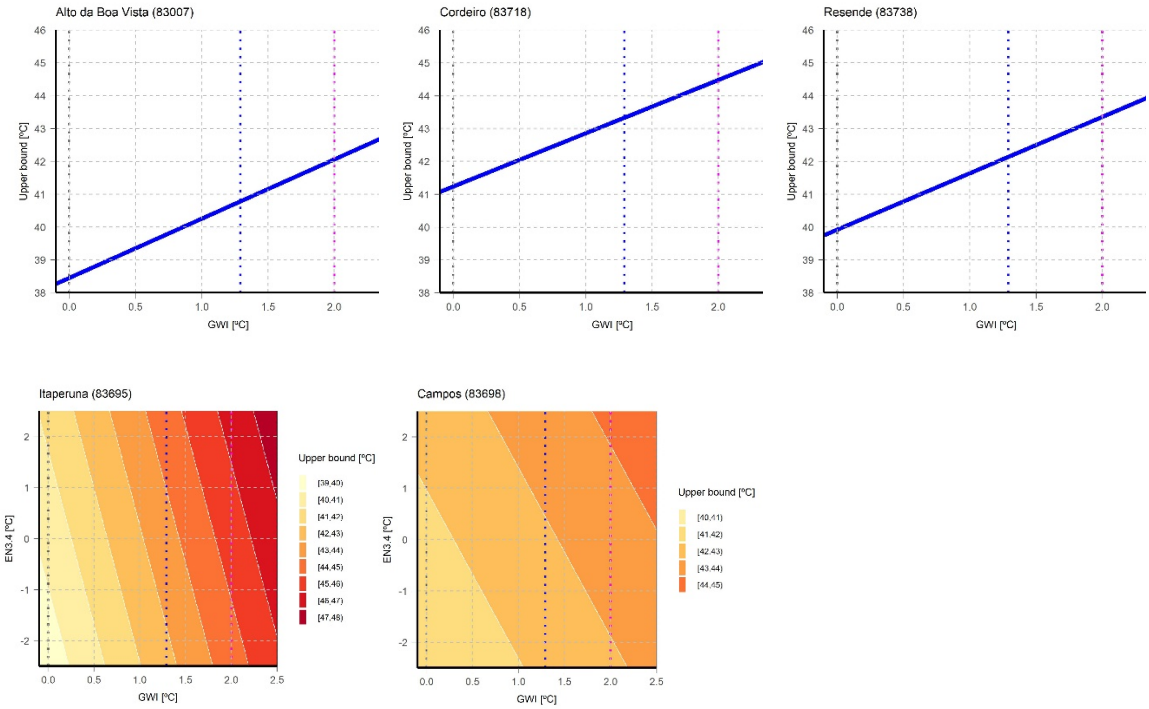

Figure S3: Upper bound of extreme temperatures obtained for the nonstationary GEV distribution with negative shape parameter [°C]. This upper bound depends linearly on the covariates GWI and EN3.4.

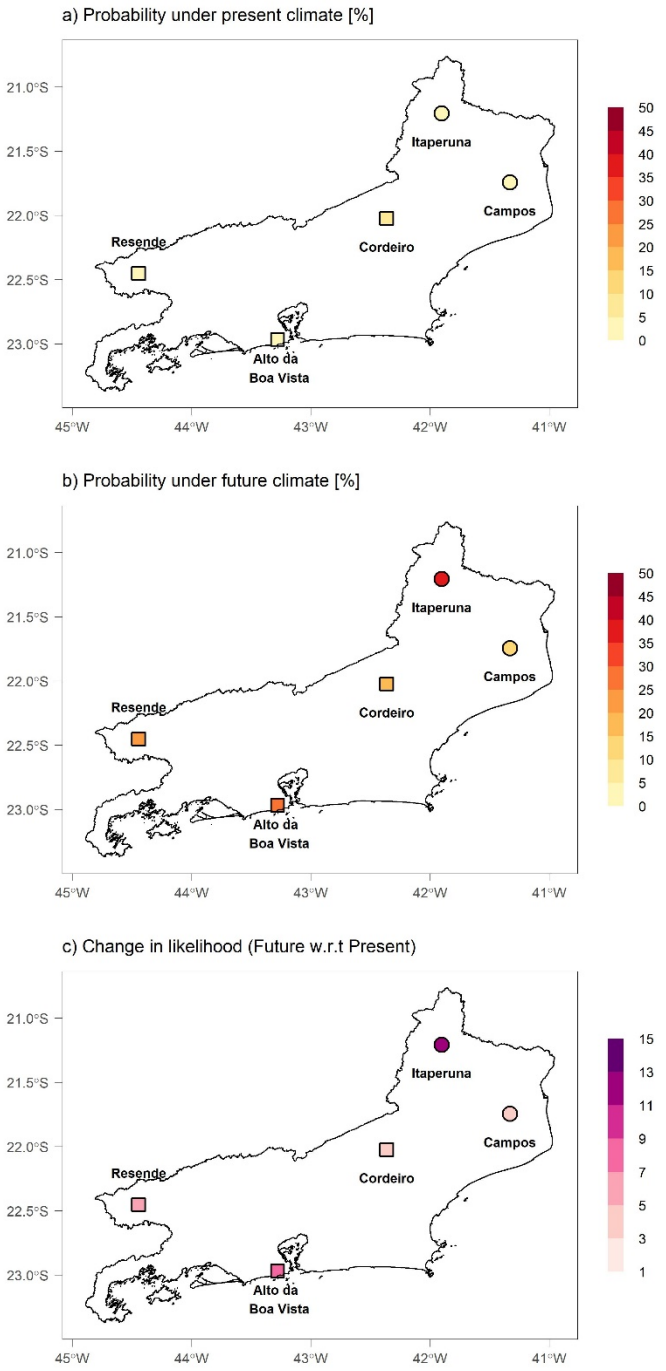

Figure S4: Changes in the likelihood of extreme temperatures. Probability of occurrence of the observed TXx in 2023 in: a) the present climate; b) the future climate; c) rate of change of probability between future and present climate. The best GEV models are used for the estimation, with squares and circles denoting M_{1_gwi} and M_{3_multi}, respectively. 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).

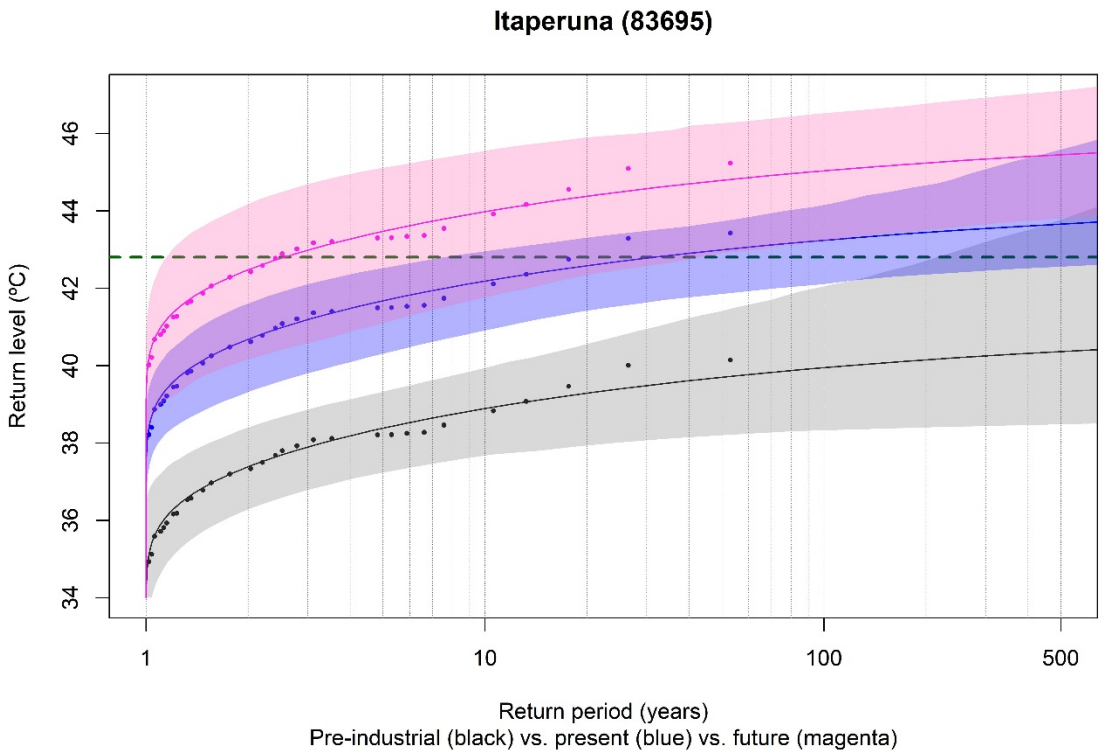

Figure S5. Frequency-magnitude TXx at Itaperuna station for 2023-like El Niño conditions and pre-industrial (black line, GWI = 0.00°C), present (blue line, GWI = 1.29°C) and future (magenta line, GWI = 2.00°C) climates according to a non-stationary GEV (M_{3_multi}). The corresponding 90% confidence intervals are shown in shading. Observations are plotted as dots. Horizontal dashed line denotes the magnitude of the observed event (2023 TXx, Table 1).

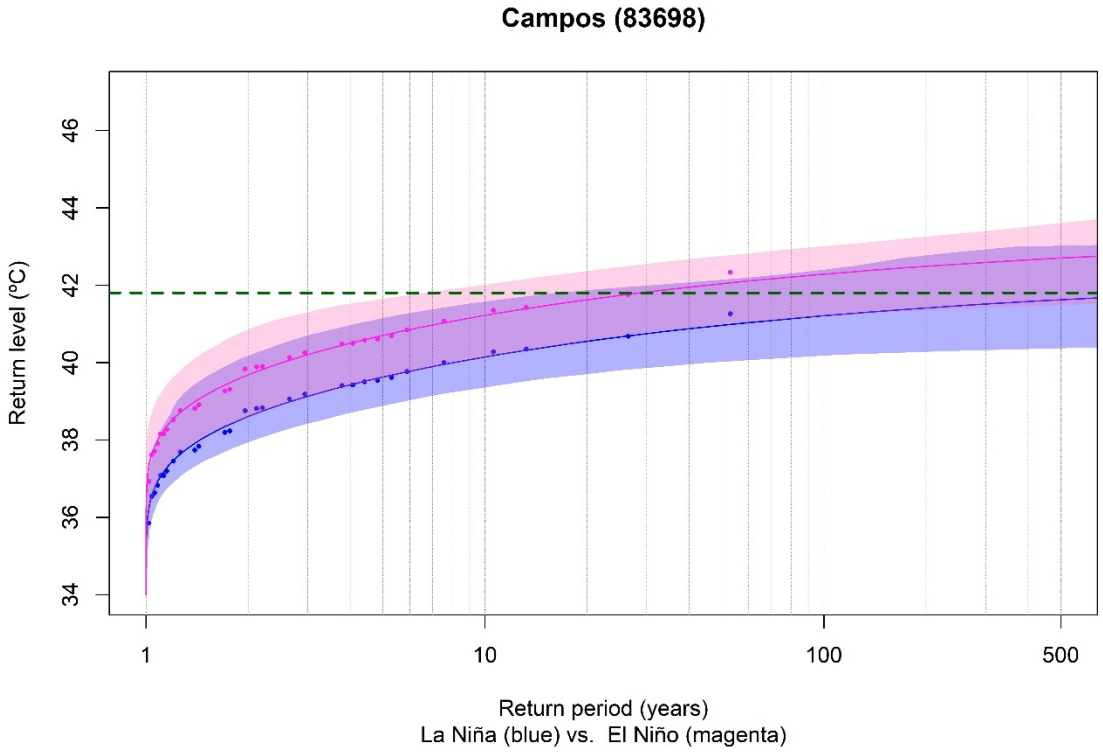

Figure S6. Frequency-magnitude curve of TXx at Campos station for present-day climate (GWI = 1.29°C) and strong La Niña (EN3.4 = -2°C) and strong El Niño (EN3.4 = 2°C) conditions according to a non-stationary GEV (M_{3_multi}). The corresponding 90% confidence intervals are shown in shading. Observations are plotted as dots. Horizontal dashed line denotes the magnitude of the observed event (2023 TXx, Table 1).

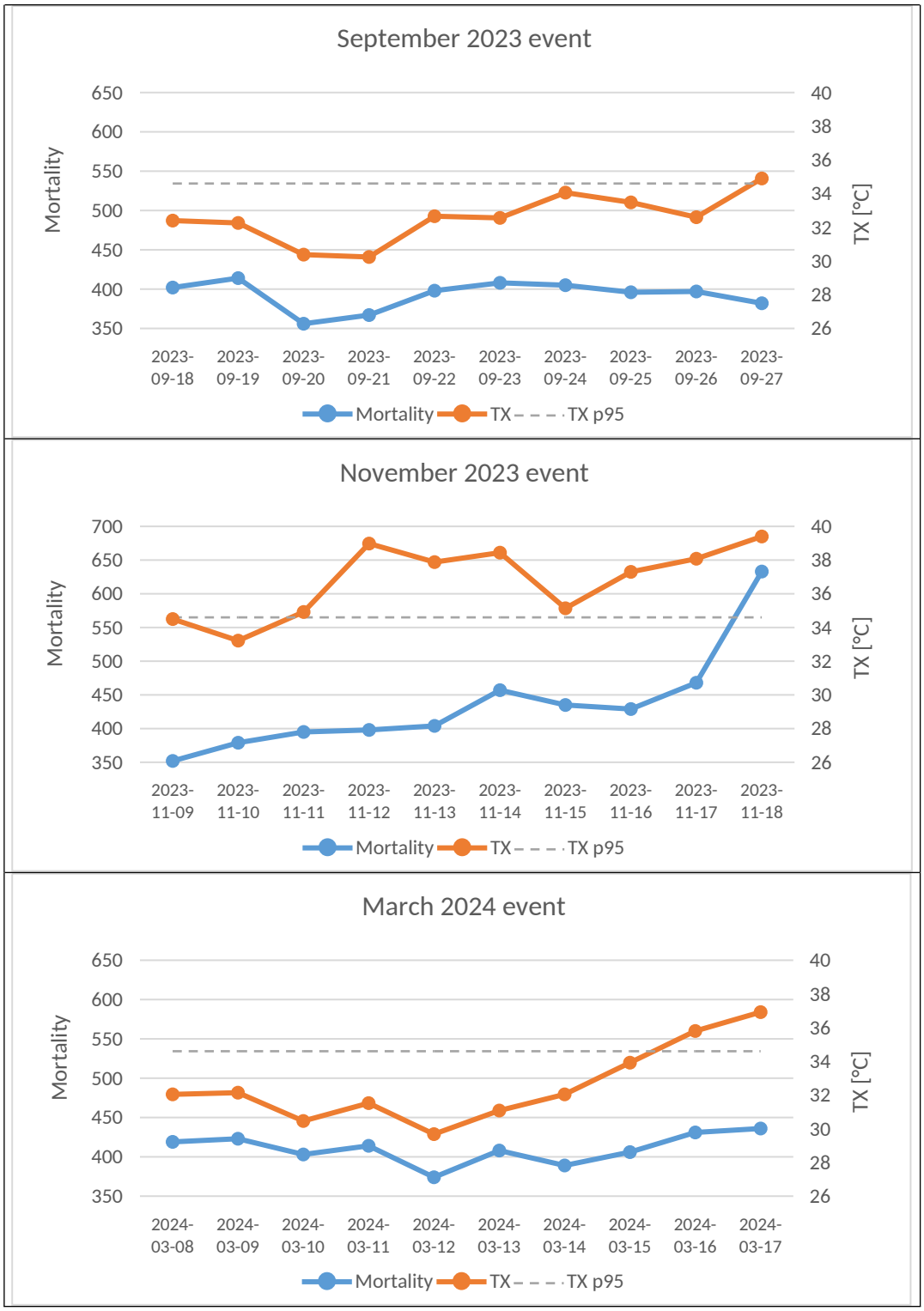

Figure S7. Evolution of mortality and maximum temperature (TX) during 10 days prior to the peak of the extreme events of September 2023, November 2023 and March 2024.

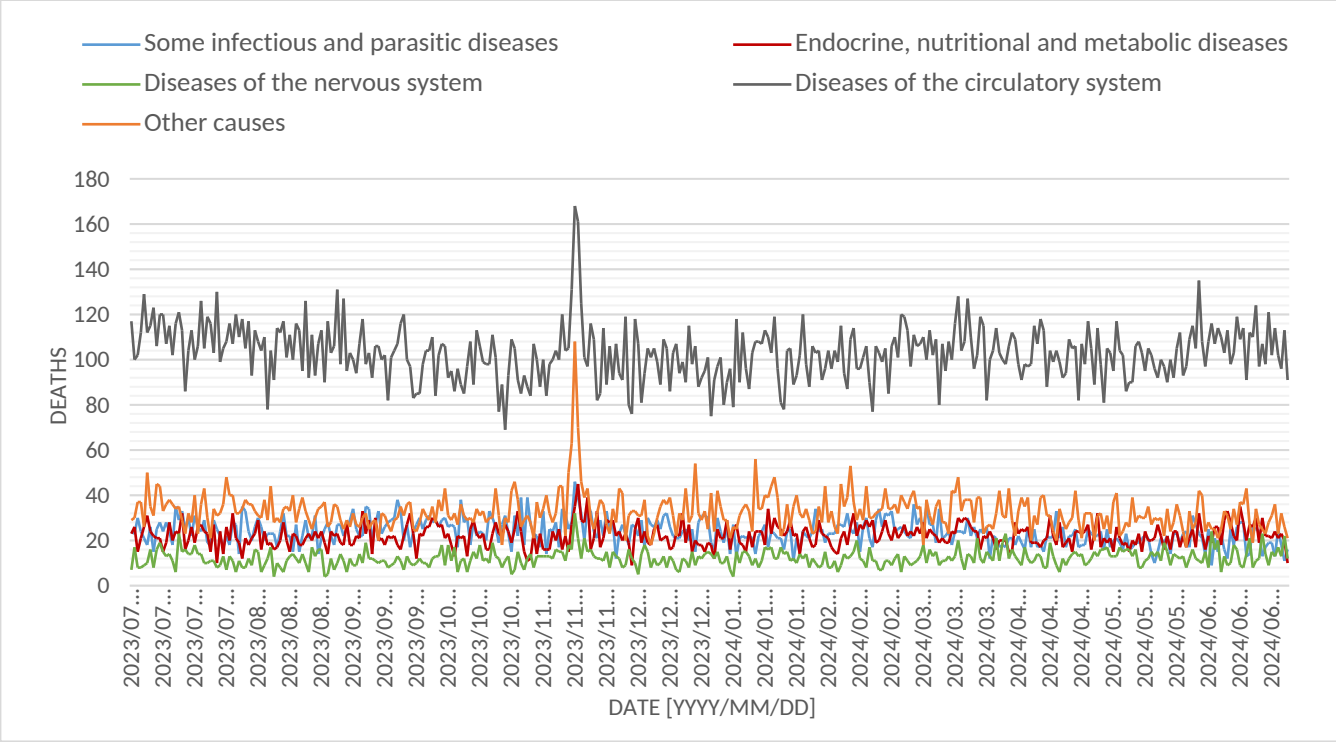

Fig. S8: Daily evolution of deaths by causality in the Rio de Janeiro State during 2023/24. Only those causes that presented a maximum on November 18, 2023 are shown.

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).

	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 S2. 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.

Sensitivity		Relative Risk		
		Pre-industrial	Present	Future
Lag	7	1.28 (CI 1.24-1.32)	1.43 (CI 1.35-1.52)	1.52 (CI 1.41-1.64)
	10	1.28 (CI 1.23-1.32)	1.40 (CI 1.31-1.50)	1.48 (CI 1.35-1.62)
	14	1.25 (CI 1.20-1-31)	1.36 (CI 1.26-1.48)	1.43 (CI 1.29-1.59)
	21	1.19 (CI 1.12-1.48)	1.25 (CI 1.12-1.39)	1.29 (CI 1.12-1.48)
crossbasis degrees of freedom of exposure	3	1.28 (CI 1.25-1.31)	1.42 (CI 1.37-1.47)	1.50 (CI 1.44-1.57)
	5	1.28 (CI 1.24-1.32)	1.43 (CI 1.35-1.52)	1.52 (CI 1.41-1.64)
	7	1.27 (CI 1.22-1.32)	1.39 (CI 1.29-1.51)	1.46 (CI 1.32-1.62)
crossbasis lag degrees of freedom	2	1.27 (CI 1.23-1.31)	1.41 (CI 1.33-1.50)	1.50 (CI 1.39-1.62)
	4	1.28 (CI 1.24-1.32)	1.43 (CI 1.35-1.52)	1.52 (CI 1.41-1.64)
	6	1.28 (CI 1.24-1.32)	1.43 (CI 1.35-1.52)	1.52 (CI 1.41-1.64)
degrees of freedom of time per year	4	1.29 (CI 1.25-1.32)	1.44 (CI 1.36-1.52)	1.53 (CI 1.43-1.64)
	8	1.28 (CI 1.24-1.32)	1.43 (CI 1.35-1.52)	1.52 (CI 1.41-1.64)
	12	1.31 (CI 1.27-1.35)	1.50 (CI 1.40-1.60)	1.61 (CI 1.49-1.75)

Table S3. Sensitivity analysis of relative risk to varying the specifications of the models used to represent the relationship between heat and mortality.

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 S4. 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.