Physical Drivers of the November 2023 Heatwave in Rio de Janeiro

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Abstract

Because extreme heat has not historically been a major hazard for the city of Rio de Janeiro, the November 2023 Heatwave magnitude and timing were staggering. Here we conduct a case study of reanalysis data and high-resolution projections to explore the event drivers and characterize the evolving extreme heat risk in the city of Rio de Janeiro. We find that the heatwave was associated with atmospheric blocking, potentially linked to the 2023-24 El Niño event. Soil moisture declines increased surface sensible heat flux, and elevated sea surface temperatures reduced coastal cooling. The heatwave was preceded by weeks of suppressed precipitation and terminated by the onset of rain. We also find a significant historical increase in the frequency of high heat days throughout Brazil and a lengthening of the heat season in the city of Rio de Janeiro. The frequency of the city's austral spring heat extremes is expected to increase further in the future, highly dependent upon our future emissions pathway. These results emphasize the rapidly emerging risk for extreme heat in the city of Rio de Janeiro.

1 Introduction

In the spring of 2023, the city of Rio de Janeiro experienced a high impact heatwave that caught the world's attention. Media sources ranging from local reporting to international news companies centered stories on the event's record-breaking temperature magnitudes and unseasonal timing, arriving earlier in the warm season than typical heatwaves (Correio Braziliense, 2023; Hughs and Jeanet, 2023). The impacts of the extreme heat were widely publicized in part due to the tragic death of a concertgoer hospitalized during a Taylor Swift performance in Rio de Janeiro on November 17, with news articles reporting heat-induced cardiovascular distress as the cause of death (Nguyen, 2023). Sources also report that the stadium in which the concert took place experienced higher temperatures than those measured in the open air, as well as a lack of cooling equipment and insufficient water for attendees (Nguyen, 2023; Jornal Nacional, 2023). Such complexities highlight that extreme heat experienced by individuals on the ground can far exceed temperatures measured at local weather stations, depending on infrastructure and the capacity for cooling interventions (Wilby et al., 2021; Nahlik et al., 2017). However, the meteorological event itself is of course one of the preconditions for societal impacts. We therefore explore the physical mechanisms behind the heatwave as one key step towards improving preparation for the impact of future extreme heat events.

46   Throughout Brazil, the highest temperatures occur climatologically in low latitude and
47   low altitude regions in the interior of the country, such as the cities of Teresina (Piauí, in the
48   Northeast region of Brazil) and Palmas (Tocantins, in the Central-West region of Brazil; Alvares
49   et al., 2013), both of which are far from Rio de Janeiro. Extreme temperatures tend to be
50   intensified by land-atmosphere interactions, as dry soils partition more energy into sensible heat
51   (Geirinhas et al., 2018). These relationships between the atmosphere and land surface processes
52   increase the likelihood of compound extreme heat and drought events and intensify impacts on
53   agriculture (Cirino et al., 2015), worker productivity for outdoor laborers (Bitencourt et al.,
54   2021), wildfire risk (Libonati et al., 2022), and direct impacts on human health (Zhao et al.,
55   2019). As the frequency and intensity of extreme heat throughout Brazil has increased
56   significantly in the past decades and is projected to continue in the future (Feron et al., 2019;
57   Regoto et al., 2021; Bitencourt et al., 2020), the widespread socio-economic impacts of these
58   events are likely to grow.
59   While Rio de Janeiro is the second most populous city in Brazil (Instituto Brasileiro de
60   Geografia e Estatística 2022) and the third most populous city in South America (United Nations
61   Department of Economic and Social Affairs Population Division 2022), few studies have
62   focused on extreme heat in the city. On one hand, Rio de Janeiro has not historically been a
63   major hotspot of extreme heat in Brazil and has experienced fewer heatwaves relative to other
64   major cities in the country (Geirinhas et al., 2018). Further, the numerous microclimates within
65   the city, influenced by its coastal setting and complex topography, complicate the study of local
66   heatwave dynamics. Indeed, there is large spatial variability in temperature extremes across the
67   Rio de Janeiro metropolitan area compared to other Brazilian cities (Alvares et al., 2013).
68   However, impactful heatwaves in recent decades have increasingly drawn attention from public
69   health officials and scientific communities alike. Recent literature has explored the dynamics and
70   mortality impacts of extreme temperatures during heatwaves in 2010 (Geirinhas et al., 2019) and
71   2013/2014 (Geirinhas et al., 2022) and has begun to investigate compound heatwave and drought
72   events throughout Southeast Brazil (Geirinhas et al., 2021). There is also building evidence that
73   temperature extremes are increasing in intensity and frequency throughout Brazil, including the
74   city of Rio de Janeiro (Regoto et al., 2021; Bitencourt et al., 2019). Climate variability also plays
75   an important role in modulating temperatures over this area, including large scale modes of
76   climate variability such as the El Niño-Southern Oscillation (Rehbein and Ambrizzi 2023; Cai et

al., 2020; Shimizu and Ambrizzi 2015), the Pacific Decadal Oscillation, and the Atlantic

Multidecadal Oscillation (He et al., 2021). Should more intense, frequent, and unseasonably

early extreme heat events take place in the future in the city of Rio de Janeiro, these heatwaves

may have increased impacts on human health due to potential exceedance of unprecedented

temperature thresholds and individuals' lack of preparation for these events. In a tropical city

where baseline temperatures are already relatively high, small shifts in the temperature

distribution can have large impacts on the frequency of extremes (Cheng et al., 2019),

particularly at thresholds relevant to human health outcomes (Vecellio et al., 2022). These health

risks are compounded by the humidity in Rio de Janeiro, a coastal city with ample moisture

sources from the ocean and surrounding vegetation, priming the region for humid heat extremes

which are physiologically more dangerous to human health than dry heat (Mora et al., 2017).

In this study, we explore the meteorological conditions that led to the extreme heat event

in November 2023 in the city of Rio de Janeiro. We identify drivers of the exceptional

magnitude and persistence of the extreme temperatures, as well as their early arrival in the

calendar year. We compare these conditions to those associated with typical heatwaves in the

region, and particularly events taking place in the spring season. We then consider how extreme

spring temperature events have shifted throughout the historical period, and how we might

expect them to change in the future with ongoing anthropogenic climate change.

2 Methods

2.1 Data

This analysis employs both station-based observations and reanalysis data. Initial

analyses are conducted on subdaily station data from the city of Rio de Janeiro, accessed via the

Met Office Hadley Center's HadISD station-based dataset (Dunn 2019) and the Rio Alert

System produced by the Rio de Janeiro City Hall (Sistema Alerta Rio da Prefeitura do Rio de

Janeiro 2024). Three airport weather stations are available from HadISD for the city of Rio de

Janeiro, namely the Galeão/Antonio Carlos Jobim International Airport (located on the island

Ilha do Governador within the Guanabara Bay), the Campo Délio Jardim De Mattos Airport (an

Air Force base located in the city's North Zone), and the Santos Dumont Airport (a waterfront

airport located near the city center). Six additional stations from the Rio Alert System dataset

record measurements from the tops of various community and commercial buildings, including

108   hotels, schools, and warehouses. These stations are located in distinct areas of the city, whose
109   topographical and coastal complexities contribute to various microclimates. These stations thus
110   record distinct values, both instantaneously and on average (see Fig. S1), a challenge that has
111   been previously identified in the literature (Lyra et al., 2018; Dereczynski et al., 2013). We
112   therefore base the majority of our analysis on reanalysis data and compare the identified patterns
113   with station data when possible. This comparison is particularly important for extreme events, as
114   the magnitude of extreme heat has been shown to be biased in reanalysis products due to their
115   spatial and temporal smoothing of observations (Rogers et al., 2021; Raymond et al., 2020).
116   Further, the human experience of heat stress is inherently hyperlocal, meaning that the distinct
117   microclimates existing throughout the city can control heat stress exposure and the efficiency of
118   adaptation strategies. However, the present study is primarily concerned with the regional drivers
119   of the extreme event rather than its absolute magnitude. Reanalysis provides continuous spatial
120   coverage and a wide array of internally consistent meteorological variables, which warrants its
121   use for the application here.
122   Hourly meteorological data are retrieved from the fifth major global reanalysis of the
123   European Centre for Medium-Range Weather Forecasts (ERA5), including 2-meter temperature,
124   2-meter dewpoint temperature, volumetric soil water for layer 1 (0-7 cm, where the surface is at
125   0 cm), surface pressure, geopotential height at 500 hPa and 200 hPa, precipitation, evaporation,
126   2-meter horizontal winds, and vertical velocity at 500 hPa (Hersbach et al., 2020). From this
127   hourly data, daily maximum temperature, daily total precipitation, and daily means of all other
128   variables are calculated from 1979-2023. Daily mean sea surface temperature (SST) data from
129   1979-2023 is also retrieved from the NOAA 1/4° Daily Optimum Interpolation Sea Surface
130   Temperature (OISST) dataset (Huang et al., 2021).
131   We also explore the future evolution of temperature extremes over the city of Rio de
132   Janeiro using the NEXGDDP dataset (Thrasher et al., 2022). This data product is statistically
133   downscaled from the Coupled Model Intercomparison Project Phase 6 (CMIP6) models, with a
134   spatial resolution of 0.25 degrees and outputs variables on a daily temporal scale. We directly
135   retrieve daily maximum temperature data through the end of the century under the Shared
136   Socioeconomic Pathways (SSPs) SSP2-4.5 and SSP5-8.5 for the 23 models which output this
137   variable and pair of scenarios for each day in the calendar year through 2100.

138   Because of Rio de Janeiro's complex coastal and mountainous terrain, projections may

139   not accurately capture fine scale differences in the city's climate. For example, recent literature

140   has shown that the coastal cooling relative to inland areas experienced in regions such as the

141   eastern United States may be underestimated by global climate models (Raymond and Mankin

142   2019). These biases are greatest in regions with large land-ocean surface temperature contrasts,

143   however, and Rio de Janeiro's location in the tropics, as well as the fact that the extreme events

144   analyzed in this study take place in the spring when this temperature gradient should be

145   relatively small, may mute these biases compared to other regions and seasons. In order to

146   address these potential sources of error, we generate a set of synthetic time series based on

147   NEXGDDP projections which retain the seasonality and variability recorded in the historical

148   reanalysis data from ERA5. We use a percentile matching technique in which we first bin all

149   data for the grid cell which includes the city of Rio de Janeiro during a historical base period

150   (1981-2013) into one-percentile bins for both the NEXGDDP and ERA5 datasets. We

151   additionally bin all NEXGDDP data from this grid cell into one-percentile bins during one

152   midcentury period (2041-2060) and one end-of-century period (2081-2100). We then calculate

153   the temperature delta for each percentile bin between the base period and both the midcentury

154   and the end-of-century periods in the NEXGDDP data. Finally, we add these percentile-specific

155   change factors to every data point in each associated bin in the historical ERA5 base period.

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157   **2.2 Methodology**

158   We first create time series for the historical day-of-year climatologies of variables in the

159   city of Rio de Janeiro and compare them to the evolution throughout 2023. All anomalies are

160   calculated relative to historical mean calendar date values (i.e., the daily maximum temperature

161   anomaly on November 18, 2023 is calculated by subtracting the mean daily maximum

162   temperatures on November 18 in all previous years in the historical record from the recorded

163   absolute magnitude of the event). We also generate maps of concurrent meteorological variables

164   relevant to the extreme heat event for the greater region outside of Rio de Janeiro. We compare

165   these spatial patterns to those experienced during previous extreme heat events in Rio de Janeiro,

166   calculated as 99th percentile daily maximum temperature days across all seasons for the grid cell

167   which includes the Galeão International Airport weather station. We then select for events that

168   occur in the September-November (SON) austral spring season.

169   We also quantify how extreme heat in the city of Rio de Janeiro is shifting using a variety

170   of methods. We first calculate the trend in the frequency of extreme temperatures over the

171   historical record in Brazil, defining these extreme temperatures using both absolute and relative

172   thresholds. We select these thresholds as 30°C and the locally defined 90th percentile daily

173   maximum temperature at each grid cell. These thresholds are chosen in order to investigate

174   impactful temperature magnitudes while ensuring sufficient sample size for the trend analysis.

175   We also visualize the broadening of the extreme heat season, calculated based on the

176   number of days between the start of the first heatwave and end of the last heatwave of the

177   season. A heatwave is defined here as a three-day period with consecutive daily maximum

178   temperatures above the 50th percentile of daily maximum temperatures across the two hottest

179   months of the year in the city of Rio de Janeiro (January and February); this 50th percentile

180   threshold is equal to about 31.4°C. This heat season definition is informed by a definition used

181   by the United States Environmental Protection Agency (US EPA 2021), adapted to better reflect

182   Rio de Janeiro's lower temporal variability in temperature due to its tropical location.

183   Finally, we calculate how spring temperature distributions have already changed in Rio

184   de Janeiro by comparing early and late historical periods in ERA5 for the grid cell which

185   includes the Galeão International Airport weather station. Distributions are calculated from

186   annual spring maximum temperatures in the city of Rio de Janeiro and fit using GEV

187   distributions, which have been shown to well capture extreme temperature distributions (Powis

188   et al., 2023; Van Oldenborgh et al., 2022). For comparison, we also plot GEV distributions for

189   early and late historical periods in the NEXGDDP model data before applying our bias-

190   correction technique. The location parameter and spread of the model data distributions during

191   these periods is much lower than that of ERA5 (Fig. S2), further motivating our use of synthetic

192   time series to explore how these distributions may change in the future.

193   We then use the bias-corrected NEXGDDP data for the 23 models which report daily

194   maximum temperature for each day in the calendar year under the aforementioned SSP2-4.5 and

195   SSP5-8.5 scenarios during a midcentury and end-of-century time period. We additionally

196   evaluate the impact of only using models which most accurately reproduce the historical

197   observed daily maximum temperature record in the city of Rio de Janeiro. We calculate the

198   Perkins skill score to evaluate the similarity between probability density functions of daily

199   maximum temperature in the reanalysis dataset (ERA5) and each of the 23 global climate models

200   during the historical period. These skill scores are calculated as the cumulative minimum

201   between the observed and modeled distributions of each binned value (Perkins et al., 2007). We

202   finally select the 6 climate models which exhibit skill scores greater than 0.8, indicating that

203   these models capture over 80% of the observed probability density functions. The result of this

204   analysis is shown in Fig. S3, but the interpretation of the results as shown in the main text using

205   all 23 models does not change.

206

207   **3 Results**

208   **3.1 Rio de Janeiro's spring 2023 heatwave**

209   The city of Rio de Janeiro experienced exceptionally high temperatures in both the

210   austral winter and spring of 2023, peaking on November 18 (Fig. 1). This record-breaking event

211   became the highest daily maximum temperature on record at the Galeão International Airport

212   weather station, reaching 41.3°C. The extreme heat event was also notable for its accompanying

213   high specific humidity, which rose alongside temperature in the days leading up to November 18

214   (Fig. 1b). The combination of elevated temperature and humidity rendered the event a humid

215   heat extreme, as measured by wet bulb temperature, which peaked at 28.2°C on November 18

216   (Fig. 1c). The coincidence of extreme dry and wet bulb temperatures is typical for extreme heat

217   events in Rio de Janeiro, where there is a statistically significant positive correlation between

218   daily maximum temperature and daily mean specific humidity (Fig. S4). This relationship is

219   facilitated by the city's abundant access to moisture from the coast and surrounding vegetation.
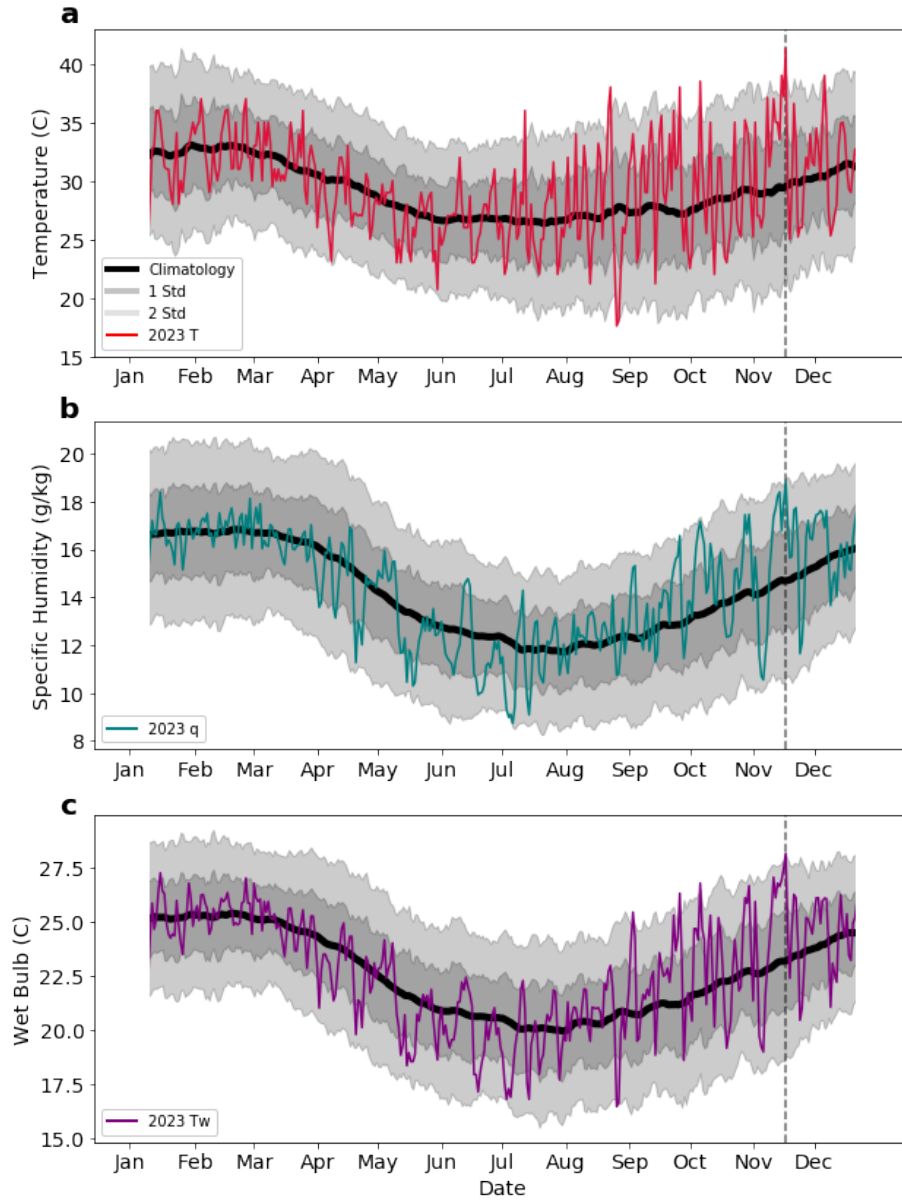
Figure 1: Historical climatology and 2023 recorded a) daily maximum temperature, b) daily mean specific humidity, and c) daily maximum wet bulb temperature in the city of Rio de Janeiro. Data from the Galeão International Airport weather station as reported by the HadISD dataset. Vertical dashed line identifies record-breaking temperature event on November 18, 2023.

Elevated temperatures occurred over an area greater than the city of Rio de Janeiro, but were spatially constrained by orography (Fig. 2). We explore the spatial patterns of the heatwave in data from the European Centre for Medium-Range Weather Forecasts (ERA5) reanalysis during the period of 1979-2023 (Hersbach et al., 2020). We see that hotspots in elevated

temperatures were located throughout the coastal region surrounding Rio de Janeiro, with sharp

declines across the mountainous terrain moving inland. These positive coastal temperature

anomalies coincide with northerly surface wind anomalies. ERA5 estimates the daily maximum

temperature on November 18 in the grid cell containing the Galeão International Airport weather

station as 40.6°C, within the range of temperatures recorded throughout weather stations in the

city (Fig. 2c; Fig. S1). This extreme event was also remarkable in length as measured by ERA5,

as daily maximum temperatures were above the locally defined 90th percentile for eight

consecutive days, and above the 99th percentile for the final three days of this period (percentiles

calculated from ERA5 across the period from 1979-2023). This multi-day interval of exceptional

temperatures rendered it difficult for residents to find relief.
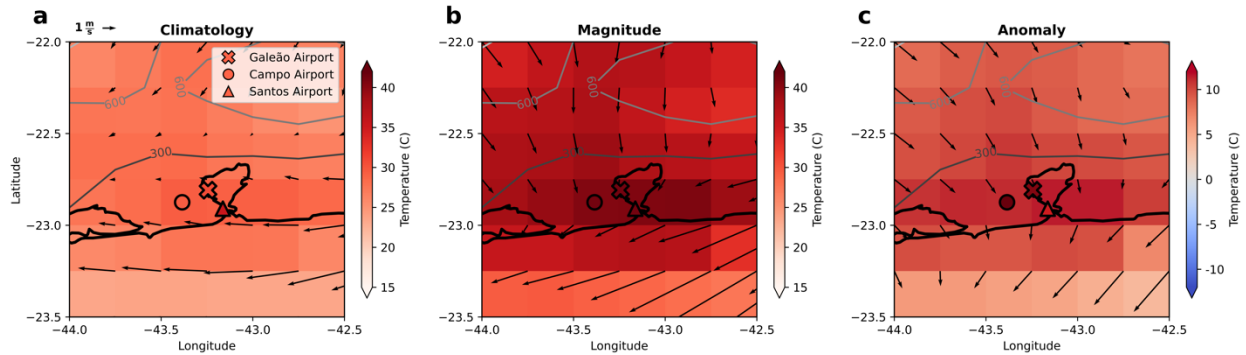
Figure 2: Spatial maps of daily maximum temperatures during the date of peak extreme heat intensity in the city of Rio de Janeiro using ERA5 data (shading) and three city weather stations with long-term temperature records (markers). Vectors represent surface winds; contours represent elevation in meters. A) Climatology during November 18 throughout the historical record. B) Magnitudes on November 18, 2023. C) Anomalies on November 18, 2023.

The maximum temperature during the event on November 18 coincided in time with

other anomalous meteorological conditions (Fig. 3; for climatological values, see Fig. S5 in the

Supplemental Materials). Positive geopotential height anomalies centered over Rio de Janeiro

were consistent with an intensification of the South American Subtropical High, a semi-

permanent anticyclonic circulation system off the Southeast coast of Brazil. The edge of this

positive high pressure anomaly was collocated with the region of positive temperature anomalies

that includes the city of Rio de Janeiro (Fig. 3b). Surface winds off the coast of Rio de Janeiro

were anomalously northerly. Anomalously northerly flow in this mountainous area can

258   exacerbate high temperatures directly through downslope winds (Stefanello et al. 2022).

259   Previous literature has also shown that anomalously northerly winds over the coast can increase

260   local sea surface temperatures through reductions in wind-driven upwelling, reducing the

261   capacity for coastal cooling (Castelao and Barth 2006; Palma and Matano 2009). Indeed, positive

262   SST anomalies of up to 2°C occurred along Rio de Janeiro's coast on the day of the peak in air

263   temperature (Fig. 3j). Anomalous winds over the interior of South America also enhanced the

264   northerly South American Low Level Jet (Marengo et al., 2004; Montini et al., 2019). Positive

265   specific humidity anomalies were present throughout Southeast and South Brazil (Fig. 3f),

266   intersecting with an area of precipitation along the edge of the low pressure system to the south

267   (Fig. 3g). The northern portion of the positive specific humidity anomaly was aligned with the

268   positive geopotential height anomaly off the coast of Southeast Brazil. Widespread negative soil

269   moisture anomalies occurred throughout most of Brazil, and the interior of South America more

270   broadly, during this event (Fig. 3d). The large spatial coverage of these negative soil moisture

271   anomalies was concurrent with Amazonian drought recorded during this time, inherited from the

272   prior season (Espinoza et al., 2024). These spatial patterns are typical of extreme heat events

273   during the spring season in the city of Rio de Janeiro, though the magnitudes of the anomalies in

274   all of these variables are dramatically higher on November 18, 2023 than during other spring

275   extreme heat events (Fig. 4). The most unique features of the November 18 event were the

276   intensified northerly winds and the degree of inland penetration of positive specific humidity

277   anomalies (Fig. 4e-f). Further, the positive local SST anomalies off the coast of Rio de Janeiro

278   were particularly exceptional in intensity and spatial scale during this event, weakening the sea-

279   air temperature contrast and sea-breeze (Fig. 4i-j). Outside of these specific distinctions, the

280   event on November 18, 2023 was an intense example of a typical spring extreme heat event in

281   the region.

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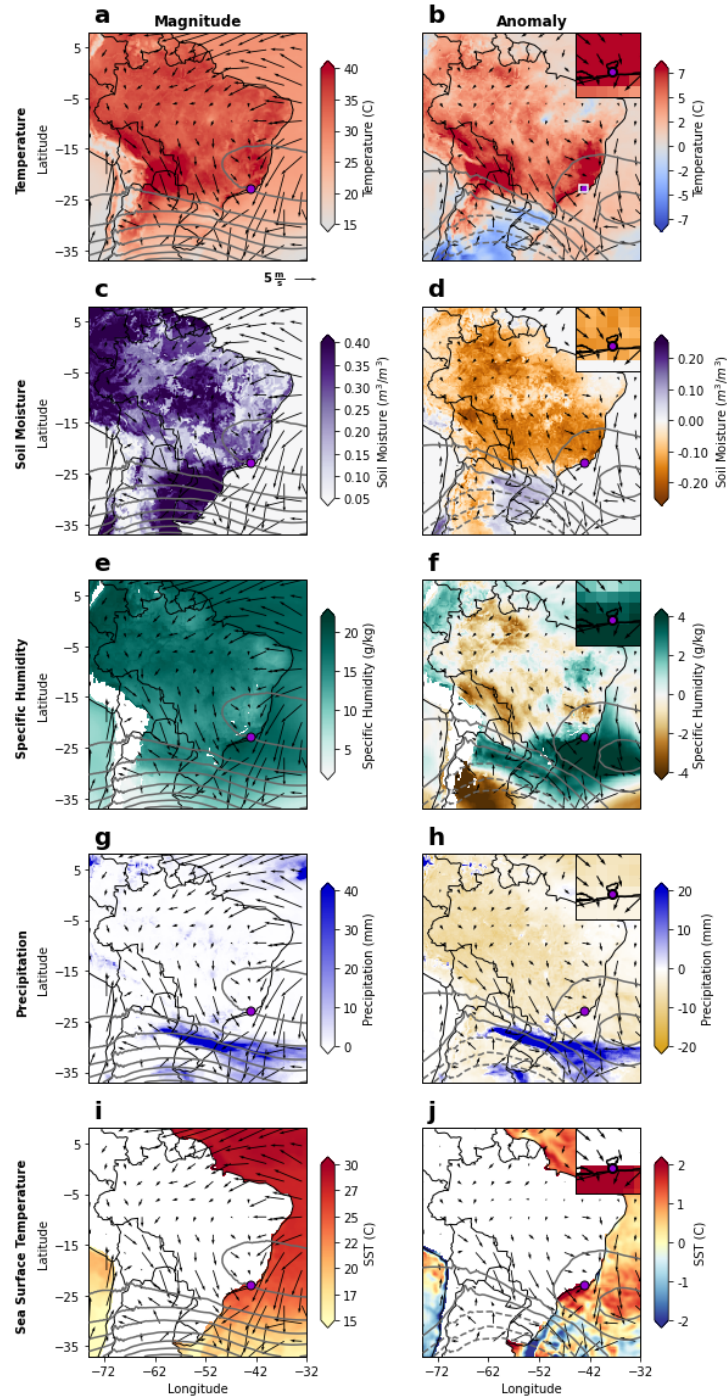
Figure 3: Magnitude (left) and anomalies (right) of daily maximum temperature, mean soil moisture, mean specific humidity, total precipitation, and mean SST on day of peak temperature in the city of Rio de Janeiro (November 18, 2023). Overlying wind vectors and 500 hPa geopotential height contours (50 m and 25 m contour levels for magnitude and anomaly plots, respectively). Anomalies calculated relative to historical calendar date mean values across the period from 1979-2023. Inset in the upper right corner of each anomaly plot zooms in on the white box surrounding the city of Rio de Janeiro (purple marker) in the top right subplot.

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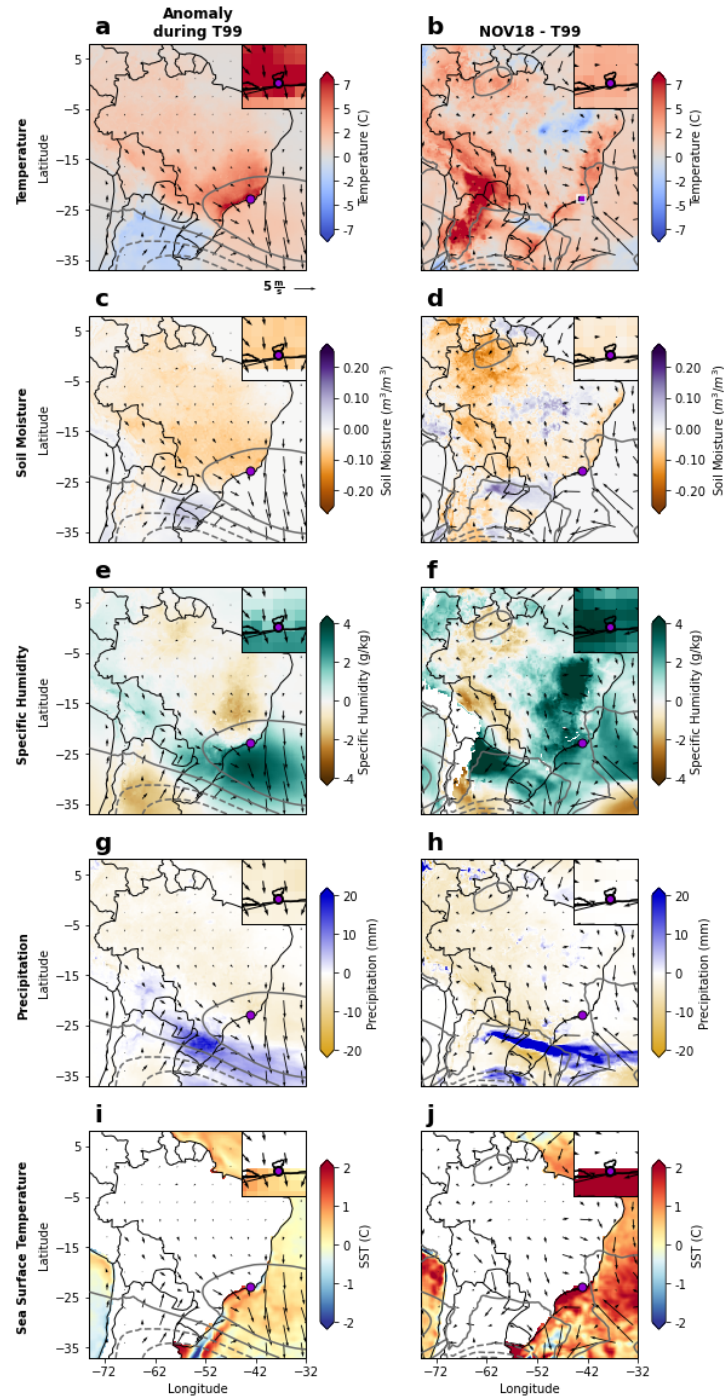
Figure 4: Anomalies in daily maximum temperature, mean soil moisture, mean specific humidity, total precipitation, and mean SST during 99th percentile extreme temperature days in the September-November (SON) season for the ERA5 grid cell which includes the Galeão International Airport weather station (left). Difference in conditions on November 18 compared to mean conditions during these 99th percentile extreme temperature days (right).

298   The time evolution of the meteorological variables described above throughout the month

299   of November 2023 uncovers the temporal development of the extreme heat event (Fig. 5). Rising

300   temperatures throughout the weeks leading up to November 18 were preceded by elevated

301   geopotential heights at 500 hPa and associated atmospheric subsidence. This was accompanied

302   by a rapid decline in soil moisture which was likely facilitated by the increased solar insolation

303   associated with the persistent high pressure system and resulting extremely low precipitation

304   from November 2-November 18. Given that the rainy season in Southeast Brazil typically begins

305   in late-October to mid-November (Coelho et al., 2021; Latinovic et al., 2018; Marengo et al.,

306   2012; Liebmann and Mechoso 2011; Raia and Cavalcanti 2008), this period of consecutive dry

307   days was unusual. Indeed, this period totals 17 days in a row with less than 5 mm of rain per day,

308   and this only happened during the month of November in one other year in the historical record

309   from ERA5 between 1979-2023 (2012). These changes in geopotential height, soil moisture, and

310   suppressed precipitation preceded changes in other variables, evidenced by the grey lines in the

311   background of each subplot. Wind direction was highly variable on a daily scale, but became

312   increasingly northerly during this same period. These changes were accompanied by a gradual

313   increase in SST off the coast of Rio de Janeiro, though delayed compared to that of the local air

314   temperature. These changes in wind direction and SSTs are likely linked, as upwelling in this

315   region can be significantly reduced through northerly wind anomalies, increasing coastal sea

316   surface temperatures (Castelao and Barth 2006; Palma and Matano 2009). Secondary pathways

317   to SST increases could include increased solar radiation to the ocean, added heat flux to the

318   ocean, and a thinning of the oceanic mixed layer. These features are common around many

319   coastlines during atmospheric heatwaves that are associated with warming coastal waters, though

320   further research would be needed to quantify their relative importance during the November

321   2023 heatwave in Rio de Janeiro. As air temperatures rose, specific humidity increased over the

322   city. This was likely related to both local evaporation from the soil (co-occurring with declining

323   soil moisture) and moisture advected from the anomalously warm coastal waters and surrounding

324   vegetation. The circulation specifically on November 18 directed wind in the larger region

325   surrounding Rio de Janeiro to intensify the South American Low Level Jet, which can

326   additionally increase moisture transport from the Amazon Basin to Southeast Brazil (Marengo et

327   al., 2004; Vera et al., 2006; Montini et al., 2019). However, convergence of the horizontal

328   moisture flux at the level nearest the surface was only stronger than its climatological values in

329   some grid cells within the northern and western areas of the city (Fig. S6). More generally,

330   specific humidity was also able to build without reaching saturation due to the increasing

331   temperatures (via the Clausius-Clapeyron relation). Finally, the heatwave was terminated when a

332   two-day precipitation event occurred from November 19-20. This precipitation induced a small

333   decline in specific humidity and SST, as well as a rapid increase in soil moisture.

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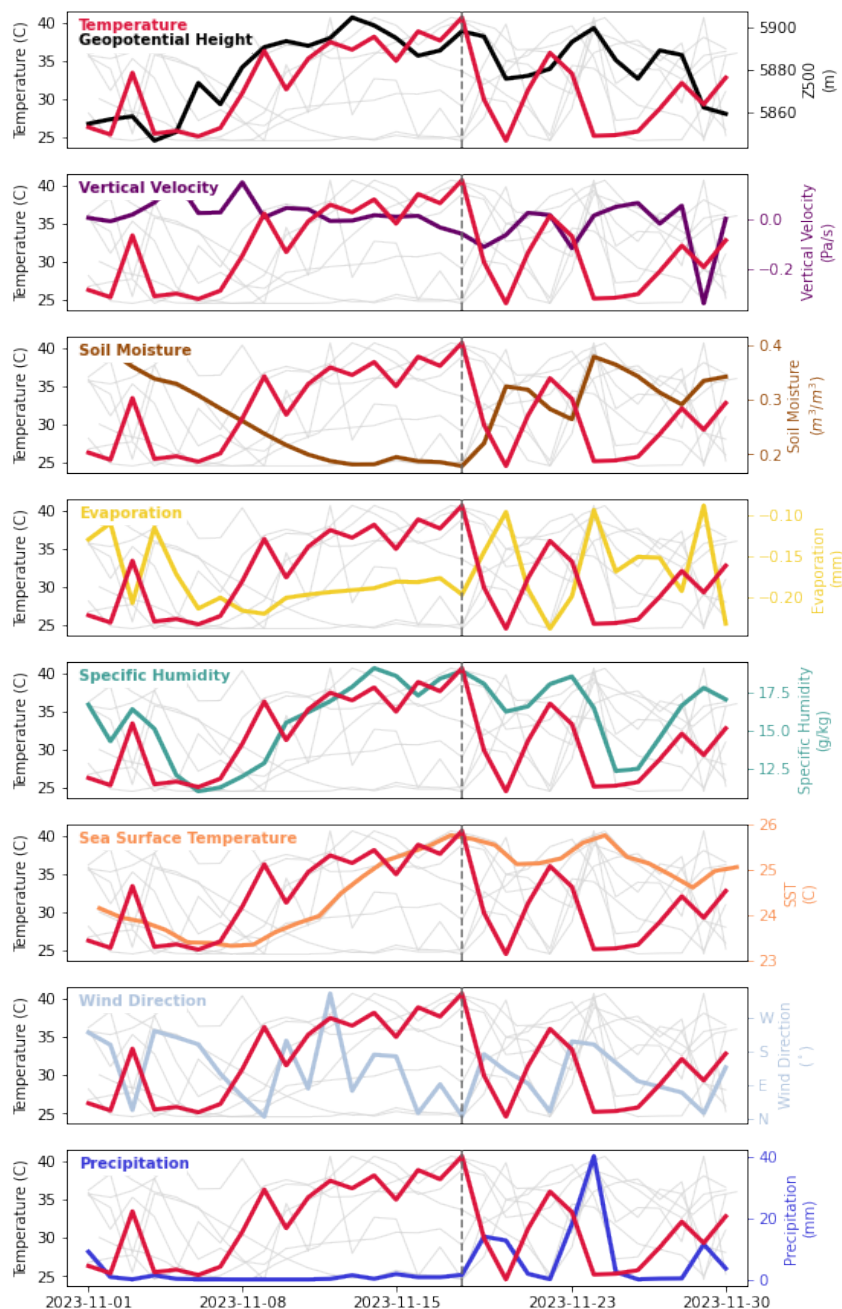
Figure 5: Evolution of meteorological conditions during the month of November 2023 in Rio de Janeiro. Grey lines in the background of each subplot show the evolution of all variables, with individual variables compared in colors to dry bulb temperature in red. Vertical dashed line identifies record-breaking temperature event on November 18, 2023. All variables are calculated for the grid cell which includes the Galeão International Airport weather station except SST, which is averaged over the box 21°S-24°S and 42°W-45°E.

The evolution of the 2023 heatwave as shown above is reminiscent of that during the 2010 heatwave analyzed by Geirinhas and coauthors (2019). Those authors explain that the extreme heat event in the summer of 2010 was initiated by a positive SST anomaly over the eastern Pacific that triggered a Rossby wave train that in turn intensified the South Atlantic Subtropical High. Modulation of this climatological high pressure system has been shown to be central to influencing weather in the city of Rio de Janeiro, and particularly temperatures there (Geirinhas et al., 2018). Here we also observe a positive SST anomaly over the equatorial Pacific throughout the month of November and a resulting anomalous wave pattern ending over the South Atlantic High that became increasingly organized and strengthened during the two weeks before November 18 (Fig. 6; see Fig. S7 in the Supplemental Materials for maps of the climatologies and absolute magnitudes of these variables). This mechanism is similar to how El Niño generally influences temperatures in Southeast Brazil on longer timescales (Cai et al., 2020), and we confirm that there is a positive correlation between the ENSO state as quantified by the Niño3.4 index and the frequency of high heat days in the city of Rio de Janeiro in the austral spring season (Fig. S8). Further, the mean spatial SST and Z200 patterns during the spring of typical El Niño years look very similar to those observed during November 2023, though the anomalies in both SST and geopotential height are much larger during November 2023 (Figure S9). 2023 was characterized by a transition from La Niña to El Niño, with the El Niño emerging in April-June 2023 and strengthening to a strong El Niño in the second half of 2023 (Becker et al., 2024). The SST anomalies associated with the El Niño could have been responsible for initiating the wave train which set off the geopotential height anomalies over Rio de Janeiro, consistent with the results of a recent analysis exploring spring and winter heatwaves throughout South America during 2023 (Marengo et al. 2025). More broadly, it has been suggested that multi-month elevations in temperature over Brazil throughout 2023 could be driven in part by El Niño (Pampuch et al. 2025). Further, the second half of 2023 was

369   exceedingly warm globally (Cattiaux et al. 2024; Perkins-Kirkpatrick et al. 2024), due in large

370   part to anthropogenic warming, indicating that climate variability and climate change both likely

371   preconditioned the November 2023 extreme heat event. We note that similar wave trains driven

372   by Pacific SST anomalies have been shown to influence weather in Southeast Brazil even during

373   neutral ENSO states (Seth et al., 2015). Additionally, the instantaneous extreme temperature

374   event and the preceding persistent dry conditions must also be linked to the synoptic weather in

375   the area. Decreases in soil moisture and horizontal moisture fluxes by intensification of the South

376   American Low Level Jet were central features of the heatwave in 2010, as they were in

377   November 2023. These overlaps in the apparent drivers of the 2010 and 2023 heatwaves

378   underscore that while the 2023 spring event was unprecedented in its magnitude and unusual in

379   its spring timing, it was not unique in its overall dynamics.

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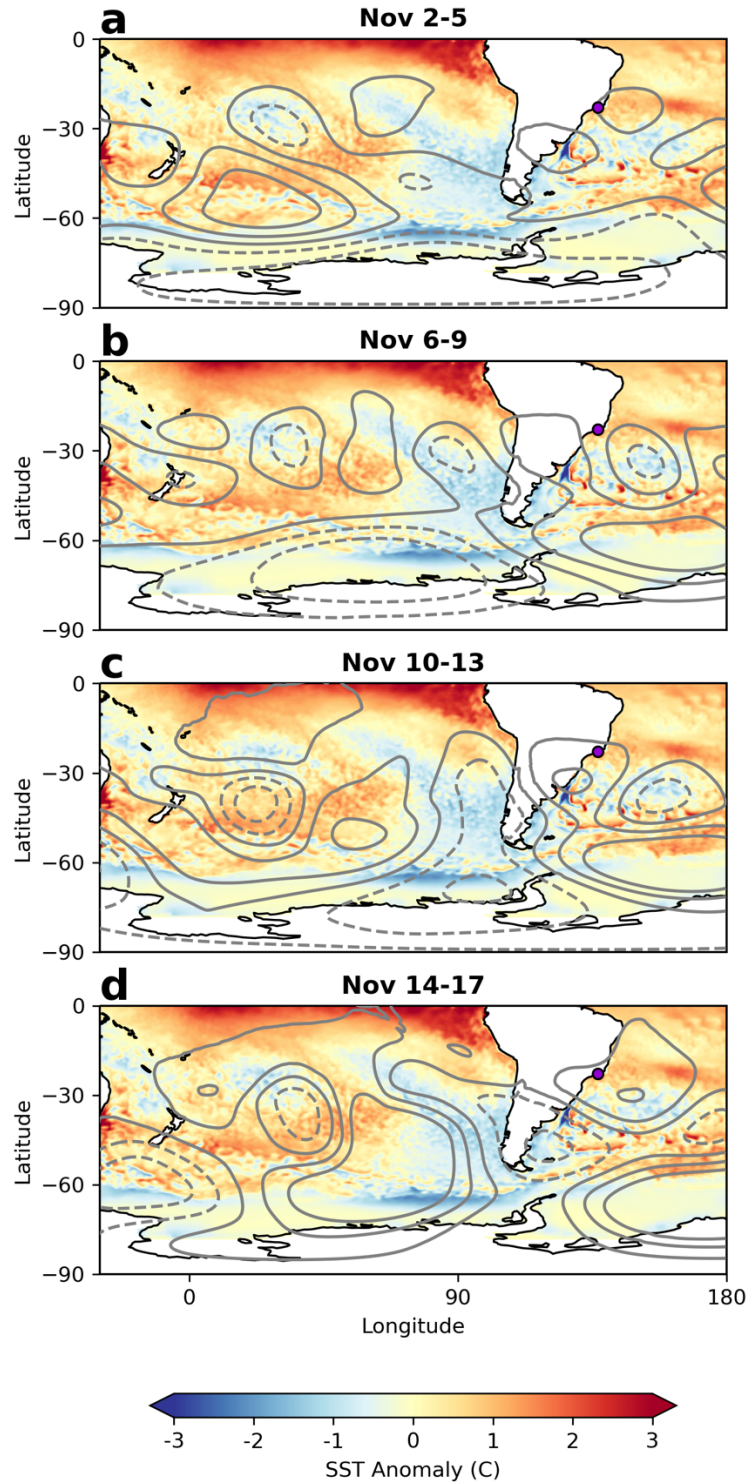
Figure 6: Evolution of the geopotential height at 200 hPa (contours) in the weeks of
suppressed precipitation leading up to the extreme heat event on November 18 in the city of
Rio de Janeiro. Geopotential height anomaly contour levels are at 100 m, with positive
(negative) anomalies in solid (dashed) contours. Across all subplots, shading indicates
November 2023 mean SST anomalies.

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3.2 Historical and future changes in extreme heat

Extreme heat events have become more frequent in the city of Rio de Janeiro and the timing of these events has shifted earlier in the calendar year. There has been a significant increase in the number of days above 30°C each year over the past 44 years throughout almost all of South America (Fig. 7a). Further, the number of 90th percentile days locally defined at each grid cell has also increased significantly throughout most of the region (Fig. 7b). In the city of Rio de Janeiro specifically, the number of 30°C days per year during the austral spring is increasing at a rate of 0.27 days/year (Fig. 7c). Relative to 1979, the city now experiences almost 12 additional days per year above 30°C during the spring season alone. Overall, the extreme heat season in Rio de Janeiro is broadening. As measured by the number of days between the first and last heatwave day of the season (a period of three or more consecutive days with daily maximum temperatures above 31.4°C), the extreme heat season has lengthened from 156 days in the 1979-1980 season to 176 days in the 2022-2023 season (Fig. 8). The broadening of the heat season is due primarily to more early season heatwave days, while the end date of the heat season has not changed significantly.
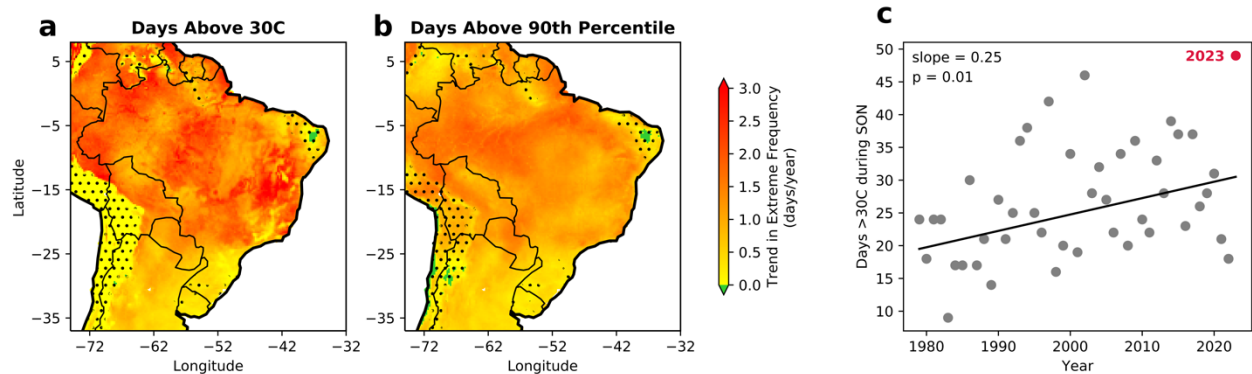
Figure 7: Historical trend from 1979-2023 in the number of days per year above a) 30°C and b) locally defined 90th percentile. Stippling shows areas which are not significant at a p = 0.05 level assessed using a Wald Test. c) Trend in number of days per year above 30°C taking place in the SON season in ERA5 for the grid cell which includes the Galeão International Airport weather station.

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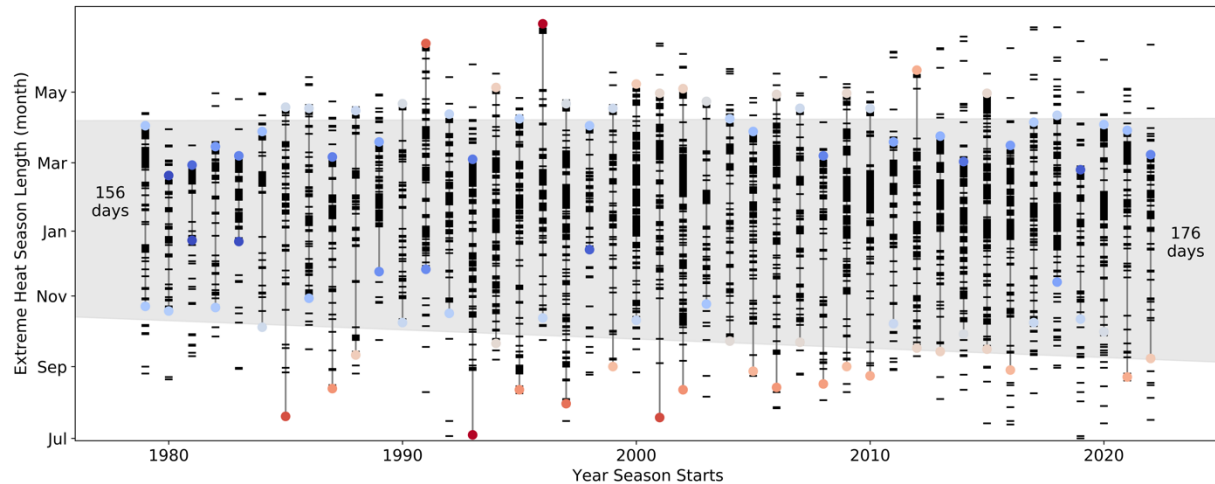
Figure 8: Shifting timing of the city of Rio de Janeiro's extreme heat season. Horizontal
axis indicates the year in which winter begins ("January" marking denotes the start of the
following calendar year). Colored markers indicate the first and last days of the extreme
heat season each year. Marker color indicates whether the start/end date is lengthening
(red) or shortening (blue) the heat season compared to historical mean start/end dates.
Dashes indicate individual additional days with daily maximum temperatures surpassing
31.4°C (no persistence required). Grey shading indicates area between trend lines in the
shifting seasonality.

418

419   The distribution of maximum spring temperatures in the city of Rio de Janeiro has shifted

420   higher over the last four decades and this pattern is projected to continue in the future. In order to

421   evaluate whether the observed historical increase in extreme heat frequency identified in Figures

422   7 and 8 may continue in the future, we fit annual maximum spring temperatures from historical

423   ERA5 reanalysis data and future projections from bias-corrected NEXGDDP data (Thrasher et

424   al., 2022) to a GEV distribution. When comparing early and late historical periods from 1979-

425   1988 and 2014-2023, respectively, the location parameter of the two GEV distributions has

426   increased by 1.7°C (Fig. 9). The distribution of maximum austral spring temperatures in the city

427   of Rio de Janeiro is also projected to continue shifting to higher values in the future, but the

428   magnitude of this change is strongly dependent upon the future emissions pathway. The

429   temperature distributions associated with mid-century periods (2041-2060) under SSP2-4.5 and

430   SSP5-8.5 future scenarios are similar to that of the last 10 years of observational data, with shifts

431   in the location parameters of 0.1°C and 0.9°C for the two emissions trajectories, respectively. A

432   larger change is projected by the end of the century (2081-2100) under each emissions scenario.

433   However, the end-of-century SSP5-8.5 scenario is distinctly separate from the other

434   distributions, with the distribution location parameter 2.8°C higher than during the last 10 years

435   of the historical record.

436   These changes to the distributions strongly influence the probability of an event with the

437   intensity of the maximum spring temperature recorded on November 18, 2023. The probability

438   density function fit to the projected annual maximum spring temperatures under each mid-

439   century period using a GEV distribution yields a return period for an extreme temperature event

440   with the daily maximum temperature at least 40.6°C in the city of Rio de Janeiro (analogous to

441   the event on November 18, 2023 as measured by ERA5) of 51 years under SSP2-4.5 and 33

442   years under SSP5-8.5. By the end of the century under either emissions scenario, an event of this

443   magnitude becomes much more likely, with return periods of 19 years or just 4 years under

444   SSP2-4.5 and SSP5-8.5, respectively. These return periods align well with estimates for station-

445   level projections from Collazo et al. 2025, which estimates a return period of 4 to 9 years for

446   heatwaves analogous to that of November 2023 for a future climate with global mean surface

447   temperatures 2°C warmer than preindustrial levels. Recent literature has suggested that the

448   SSP5-8.5 scenario may not be realistic given our current socioeconomic, political, and physical

449   landscape (Hausfather and Peters 2020; Burgess et al., 2020; Ritchie and Dowlatabadi 2017).

450   However, these results indicate that an austral spring heatwave of the magnitude experienced in

451   the city of Rio de Janeiro on November 18 is projected to become much more frequent in the

452   future, even under the more stringent SSP2-4.5 emission pathway. As temperatures rise and the

453   city of Rio de Janeiro maintains its ample moisture sources from the nearby ocean and

454   vegetation, we expect that humid heat extremes will also become more frequent and intense,

455   though at a slower rate than dry bulb temperature extremes as dictated by tropical atmospheric

456   dynamics (Coffel et al. 2018; Zhang et al., 2021; Matthews et al., 2025). We must also note that

457   it is difficult to evaluate whether the models are missing emerging factors that could increase the

458   frequency and intensity of these extreme heat events – such as Amazonian deforestation or

459   declines in sea ice – reducing their ability to capture the possible future spring temperature

460   distributions in Rio de Janeiro.

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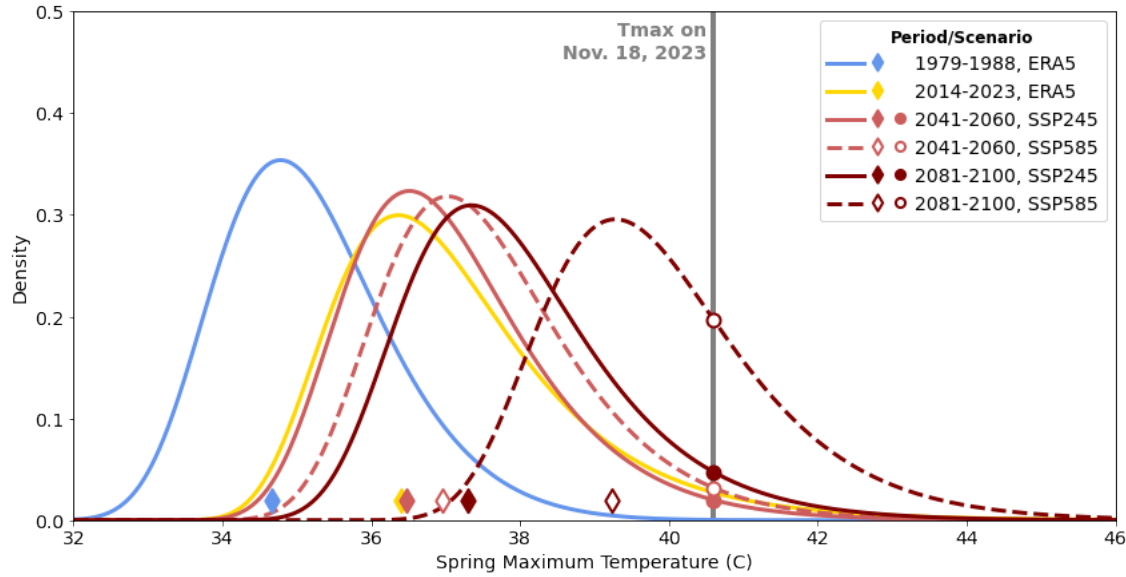
Figure 9: Generalized Extreme Value distributions for SON maximum temperatures during early and late historical periods (observed in ERA5), mid-century periods, and end-of-century periods under SSP2-4.5 and SSP5-8.5 (projections from bias-corrected NEXGDDP data). Diamonds indicate the value of the location parameter for each distribution. Vertical grey line shows the magnitude of the extreme temperature event on November 18, 2023, and circles indicate intersections of future distributions with this spring maximum temperature magnitude.

4 Conclusions

The November 2023 heatwave in the city of Rio de Janeiro was a record-breaking event characterized by meteorological conditions largely typical of spring extreme temperature events, but exceptional in their magnitudes. Rising temperatures were associated with positive geopotential height anomalies and corresponding atmospheric subsidence which facilitated clear sky conditions and increased sensible heat flux at the surface. These high pressure anomalies centered over the South Atlantic Subtropical High were likely related to the strong 2023-24 El Niño event. The subsidence near Rio de Janeiro associated with the geopotential height anomalies also suppressed precipitation and facilitated evaporation from the land surface, leading to decreased soil moisture and increased specific humidity. Moisture was available from multiple sources to facilitate these humidity increases, as Rio de Janeiro is a coastal city and downwind of both the Amazon and more local vegetation. SSTs off the coast of Rio de Janeiro were also highly elevated in the days before the heatwave peak, reducing the potential for coastal cooling. Finally, the event was terminated on November 19 due to the evaporative cooling, shading, and

484   mixing associated with the onset of precipitation. The combination of changes in circulation,

485   land surface feedbacks, and atmosphere-ocean interactions generated the conditions for an

486   exceptionally intense and persistent extreme heat event in the city of Rio de Janeiro.

487   The risk of extreme heat in austral spring is increasing significantly in Rio de Janeiro. We

488   find that extreme spring temperature events are becoming more frequent and that the extreme

489   heat season is starting earlier and lasting longer than in previous decades. Further, spring extreme

490   heat of the magnitude on November 18, 2023 may become much more likely by mid- and end-

491   of-century periods. However, the absolute increase in the frequency of similar heatwaves is

492   largely dependent upon our future emissions pathway.

493   The November 2023 heatwave had devastating impacts, including loss of life. As our

494   climate continues to change and extreme heat in the city of Rio de Janeiro continues to increase

495   in intensity and frequency, we can expect more strain on human health and cascading

496   socioeconomic impacts. This extreme heat event was exceptional not only in its intensity, but

497   also in its persistence. Consecutive extreme heat days have been shown to have nonlinear

498   impacts on human health, in Brazil and in other countries, as they prevent individuals, buildings,

499   and critical electrical equipment from cooling down between heat events (Geirinhas et al., 2020;

500   Baldwin et al., 2019). More broadly, the direct impacts of heatwaves on hospitalizations

501   throughout Brazil have been documented, with the largest effects occurring in long duration

502   events (Zhao et al., 2019). These impacts of heatwaves on mortality are projected to increase,

503   with particular consequences for elderly populations, especially if targeted adaptation measures

504   are not put in place (Diniz et al., 2020). Continuing to improve our understanding of how and

505   when extreme heat occurs is thus essential as our climate continues to change. This is

506   particularly true for locations such as Rio de Janeiro, which historically has not been a hotspot of

507   extreme heat – especially in the shoulder seasons – and thus individuals may not be well

508   acclimated to extreme temperatures then (Periard et al., 2015; Horowitz 2016). The human health

509   impacts of unusually intense events may be exacerbated by the shifting timing of extreme heat,

510   as record-breaking exceptional heat events are now occurring outside of the traditional extreme

511   heat season when individuals may not be prepared to utilize heat mitigation strategies (De Freitas

512   & Grigorieva, 2015). Because Rio de Janeiro is an area of emerging risk for extreme heat, further

513   research on models' ability to capture the historical drivers and timing of heatwaves in this

514   region and evaluations of how these characteristics might shift in the future should be pursued.

515   The meteorological conditions surrounding the extreme heat event analyzed here
516   demonstrate the potential for compound hazards throughout Brazil. The identified circulation
517   pattern that establishes the atmospheric blocking associated with heatwaves in Rio de Janeiro is
518   also likely linked to heavy precipitation events in South Brazil. Such an extreme precipitation
519   event occurred in May 2024 in the center-north of Rio Grande do Sul, including the metropolitan
520   area of Porto Alegre, displacing hundreds of thousands and killing at least 155 people (Rogero
521   2024). The temporal compounding of these extreme temperature and flooding events within
522   Brazil has the potential to strain the country's disaster management systems more than events
523   occurring in isolation. Furthermore, the exceptional spatial area within Brazil that experienced
524   anomalous heat in the November 2023 event, relative to 99th percentile heat events in the city of
525   Rio de Janeiro, underscores the potential for spatially compounding heat that could lead to
526   outsized impacts. Exploring how unprecedented global surface ocean and surface temperatures,
527   along with regional features like the broader heat and drought across much of Brazil, may
528   contribute to extreme heat in the city of Rio de Janeiro will be an important component to
529   improving our understanding of these compound events' drivers, prediction capacity, and
530   potential to change in the future.
531   The evolving meteorological conditions associated with this heatwave were strongly
532   impacted by the lack of precipitation in the first two weeks of November. This is particularly
533   unexpected due to the fact that the active phase of the South American Monsoon System
534   typically begins in late October or early November in this region (Marengo et al., 2012;
535   Liebmann and Mechoso 2011; Raia and Cavalcanti 2008), which is linked to an increase in
536   convective activity in tropical South America in the warm season (Jones and Carvalho 2013).
537   Observational and modeling studies suggest that the South American Monsoon System dry
538   season is lengthening (Arias et al., 2015; Fu et al., 2013) and that the onset of the active phase is
539   delaying (Gomes et al., 2022; Pascale et al., 2019). These trends are projected to continue to
540   some degree in the future with further climate change, particularly in light of ongoing
541   deforestation which contributes to regional drying trends in the Amazon and other areas of Brazil
542   (Boisier et al., 2015; Swann et al., 2015). Given Rio de Janeiro is a city with abundant access to
543   moisture due to its proximity to the coast and vegetation, the increasingly constrained active
544   monsoon phase could lead to increased frequency and intensity of extreme humid heat in the
545   spring season (Ivanovich et al., 2024). These changes could be responsible for the evident

546 asymmetrical historical increase in heat season length during the spring versus fall as
547 demonstrated here, and extensions of this work should be devoted to an exploration of these
548 potential relationships.

549   This work highlights the challenge of analyzing the drivers of weather extremes in such a
550 climatically diverse city as Rio de Janeiro and emphasizes the need for future research to explore
551 high resolution comparisons of mechanisms controlling the city's microclimates. Differences
552 between conditions recorded at individual weather stations within the city's boundaries
553 demonstrate the degree to which the dynamics of events in each neighborhood depend on the
554 station's location relative to the coast versus interior (Raymond and Mankin 2019), elevation
555 (Raymond et al., 2022; Pepin et al., 2015), and degree of urbanization (Kruger et al., 2024;
556 Chakraborty et al., 2022; Tan et al., 2010). Higher temporal resolution analysis would also better
557 capture sub-daily processes such as sea breeze and their effect on extreme heat throughout the
558 city. Further, many of these mechanisms influencing the intracity variability of heat stress
559 exposure only focus on the effect of differences in dry bulb temperature. Factoring in the spatial
560 variation in humidity, solar insolation, and windspeed complicate understanding, but are
561 essential for capturing humans' exposure to heat stress conditions. These intracity differences
562 also meaningfully impact compound events with non-heat environmental hazards, such as floods,
563 landslides, droughts, and air pollution, as well as how exposure to these hazards intersects with
564 areas of social vulnerability. Future work should be devoted to investigating the different
565 magnitudes of extreme heat and controlling mechanisms throughout Rio de Janeiro in order to
566 inform targeted extreme heat adaptation plans for individual neighborhoods within the city.
567
568 *Data Availability:* The publicly available datasets used in this analysis are accessible via the
569 following websites: HadISD, https://www.metoffice.gov.uk/hadobs/hadisd/; ERA5,
570 https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview and
571 https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels?tab=overview; OISST,
572 https://www.ncei.noaa.gov/products/optimum-interpolation-sst; and NEXGDDP,
573 https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6.
574 Station data from the Rio Alert System are uploaded and accessible via a GitHub repository at
575 the following link: https://github.com/ccivanovich/November2023_Rio_Heatwave/.
576

577 *Code Availability:* All code used for the derivations, calculations, and data visualization are
578 publicly available via a GitHub repository the following link:
579 https://github.com/ccivanovich/November2023_Rio_Heatwave/.
580

581 *Author Contributions:*
582 S.J.C. conceived of the initial project concept. All co-authors contributed to study design, and
583 C.I. performed the analysis. C.I. wrote the initial manuscript draft with the feedback and
584 interpretation of all co-authors. All co-authors read and edited the manuscript.
585

586 *Competing Interests:*
587 The authors declare that they have no conflict of interest.
588

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References

Alvares, C. A., Stape, J. L., Sentelhas, P. C., & De Moraes Gonçalves, J. L. (2013). Modeling monthly mean air temperature for Brazil. Theoretical and Applied Climatology, 113(3–4), 407–427. https://doi.org/10.1007/s00704-012-0796-6

Alvarez, M. S., Vera, C. S., Kiladis, G. N., & Liebmann, B. (2016). Influence of the Madden Julian Oscillation on precipitation and surface air temperature in South America. Climate Dynamics, 46(1), 245–262. https://doi.org/10.1007/s00382-015-2581-6

Arias, P. A., Fu, R., Vera, C., & Rojas, M. (2015). A correlated shortening of the North and South American monsoon seasons in the past few decades. Climate Dynamics, 45(11), 3183–3203. https://doi.org/10.1007/s00382-015-2533-1

Baldwin, J. W., Dessy, J. B., Vecchi, G. A., & Oppenheimer, M. (2019). Temporally Compound Heat Wave Events and Global Warming: An Emerging Hazard. Earth's Future, 7(4), 411–427. https://doi.org/10.1029/2018EF000989

Becker, E., L'Heureux, M., Hu, Z.-Z., & Kumar, A. (2024). ENSO and the tropical Pacific. In "State of the Climate in 2023". *Bull. Amer. Meteor. Soc.*, 105 (8), S221-S224, https://doi.org/10.1175/BAMS-D-24-0098.1

Bitencourt, Daniel P., Fuentes, M. V., Franke, A. E., Silveira, R. B., & Alves, M. P. A. (2020). The climatology of cold and heat waves in Brazil from 1961 to 2016. International Journal of Climatology, 40(4), 2464–2478. https://doi.org/10.1002/joc.6345

Bitencourt, Daniel Pires, Muniz Alves, L., Shibuya, E. K., De Ângelo Da Cunha, I., & Estevam De Souza, J. P. (2021). Climate change impacts on heat stress in Brazil—Past, present, and future implications for occupational heat exposure. International Journal of Climatology, 41(S1). https://doi.org/10.1002/joc.6877

Boisier, J. P., Ciais, P., Ducharne, A., & Guimberteau, M. (2015). Projected strengthening of Amazonian dry season by constrained climate model simulations. Nature Climate Change, 5(7), 656–660. https://doi.org/10.1038/nclimate2658

Burgess, M. G., Ritchie, J., Shapland, J., & Pielke, R. (2020). IPCC baseline scenarios have over-projected CO2 emissions and economic growth. Environmental Research Letters, 16(1), 014016. https://doi.org/10.1088/1748-9326/abcdd2

Cai, W., McPhaden, M. J., Grimm, A. M., Rodrigues, R. R., Taschetto, A. S., Garreaud, R. D., et al., (2020). Climate impacts of the El Niño–Southern Oscillation on South America.

Nature Reviews Earth & Environment, 1(4), 215–231. https://doi.org/10.1038/s43017-020-0040-3

Castelao, R. M., & Barth, J. A. (2006). Upwelling around Cabo Frio, Brazil: The importance of wind stress curl. Geophysical Research Letters, 33(3), 2005GL025182. https://doi.org/10.1029/2005GL025182

Cattiaux, J., Ribes, A., & Cariou, E. (2024). How Extreme Were Daily Global Temperatures in 2023 and Early 2024? *Geophysical Research Letters*, *51*(19), e2024GL110531. https://doi.org/10.1029/2024GL110531

Chakraborty, T., Venter, Z. S., Qian, Y., & Lee, X. (2022). Lower Urban Humidity Moderates Outdoor Heat Stress. AGU Advances, 3(5), e2022AV000729. https://doi.org/10.1029/2022AV000729

Cheng, Y.-T., Lung, S.-C. C., & Hwang, J.-S. (2019). New approach to identifying proper thresholds for a heat warning system using health risk increments. Environmental Research, 170, 282–292. https://doi.org/10.1016/j.envres.2018.12.059

Cirino, P. H., Féres, J. G., Braga, M. J., & Reis, E. (2015). Assessing the Impacts of ENSO-related Weather Effects on the Brazilian Agriculture. Procedia Economics and Finance, 24, 146–155. https://doi.org/10.1016/S2212-5671(15)00635-8

Coelho, C. A. S., De Souza, D. C., Kubota, P. Y., Cavalcanti, I. F. A., Baker, J. C. A., Figueroa, S. N., et al., (2022). Assessing the representation of South American monsoon features in Brazil and U.K. climate model simulations. Climate Resilience and Sustainability, 1(1), e27. https://doi.org/10.1002/cli2.27

Coffel, E. D., Horton, R. M., & de Sherbinin, A. (2018). Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century. *Environmental Research Letters*, *13*(1), 014001. https://doi.org/10.1088/1748-9326/aaa00e

Collazo, S., Barriopedro, D., García-Herrera, R., & Beguería, S. (2025). Extreme heat and mortality in the state of Rio de Janeiro in November 2023: attribution to climate change and ENSO. *Natural Hazards and Earth System Sciences*, *25*(9), 3221–3238. https://doi.org/10.5194/nhess-25-3221-2025

660   Collins, J. M., Chaves, R. R., & Marques, V. da S. (2009). Temperature Variability over South
661   America. Journal of Climate, 22(22), 5854–5869.
662   https://doi.org/10.1175/2009JCLI2551.1

663   Cordero Simões dos Reis, N., Boiaski, N. T., & Ferraz, S. E. T. (2019). Characterization and
664   Spatial Coverage of Heat Waves in Subtropical Brazil. Atmosphere, 10(5), 284.
665   https://doi.org/10.3390/atmos10050284

666   Correio Braziliense. (2023, November 18). Rio bate recorde de calor do ano neste sábado (18/11)
667   com 42,5°C. Retrieved May 14, 2024, from
668   https://www.correiobraziliense.com.br/brasil/2023/11/6657444-rio-bate-recorde-de-calor-
669   do-ano-neste-sabado-18-11-com-425-c.html

670   De Freitas, C., & Grigorieva, E. (2015). Role of Acclimatization in Weather-Related Human
671   Mortality During the Transition Seasons of Autumn and Spring in a Thermally Extreme
672   Mid-Latitude Continental Climate. International Journal of Environmental Research and
673   Public Health, 12(12), 14974–14987. https://doi.org/10.3390/ijerph121214962

674   Dereczynski, C., Silva, W. L., & Marengo, J. (2013). Detection and Projections of Climate
675   Change in Rio de Janeiro, Brazil, 2013. https://doi.org/10.4236/ajcc.2013.21003

676   Diniz, F. R., Gonçalves, F. L. T., & Sheridan, S. (2020). Heat Wave and Elderly Mortality:
677   Historical Analysis and Future Projection for Metropolitan Region of São Paulo, Brazil.
678   Atmosphere, 11(9), 933. https://doi.org/10.3390/atmos11090933

679   Dunn, R. J. H. (2019). HadISD version 3: monthly updates. Hadley Centre Technical Note.

680   Espinoza, J.-C., Jimenez, J. C., Marengo, J. A., Schongart, J., Ronchail, J., Lavado-Casimiro, W.,
681   & Ribeiro, J. V. M. (2024). The new record of drought and warmth in the Amazon in
682   2023 related to regional and global climatic features. Scientific Reports, 14(1), 8107.
683   https://doi.org/10.1038/s41598-024-58782-5

684   Feron, S., Cordero, R. R., Damiani, A., Llanillo, P. J., Jorquera, J., Sepulveda, E., et al., (2019).
685   Observations and Projections of Heat Waves in South America. Scientific Reports, 9(1),
686   8173. https://doi.org/10.1038/s41598-019-44614-4

687   Fu, R., Yin, L., Li, W., Arias, P. A., Dickinson, R. E., Huang, L., et al., (2013). Increased dry-
688   season length over southern Amazonia in recent decades and its implication for future
689   climate projection. Proceedings of the National Academy of Sciences, 110(45), 18110–
690   18115. https://doi.org/10.1073/pnas.1302584110

691   Geirinhas, J. L., Russo, A. C., Libonati, R., Miralles, D. G., Sousa, P. M., Wouters, H., & Trigo,
692   R. M. (2022). The influence of soil dry-out on the record-breaking hot 2013/2014
693   summer in Southeast Brazil. Scientific Reports, 12(1), 5836.
694   https://doi.org/10.1038/s41598-022-09515-z

695   Geirinhas, João L., Trigo, R. M., Libonati, R., Coelho, C. A. S., & Palmeira, A. C. (2018).
696   Climatic and synoptic characterization of heat waves in Brazil. International Journal of
697   Climatology, 38(4), 1760–1776. https://doi.org/10.1002/joc.5294

698   Geirinhas, João L., Trigo, R. M., Libonati, R., Castro, L. C. O., Sousa, P. M., Coelho, C. A. S., et
699   al., (2019). Characterizing the atmospheric conditions during the 2010 heatwave in Rio
700   de Janeiro marked by excessive mortality rates. Science of The Total Environment, 650,
701   796–808. https://doi.org/10.1016/j.scitotenv.2018.09.060

702   Geirinhas, João L., Russo, A., Libonati, R., Trigo, R. M., Castro, L. C. O., Peres, L. F., et al.,
703   (2020). Heat-related mortality at the beginning of the twenty-first century in Rio de
704   Janeiro, Brazil. International Journal of Biometeorology, 64(8), 1319–1332.
705   https://doi.org/10.1007/s00484-020-01908-x

706   Geirinhas, João L., Russo, A., Libonati, R., Sousa, P. M., Miralles, D. G., & Trigo, R. M. (2021).
707   Recent increasing frequency of compound summer drought and heatwaves in Southeast
708   Brazil. Environmental Research Letters, 16(3), 034036. https://doi.org/10.1088/1748-
709   9326/abe0eb

710   Gomes, G.D., Nunes, A.M.B., Libonati, R., & Ambrizzi, T. (2022). Projections of subcontinental
711   changes in seasonal precipitation over the two major river basins in South America under
712   an extreme climate scenario. Climate Dynamics, 58, 1147–1169.
713   https://doi.org/10.1007/s00382-021-05955-x

714   Grimm, A. M. (2019). Madden–Julian Oscillation impacts on South American summer monsoon
715   season: precipitation anomalies, extreme events, teleconnections, and role in the MJO
716   cycle. Climate Dynamics, 53(1), 907–932. https://doi.org/10.1007/s00382-019-04622-6

717   Hausfather, Z., & Peters, G. P. (2020). Emissions – the 'business as usual' story is misleading.
718   Nature, 577(7792), 618–620. https://doi.org/10.1038/d41586-020-00177-3

719   He, Z., Dai, A., & Vuille, M. (2021). The Joint Impacts of Atlantic and Pacific Multidecadal
720   Variability on South American Precipitation and Temperature. Journal of Climate,
721   34(19), 7959–7981. https://doi.org/10.1175/JCLI-D-21-0081.1

722   Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al., (2020).

723   The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society,

724   146(730), 1999–2049. https://doi.org/10.1002/qj.3803

725   Horowitz, M. (2016). Epigenetics and cytoprotection with heat acclimation. Journal of Applied

726   Physiology (Bethesda, Md.: 1985), 120(6), 702–710.

727   https://doi.org/10.1152/japplphysiol.00552.2015

728   Huang, B., Liu, C., Banzon, V., Freeman, E., Graham, G., Hankins, B., et al., (2021).

729   Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST)

730   Version 2.1. Journal of Climate, 34(8), 2923–2939. https://doi.org/10.1175/JCLI-D-20-

731   0166.1

732   Hughs, E., & Jeantet, D. (2023, November 15). It's not yet summer in Brazil, but a dangerous

733   heat wave is sweeping the country. Retrieved May 14, 2024, from

734   https://apnews.com/article/brazil-heat-wave-climate-environment-wildfires-

735   1e4714fb2c6566120c13cf4e2b657f7d

736   Instituto Brasileiro de Geografia e Estatística. (2022). Demographic Census 2022. Retrieved

737   from https://sidra.ibge.gov.br/pesquisa/censo-demografico/demografico-2022/primeiros-

738   resultados-populacao-e-domicilios

739   Ivanovich, C. C., Horton, R. M., Sobel, A. H., & Singh, D. (2024). Subseasonal Variability of

740   Humid Heat During the South Asian Summer Monsoon. Geophysical Research Letters,

741   51(6), e2023GL107382. https://doi.org/10.1029/2023GL107382

742   Jones, C., & Carvalho, L. M. V. (2013). Climate change in the South American Monsoon

743   System: Present climate and CMIP5 projections. Journal of Climate, 26(17), 6660–6678.

744   https://doi.org/10.1175/JCLI-D-12-00412.1

745   Jornal Nacional. (2023, November 18). Taylor Swift: segundo show é adiado, por causa do calor

746   extremo no Rio. Retrieved April 16, 2024, from https://g1.globo.com/jornal-

747   nacional/noticia/2023/11/18/taylor-swift-show-e-adiado-apos-morte-de-fa.ghtml

748   Krüger, E., Gobo, J. P. A., Tejas, G. T., da Silva de Souza, R. M., Neto, J. B. F., Pereira, G., et

749   al., (2024). The impact of urbanization on heat stress in Brazil: A multi-city study. Urban

750   Climate, 53, 101827. https://doi.org/10.1016/j.uclim.2024.101827

751   Lanzante, J. R., Dixon, K. W., Nath, M. J., Whitlock, C. E., & Adams-Smith, D. (2018). Some

752   Pitfalls in Statistical Downscaling of Future Climate. Bulletin of the American

753   Meteorological Society, 99(4), 791–803. https://doi.org/10.1175/BAMS-D-17-0046.1

754   Latinović, D., Chou, S. C., Rančić, M., Medeiros, G. S., & Lyra, A. D. A. (2019).

755   Seasonal climate and the onset of the rainy season in western-central Brazil simulated by

756   Global Eta Framework model. International Journal of Climatology, 39(3), 1429–1445.

757   https://doi.org/10.1002/joc.5892

758   Lemus-Canovas, M., Insua-Costa, D., Trigo, R. M., & Miralles, D. G. (2024). Record-shattering

759   2023 Spring heatwave in western Mediterranean amplified by long-term drought. Npj

760   Climate and Atmospheric Science, 7(1), 1–8. https://doi.org/10.1038/s41612-024-00569-

761   6

762   Libonati, R., Geirinhas, J. L., Silva, P. S., Monteiro Dos Santos, D., Rodrigues, J. A., Russo, A.,

763   et al., (2022). Drought–heatwave nexus in Brazil and related impacts on health and fires:

764   A comprehensive review. Annals of the New York Academy of Sciences, 1517(1), 44–

765   62. https://doi.org/10.1111/nyas.14887

766   Liebmann, B., & Mechoso, C. R. (2011). THE SOUTH AMERICAN MONSOON SYSTEM. In

767   C.-P. Chang, Y. Ding, N.-C. Lau, R. H. Johnson, B. Wang, & T. Yasunari, World

768   Scientific Series on Asia-Pacific Weather and Climate (2nd ed., Vol. 5, pp. 137–157).

769   WORLD SCIENTIFIC. https://doi.org/10.1142/9789814343411_0009

770   Lyra, G. B., Correia, T. P., de Oliveira-Júnior, J. F., & Zeri, M. (2018). Evaluation of methods of

771   spatial interpolation for monthly rainfall data over the state of Rio de Janeiro, Brazil.

772   Theoretical and Applied Climatology, 134(3), 955–965. https://doi.org/10.1007/s00704-

773   017-2322-3

774   Marengo, J. A., Costa, M. C., Cunha, A. P., Espinoza, J.-C., Jimenez, J. C., Libonati, R., et al.

775   (2025). Climatological patterns of heatwaves during winter and spring 2023 and trends

776   for the period 1979–2023 in central South America. *Frontiers in Climate*, 7.

777   https://doi.org/10.3389/fclim.2025.1529082

778   Marengo, J. A., Liebmann, B., Grimm, A. M., Misra, V., Silva Dias, P. L., Cavalcanti, I. F. A., et

779   al., (2012). Recent developments on the South American monsoon system. International

780   Journal of Climatology, 32(1), 1–21. https://doi.org/10.1002/joc.2254

781   Marengo, Jose A., Soares, W. R., Saulo, C., & Nicolini, M. (2004). Climatology of the Low-

782   Level Jet East of the Andes as Derived from the NCEP–NCAR Reanalyses:

783   Characteristics and Temporal Variability. Journal of Climate, 17(12), 2261–2280.

784   https://doi.org/10.1175/1520-0442(2004)017<2261:COTLJE>2.0.CO;2

785   Montini, T. L., Jones, C., & Carvalho, L. M. V. (2019). The South American Low-Level Jet: A

786   New Climatology, Variability, and Changes. Journal of Geophysical Research:

787   Atmospheres, 124(3), 1200–1218. https://doi.org/10.1029/2018JD029634

788   Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, C. R., et

789   al., (2017). Global risk of deadly heat. Nature Climate Change, 7(7), 501–506.

790   https://doi.org/10.1038/nclimate3322

791   Nahlik, M. J., Chester, M. V., Pincetl, S. S., Eisenman, D., Sivaraman, D., & English, P. (2017).

792   Building Thermal Performance, Extreme Heat, and Climate Change. Journal of

793   Infrastructure Systems, 23(3), 04016043. https://doi.org/10.1061/(asce)is.1943-

794   555x.0000349

795   NASA JPL. (2024, January 23). El Niño 2023 | El Niño/La Niña Watch & PDO. Retrieved May

796   14, 2024, from https://sealevel.jpl.nasa.gov/data/el-nino-la-nina-watch-and-pdo/el-nino-

797   2023

798   Nguyen, B. (2023, December 27). Brazilian Taylor Swift Fan Died Of Heat Exhaustion At Rio

799   Concert. Retrieved April 16, 2024, from

800   https://www.forbes.com/sites/britneynguyen/2023/12/27/brazilian-taylor-swift-fan-died-

801   of-heat-exhaustion-at-rio-concert/

802   Palma, E. D., & Matano, R. P. (2009). Disentangling the upwelling mechanisms of the South

803   Brazil Bight. Continental Shelf Research, 29(11), 1525–1534.

804   https://doi.org/10.1016/j.csr.2009.04.002

805   Pampuch, L. A., Bueno, P. G., Reboita, M. S., Tomaziello, A. C. N., Nunes, A. M. P., Cardoso,

806   A. A., et al. (2025). Brazil climate highlights 2023. *Annals of the New York Academy of*

807   *Sciences*, *1549*(1), 120–138. https://doi.org/10.1111/nyas.15394

808   Pascale, S., Carvalho, L. M. V., Adams, D. K., Castro, C. L., & Cavalcanti, I. F. A. (2019).

809   Current and Future Variations of the Monsoons of the Americas in a Warming Climate.

810   Current Climate Change Reports, 5(3), 125–144. https://doi.org/10.1007/s40641-019-

811   00135-w

812   Pepin, N., Bradley, R. S., Diaz, H. F., Baraer, M., Caceres, E. B., Forsythe, N., et al., (2015).

813   Elevation-dependent warming in mountain regions of the world. Nature Climate Change,

814   5(5), 424–430. https://doi.org/10.1038/nclimate2563

815   Périard, J. D., Racinais, S., & Sawka, M. N. (2015). Adaptations and mechanisms of human heat

816   acclimation: Applications for competitive athletes and sports. Scandinavian Journal of

817   Medicine & Science in Sports, 25 Suppl 1, 20–38. https://doi.org/10.1111/sms.12408

818   Powis, C. M., Byrne, D., Zobel, Z., Gassert, K. N., Lute, A. C., & Schwalm, C. R. (2023).

819   Observational and model evidence together support wide-spread exposure to

820   noncompensable heat under continued global warming. Science Advances, 9(36),

821   eadg9297. https://doi.org/10.1126/sciadv.adg9297

822   Perkins-Kirkpatrick, S., Barriopedro, D., Jha, R., Wang, L., Mondal, A., Libonati, R., &

823   Kornhuber, K. (2024). Extreme terrestrial heat in 2023. *Nature Reviews Earth &*

824   *Environment*, 5(4), 244–246. https://doi.org/10.1038/s43017-024-00536-y

825   Perkins, S. E., Pitman, A. J., Holbrook, N. J., & McAneney, J. (2007). Evaluation of the AR4

826   Climate Models' Simulated Daily Maximum Temperature, Minimum Temperature, and

827   Precipitation over Australia Using Probability Density Functions. Journal of Climate,

828   20(17), 4356–4376. https://doi.org/10.1175/JCLI4253.1

829   Raia, A., & Cavalcanti, I. F. A. (2008). The Life Cycle of the South American Monsoon System.

830   Journal of Climate, 21(23), 6227–6246. https://doi.org/10.1175/2008JCLI2249.1

831   Raymond, C., & Mankin, J. S. (2019). Assessing present and future coastal moderation of

832   extreme heat in the Eastern United States. Environmental Research Letters, 14(11),

833   114002. https://doi.org/10.1088/1748-9326/ab495d

834   Raymond, C., Matthews, T., & Horton, R. M. (2020). The emergence of heat and humidity too

835   severe for human tolerance. Science Advances, 6(19), eaaw1838.

836   https://doi.org/10.1126/sciadv.aaw1838

837   Raymond, C., Waliser, D., Guan, B., Lee, H., Loikith, P., Massoud, E., et al., (2022). Regional

838   and Elevational Patterns of Extreme Heat Stress Change in the US. Environmental

839   Research Letters. https://doi.org/10.1088/1748-9326/ac7343

840   Regoto, P., Dereczynski, C., Chou, S. C., & Bazzanela, A. C. (2021). Observed changes in air

841   temperature and precipitation extremes over Brazil. International Journal of Climatology,

842   41(11), 5125–5142. https://doi.org/10.1002/joc.7119

Rehbein, A., & Ambrizzi, T. (2023). ENSO teleconnections pathways in South America. Climate Dynamics, 61(3), 1277–1292. https://doi.org/10.1007/s00382-022-06624-3

Ritchie, J., & Dowlatabadi, H. (2017). Why do climate change scenarios return to coal? Energy, 140, 1276–1291. https://doi.org/10.1016/j.energy.2017.08.083

Rogero, T. (2024, May 19). Brazil counts cost of worst-ever floods with little hope of waters receding soon. The Guardian. Retrieved from https://www.theguardian.com/world/article/2024/may/19/brazil-floods-toll

Rogers, C. D. W., Ting, M., Li, C., Kornhuber, K., Coffel, E. D., Horton, R. M., et al., (2021). Recent Increases in Exposure to Extreme Humid-Heat Events Disproportionately Affect Populated Regions. Geophysical Research Letters, 48(19). https://doi.org/10.1029/2021GL094183

Shimizu, M. H., & Ambrizzi, T. (2016). MJO influence on ENSO effects in precipitation and temperature over South America. Theoretical and Applied Climatology, 124(1), 291–301. https://doi.org/10.1007/s00704-015-1421-2

Shreevastava, A., Raymond, C., & Hulley, G. C. (2023). Contrasting Intraurban Signatures of Humid and Dry Heatwaves over Southern California. Journal of Applied Meteorology and Climatology, 62(6), 709–720. https://doi.org/10.1175/JAMC-D-22-0149.1

Sistema Alerta Rio da Prefeitura do Rio de Janeiro. (2024). Meteorological Data. Retrieved from https://alertario.rio.rj.gov.br/download/dados-meteorologicos/

Sistema IBGE de Recuperação Automática - SIDRA. (n.d.). Retrieved April 21, 2024, from https://sidra.ibge.gov.br/pesquisa/censo-demografico/demografico-2022/primeiros-resultados-populacao-e-domicilios

Son, J.-Y., Gouveia, N., Bravo, M. A., de Freitas, C. U., & Bell, M. L. (2016). The impact of temperature on mortality in a subtropical city: effects of cold, heat, and heat waves in São Paulo, Brazil. International Journal of Biometeorology, 60(1), 113–121. https://doi.org/10.1007/s00484-015-1009-7

Stefanello, M., Ewerling da Rosa, C., Bresciani, C., Cordero Simões dos Reis, N., Stefanello Facco, D., Teleginski Ferraz, S. E., et al., (2022). Spatial–temporal analysis of a summer heat wave associated with downslope flows in southern Brazil: implications in the atmospheric boundary layer. Atmosphere 14(1). 64. https://doi.org/10.3390/atmos14010064

874 Swann, A. L. S., Longo, M., Knox, R. G., Lee, E., & Moorcroft, P. R. (2015). Future

875   deforestation in the Amazon and consequences for South American climate. Agricultural

876   and Forest Meteorology, 214–215, 12–24.

877   https://doi.org/10.1016/j.agrformet.2015.07.006

878 Tan, J., Zheng, Y., Tang, X., Guo, C., Li, L., Song, G., et al., (2010). The urban heat island and

879   its impact on heat waves and human health in Shanghai. International Journal of

880   Biometeorology, 54(1), 75–84. https://doi.org/10.1007/s00484-009-0256-x

881 Thrasher, B., Wang, W., Michaelis, A., Melton, F., Lee, T., & Nemani, R. (2022). NASA Global

882   Daily Downscaled Projections, CMIP6. Scientific Data, 9(1), 262.

883   https://doi.org/10.1038/s41597-022-01393-4

884 United Nations Department of Economic and Social Affairs Population Division. (2022).

885   Population of Urban Agglomerations with 300,000 Inhabitants or More in 2018, by

886   country, 1950-2035 (thousands). Retrieved from

887   https://population.un.org/wup/Download/

888 US EPA, O. (2021, February 4). Climate Change Indicators: Heat Waves [Reports and

889   Assessments]. Retrieved April 23, 2024, from https://www.epa.gov/climate-

890   indicators/climate-change-indicators-heat-waves

891 Vecellio, D. J., Wolf, S. T., Cottle, R. M., & Kenney, W. L. (2022). Evaluating the 35°C wet-

892   bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT Project).

893   Journal of Applied Physiology, 132(2), 340–345.

894   https://doi.org/10.1152/japplphysiol.00738.2021

895 Vera, C., Baez, J., Douglas, M., Emmanuel, C. B., Marengo, J., Meitin, J., et al., (2006). The

896   South American Low-Level Jet Experiment. Bulletin of the American Meteorological

897   Society, 87(1), 63–78. https://doi.org/10.1175/BAMS-87-1-63

898 Wilby, R. L., Kasei, R., Gough, K. V., Amankwaa, E. F., Abarike, M., Anderson, N. J., et al.,

899   (2021). Monitoring and moderating extreme indoor temperatures in low-income urban

900   communities. Environmental Research Letters, 16(2), 024033.

901   https://doi.org/10.1088/1748-9326/abdbf2

902 You, Y., Ting, M., & Biasutti, M. (2024). Climate warming contributes to the record-shattering

903   2022 Pakistan rainfall. Npj Climate and Atmospheric Science, 7(1), 1–8.

904   https://doi.org/10.1038/s41612-024-00630-4

905   Zhao, Q., Li, S., Coelho, M. S. Z. S., Saldiva, P. H. N., Hu, K., Huxley, R. R., et al., (2019). The

906   association between heatwaves and risk of hospitalization in Brazil: A nationwide time

907   series study between 2000 and 2015. PLOS Medicine, 16(2), e1002753.

908   https://doi.org/10.1371/journal.pmed.1002753