Physical Drivers of the November 2023 Heatwave in Rio de Janeiro

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15 **Abstract**

16 As extreme heat has not historically been a major hazard for the city of Rio de Janeiro, the

17 November 2023 Heatwave magnitude and timing were staggering. Here we conduct a case study

18 of reanalysis data and high-resolution projections to explore the event drivers and characterize

19 the evolving extreme heat risk in the city of Rio de Janeiro. We find that the heatwave was

20 associated with atmospheric blocking, potentially linked to the 2023-24 El Niño event. Soil

21 moisture declines increased surface sensible heat flux, and elevated sea surface temperatures

22 reduced coastal cooling. The heatwave was preceded by weeks of suppressed precipitation and

23 terminated by the onset of rain. We also find a significant historical increase in the frequency of

24 high heat days throughout Brazil and a lengthening of the heat season in the city of Rio de

25 Janeiro. The frequency of the city's austral spring heat extremes is expected to increase further in

26 the future, highly dependent upon our future emissions pathway. These results emphasize the

27 rapidly emerging risk for extreme heat in the city of Rio de Janeiro.

28

29 **1 Introduction**

30   In the spring of 2023, the city of Rio de Janeiro experienced a high impact heatwave that

31 caught the world's attention. Media sources ranging from local reporting to international news

32 companies centered stories on the event's record-breaking temperature magnitudes and

33 unseasonal timing, arriving earlier in the warm season than typical heatwaves (Correio

34 Braziliense, 2023; Hughs and Jeanet, 2023). The impacts of the extreme heat were widely

35 publicized in part due to the tragic death of a concertgoer hospitalized during a Taylor Swift

36 performance in Rio de Janeiro on November 17, with news articles reporting heat-induced

37 cardiovascular distress as the cause of death (Nguyen, 2023). Sources also report that the stadium

38 in which the concert took place experienced higher temperatures than those measured in the open

39 air, as well as a lack of cooling equipment and insufficient water for attendees (Nguyen, 2023;

40 Jornal Nacional, 2023). Such complexities highlight that extreme heat experienced by

41 individuals on the ground can far exceed temperatures measured at local weather stations,

42 depending on infrastructure and the capacity for cooling interventions (Wilby et al., 2021; Nahlik

43 et al., 2017). However, the meteorological event itself is of course one of the preconditions for

44 societal impacts. We therefore explore the physical mechanisms behind the heatwave as one key

45 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

77   al., 2020; Shimizu and Ambrizzi 2015), the Pacific Decadal Oscillation, and the Atlantic
78   Multidecadal Oscillation (He et al., 2021). Should more intense, frequent, and unseasonably
79   early extreme heat events take place in the future in the city of Rio de Janeiro, these heatwaves
80   may have increased impacts on human health due to potential exceedance of unprecedented
81   temperature thresholds and individuals' lack of preparation for these events. In a tropical city
82   where baseline temperatures are already relatively high, small shifts in the temperature
83   distribution can have large impacts on the frequency of extremes (Cheng et al., 2019),
84   particularly at thresholds relevant to human health outcomes (Vecellio et al., 2022). These health
85   risks are compounded by the humidity in Rio de Janeiro, a coastal city with ample moisture
86   sources from the ocean and surrounding vegetation, priming the region for humid heat extremes
87   which are physiologically more dangerous to human health than dry heat (Mora et al., 2017).
88   In this study, we explore the meteorological conditions that led to the extreme heat event
89   in November 2023 in the city of Rio de Janeiro. We identify drivers of the exceptional
90   magnitude and persistence of the extreme temperatures, as well as their early arrival in the
91   calendar year. We compare these conditions to those associated with typical heatwaves in the
92   region, and particularly events taking place in the spring season. We then consider how extreme
93   spring temperature events have shifted throughout the historical period, and how we might
94   expect them to change in the future with ongoing anthropogenic climate change.
95
96   **2 Methods**
97   **2.1 Data**
98   This analysis employs both station-based observations and reanalysis data. Initial
99   analyses are conducted on subdaily station data from the city of Rio de Janeiro, accessed via the
100 Met Office Hadley Center's HadISD station-based dataset (Dunn 2019) and the Rio Alert
101 System produced by the Rio de Janeiro City Hall (Sistema Alerta Rio da Prefeitura do Rio de
102 Janeiro 2024). Three airport weather stations are available from HadISD for the city of Rio de
103 Janeiro, namely the Galeão/Antonio Carlos Jobim International Airport (located on the island
104 Ilha do Governador within the Guanabara Bay), the Campo Délio Jardim De Mattos Airport (an
105 Air Force base located in the city's North Zone), and the Santos Dumont Airport (a waterfront
106 airport located near the city center). Six additional stations from the Rio Alert System dataset
107 record measurements from the tops of various community and commercial buildings, including

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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.

156

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

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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.
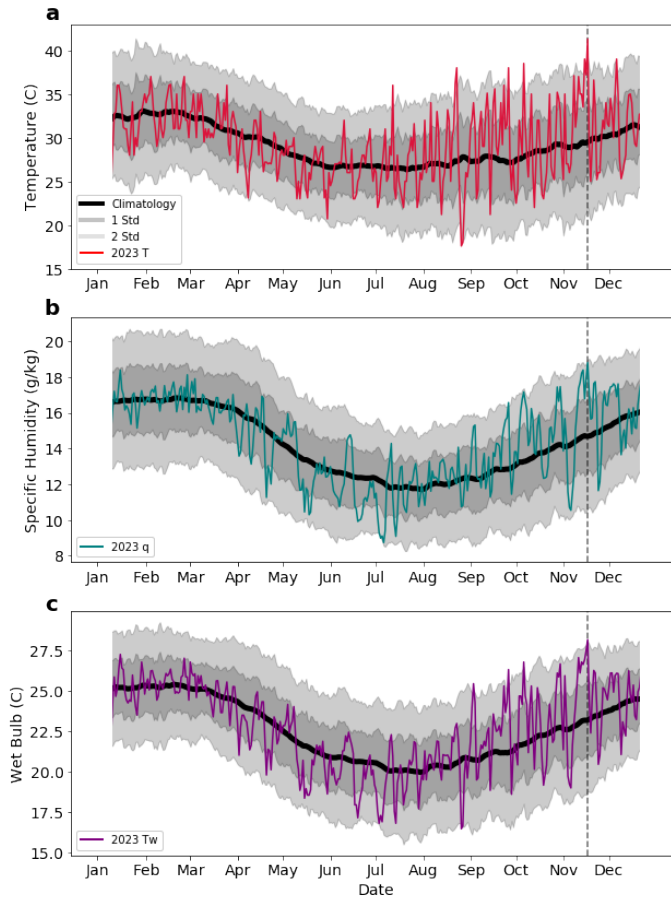
Figure 1: Historical climatology and 2023 recorded a) daily maximum temperature, b) daily mean specific humidity, and c) daily maximum wet bulb temperature in the city of Rio de Janeiro. Data from the Galeão International Airport weather station as reported by the HadISD dataset. Vertical dashed line 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

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

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

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

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

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

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

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

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

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

240 temperatures rendered it difficult for residents to find relief.

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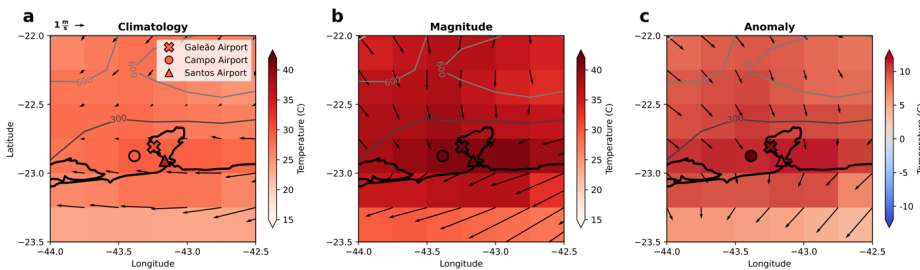
Figure 2: Spatial maps of daily maximum temperatures during the date of peak extreme heat intensity in the city of Rio de Janeiro using ERA5 data (shading) and three city weather stations with long-term temperature records (markers). Vectors represent surface winds; contours represent elevation in meters.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

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

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

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

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

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

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

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

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

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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
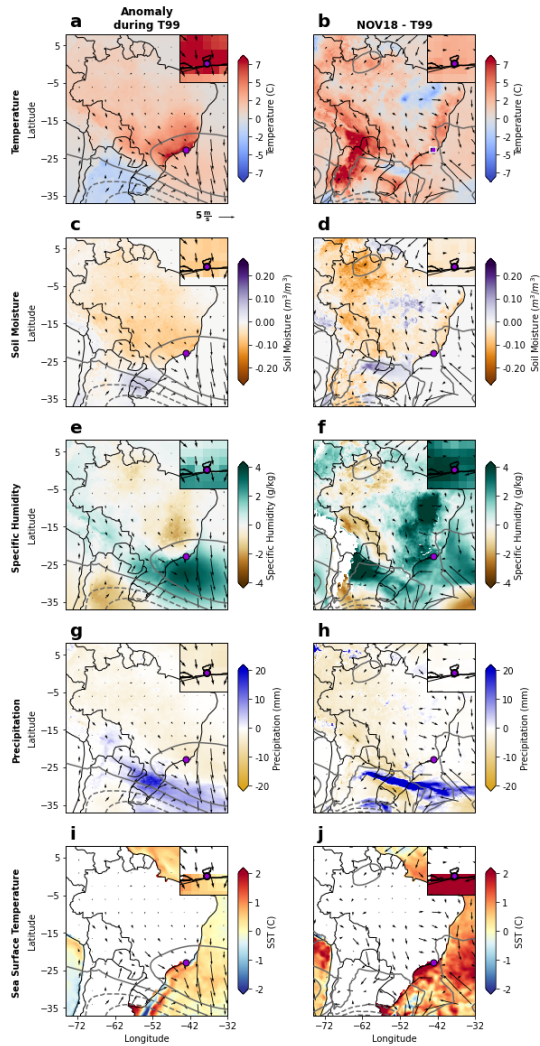281 the region.
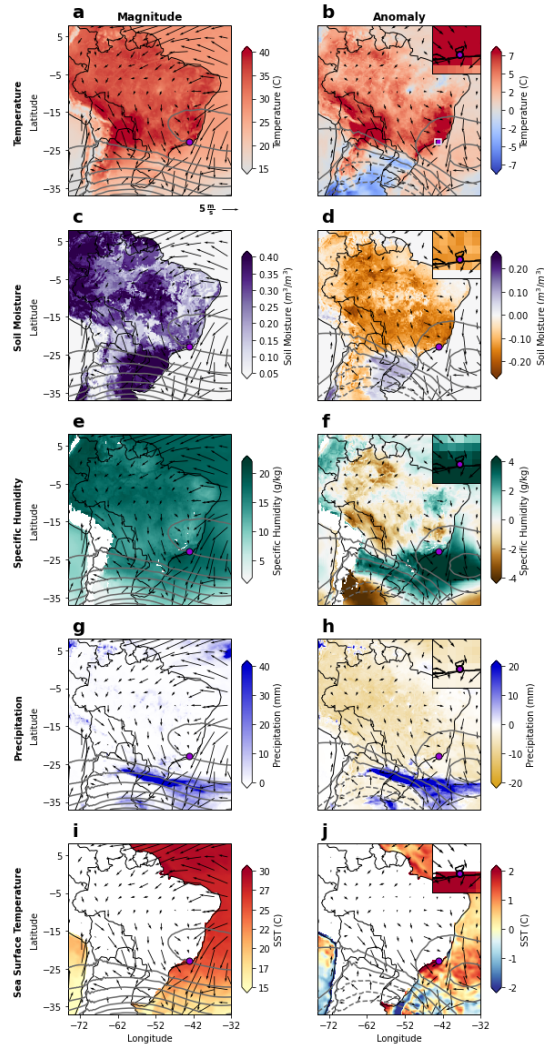
Figure 3: Magnitude (left) and anomalies (right) of daily maximum temperature, mean soil moisture, mean specific humidity, total precipitation, and mean SST on day of peak temperature in the city of Rio de Janeiro (November 18, 2023). Overlying wind vectors and 500 hPa geopotential height contours (50 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

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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 (and the Clausius-Clapeyron relation). Finally, the heatwave was terminated when

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

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

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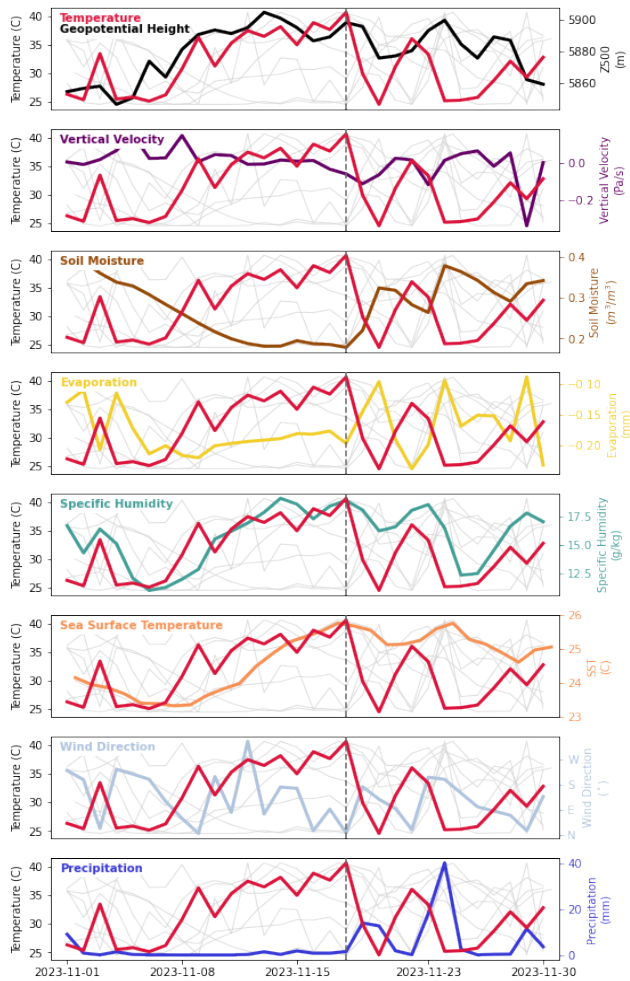
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Figure 5: Evolution of meteorological conditions during the month of November 2023 in Rio de Janeiro. Grey lines in the background of each subplot show the evolution of all variables, with individual variables compared in colors to dry bulb temperature 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

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

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

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

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

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

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

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

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

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

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

380 its spring timing, it was not unique in its overall dynamics.
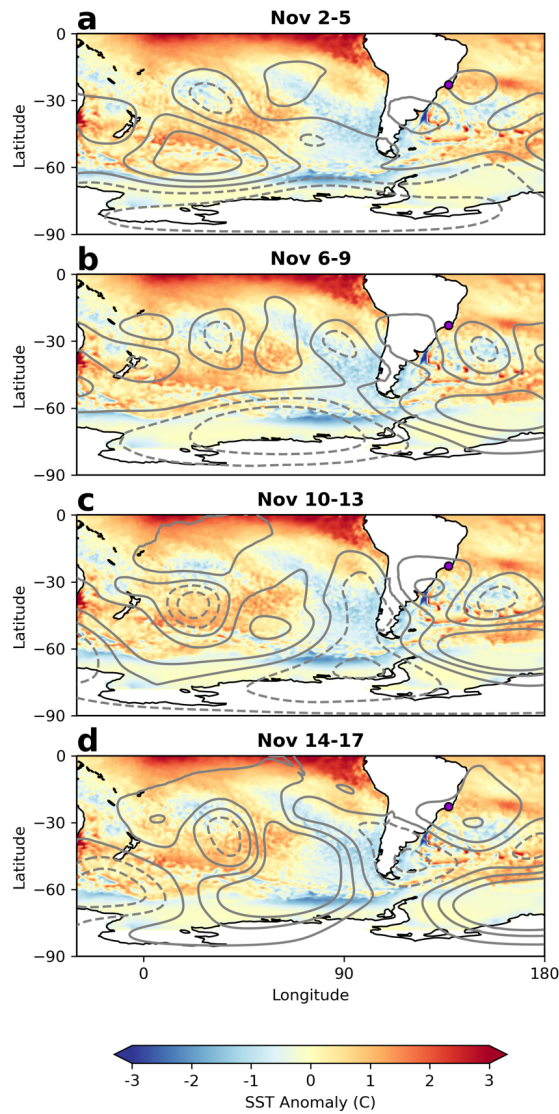
Figure 6: Evolution of the geopotential height at 200 hPa (contours) in the weeks of suppressed precipitation leading up to the extreme heat event on November 18 in the city of Rio de Janeiro. Geopotential height anomaly contour levels are at 100 m, with positive (negative) anomalies in solid (dashed) 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.
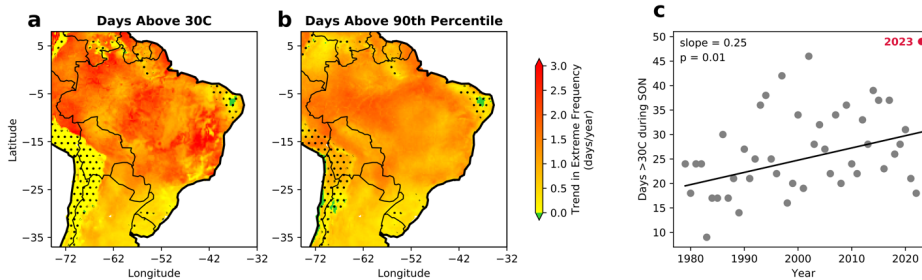
Figure 7: Historical trend from 1979-2023 in the number of days per year above a) 30°C and b) locally defined 90th percentile. Stippling shows areas which are not significant at a p = 0.05 level assessed using a Wald Test. c) Trend in number of days per year above 30°C taking place in the SON season in ERA5 for the grid cell which includes the Galeão International Airport weather station.

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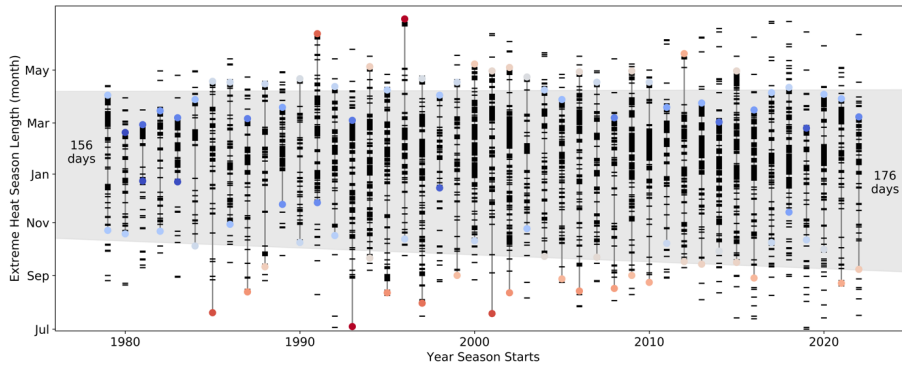
Figure 8: Shifting timing of the city of Rio de Janeiro extreme heat season. Horizontal axis indicates the year in which winter begins ("January" marking denotes the start of the following calendar year). Colored markers indicate the first and last days of the extreme heat season each year. Marker color 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.

The distribution of maximum spring temperatures in the city of Rio de Janeiro has shifted higher over the last four decades and this pattern is projected to continue in the future. In order to evaluate whether the observed historical increase in extreme heat frequency identified in Figures 7 and 8 may continue in the future, we fit annual maximum spring temperatures from historical ERA5 reanalysis data and future projections from bias-corrected NASA Earth Exchange Global Daily Downscaled Projections (NEXGDDP) data (Thrasher et al., 2022, see Methods) to a Generalized Extreme Value (GEV) distribution. When comparing early and late historical periods from 1979-1988 and 2014-2023, respectively, the location parameter of the two GEV distributions has increased by 1.7°C (Fig. 9). The distribution of maximum austral spring temperatures in the city of Rio de Janeiro is also projected to continue shifting to higher values in the future, but the magnitude of this change is strongly dependent upon the future emissions pathway. The temperature distributions associated with mid-century periods (2041-2060) under SSP2-4.5 and SSP5-8.5 future scenarios are similar to that of the last 10 years of observational data, with shifts in the location parameters of 0.1°C and 0.9°C for the two emissions trajectories,

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434 respectively. A larger change is projected by the end of the century (2081-2100) under each
435 emissions scenario. However, the end-of-century SSP5-8.5 scenario is distinctly separate from
436 the other distributions, with the distribution location parameter 2.8°C higher than during the last
437 10 years.
438   These changes to the distributions strongly influence the probability of an event with the
439 intensity of the maximum temperature recorded on November 18, 2023. The probability density
440 function fit to the projected annual maximum spring temperatures under each mid-century period
441 using a GEV distribution yields a return period for an extreme temperature event with the daily
442 maximum temperature at least 40.6°C in the city of Rio de Janeiro (analogous to the event on
443 November 18, 2023 as measured by ERA5) of 51 years under SSP2-4.5 and 33 years under
444 SSP5-8.5. By the end of the century under either emissions scenario, an event of this magnitude
445 becomes much more likely, with return periods of 19 years or just 4 years under SSP2-4.5 and
446 SSP5-8.5, respectively. These return periods align well with estimates for station-level
447 projections from Collazo et al. 2025, which estimates a return period of 4 to 9 years for
448 heatwaves analogous to that of November 2023 for a future climate with global mean surface
449 temperatures 2°C warmer than preindustrial levels. Recent literature has suggested that the
450 SSP5-8.5 scenario may not be realistic given our current socioeconomic, political, and physical
451 landscape (Hausfather and Peters 2020; Burgess et al., 2020; Ritchie and Dowlatabadi 2017).
452 However, these results indicate that an austral spring heatwave of the magnitude experienced in
453 the city of Rio de Janeiro on November 18 is projected to become much more frequent in the
454 future, even under the more stringent SSP2-4.5 emission pathway. As temperatures rise and the
455 city of Rio de Janeiro maintains its ample moisture sources from the nearby ocean and
456 vegetation, we expect that humid heat extremes will also become more frequent and intense,
457 though at a slower rate than dry bulb temperature extremes as dictated by tropical atmospheric
458 dynamics (Coffel et al. 2018; Zhang et al., 2021; Matthews et al., 2025). We must also note that
459 it is difficult to evaluate whether the models are missing emerging factors that could increase the
460 frequency and intensity of these extreme heat events – such as Amazonian deforestation or
461 declines in sea ice – reducing their ability to capture the possible future spring temperature
462 distributions in Rio de Janeiro.
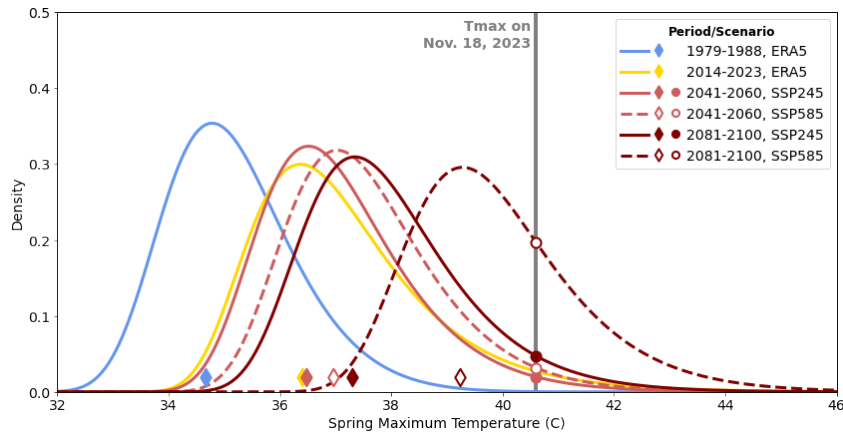
Figure 9: Generalized Extreme Value distributions for SON maximum temperatures during early and late historical periods (observed in ERA5), mid-century periods, and end-of-century periods under SSP2-4.5 and SSP5-8.5 (projections from bias-corrected NEXGDDP data). Diamonds indicate the value of the location parameter for each distribution. Vertical grey line shows the magnitude of the extreme temperature event on November 18, 2023.

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

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486 land surface feedbacks, and atmosphere-ocean interactions generated the conditions for an
487 exceptionally intense and persistent extreme heat event in the city of Rio de Janeiro.

488   The risk of extreme heat in austral spring is increasing significantly in Rio de Janeiro. We
489 find that extreme spring temperature events are becoming more frequent and that the extreme
490 heat season is starting earlier and lasting longer than in previous decades. Further, extreme heat
491 of the magnitude on November 18, 2023 may become much more likely by mid- and end-of-
492 century periods. However, the absolute increase in the frequency of similar heatwaves is largely
493 dependent upon our future emissions pathway.

494   The November 2023 heatwave had devastating impacts, including loss of life. As our
495 climate continues to change and extreme heat in the city of Rio de Janeiro continues to increase
496 in intensity and frequency, we can expect more strain on human health and cascading
497 socioeconomic impacts. This extreme heat event was exceptional not only in its intensity, but
498 also in its persistence. Consecutive extreme heat days have been shown to have nonlinear
499 impacts on human health, in Brazil and in other countries, as they prevent individuals, buildings,
500 and critical electrical equipment from cooling down between heat events (Geirinhas et al., 2020;
501 Baldwin et al., 2019). More broadly, the direct impacts of heatwaves on hospitalizations
502 throughout Brazil have been documented, with the largest effects occurring in long duration
503 events (Zhao et al., 2019). These impacts of heatwaves on mortality are projected to increase,
504 with particular consequences for elderly populations, especially if targeted adaptation measures
505 are not put in place (Diniz et al., 2020). Continuing to improve our understanding of how and
506 when extreme heat occurs is thus essential as our climate continues to change. This is
507 particularly true for locations such as Rio de Janeiro, which historically has not been a hotspot of
508 extreme heat – especially in the shoulder seasons – and thus individuals may not be well
509 acclimated to extreme temperatures then (Periard et al., 2015; Horowitz 2016). The human health
510 impacts of unusually intense events may be exacerbated by the shifting timing of extreme heat,
511 as record-breaking exceptional heat events are now occurring outside of the traditional extreme
512 heat season when individuals may not be prepared to utilize heat mitigation strategies (De Freitas
513 & Grigorieva, 2015). Because Rio de Janeiro is an area of emerging risk for extreme heat, further
514 research on models' ability to capture the historical drivers and timing of heatwaves in this
515 region and evaluations of how these characteristics might shift in the future should be pursued.

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

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547 asymmetrical historical increase in heat season length during the spring versus fall as
548 demonstrated here, and extensions of this work should be devoted to an exploration of these
549 potential relationships.
550   This work highlights the challenge of analyzing the drivers of weather extremes in such a
551 climatically diverse city as Rio de Janeiro and emphasizes the need for future research to explore
552 high resolution comparisons of mechanisms controlling the city's microclimates. Differences
553 between conditions recorded at individual weather stations within the city's boundaries
554 demonstrate the degree to which the dynamics of events in each neighborhood depend on the
555 station's location relative to the coast versus interior (Raymond and Mankin 2019), elevation
556 (Raymond et al., 2022; Pepin et al., 2015), and degree of urbanization (Kruger et al., 2024;
557 Chakraborty et al., 2022; Tan et al., 2010). Higher temporal resolution analysis would also better
558 capture sub-daily processes such as sea breeze and their effect on extreme heat throughout the
559 city. Further, many of these mechanisms influencing the intracity variability of heat stress
560 exposure only focus on the effect of differences in dry bulb temperature. Factoring in the spatial
561 variation in humidity, solar insolation, and windspeed complicate understanding, but are
562 essential for capturing humans' exposure to heat stress conditions. These intracity differences
563 also meaningfully impact compound events with non-heat environmental hazards, such as floods,
564 landslides, droughts, and air pollution, as well as how exposure to these hazards intersects with
565 areas of social vulnerability. Future work should be devoted to investigating the different
566 magnitudes of extreme heat and controlling mechanisms throughout Rio de Janeiro in order to
567 inform targeted extreme heat adaptation plans for individual neighborhoods within the city.
568
569 *Data Availability:* The publicly available datasets used in this analysis are accessible via the
570 following websites: HadISD, https://www.metoffice.gov.uk/hadobs/hadisd/; ERA5,
571 https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview and
572 https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels?tab=overview; OISST,
573 https://www.ncei.noaa.gov/products/optimum-interpolation-sst; and NEXGDDP,
574 https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6.
575 Station data from the Rio Alert System will be uploaded and accessible via a GitHub repository
576 upon manuscript publication.
577

578 *Code Availability:* All code used for the derivations, calculations, and data visualization will be
579 made publicly available via a GitHub repository upon manuscript publication.
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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