Physical Drivers of the November 2023 Heatwave in Rio de Janeiro

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15 **Abstract.** As extreme heat has not historically been a major hazard for the city of Rio de Janeiro,
16 the November 2023 Heatwave magnitude and timing were staggering. Here we conduct a case
17 study of reanalysis data and high-resolution projections to explore the event drivers and
18 characterize the evolving extreme heat risk in the city of Rio de Janeiro. We find that the
19 heatwave was associated with atmospheric blocking, potentially linked to the 2023-24 El Niño
20 event. Soil moisture declines increased surface sensible heat flux, and elevated sea surface
21 temperatures reduced coastal cooling. The heatwave was preceded by weeks of suppressed
22 precipitation and terminated by the onset of rain. We also find a significant historical increase in
23 the frequency of high heat days throughout Brazil and a lengthening of the heat season in the city
24 of Rio de Janeiro. The frequency of the city's austral spring heat extremes is expected to increase
25 further in the future, highly dependent upon our future emissions pathway. These results
26 emphasize the rapidly emerging risk for extreme heat in the city of Rio de Janeiro.
27

1 Introduction

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

94

95 **2 Methods**

96 **2.1 Data**

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

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

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

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

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

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

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

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

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

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

107   hotels, schools, and warehouses. These stations are located in distinct areas of the city, whose

108   topographical and coastal complexities contribute to various microclimates. These stations thus

109   record distinct values, both instantaneously and on average (see Fig. S1), a challenge that has

110   been previously identified in the literature (Lyra et al., 2018; Dereczynski et al., 2013). We

111   therefore base the majority of our analysis on reanalysis data and compare the identified patterns

112   with station data when possible. This comparison is particularly important for extreme events, as

113   the magnitude of extreme heat has been shown to be biased in reanalysis products due to their

114   spatial and temporal smoothing of observations (Rogers et al., 2021; Raymond et al., 2020).

115   Further, the human experience of heat stress is inherently hyperlocal, meaning that the distinct

116   microclimates existing throughout the city can control heat stress exposure and the efficiency of

117   adaptation strategies. However, the present study is primarily concerned with the regional drivers

118   of the extreme event rather than its absolute magnitude. Reanalysis provides continuous spatial

119   coverage and a wide array of internally consistent meteorological variables, which warrants its

120   use for the application here.

121   Hourly meteorological data are retrieved from the fifth major global reanalysis of the

122   European Centre for Medium-Range Weather Forecasts (ERA5), including 2-meter temperature,

123   2-meter dewpoint temperature, volumetric soil water for layer 1 (0-7 cm, where the surface is at

124   0 cm), surface pressure, geopotential height at 500 hPa and 200 hPa, precipitation, evaporation,

125   2-meter horizontal winds, and vertical velocity at 500 hPa (Hersbach et al., 2020). From this

126   hourly data, daily maximum temperature, daily total precipitation, and daily means of all other

127   variables are calculated from 1979-2023. Daily mean sea surface temperature (SST) data from

128   1979-2023 is also retrieved from the NOAA 1/4° Daily Optimum Interpolation Sea Surface

129   Temperature (OISST) dataset (Huang et al., 2021).

130   We also explore the future evolution of temperature extremes over the city of Rio de

131   Janeiro using the NEXGDDP dataset (Thrasher et al., 2022). This data product is statistically

132   downscaled from the Coupled Model Intercomparison Project Phase 6 (CMIP6) models, with a

133   spatial resolution of 0.25 degrees and outputs variables on a daily temporal scale. We directly

134   retrieve daily maximum temperature data through the end of the century under the Shared

135   Socioeconomic Pathways (SSPs) SSP2-4.5 and SSP5-8.5 for the 23 models which output this

136   variable and pair of scenarios for each day in the calendar year through 2100.

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

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

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

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

141   2019). These biases are greatest in regions with large land-ocean surface temperature contrasts,

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

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

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

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

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

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

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

149   (1981-2013) into one-percentile bins for both the NEXGDDP and ERA5 datasets. We

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

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

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

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

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

155

156   **2.2 Methodology**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

204 all 23 models does not change.

205

206 **3 Results**

207 **3.1 Rio de Janeiro's spring 2023 heatwave**

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

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

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

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

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

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

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

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

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

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

218 facilitated by the city's abundant access to moisture from the coast and surrounding vegetation.
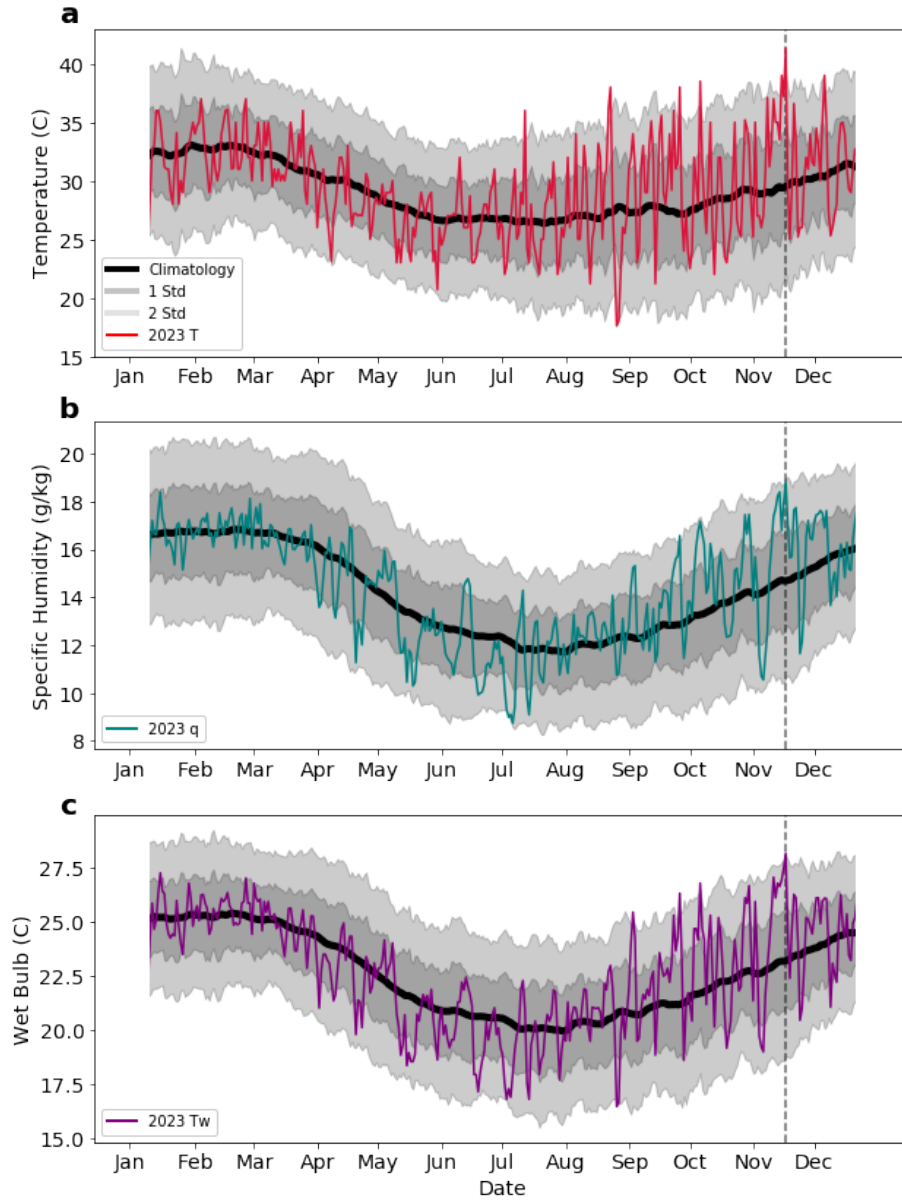
Figure 1: Historical climatology and 2023 recorded a) daily maximum temperature, b) daily mean specific humidity, and c) daily maximum wet bulb temperature in the city of Rio de Janeiro. Data from the Galeão International Airport weather station as reported by the HadISD dataset. Vertical dashed line 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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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. 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
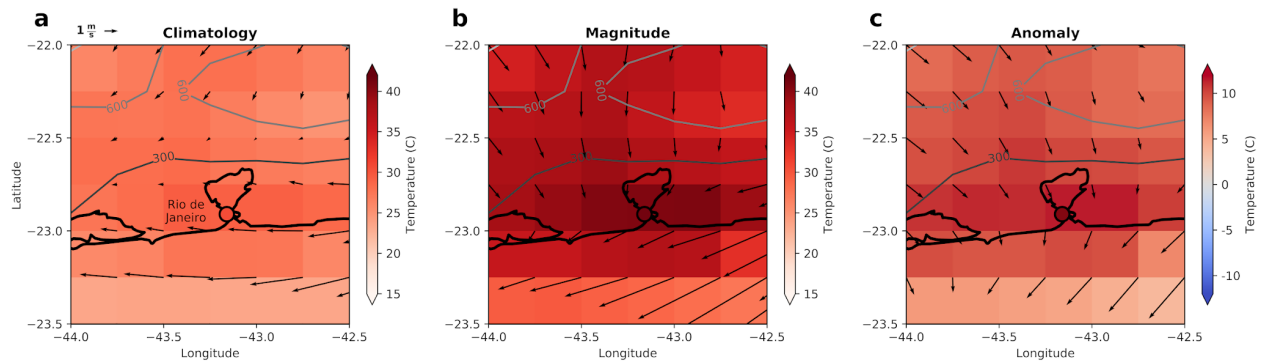rendered it difficult for residents to find relief.

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 the Galeão International Airport weather station (marker). 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.

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. Surface winds off the coast of Rio de Janeiro were
anomalously northerly. Previous literature has shown that such anomalously northerly winds

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256   over the coast can increase local sea surface temperatures through reductions in wind-driven

257   upwelling, reducing the capacity for coastal cooling (Castelao and Barth 2006; Palma and

258   Matano 2009). Further, anomalously northerly flow in this mountainous area can exacerbate high

259   temperatures directly through downslope winds (Stefanello et al. 2022). Anomalous winds over

260   the interior of South America also enhanced the northerly South American Low Level Jet

261   (Marengo et al., 2004; Montini et al., 2019). Positive specific humidity anomalies were present

262   throughout Southeast and South Brazil, intersecting with an area of precipitation along the edge

263   of the low pressure system to the south. The northern portion of the positive specific humidity

264   anomaly was aligned with the positive geopotential height anomaly off the coast of Southeast

265   Brazil. Widespread negative soil moisture anomalies occurred throughout most of Brazil, and the

266   interior of South America more broadly, during this event. The large spatial coverage of these

267   negative soil moisture anomalies was concurrent with Amazonian drought recorded during this

268   time, inherited from the prior season (Espinoza et al., 2024). Finally, positive SSTs of up to 2°C

269   occurred along Rio de Janeiro's coast. These spatial patterns are typical of extreme heat events

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

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

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

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

274   anomalies. Further, the positive local SST anomalies off the coast of Rio de Janeiro were

275   particularly exceptional in intensity and spatial scale during this event, weakening the sea-air

276   temperature contrast and sea-breeze. Outside of these specific distinctions, the event on

277   November 18, 2023 was an intense example of a typical spring extreme heat event in the region.
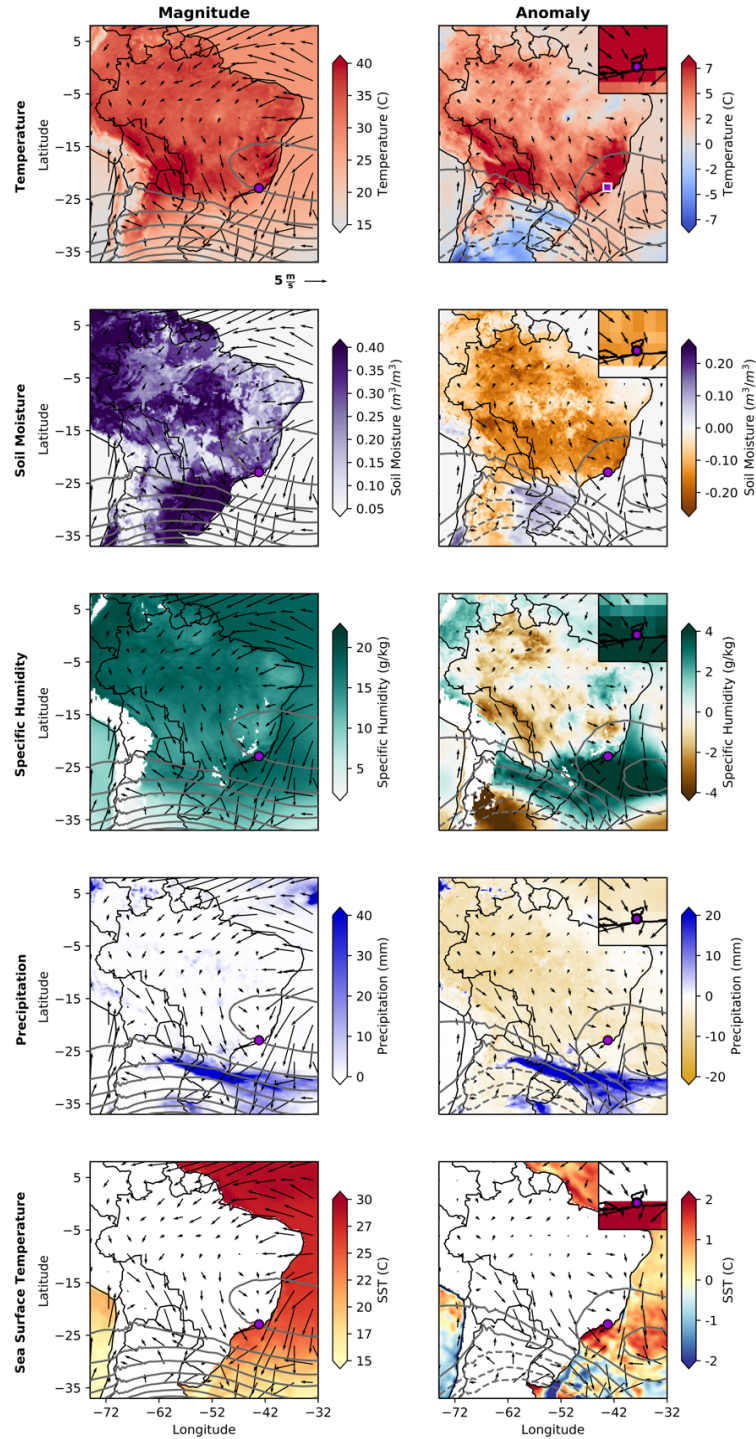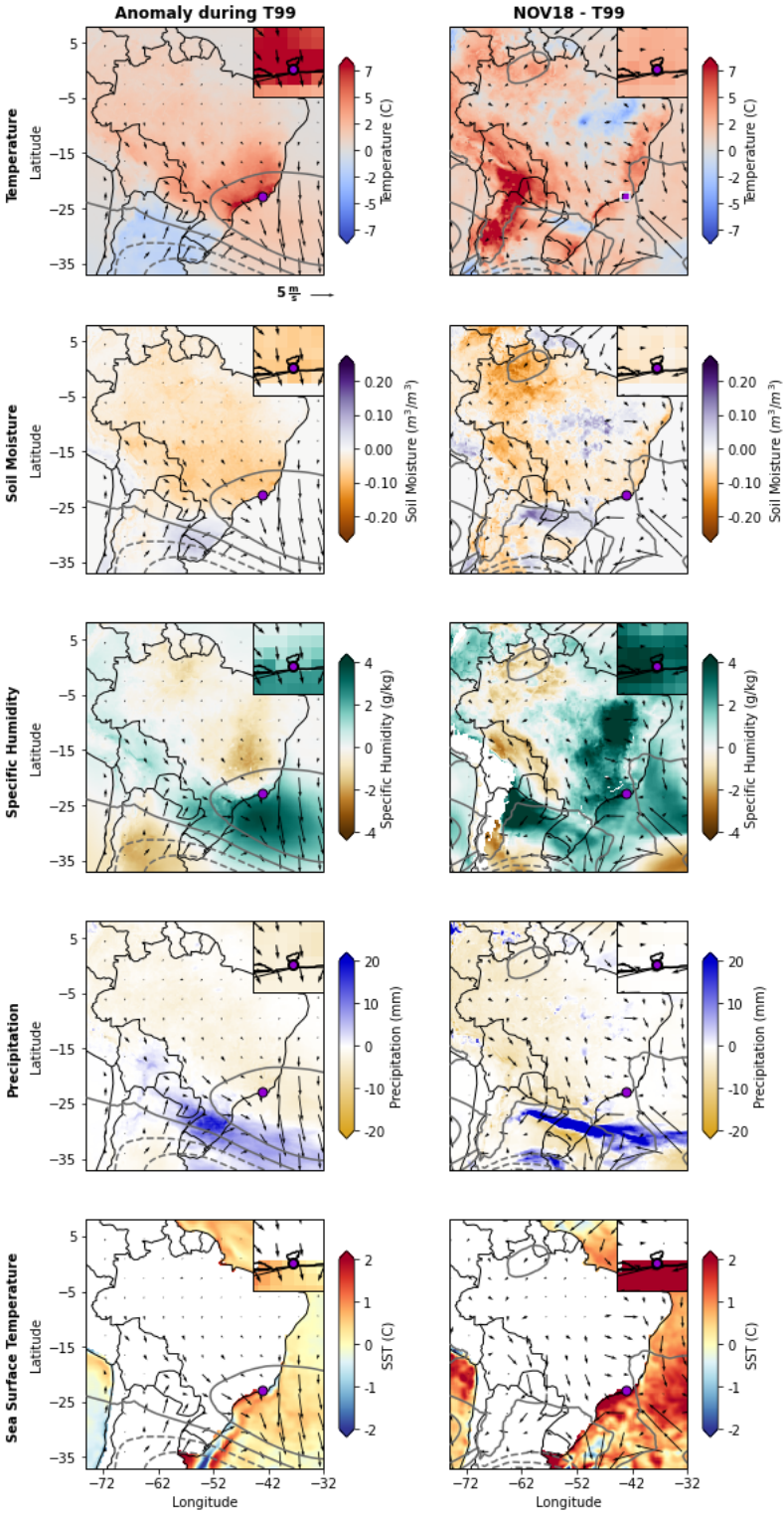
Figure 3: Magnitude (left) and anomalies (right) of daily maximum temperature, mean soil moisture, mean specific humidity, total precipitation, and mean SST on day of peak temperature in the city of Rio de Janeiro (November 18, 2023). Overlying wind vectors and 500 hPa geopotential height contours (50 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

285 **plot zooms in on the white box surrounding the city of Rio de Janeiro (purple marker) in**
286 **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).

The time evolution of the meteorological variables described above throughout the month of November 2023 uncovers the temporal development of the extreme heat event (Fig. 5). Rising temperatures throughout the weeks leading up to November 18 were preceded by elevated geopotential heights at 500 hPa and associated atmospheric subsidence. This was accompanied by a rapid decline in soil moisture which was likely facilitated by the increased solar insolation associated with the persistent high pressure system and resulting extremely low precipitation from November 2-November 18. Given that the rainy season in Southeast Brazil typically begins in late-October to mid-November (Coelho et al., 2021; Latinovic et al., 2018; Marengo et al., 2012; Liebmann and Mechoso 2011; Raia and Cavalcanti 2008), this period of consecutive dry days was unusual. Indeed, this period totals 17 days in a row with less than 5 mm of rain per day, and this only happened during the month of November in one other year in the historical record from ERA5 between 1979-2023 (2012). These changes in geopotential height, soil moisture, and suppressed precipitation preceded changes in other variables, evidenced by the grey lines in the background of each subplot. There was also a gradual increase in SST off the coast of Rio de Janeiro, though delayed compared to that of the local air temperature. Wind direction was highly variable on a daily scale, but became increasingly northerly during this same period. As air temperatures rose, specific humidity increased over the city. This was likely related to both local evaporation from the soil (co-occurring with declining soil moisture) and moisture advected from the coast and surrounding vegetation. The circulation specifically on November 18 directed wind in the larger region surrounding Rio de Janeiro to intensify the South American Low Level Jet, which can additionally increase moisture transport from the Amazon Basin to Southeast Brazil (Marengo et al., 2004; Vera et al., 2006; Montini et al., 2019). However, convergence of the horizontal moisture flux at the level nearest the surface was only stronger than its climatological values in some grid cells within the northern and western areas of the city (Fig. S6). More generally, specific humidity was also able to build without reaching saturation due to the increasing temperatures (and the Clausius-Clapeyron relation). Finally, the heatwave was

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321 terminated when a two-day precipitation event occurred from November 19- 20. This

322 precipitation induced a small decline in specific humidity and SST, as well as a rapid increase in
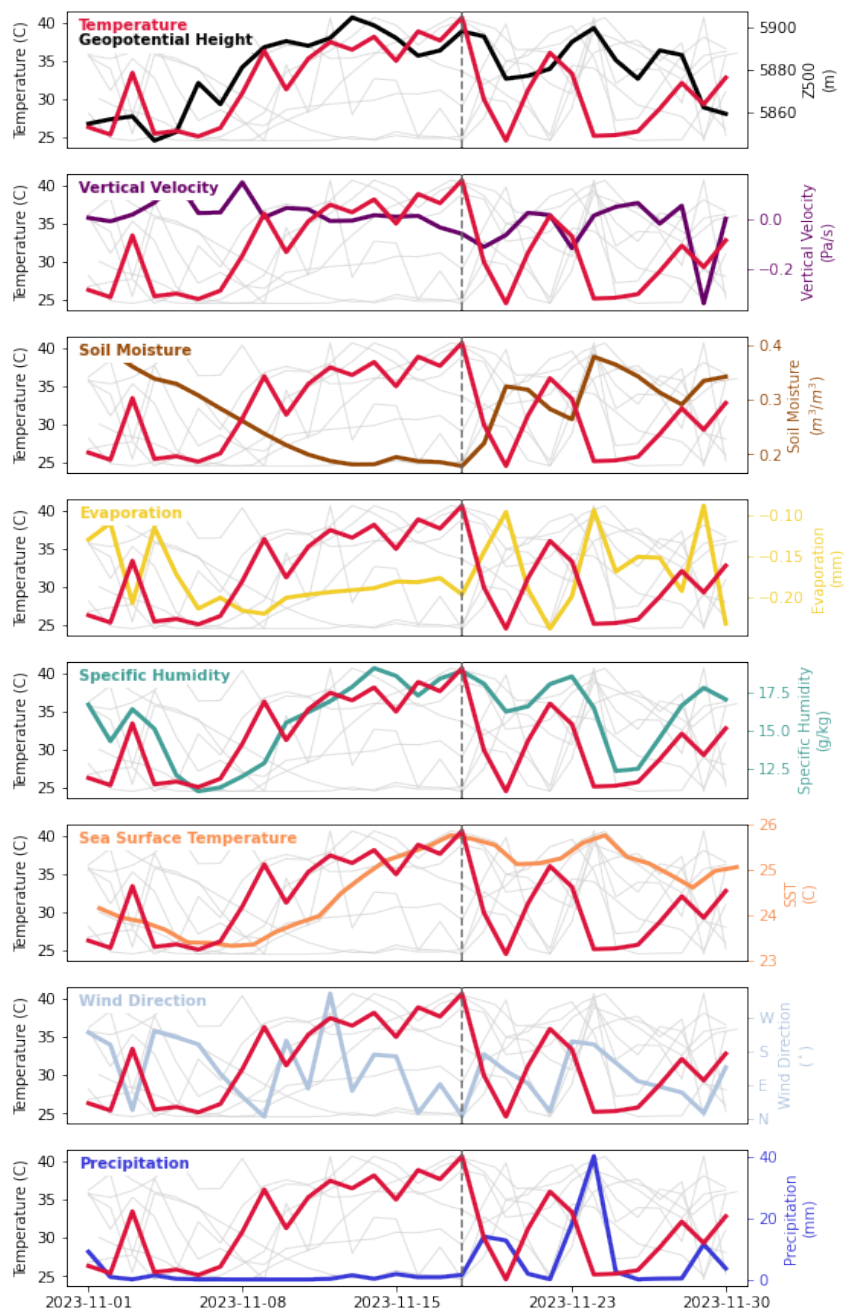
323 soil moisture.

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325 **Figure 5: Evolution of meteorological conditions during the month of November 2023 in**
326 **Rio de Janeiro. Grey lines in the background of each subplot show the evolution of all**
327 **variables, with individual variables compared in colors to dry bulb temperature in red.**
328 **Vertical dashed line identifies record-breaking temperature event on November 18, 2023.**
329 **All variables are calculated for the grid cell which includes the Galeão International**

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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. We note that similar wave trains driven by Pacific SST anomalies have been shown to influence weather in Southeast Brazil even during neutral ENSO states (Seth et al., 2015). Additionally, the instantaneous extreme temperature event and the preceding persistent dry conditions must also be linked to the synoptic weather in the area. Decreases in soil moisture and horizontal moisture fluxes by intensification of the South American Low Level Jet were central features of the heatwave in 2010, as they were in November 2023. These overlaps in the apparent drivers of the 2010 and 2023 heatwaves underscore that while last year's spring event was

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361 unprecedented in its magnitude and unusual in its spring timing, it was not unique in its overall
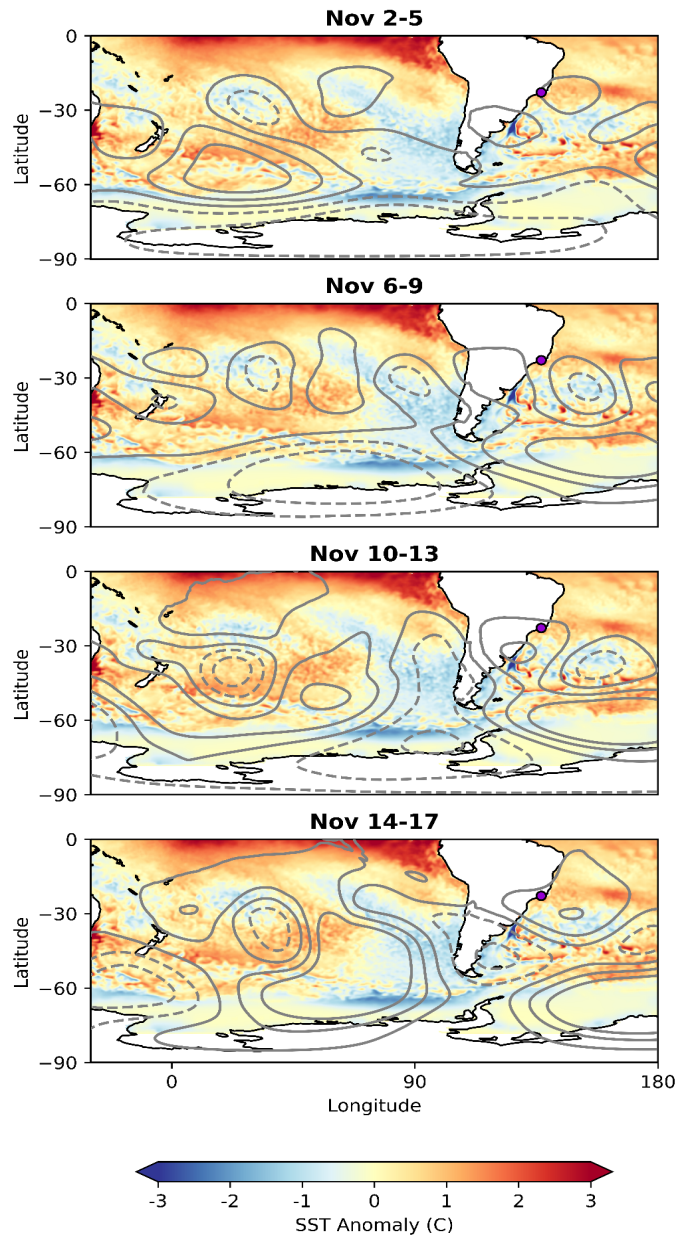
362 dynamics.

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.

3.2 Historical and future changes in extreme heat

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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.
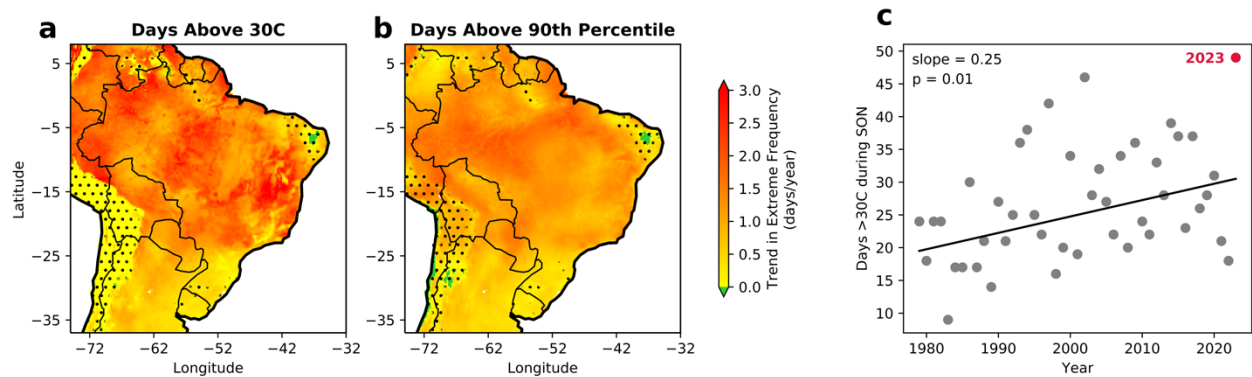

Figure 7: Historical trend from 1979-2023 in the number of days per year above a) 30°C and b) locally defined 90th percentile. Stippling shows areas which are not significant at a p = 0.05 level assessed using a Wald Test. c) Trend in number of days per year above 30°C taking place in the SON season in ERA5 for the grid cell which includes the Galeão International Airport weather station.
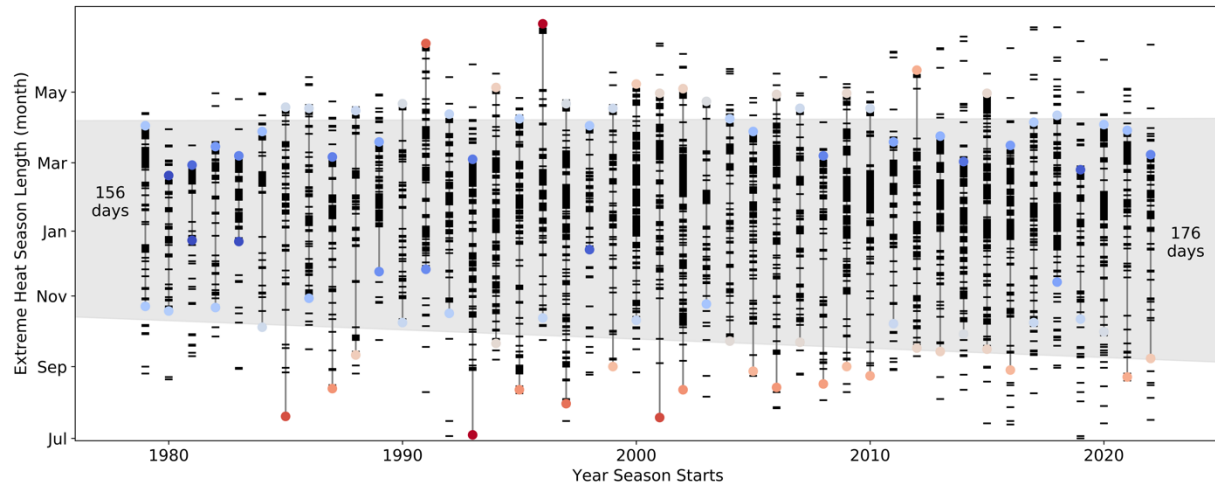
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Figure 8: Shifting timing of the city of Rio de Janeiro extreme heat season. Horizontal axis indicates the year in which winter begins ("January" marking denotes the start of the following calendar year). Colored markers indicate the first and last 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,

19

416   respectively. A larger change is projected by the end of the century (2081-2100) under each

417   emissions scenario. However, the end-of-century SSP5-8.5 scenario is distinctly separate from

418   the other distributions, with the distribution location parameter 2.8°C higher than during the last

419   10 years.

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

421   intensity of the maximum temperature recorded on November 18, 2023. The probability density

422   function fit to the projected annual maximum spring temperatures under each mid-century period

423   using a GEV distribution yields a return period for an extreme temperature event with the daily

424   maximum temperature at least 40.6°C in the city of Rio de Janeiro (analogous to the event on

425   November 18, 2023 as measured by ERA5) of 51 years under SSP2-4.5 and 33 years under

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

427   becomes much more likely, with return periods of 19 years or just 4 years under SSP2-4.5 and

428   SSP5-8.5, respectively. Recent literature has suggested that the SSP5-8.5 scenario may not be

429   realistic given our current socioeconomic, political, and physical landscape (Hausfather and

430   Peters 2020; Burgess et al., 2020; Ritchie and Dowlatabadi 2017). However, these results

431   indicate that an austral spring heatwave of the magnitude experienced in the city of Rio de

432   Janeiro on November 18 is projected to become much more frequent in the future, even under

433   the more stringent SSP2-4.5 emission pathway. We must also note that it is difficult to evaluate

434   whether the models are missing emerging factors that could increase the frequency and intensity

435   of these extreme heat events – such as Amazonian deforestation or declines in sea ice – reducing

436   their ability to capture the possible future spring temperature distributions in Rio de Janeiro.
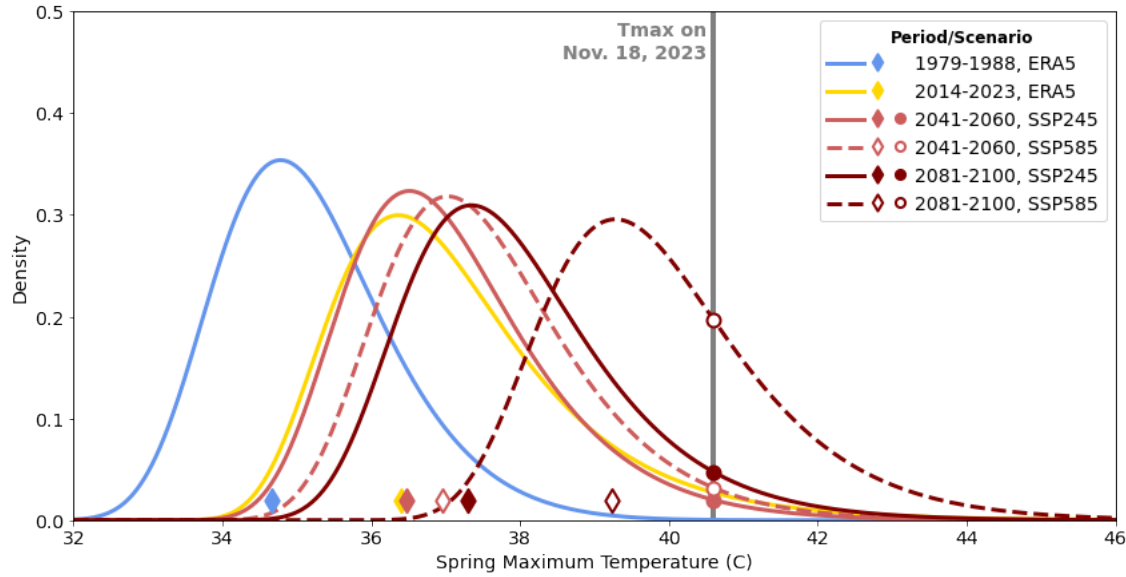
Figure 9: Generalized Extreme Value distributions for SON maximum temperatures during early and late historical periods (observed in ERA5), mid-century periods, and end-of-century periods under SSP2-4.5 and SSP5-8.5 (projections from bias-corrected NEXGDDP data). Diamonds indicate the value of the location 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,

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

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

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

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

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

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

466   century periods. However, the absolute increase in the frequency of similar heatwaves is largely

467   dependent upon our future emissions pathway.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

490   The meteorological conditions surrounding the extreme heat event analyzed here

491   demonstrate the potential for compound hazards throughout Brazil. The identified circulation

492   pattern that establishes the atmospheric blocking associated with heatwaves in Rio de Janeiro is

493   also likely linked to heavy precipitation events in South Brazil, an extreme case of which

494   occurred in May 2024 in center-north of Rio Grande do Sul, including the metropolitan area of

495   Porto Alegre, displacing hundreds of thousands and killing at least 155 people (Rogero 2024).

496   The temporal compounding of these extreme temperature and flooding events within Brazil has

497   the potential to strain the country's disaster management systems more than events occurring in

498   isolation. Furthermore, the exceptional spatial area within Brazil that experienced anomalous

499   heat in the November 2023 event, relative to 99th percentile heat events in the city of Rio de

500   Janeiro, underscores the potential for spatially compounding heat that could lead to outsized

501   impacts. Exploring how unprecedented global surface ocean and surface temperatures, along

502   with regional features like the broader heat and drought across much of Brazil, may contribute to

503   extreme heat in the city of Rio de Janeiro will be an important component to improving our

504   understanding of these compound events' drivers, prediction capacity, and potential to change in

505   the future.

506   The evolving meteorological conditions associated with this heatwave were strongly

507   impacted by the lack of precipitation in the first two weeks of November. This is particularly

508   unexpected due to the fact that the active phase of the South American Monsoon System

509   typically begins in late October or early November in this region (Marengo et al., 2012;

510   Liebmann and Mechoso 2011; Raia and Cavalcanti 2008), which is linked to an increase in

511   convective activity in tropical South America in the warm season (Jones and Carvalho 2013).

512   Observational and modeling studies suggest that the South American Monsoon System dry

513   season is lengthening (Arias et al., 2015; Fu et al., 2013) and that the onset of the active phase is

514   delaying (Gomes et al., 2022; Pascale et al., 2019). These trends are projected to continue to

515   some degree in the future with further climate change, particularly in light of ongoing

516   deforestation which contributes to regional drying trends in the Amazon and other areas of Brazil

517   (Boisier et al., 2015; Swann et al., 2015). Given Rio de Janeiro is a city with abundant access to

518   moisture due to its proximity to the coast and vegetation, the increasingly constrained active

519   monsoon phase could lead to increased frequency and intensity of extreme humid heat in the

520   spring season (Ivanovich et al., 2024). These changes could be responsible for the evident

23

521   asymmetrical historical increase in heat season length during the spring versus fall as

522   demonstrated here, and extensions of this work should be devoted to an exploration of these

523   potential relationships.

524   This work highlights the challenge of analyzing the drivers of weather extremes in such a

525   climatically diverse city as Rio de Janeiro and emphasizes the need for future research to explore

526   high resolution comparisons of mechanisms controlling the city's microclimates. Differences

527   between conditions recorded at individual weather stations within the city's boundaries

528   demonstrate the degree to which the dynamics of events in each neighborhood depend on the

529   station's location relative to the coast versus interior (Raymond and Mankin 2019), elevation

530   (Raymond et al., 2022; Pepin et al., 2015), and degree of urbanization (Kruger et al., 2024;

531   Chakraborty et al., 2022; Tan et al., 2010). Higher temporal resolution analysis would also better

532   capture sub-daily processes such as sea breeze and their effect on extreme heat throughout the

533   city. Further, many of these mechanisms influencing the intracity variability of heat stress

534   exposure only focus on the effect of differences in dry bulb temperature. Factoring in the spatial

535   variation in humidity, solar insolation, and windspeed complicate understanding, but are

536   essential for capturing humans' exposure to heat stress conditions. These intracity differences

537   also meaningfully impact compound events with non-heat environmental hazards, such as floods,

538   landslides, droughts, and air pollution, as well as how exposure to these hazards intersects with

539   areas of social vulnerability. Future work should be devoted to investigating the different

540   magnitudes of extreme heat and controlling mechanisms throughout Rio de Janeiro in order to

541   inform targeted extreme heat adaptation plans for individual neighborhoods within the city.

542

543   *Data Availability:* The publicly available datasets used in this analysis are accessible via the

544   following websites: HadISD, https://www.metoffice.gov.uk/hadobs/hadisd/; ERA5,

545   https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview and

546   https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels?tab=overview; OISST,

547   https://www.ncei.noaa.gov/products/optimum-interpolation-sst; and NEXGDDP,

548   https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6.

549   Station data from the Rio Alert System will be uploaded and accessible via a GitHub repository

550   upon manuscript publication.

551

552   *Code Availability:* All code used for the derivations, calculations, and data visualization will be

553   made publicly available via a GitHub repository upon manuscript publication.

554

555   *Author Contributions:*

556   S.J.C. conceived of the initial project concept. All co-authors contributed to study design, and

557   C.I. performed the analysis. C.I. wrote the initial manuscript draft with the feedback and

558   interpretation of all co-authors. All co-authors read and edited the manuscript.

559

560   *Competing Interests:*

561   The authors declare that they have no conflict of interest.

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