Physical Drivers of the November 2023 Heatwave in Rio de Janeiro

Catherine Ivanovich, Adam Sobel, Radley Horton, Ana Nunes, Rosmeri Rocha, and Suzana Camargo

We greatly appreciate the thoughtful comments and helpful suggestions provided by the Editor. Below, we have provided information on the major modifications to the text and responded point-by-point to comments (Editor comments in blue, responses in black, with **bold** language indicating relevant changes to the text). When referring to page number X and line number Y, we use the abbreviation PXLY.

Editor's Comments

The authors present a careful analysis of the physical drivers behind the November 2023 heatwave in Rio de Janeiro. After the first review round, both referees are satisfied with the manuscript. I agree the paper is close to acceptance; however, I believe a few targeted improvements would strengthen both the science and the presentation. I do not plan to send the paper out for another review cycle, but I ask the authors to address the comments below in a revised version and brief response.

We are glad to hear that the Reviewers were satisfied with our responses to their comments and the associated changes we made to the manuscript. We thank the Editor for following up about these remaining concerns, which we respond to point-by-point below.

Major comments

1. Quantifying drivers and the role of moisture vs. temperature
Focusing only on temperature makes it hard to apportion contributions among drivers. Your results suggest soil moisture influenced both heating and near-surface moisture over Rio. At the same time, Fig. 5 shows that SST increased by ~3 °C during the 10 days preceding the event. Very little is said about the dynamics behind this abrupt SST rise.

Please expand on possible mechanisms and timescales for the SST increase and its coupling to boundary-layer moisture over land.

Previous literature has identified that wind-driven upwelling in this region is highly sensitive to wind direction and can greatly impact SSTs. We include discussion of these mechanisms throughout the text, but the connection with the present SST anomalies was not sufficiently clear. We have rearranged and expanded the discussion of these mechanisms in the discussion of Figures 3 and 5, which we have reproduced below. We also identify potential secondary drivers of the elevated sea surface temperatures including increased solar radiation to the ocean, added heat flux to the ocean, and a shallowing of the mixed layer.

Starting on P10L257, the text discussing Figure 3 now reads:

"Surface winds off the coast of Rio de Janeiro were anomalously northerly. ***Anomalously northerly flow in this mountainous area can exacerbate high temperatures directly through downslope winds (Stefanello et al. 2022).*** *Previous literature has* **also** *shown that anomalously northerly winds over the coast can increase local sea surface temperatures through reductions in wind-driven upwelling, reducing the capacity for coastal cooling (Castelao and Barth 2006; Palma and Matano 2009).* ***Indeed, positive SST anomalies of up to 2°C occurred along Rio de Janeiro's coast on the day of the peak in air temperature (Fig. 3j).****"*

The updated text discussing Figure 5 from P14L331 now reads:

"***Wind direction was highly variable on a daily scale, but became increasingly northerly during this same period. These changes were accompanied by*** *a gradual increase in SST off the coast of Rio de Janeiro, though delayed compared to that of the local air temperature.* ***These changes in wind direction and SSTs are likely linked, as upwelling in this region can be significantly reduced through northerly wind anomalies, increasing coastal sea surface temperatures (Castelao and Barth 2006; Palma and Matano 2009). Secondary pathways to SST increases could include increased solar radiation to the ocean, added heat flux to the ocean, and a thinning of the oceanic mixed layer. These features are common around many coastlines during atmospheric heatwaves that are associated with warming coastal waters, though further research would be needed to quantify their relative importance during the November 2023 heatwave in Rio de Janeiro.*** *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* ***anomalously warm coastal waters*** *and surrounding vegetation."*

2. Because health impacts depend strongly on humidity, a more informative target variable than dry-bulb temperature is wet-bulb temperature. Simple calculations (holding RH fixed while perturbing T) suggest humidity's contribution to wet-bulb can be slightly larger than that of temperature.

Questions: How independent are the variations of temperature and humidity in your data? If they are largely independent, then reaching 40 °C in future climates (as discussed later in the paper) may not be an appropriate proxy for this event, since 40 °C can occur under lower humidity and thus have milder health effects.

Daily scale temperature and humidity variations are highly correlated during the full calendar year and during the spring more specifically, as evidenced by Figure S4. This indicates that almost every hot day is also very humid in the city of Rio de Janeiro, and that historical and future increases in temperature would also facilitate increases in humid heat. Given that Rio de Janeiro is a coastal, tropical city, we can expect that it will maintain its plentiful moisture source in the future.

With this in mind, we feel confident about using temperature as the primary metric of study for this analysis. For more discussion on the use of dry versus humid heat metrics in projections, please see our response below to Comment 5.

3. Large-scale warm background (July–December 2023)

The heatwave occurred against an extended warm anomaly that lasted from ~July to December and exceeded the prior two weeks. Please discuss candidate explanations for this multi-month pattern (e.g., oceanic forcing, circulation regimes, soil-moisture memory, or other modes), and clarify how it conditioned the event.

The monthly-scale warm anomalies that surrounded the extreme event we focus on in the present study are likely linked to El Niño, as discussed throughout the paper as a primary contributor to the November 2023 extreme event itself. We have added text to underscore the fact that El Niño is likely playing a role in longer-term increases in temperature throughout Brazil by citing published literature which has investigated elevated temperatures in the region during 2023 more broadly. We also want to acknowledge the fact that the second half of 2023 was exceedingly warm globally, relating in large part to anthropogenic warming. Together on P16L391, this text reads:

"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 exceedingly warm globally (Cattiaux et al. 2024; Perkins-Kirkpatrick et al. 2024), due in large part to anthropogenic warming, indicating that climate variability and climate change both likely preconditioned the November 2023 extreme heat event."

4. Section 3.2 — Future projections in terms of wet-bulb

Given the relevance for human health, Section 3.2 should, where feasible, incorporate wet-bulb temperature (noting that radiation and wind also matter).

How feasible would it be to compute future wet-bulb distributions with your datasets?

Would amplification factors or return frequencies change materially if the analysis used wet-bulb rather than dry-bulb temperature (as expected in a moist tropical climate)?

If such an analysis is not currently possible, please discuss explicitly how you expect humidity to modulate future heatwaves in the region.

We appreciate this note about metric use when describing the impact of extreme heat (dry versus humid). As discussed in our response to Comment 2 above, our supplemental Figure S4 demonstrates that there is a high correlation between temperature and specific humidity in Rio de Janeiro, meaning that extreme heat days tend to be very humid. This is why we see that the peak in temperatures that occurs on November 18, 2023 is not only a record-breaking dry bulb temperature day, but also an extreme wet bulb temperature day (Figure 1). As authors on this manuscript have previously shown, regions with high moisture availability tend to experience humid heat extremes through mechanisms which increase local dry bulb temperatures (e.g., Ivanovich et al. 2024; Ivanovich et al. 2022). We thus find the question of how dry bulb temperatures are changing with time in the city of Rio de Janeiro to be more compelling and link more closely to the unusual features of the November 2023 heatwave.

With respect to how these relationships are changing and may continue to evolve, recent research has shown that annual maximum wet bulb temperatures in the tropics are constrained by atmospheric dynamics and convective capping (given that wet bulb temperature is so closely related to moist static energy and thus vertical stability), which means that tropical annual maximum wet bulb temperatures rise roughly in a 1:1 ratio with tropical mean temperature (Zhang et al. 2021). This also means that annual maximum wet bulb temperatures will rise less quickly than annual maximum temperatures in the tropics (Matthews et al. 2025; Zhang et al. 2021). Thus, we might expect that the return periods would be larger if we repeated the analysis with wet bulb temperature and that the frequency of such events would not increase as rapidly as for dry bulb temperatures, as suggested by papers such as Coffel et al. 2018. This is further motivation for focusing on the dry bulb temperature component of the November 2023 heatwave and how this variable, rather than humidity, evolves in time.

We have added some comments about these relationships to the text on PXLY, which reads:

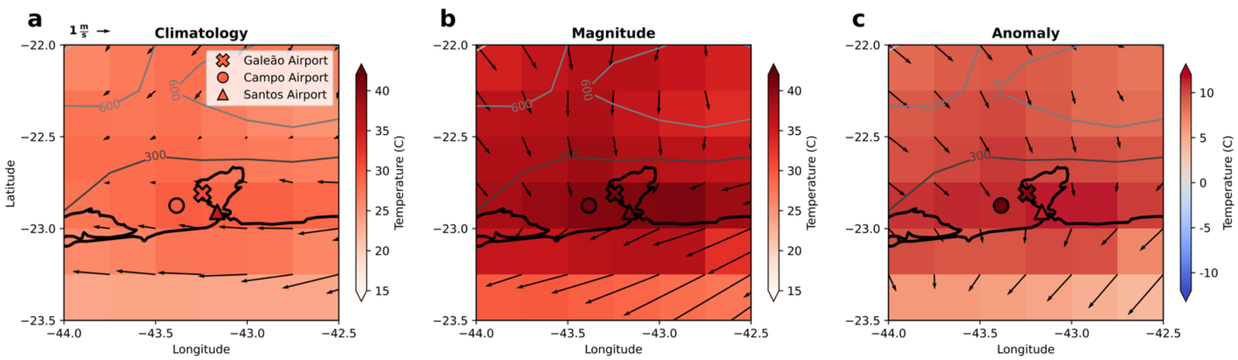
"As temperatures rise and the city of Rio de Janeiro maintains its ample moisture sources from the nearby ocean and vegetation, we expect that humid heat extremes will also become more frequent and intense, though at a slower rate than dry bulb temperature extremes as dictated by tropical atmospheric dynamics (Coffel et al. 2018; Zhang et al., 2021; Matthews et al., 2025)."

Minor comments

5. Figure 2: In the main text figure, please add the remaining surface stations as done in the Supplementary figures.

Thank you for this suggestion. Because this figure plots the temperature magnitude on November 18, as well as the anomaly on that day and the average climatology during November 18 throughout the historical record, we can only include stations which have a long temperature record. Unfortunately, most stations from the Rio Alert System only have temperature data for the last ~10 years.

We are, however, able to include two more stations from the HadISD dataset, which are airport weather stations (in total, the Galeão Airport, Campo Airport, and Santos Airport). We now include all three stations with multi-decadal historical records on the maps in Figure 2 identified by three different symbols. This change also better emphasizes that the anomalies measured by ERA5 fall within those recorded by the range of stations in the city. We have reproduced the updated version of Figure 2 below, for reference:



Updated 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.

6. Figures 3–4: The discussion on pp. 10–11 would read more clearly if tied to specific panel labels. Please label panels (a), (b), (c), etc., and reference them in the text.

Thank you for this suggestion. We have added labels to all panels and referenced them throughout the text.

7. Page 16 wording: Replace "last year's spring event" with "the 2023 spring event."

Thank you for this suggestion. We have made this edit to the text.

8. Figure 6: Panel labels would again help. Also, geopotential height is not ideal for diagnosing tropical teleconnections because fields become relatively flat near the equator. Consider showing 200-hPa streamfunction anomalies (or a similar level) for a clearer depiction of large-scale tropical wave patterns.

We have added panel labels to this figure, as well. We appreciate your suggestion about switching the contours from geopotential height anomalies to stream function anomalies. However, we prefer to keep the geopotential height anomalies because we compare the results we see here with previously published literature (including Geirinhas et al. 2018, Geirinhas et al. 2019, and Cai et al. 2020) which use geopotential height anomalies to describe these ENSO teleconnections. We are encouraged by the fact that the wave pattern is easily visible in the current version of the figure through the use of geopotential height anomalies.

Thank you for the solid work and responsiveness so far. I look forward to a concise revision and response addressing the points above.

Thank you for the kind words of encouragement. We appreciate your feedback and guidance on the review process thus far.

References

Cai, W., McPhaden, M. J., Grimm, A. M., Rodrigues, R. R., Taschetto, A. S., Garreaud, R. D., et al., (2020). Climate impacts of the El Niño–Southern Oscillation on South America. Nature Reviews Earth & Environment, 1(4), 215–231. https://doi.org/10.1038/s43017-020-0040-3

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

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

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

Ivanovich, C., Anderson, W., Horton, R., Raymond, C., & Sobel, A. (2022). The Influence of Intraseasonal Oscillations on Humid Heat in the Persian Gulf and South Asia. *Journal of Climate*, *35*(13), 4309–4329. https://doi.org/10.1175/JCLI-D-21-0488.1

Ivanovich, C. C., Horton, R. M., Sobel, A. H., & Singh, D. (2024). Subseasonal Variability of Humid Heat During the South Asian Summer Monsoon. Geophysical Research Letters, 51(6), e2023GL107382. https://doi.org/10.1029/2023GL107382

Matthews, T., Raymond, C., Foster, J., Baldwin, J. W., Ivanovich, C., Kong, Q., et al. (2025). Mortality impacts of the most extreme heat events. *Nature Reviews Earth & Environment*, 1–18. https://doi.org/10.1038/s43017-024-00635-w

Zhang, Y., Held, I., & Fueglistaler, S. (2021). Projections of tropical heat stress constrained by atmospheric dynamics. *Nature Geoscience*, *14*(3), 133–137. https://doi.org/10.1038/s41561-021-00695-3