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INTRODUCTION

Droughts are a recurrent phenomenon in the Amazon region (AMZ), usually affecting water resources, with significantly lower river levels, damaging ecosystems, and increasing forest fires [1]. **The AMZ suffered an outstanding drought event in 2023**, which was even more severe to the point of **being considered a once-in-a-century drought event**. The 2023 drought was characterised by **minimal precipitation** (deficit of 50 to 100 mm/month), the **occurrence of seven heat waves** (e.g. September to November 2023 recorded mean temperatures of +3°C regarding long term average), a **large decrease in streamflow** and an **increase in the frequency and surface of forest fires**.

The precipitation deficits and temperature excesses observed in the AMZ can be closely related to the strong air moisture that reaches the area and which can be stored in the overlying air column according to the Clausius-Clapeyron (CC) relationship.

However, the origin of the air moisture and temperature excesses for this drought event is unknown.

General Objective

This study aims to elucidate the origin of highly anomalous moisture and temperature excesses and their role in the development of the 2023 drought over the AMZ.

1. DATA & METHODOLOGY

Model and Data used:

Lagrangian moisture uptake (MU) was computed for 1994–2023 using the **FLEXPART** particle dispersion model [2] driven by the **ERA5** reanalysis. ERA5 fields (0.5° resolution) were also used to derive vertical velocity (Ω), 2-m temperature (T2), total precipitation (P), vertically integrated water vapour transport (IVT), and the variables required to calculate Standardised Precipitation-Evapotranspiration Index at 9 months (**SPEI-9**).

Definition of the target region for moisture tracking:

The drought-affected area used was that for the last month of the studied event, December 2023 with SPEI-9 threshold less than -1.65.

Determination of moisture sources and sinks:

To compute MU reaching the AMZ from its sources, the changes in the specific moisture content (q) over time (every 6 h) along the tracks described by each atmospheric particle (of m mass) into which the atmosphere was divided were computed [2].

The particle trajectories were followed backwards for 10 days (considered the average residence time of water vapour particles in the atmosphere) and for those particles with a decrease in specific humidity of more than 0.1 g/kg in the 6 h before reaching the target region.

Determination of temperature anomaly sources:

The method by Papritz and Röthlisberger (2023) [3] was used to determine the sources of temperature anomalies into contributions from horizontal advection, adiabatic processes, diabatic heating, and seasonality.

2. RESULTS : Anomalous moisture and temperature excesses sources

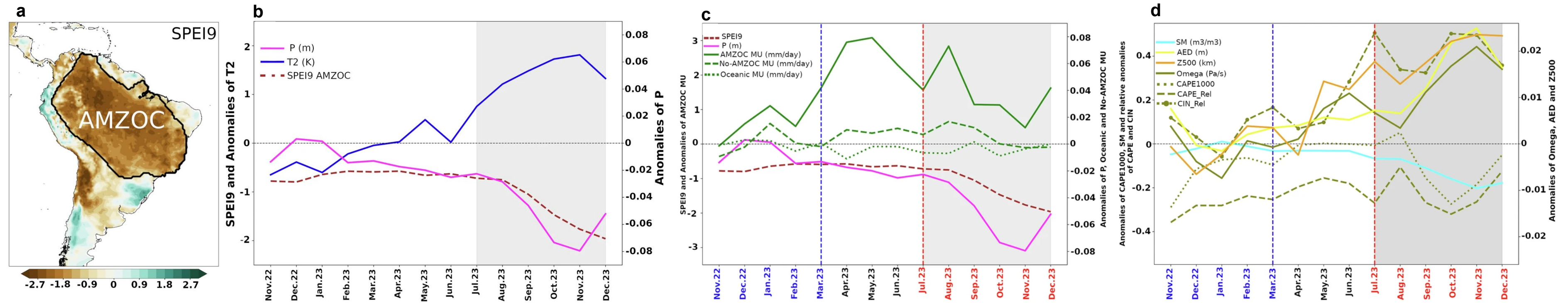


Figure 1: Time series of the monthly anomalies of different meteorological variables for the 2023 Amazon drought | a) Area of study (AMZ) defined by SPEI9 < -1.65 value for Dec 2023 (brown line). **b-d)** Anomalies for drought-related variables in the AMZ region from Nov22 to Dec23.

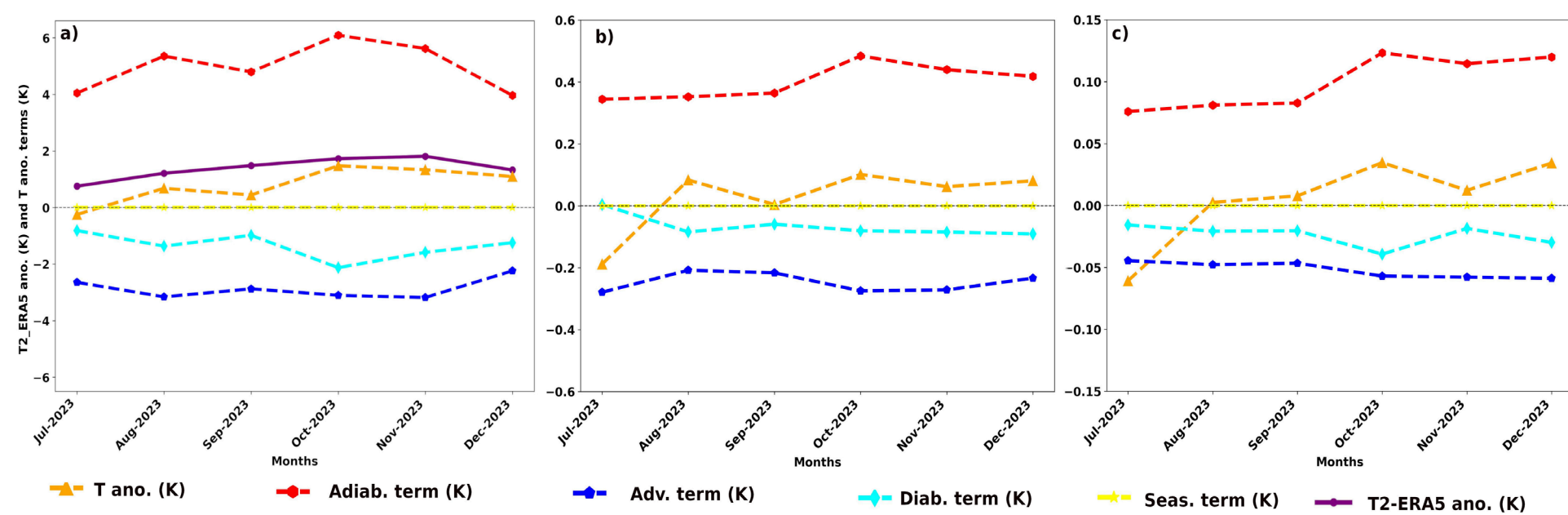


Figure 2: Monthly series of 2023 drought-related T anomaly sources |

Purple solid line: T anomaly using ERA5. Dashed lines: T Lagrangian sources anomalies of the total T (orange) and individual T terms -> seasonal [yellow], adiabatic [red], diabatic [cyan], and advective [blue]. **a)** for the AMZ region, **b)** ocean region, and **c)** land without the target region.

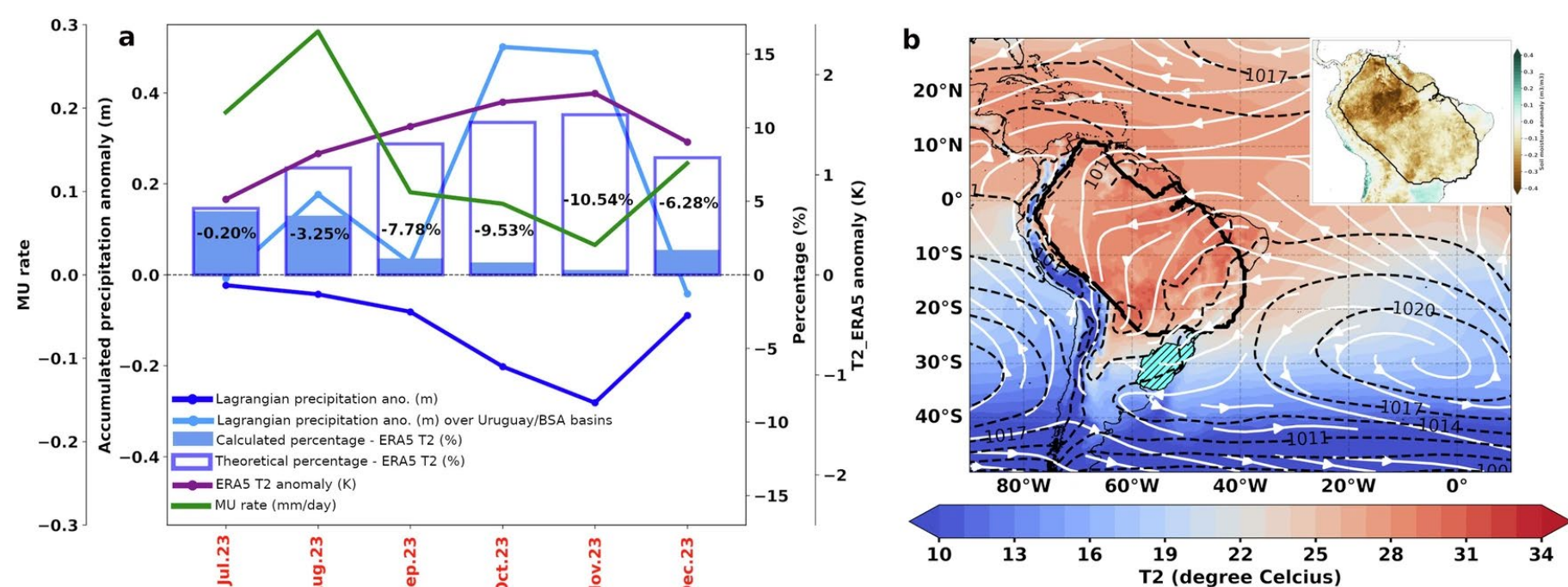


Figure 3: Behaviour of different variables related to the drought in July-Dec23 | a) Mean variables calculated over the AMZ region: theoretical (not-filled bar) and calculated (filled bar) percentages of moisture content in the atmosphere using the Clausius-Clapeyron relationship, MU rate (green), T2 anomaly from ERA5 (purple), and Lagrangian precipitation anomaly (magenta). **b)** Mean fields during Sep-Nov23 for T2 (°C), 10m-wind (white streamlines, m/s) and MSLP (black dashed lines, hPa). Upper right corner subfigure: SM anomalies.

- During the record-breaking 2022–24 Amazon-drought, despite an initial increase in moisture transport from remote sources or the region itself (c, green lines), **the absence of atmospheric instability** (d, omega, CAPE & CIN), **resulted in precipitation deficits (magenta) over most of the Amazon region**.

- Although atmospheric moisture was anomalously high, it was insufficient to compensate the **elevated temperatures** (a, blue) resulted in an increase in the evaporative demand (d, AED, yellow) in the region, leading to a significant increase in soil evaporation (d, SM, soil moisture) from the area and contributing to the intensification of the drought episode (SPEI-9).

- The **temperature anomaly** over the target region **had two sources** (Figure 2): a local one contributing to warming and an external one contributing to cooling. The results show the importance of **adiabatic warming** due to subsidence in the region itself (atmospheric stability) and **outside the region** (anticyclonic circulation).

- Despite the increase in moisture uptake, it remained insufficient to meet the additional atmospheric moisture demand** predicted by Clausius-Clapeyron scaling ($\sim 6\text{--}7\%$ °C⁻¹). The mismatch was greatest during September–November, with **deficits of approximately 8–11%** relative to the theoretical moisture requirement (Figure 3a), **further intensifying the drought**.

- Moisture that did not precipitate** in the region because of atmospheric stability **was transported** to areas where there was sufficient instability for convection resulting in very high precipitation and floods in the **Uruguay/Brazilian-South-Atlantic-Marginal river basins in September-October/2023** (Figure 3b, filled blue region).

TAKE-HOME MESSAGES

-  **1** Moisture availability was anomalously high in 2023.
-  **2** Persistent subsidence and atmospheric stability suppressed convection and rainfall.
-  **3** Adiabatic and advective warming drove the exceptional temperature excesses.
-  **4** Excess moisture was exported to the La Plata basin, producing floods.

PUBLICATION

JC. Fernández-Álvarez, R. Nieto, S. Vicente-Serrano, D. Carvalho, L. Gimeno (2025)

Moisture and temperature sources were key drivers of the anomalies for the record-breaking of 2023 Amazon drought,

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REFERENCES

-  **[1]** Marengo JA et al. The Drought of Amazonia in 2023-2024. *Am. J. Clim. Change*, 13(3), 567-597 (2024).
-  **[2]** Stohl A & James PA. A Lagrangian analysis of the atmospheric branch of the global water cycle: Part II: Earth's river catchments ocean basins, and moisture transports between them. *J. Hydrometeorol.* 6, 961-984 (2005).
-  **[3]** Papritz L & Röthlisberger M. A novel temperature anomaly source diagnostic: method and application to the 2021 heatwave in the Pacific Northwest. *Geophys. Res. Lett.*, 50(23), e2023GL105641 (2023).

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