Atmospheric moisture and near-surface temperature anomalies: key drivers in the 2022 European mega-drought

Proposal for publication in Natural Hazards and Earth System Sciences (NHESS)

ROUND 1 (Feb/Aug 2026)

REVIEWER 1

Reviewer Comments: *The manuscript shows the underlying physical mechanisms that gave rise to the 2022 european drought, placing special emphasis on the behavior of atmospheric moisture transport from source regions. From this point of view, the work is revealing and should be published after revisions. The following comments are intended to strengthen clarity, they do not affect the core findings of the study.*

We thank the reviewer for the time and effort invested in this first revision of the manuscript. His/her contribution has helped greatly in producing a much higher quality version of the article. A reply to all his/her suggestions and questions is attached below.

Fernández-Alvarez et al. (2026)

General Comments

Comment 1: According to the SPEI-6 values shown in the figure S1 and described in the supplementary methods, the study region corresponds to areas with SPEI 6 ≤ –1.28 from June to August 2022. However, throughout the manuscript the peak period is defined as May–August. Furthermore, Figure 1c shows that SPEI-6 anomalies in the NW region are larger in November–December 2022 than during the months of the proposed peak period. A clearer justification of the selected peak period and the delimitation of target regions should be provided.

> ***Response:*** *We thank the reviewer for raising this important point regarding the spatial and temporal metrics used in our study. We agree that a clearer distinction between the spatial delimitation criterion and the temporal analysis of the drought peak is needed, and we have clarified this in the revised manuscript.*
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> ***Delimitation of target regions vs. Drought peak period****: The spatial target regions were defined based on SPEI-6 for June–August (JJA) 2022 (≤ -1.28) to isolate the areas severely affected during the core summer period, when the compound heatwave-drought impacts (evaporative demand, agricultural losses, and thermal stress) were most acute (Garrido-Pérez et al., 2024). On the other hand, the May–August (MJJA) period framed in Figure 1 represents the extended hydro-climatic drought peak, as May marks the sharp onset of persistent precipitation deficits (P), soil moisture depletion (SM), and elevated evaporative demand (AED) preceding the summer maximum (Figs. 1b, d, e). We have adjusted the wording in the text to explicitly clarify this distinction.*
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> ***SPEI-6 behavior in late 2022 (November–December)****: The multi-scalar nature of the SPEI6 index inherently incorporates a 6-month memory effect. Consequently, the minimum SPEI6 values observed in late autumn (e.g., November–December in NW_Europe) reflect the cumulative lagged response of the severe hydrological and atmospheric deficits accumulated throughout the preceding spring and summer, rather than an active intensification of drought drivers during late autumn itself. Indeed, the monthly flux anomalies (Fig. 1b) show that rainfall deficits and atmospheric stability (Z850, omega500, Fig. 1f,g) peaked between May and August, followed by partial recovery in September.*
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> *To make this explicitly clear to the reader, the corresponding text in the* ***Main text*** *has been revised as follows:*
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> *(…) Persistent deficits in precipitation (Fig. 1b) and soil moisture (Fig. 1e), together with strong increases in atmospheric evaporative demand (Fig. 1d) and thermal excess (Fig. 1h), concentrated primarily during May–August 2022—representing the active hydro-climatic peak period of the drought. While cumulative multi-scalar indices like SPEI6 (Fig. 1c) display their lowest values later in autumn due to the 6-month memory effect of preceding deficits, the active atmospheric drivers (precipitation suppression, high atmospheric demand, and thermal stress, Garrido-Pérez et al., 2024) clearly peaked during the May–August window (…).*

<u>Comment 2</u>: Figure 1 is difficult to follow without consulting the supplementary material. The figure includes numerous bar charts without titles, and the legends are placed at the end of the caption, which makes interpretation considerably less intuitive. I recommend making the legend (indicating the meaning of color intensity) more prominent. Additionally, the font size of the x and y axis labels is very small and should be increased to improve readability.

> ***<u>Response:</u>*** *We thank the reviewer for this constructive comment. Following the recommendation—and in agreement with a similar suggestion by Reviewer 1— Figure 1 has been redesigned to improve its clarity and overall readability. Specifically, the original figure has now been split into two separate figures, which is fully compliant with the journal's limit of three figures for Brief Communications. This division reduces visual overload and allows each set of variables to be presented more clearly. In addition, label sizes have been increased, a consistent colour scheme has been applied, and a legend distinguishing NW_Europe and SE_Europe has been added. These changes substantially enhance the legibility and interpretability of the figure. The updated figures are included in the revised manuscript.*

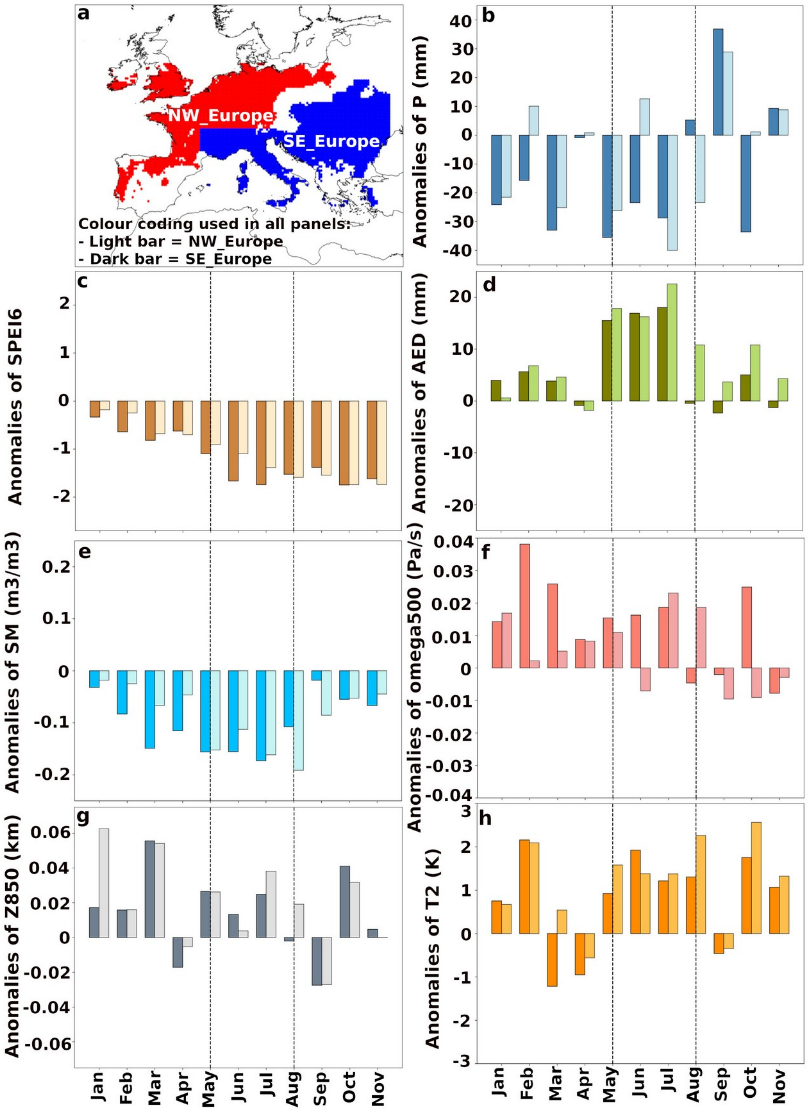

Fig. Rev. 1 (Included in the Manuscript) Target regions and hydro-climatic monthly anomalies during the 2022 European drought | a *Target regions considered in this study: northern-western Europe (NW_Europe, red) and southern-eastern Europe (SE_Europe, blue).* ***b–h*** *Monthly averaged anomalies of key hydro-climatic variables, calculated relative to the 1994–2023 climatology using ERA5 reanalysis data:* ***b****, accumulated precipitation (P, mm);* ***c****, 6-month Standardized Precipitation–Evapotranspiration Index (SPEI6);* ***d****, atmospheric evaporative demand (AED, mm);* ***e****, soil moisture (SM, m^3/m^3);* ***f****, vertical velocity at 500 hPa (omega500, Pa/s);* ***g****, geopotential height at 850 hPa (Z850, km); and* ***h****, 2-meter temperature (T2, K). Colour intensity indicates each region: higher intensity for SE_Europe and lower intensity for NW_Europe. The framed period highlights the active hydro-climatic drought peak period (May–August*

2022). The spatial patterns and corresponding anomalies used to determine the monthly anomaly series are shown in Figs. S1-S3.

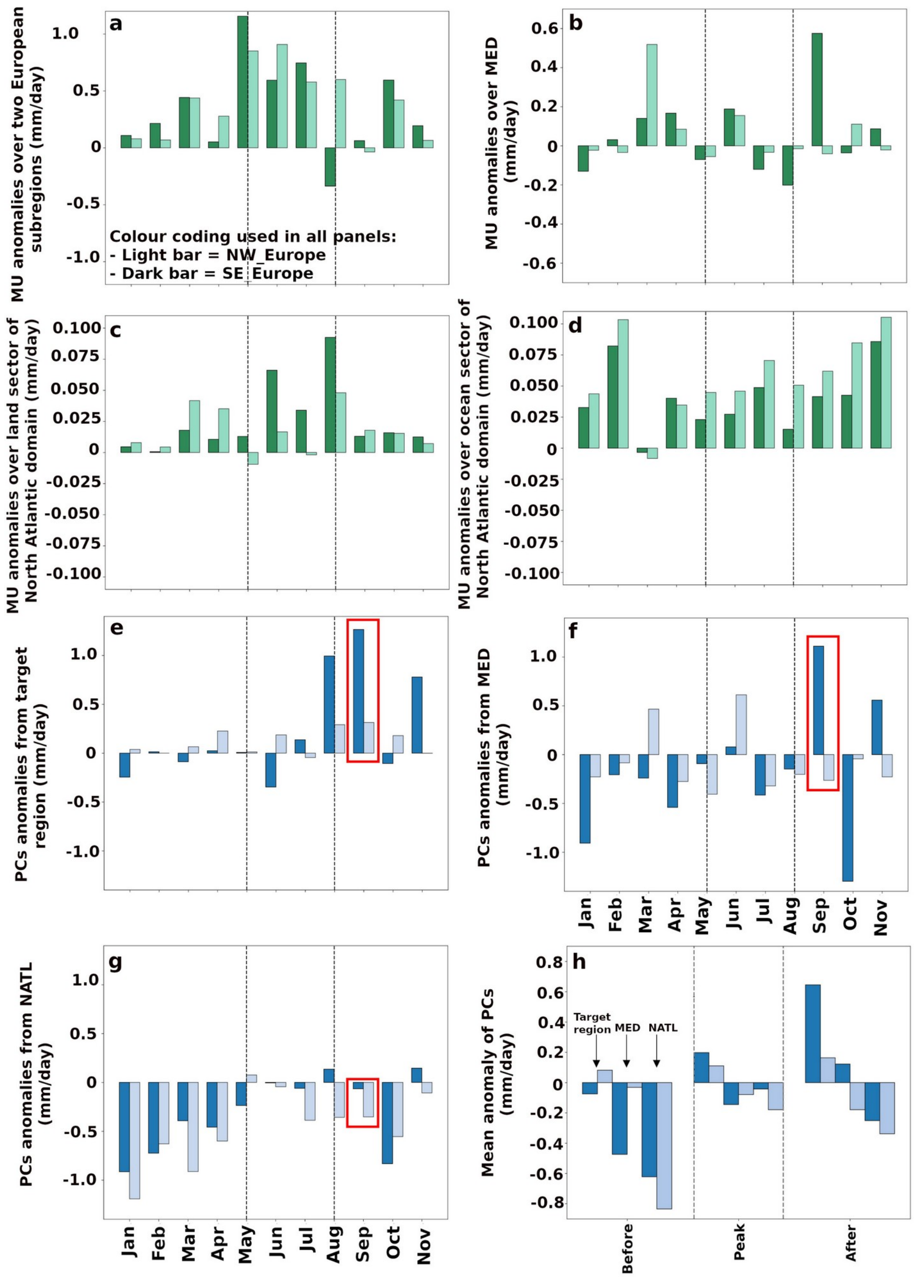

Fig. Rev. 2 (Included in the Manuscript) Moisture uptake (MU) and precipitation contributions (PCs) associated with the 2022 European drought | *Colour bar intensity indicates each European subregion: higher intensity for SE_Europe and lower intensity for NW_Europe. The framed period highlights the peak drought months (May–August 2022).* ***a–d*** *MU monthly anomalies (in mm/day, green plots) computed over:* ***a****, each European subregion;* ***b****, the Mediterranean Sea;* ***c****, land; and* ***d****, ocean sectors of the North Atlantic domain.* ***e–h*** *Monthly anomalies of PCs (mm/day, blue bars) from:* ***f****, the Mediterranean (MED) moisture source;* ***g****, the NATL; and* ***e****, the two European subregions. The red rectangle indicates the month considered the drought-breaking month, September 2023.* ***h*** *Average PCs anomaly for each source for the periods Before (January–April), Peak (May–August), and After (September–November). The framed period highlights the active hydro-climatic drought peak period (May–August 2022). The period considered for the calculation of the anomalies is 1994–2023, and the spatial patterns and corresponding anomalies used to determine the monthly anomaly series are shown in Figs. S6–S8.*

<u>Comment 3</u>: From figure S5, it is not clear what the authors mean by the “land and ocean sectors of the North Atlantic domain.” The manuscript does not specify whether the “land sector” corresponds to the broader European land area, nor whether the NE and NW regions are included or excluded when defining these sectors. The same regarding whether the Atlantic oceanic sector refers to the whole Atlantic or whether it excludes the NATL region.

<u>Response:</u> *We thank the reviewer for pointing out this lack of clarity. To eliminate any ambiguity regarding the spatial extent and potential spatial overlaps, we have updated Supplementary Figure 5 into two distinct panels according to the specific analyses performed in this study:*

- ***Moisture Uptake (MU) and Temperature Anomaly analyses (Fig. S5a)**: Evaluated over the broader North Atlantic domain, divided into three primary source sectors: the land sector (green), the ocean sector (blue), and the Mediterranean Sea (MED, magenta), alongside the two European target subregions (NE_Europe and NW_Europe, defined as in Fig. 1a). Crucially, to prevent spatial overlap during these analyses, when evaluating a specific European target subregion, that area is dynamically excluded from the broader green land mask.*
- ***Precipitation Contribution (PC) analysis (Fig. S5b)**: Evaluated using specific, non-overlapping source masks: the North Atlantic Ocean (NATL, red), the Mediterranean Sea (MED, magenta), and the two European target subregions (NE_Europe and NW_Europe).*

The caption of Supplementary Figure 5 and the corresponding text in both the Supplementary Material (Supplementary Methods section) and the Main Manuscript have been revised accordingly to explain this masking logic in detail. Specifically, the following clarifications have been added to the main text:

- *<u>Regarding MU and PC analyses</u>:*

  (…) First, to evaluate moisture uptake (MU) feeding the study regions, backward trajectories were tracked to identify region with evaporation minus precipitation greater than zero. MU anomalies were then averaged over five predefined, non-overlapping domains (Fig. S5a): the two European subregions affected by the drought (NE_Europe and NW_Europe; Fig. 1a), the MED, the broader North Atlantic ocean sector, and the remaining continental North Atlantic land area (dynamically excluding the evaluated European subregion). Quantifying MU was crucial for assessing the contributions from each source and capturing the key components of the moisture transport dynamics shaping drought conditions. Second, to quantify the precipitation contribution (PC), forward simulations were conducted to track moisture loss (evaporation minus precipitation < 0) originating from Europe’s primary moisture sources—the NATL and the MED (Fig. S5b, Gimeno et al., 2012; Gimeno-Sotelo et al., 2024)—as well as from the two drought-affected European subregions themselves (Fig. 1a) (…)

- *<u>Regarding Temperature Anomaly analysis</u>:*

  (…) To assess the spatial origin of these processes, the contributing physical drivers were evaluated over the predefined North Atlantic land and ocean sectors, as well as the MED, maintaining non-overlapping boundaries with the evaluated European subregions (Fig. S5a) (...)

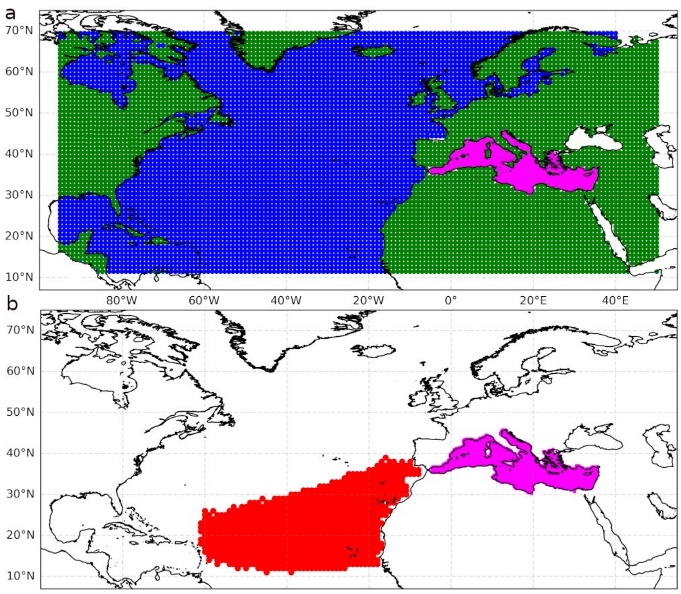

Fig. Rev. 3 (Included in the Supplementary Material) Spatial domains and masks used in this study. a) *Masks defined for the Moisture Uptake (MU) and temperature anomaly analyses within the North Atlantic domain, comprising the general land sector (green), the ocean sector (blue), and the Mediterranean Sea (MED, magenta). Note that when evaluating a specific European target subregion (NE_Europe or NW_Europe; see Fig. 1a), that subregion is dynamically excluded from the general green land sector to guarantee non-overlapping domains.* ***b)*** *Masks defined for the Precipitation Contribution (PC) analysis, including the North Atlantic Ocean source region (NATL, red), the Mediterranean Sea source region (MED, magenta), and the two target European subregions (NE_Europe and NW_Europe). All masks are mutually exclusive to prevent spatial overlap.*

Comment 4: Lines 159–160 state that averages for the two European subregions reveal distinct temporal and regional behaviours (Fig. 2). However, the three components of the temperature anomaly sources (adiabatic, diabatic, and advective) show broadly similar behaviours overall, as described in the subsequent lines. In addition, the patterns shown in the figures of the supplementary materials are also quite similar for both regions.

Response: *We thank the reviewer for this insightful comment. We agree that both subregions share the same qualitative thermodynamic mechanism—namely, a dominant positive adiabatic warming term driven by subsidence, partially offset by negative advective and diabatic contributions (Fig 2 → Fig. 3 in the new version).*

However, important quantitative variations emerge upon closer examination of individual components and remote domain influences:

- ***Advective cooling****: The negative advective term is visibly stronger over NW_Europe during the summer peak (July–August; Fig. 3b) compared to SE_Europe (Fig. 3a).*
- ***Mediterranean influence****: The remote adiabatic warming originating from the Mediterranean Sea is remarkably continuous throughout the year for SE_Europe (Fig. 3g), whereas for NW_Europe (Fig. 3h) its contribution is weaker and restricted to specific months.*

To reflect this more accurately and avoid overstating regional divergence, we have revised the text in the Main Manuscript to emphasize that while both subregions share the same core physical drivers, they exhibit subtle quantitative variations across periods and domains. The sentence in the Main Manuscript has been modified as follows:

(…) Averaged series for both subregions reveal a shared physical baseline dominated by adiabatic warming, with subtle quantitative variations across periods and domains (Fig. 3) (...)

Comment 5: Lines 212–213 state that "a long lasting anticyclonic pattern blocked convection." It may be more accurate to refer to precipitation rather than convection, since anticyclones typically suppress frontal precipitation during winter months as well. In addition, the OLR anomalies shown in Figure S12 display different signs throughout the year.

Response: *We thank the reviewer for this constructive observation. We agree that anticyclonic blocking suppresses large-scale dynamic uplift and frontal precipitation systems in addition to deep convection, making "precipitation" a more accurate and comprehensive term. We have adjusted the wording in the text accordingly.*

Regarding the OLR anomalies (Fig. S12), we appreciate the reviewer pointing out their temporal variability. As shown in Figure S12, while OLR anomalies fluctuate across seasons (exhibiting negative anomalies in months such as April or November), they are predominantly positive over the drought-affected regions during the core summer peak period (June–August), reflecting reduced cloud cover and enhanced net radiative heat loss under clear-sky anticyclonic conditions. We have refined the manuscript text to explicitly specify that this radiative mechanism operates primarily during the peak drought months, rather than uniformly throughout the entire year.

The corresponding sentences in the Summary and Conclusions have been modified as follows:

In Summary and Conclusions:

(…) A long-lasting anticyclonic pattern suppressed precipitation, diverted humid Atlantic and Mediterranean inflows, and triggered widespread adiabatic warming that locked the region into deep dryness (...)

<u>Comment 6</u>: Finally, I would like to suggest that the authors consider submitting the manuscript as a research article rather than a brief communication. Although the topic is of social relevance and fits within the brief comunication's scope, in my opinion the manuscript, in its current form, is difficult to fully understand without consulting the supplementary material. The main text is limited to 20 bibliographic references, but the supplementary material contains a nearly equivalent number of figures.

> ***<u>Response:</u>*** *We thank the reviewer for this thoughtful suggestion and for highlighting the social relevance and value of our work.*
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> *After careful consideration, we respectfully prefer to maintain the manuscript in its current Brief Communication format. Transitioning to a full research article would require a substantial restructuring of the manuscript's narrative and framework. We strongly believe that the Brief Communication format is the most suitable format for this study, as it allows us to deliver a concise, high-impact, and focused message without diluting the primary narrative with secondary technical analyses.*
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> *The supplementary material is intentionally designed to provide supporting, self-contained calculations that reinforce our main findings for interested readers, without encumbering the core scientific story presented in the main text. However, to address the reviewer's concern regarding readability, we have carefully refined the main text to ensure that all key concepts and findings are fully clear, coherent, and standalone without strictly requiring immediate reference to the supplementary material.*

<u>References</u>

Garrido-Perez, J. M., Vicente-Serrano, S. M., Barriopedro, D., Garcia-Herrera, R., Trigo, R., & Begueria, S. (2024). Examining the outstanding Euro-Mediterranean drought of 2021–2022 and its historical context. *Journal of Hydrology*,*630*, 130653.