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: *This brief communication analyzes the 2022 drought from a Lagrangian perspective, highlighting the role of moisture sources and the nature of the heating that enhanced the drought. It is an interesting contribution; however, the degree of novelty appears moderate. Despite the very notable tracking techniques employed, the manuscript ultimately provides incremental progress in our understanding of the 2022 drought. I recommend publication after revision, provided that the comments below are addressed.*

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)

<u>**General comment**</u>

The main statement in the abstract is that the 2022 drought was driven by "a sharp reduction in precipitation contributions from Atlantic and Mediterranean moisture sources, despite enhanced atmospheric moisture uptake." However, is this result truly surprising? There are many regions in the world where precipitable water (PW) is abundant in the atmosphere, yet conditions remain dry (for example, the Red Sea region). It is well established that it is not the IVT of PW itself that determines rainfall, but rather the convergence of low-level IVT. I therefore encourage the authors to better clarify - in case I may have misunderstood or overlooked something - what the main points of novelty are.

> ***<u>Response:</u>*** *We thank the reviewer for this insightful comment. We agree that high atmospheric moisture content does not necessarily lead to precipitation, as rainfall fundamentally depends on the convergence of low-level moisture transport rather than on precipitable water or moisture uptake alone. Our intention was not to imply that enhanced moisture uptake should have produced more rainfall, but to highlight a specific and previously undocumented feature of the 2022 European drought: a marked decoupling between (i) enhanced regional moisture uptake driven by anomalously warm and dry land–atmosphere conditions, and (ii) a sharp reduction in precipitation contributions from the Atlantic and Mediterranean moisture sources, which normally supply most of the rainfall to the affected regions.*
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> *The novelty of our work lies in three aspects that we now clarify more explicitly in the revised manuscript:*
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> - ***Quantification of anomalous moisture-source behaviour****. Using a Lagrangian framework, we show that both Noth Atlantic ocean (NATL) and Mediterranean sea (MED) sources exhibited strongly negative precipitation contributions throughout most of 2022, even during months when moisture uptake over Europe was anomalously high. This behaviour is not intuitive and had not been quantified for the 2022 event.*
> - ***Identification of the dynamical mechanism behind the decoupling****. Our results demonstrate that persistent anticyclonic circulation (positive Z850 anomalies), and widespread subsidence (positive omega500 anomalies), reduced atmospheric instability, limiting the development of precipitation despite enhanced moisture availability. This explains why increased moisture availability did not translate into rainfall. These dynamical constraints are consistent with the blocking patterns documented in previous studies (Faranda et al., 2023; Garrido-Pérez et al., 2024), but here we show their direct impact on source-specific precipitation contributions.*

- ***Integration of moisture and temperature source diagnostics***. *By combining moisture-uptake/precipitation-contribution analysis with a Lagrangian temperature-source decomposition, we show that adiabatic warming induced by subsidence was the dominant thermal driver sustaining the drought. This provides a physically consistent picture linking moisture deficits, suppressed convection, and subsidence-driven warming; an integrated perspective not previously applied to the 2022 drought.*
- ***Regional separation based on dominant moisture sources***. *A further novelty is the explicit separation of Europe into two subregions (NW_Europe and SE_Europe) according to their dominant oceanic moisture sources (NATL and MED, respectively). This allows us to distinguish how the drought evolved in areas primarily fed by Atlantic versus Mediterranean moisture, revealing contrasting behaviours in moisture uptake and precipitation contribution anomalies that would be obscured in a continent-wide analysis. This source-based regionalisation provides a more physically meaningful characterisation of the drought's spatial structure.*
- ***Period-based analysis of the drought evolution (before, during, and after the peak)***. *By structuring the analysis into three distinct phases, pre-drought (January–April), hydro-climatic peak drought (May–August), and drought-breaking period (September–November), we capture the temporal transition between enhanced moisture uptake, suppressed precipitation contributions, and the eventual reactivation of regional moisture sources. This period-based framework reveals how the decoupling between moisture availability and precipitation evolved through time, highlighting the mechanisms sustaining the drought and those responsible for its abrupt termination.*

We have revised the abstract and summary and conclusions to clarify these points and to better articulate the mechanisms and novelty of our findings.

Abstract:

(…)This reflects a previously undocumented decoupling between moisture availability and precipitation formation, caused by persistent anticyclonic circulation that diverted moisture fluxes and suppressed convection (…).

Main:

(…) This behaviour reflects the decoupling identified in our analysis: despite enhanced regional moisture uptake, precipitation contributions from the Atlantic and Mediterranean sources remained strongly suppressed due to persistent anticyclonic circulation and divergent moisture transport patterns (...).

Summary and Conclusions:

(…) Beyond characterising these mechanisms, our analysis provides new quantitative evidence of a marked decoupling between moisture availability and precipitation formation: despite enhanced regional moisture uptake, precipitation contributions from the Atlantic and Mediterranean sources remained strongly negative throughout most of the year. This behaviour, revealed through Lagrangian moisture-source diagnostics, had not been documented for the 2022 event (…).

Specific comments

1) L46: Is the choice of June–August arbitrary? Why not consider October–December, when SPEI6 also shows very low values?.

Response: *We thank the reviewer for this insightful comment. The choice of June–August (JJA) is not arbitrary; rather, it isolates the peak phase of the event where the drought was strongly driven by extreme thermodynamic anomalies and heatwaves.*

SPEI6 confirms that JJA represents the maximum intensity of the drought, as also reported by Garrido-Pérez et al. (2024). Because our study employs a Lagrangian framework to analyze temperature anomalies separated by adiabatic, diabatic, and advective terms, selecting JJA is essential: this period coincides with the peak of extreme surface temperatures and maximum atmospheric evaporative demand and our objective, in addition to identifying moisture source anomalies, is to determine this thermal footprint with our Lagrangian analysis.

In contrast, the later period (e.g., October–December / September–November) marks the onset of the drought-breaking phase, characterized by a shift toward synoptic instability, decreased thermal anomalies, and partial hydrological recovery (Fig. 2h; Fig. S8). Considering a year-end period would obscure the strong thermal and atmospheric signals that drive the peak of the drought.

Therefore, focusing on JJA ensures that the spatial mask strictly captures the core drought conditions and the maximum positive temperature anomalies, avoiding contamination from the recovery phase. We have revised the text in the Supplementary Material to clarify this justification:

(…) The final study region represents the combined area affected from June to August 2022 (Fig. 1a in Manuscript), which corresponds to the peak of the event according to our analysis (Fig. 1c in Manuscript) and previous assessments of the 2021–2022 Euro-Mediterranean drought (Garrido-Pérez et al.[7]).

Crucially, this summer window (JJA) encapsulates the maximum atmospheric evaporative demand driven by record-breaking temperature anomalies and persistent heatwaves—key drivers for our atmospheric and Lagrangian temperature anomaly analysis. Although SPEI6 also exhibits negative values in later months, those periods coincide with lower thermal anomalies, increased synoptic instability, and the onset of hydrological recovery (Fig. 2 in Manuscript). Using June–August therefore ensures that the study mask targets the peak compound heat–drought conditions, avoiding contamination from the drought-breaking phase (...).

2) L53–54: It seems that something is missing before "SPEI6." Moreover, SPEI6 remains low for the entire period until November, so this statement does not appear to be fully supported by the evidence.

Response: *We thank the reviewer for pointing out the grammatical oversight and raising this important technical observation. We have corrected the text syntax accordingly.*

Regarding the temporal evolution of SPEI6, we agree that very low (and even lower) negative values persist through November in regions such as NW_Europe (Fig. 1c). However, there is a fundamental physical distinction between the active drought peak and the late-autumn values:

- *May–August (MJJA) represents the active hydro-climatic peak period of the drought, characterized by maximum precipitation deficits (P), peak thermal anomalies (T2), and extreme atmospheric evaporative demand (AED) (Figs. 1b, d, h).*
- *The persistent or even lower SPEI6 values observed from September onward do not reflect an active intensification of drought drivers, but rather the inherent 6-month memory effect of the multi-scalar index, which accumulates the severe deficits from preceding months. This late period actually coincides with decaying thermal stress, increased synoptic instability, and the onset of hydrological recovery (Figs. 1b, f and 2h).*

To clarify this distinction, remove any confusion, and address the grammatical issue, the text in the Main Manuscript has been revised as follows:

(…) 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 (...)

3) Figure S3: The decision to show all anomalies using dashed contours is unfortunate, as it makes it difficult to distinguish positive from negative anomalies. Why not represent anomalies using color shading and the mean field with contours?.

Response:

We thank the reviewer for this helpful suggestion. Following the recommendation, Figure S3 has been updated accordingly. The anomalies are now represented using colour shading, while the mean field is shown with contour lines. This modification improves the visual distinction between positive and negative anomalies and enhances the overall readability of the figure. The updated version is now included in the revised Supplementary Material.

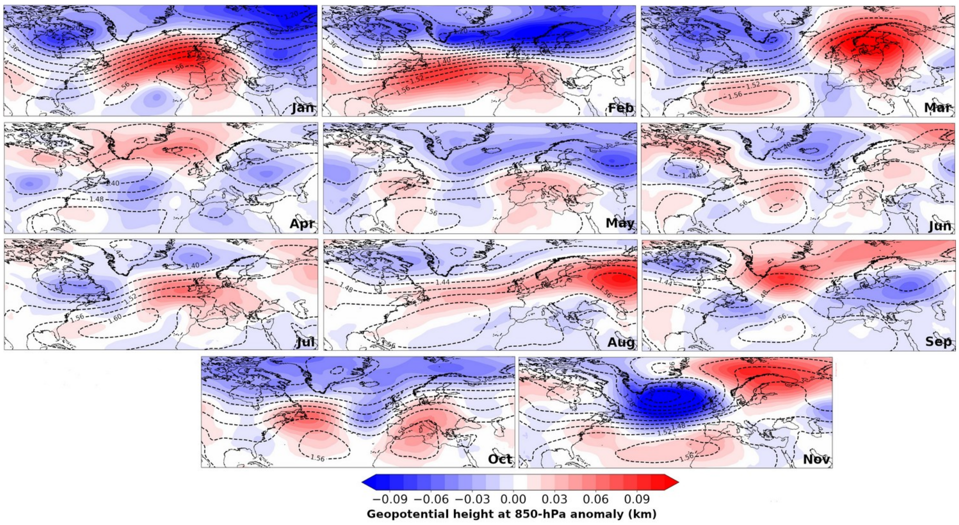

Fig. Rev. 1 (Included in Material Supplementary) The geopotential height at 850 hPa (Z850) monthly anomaly and its absolute field for the North Atlantic region and Europe | *The figure presents the monthly anomaly of Z850 (km, coloured filled) and the Z850 module (km, black contours) from January to November 2022 (top to bottom). The analysis covers the period from 1994 to 2023. Data from the ERA5 reanalysis.*

4) L65–70: Why not consider the divergence of IVT rather than IVT itself? Ultimately, we know that divergence is related to E–P (from the water balance equation), not IVT per se.

> ***Response:*** *We thank the reviewer for this important clarification. Our intention in this paragraph was not to diagnose the E–P balance directly, but to illustrate the large-scale moisture-transport patterns that modulated the drought. While the divergence of IVT is indeed the quantity directly linked to E–P through the atmospheric water-balance equation, the dynamical effects of moisture-flux divergence are already captured in our analysis through the Lagrangian precipitation-contribution (PC) diagnostics and through vertical-motion and stability fields (omega500 and Z850), which explicitly describe the suppression of convergence and convection. For this reason, IVT is used solely to characterise the transport pathways and the synoptic-scale circulation context, rather than as a diagnostic of E–P.*

5) Figure 1. This figure is poorly designed: it contains too many panels, the labels are very small and difficult to read, and there is no legend indicating which bars refer to NW Europe or SE Europe. I strongly encourage the authors to improve its legibility and overall quality.

> ***Response:*** *We thank the reviewer for this constructive comment. Following the recommendation, 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.*

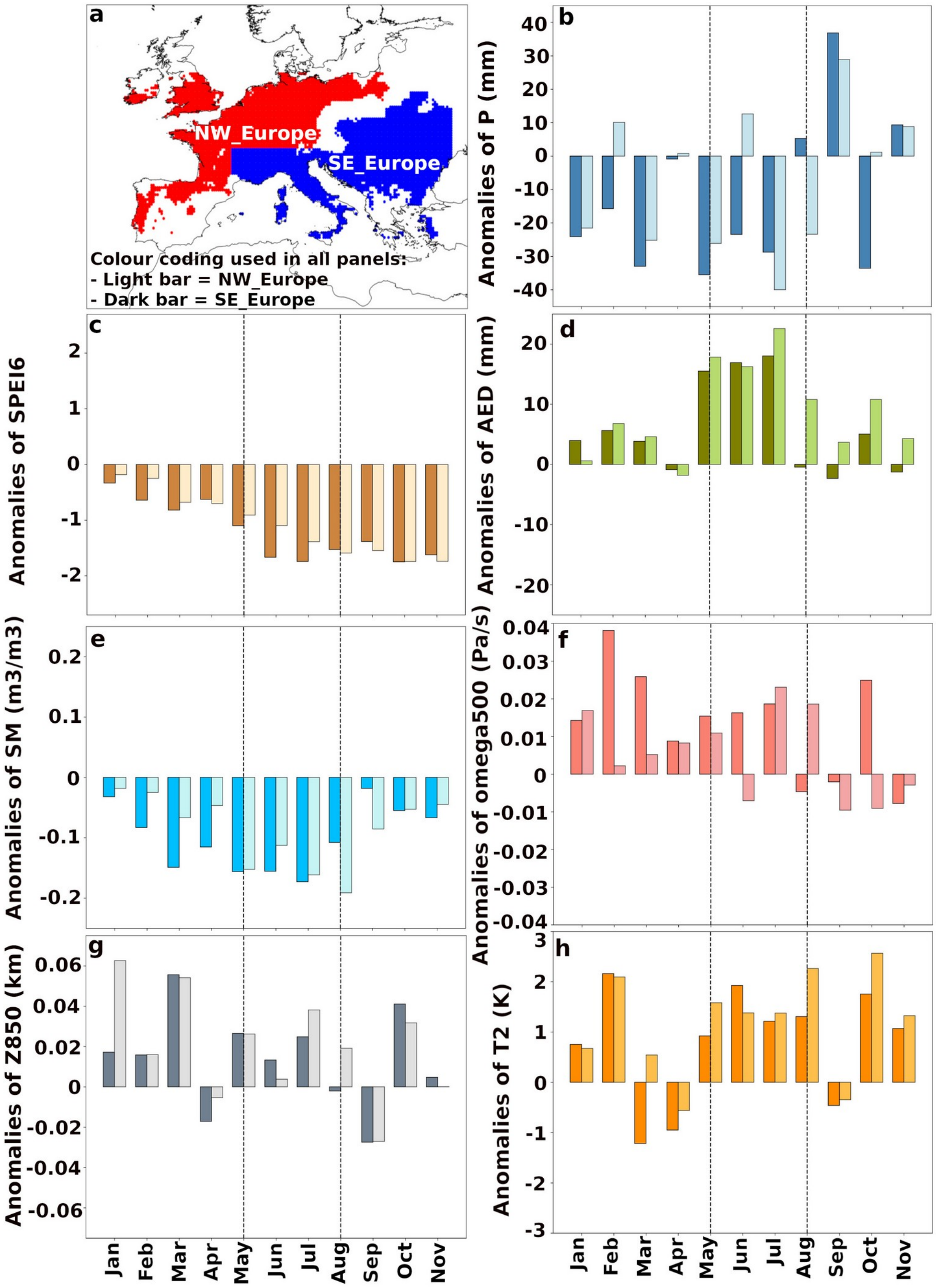

Fig. Rev. 2 (Included in the Manuscript) Target regions and hydro-climatic monthly anomalies during the 2022 European drought | a *Target regions considered in this study: northern-western Europe (NW_Europe, red) and southern-eastern Europe (SE_Europe, blue).* ***b–h*** *Monthly averaged anomalies of 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, m³/m³);* ***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.*

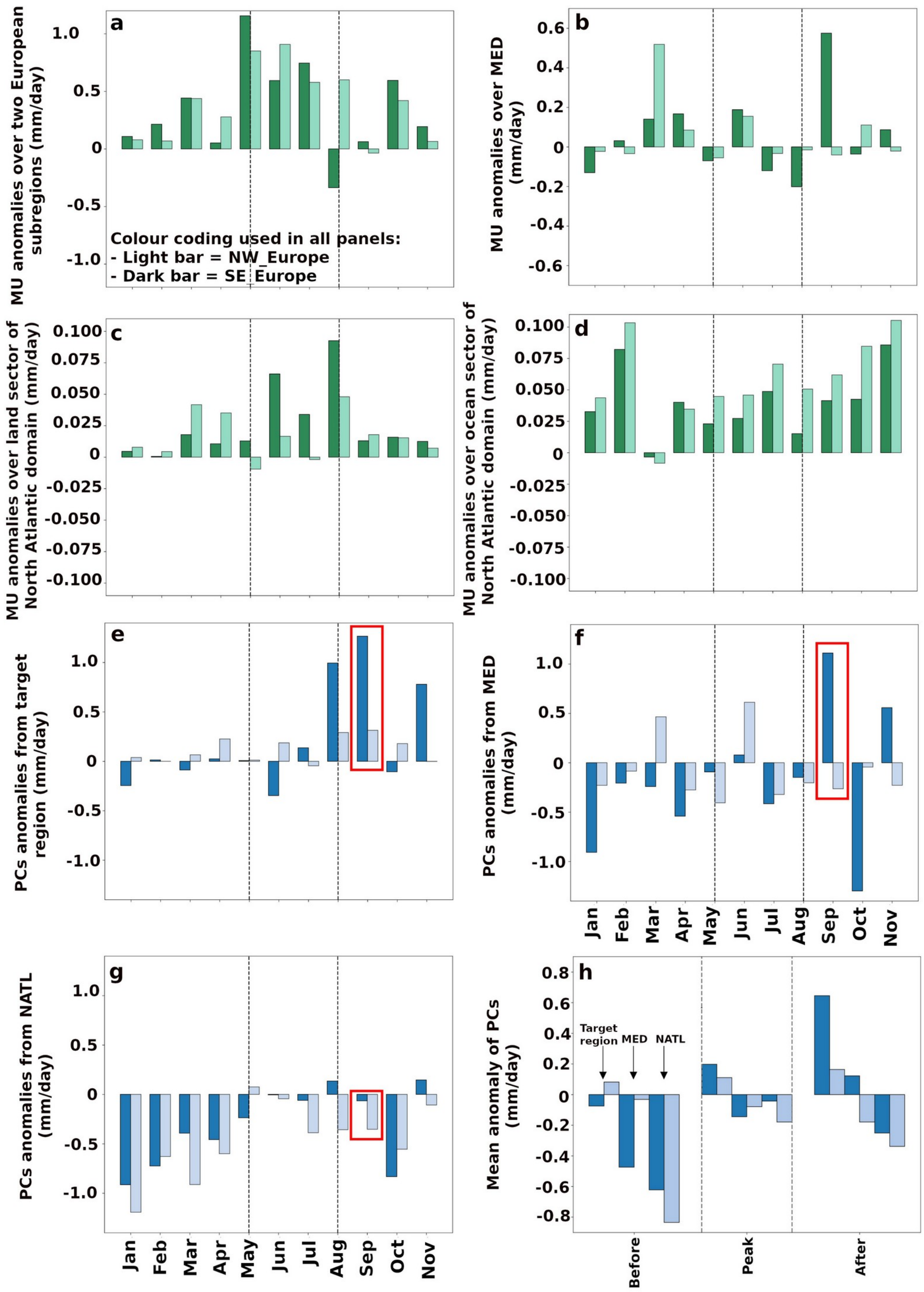

Fig. Rev. 3 (Included in the Manuscript) Moisture uptake (MU) and precipitation contributions (PCs) associated with the 2022 European drought* |** *Colour bar intensity indicates each European subregion: higher intensity for SE_Europe and lower intensity for NW_Europe. The framed period highlights the 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.*

6) Figure 2. Why are April and September missing from this diagram?.

> ***Response:*** *We thank the reviewer for this observation. April and September were excluded from the Lagrangian temperature-source decomposition because neither region exhibited positive near-surface temperature anomalies during these months (Fig. 1h in Manuscript). Furthermore, for the SE_Europe subregion, March was also excluded for the same reason, as no positive temperature anomalies were observed. Since our Lagrangian temperature-source analysis is specifically designed to decompose anomalous warming events into adiabatic, diabatic, and advective components, the decomposition is only physically meaningful for months experiencing significant positive temperature anomalies. Consequently, months lacking warming anomalies (April and September for both regions, plus March for SE_Europe) were omitted from this specific analysis. We have clarified this distinction in the revised manuscript as follows:*
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> *(…) Only months exhibiting positive near-surface temperature anomalies over the drought-affected regions were included in the Lagrangian temperature-source decomposition (...).*

7) L211–212: Is this result truly surprising? Please see my comment in the General section.

Reviewer Comments: *Our results show that the driving force behind the 2022 European mega-drought was not a lack of atmospheric moisture, but persistent atmospheric stability that prevented moisture from becoming rainfall.*

> ***Response:*** *We thank the reviewer for this comment and for the broader clarification requested in the General section. As detailed in our response to Comment 1, the novelty of our result does not lie in the general fact that high atmospheric moisture does not guarantee precipitation, but in the previously undocumented decoupling between enhanced regional moisture uptake and strongly suppressed precipitation contributions from the Atlantic and Mediterranean sources during the 2022 drought. We have revised the manuscript to make this point explicit and to clarify why this behaviour is scientifically relevant.*

References

Faranda, D., Pascale, S. and Bulut, B.: Persistent anticyclonic conditions and climate change exacerbated the exceptional 2022 European-Mediterranean drought. Environ. Res. Lett. 18, 034030 (2023).

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.