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

José C. Fernández-Alvarez[1,2*], Raquel Nieto[3,4,5], Sergio M. Vicente-Serrano[6], David Carvalho[2], Luis Gimeno[3,4,5]

[1]Galicia Supercomputing Center (CESGA), Climate System Research Unit, Santiago de Compostela, 15705, Spain
[2]CESAM, Departamento de Física, Universidade de Aveiro, 3810-193, Aveiro, Portugal.
[3]Centro de Investigación Mariña, Universidade de Vigo, Environmental Physics Laboratory (EPhysLab), Ourense, 32004, Spain
[4]Climate System Research Unit, UVigo-CESGA, Ourense, 32004, Spain
[5]Unidad Asociada CSIC-Universidad de Vigo: Grupo de Física de la Atmósfera y del Océano, Ourense, Spain
[6]Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE–CSIC), Zaragoza, Spain

Correspondence to: José C. Fernández-Alvarez (jcfernandez@cesga.es)

Abstract. Using an integrated Lagrangian moisture and temperature diagnostic framework, we reveal previously undocumented dynamics driving the 2022 European mega-drought across three phases (before, during, and after its peak). We quantify a marked decoupling: despite enhanced regional moisture uptake, precipitation contributions from Atlantic and Mediterranean sources were severely suppressed. Source-based regionalization (North-Western vs. South-Eastern Europe) highlights distinct trajectories driven by persistent anticyclonic anomalies and widespread subsidence, which suppressed convection while inducing adiabatic warming as the primary heat driver. The abrupt drought termination demonstrates that future European drought severity depends on large-scale atmospheric dynamics controlling rainfall triggering rather than moisture availability alone.

1 Main

Europe experienced an exceptional drought in 2022, resulting in widespread agricultural losses (Baruth et al., 2022; Toreti et al., 2022; Faranda et al., 2023), reductions in hydropower and wind energy, increased solar potential (Toreti et al., 2022; Copernicus, 2022a), disruptions to river transport and ecosystems, severe water shortages, forest fires, and substantial anomalies in carbon emissions (Toreti et al., 2022; Faranda et al., 2023; Copernicus, 2022b; Gharun et al., 2024).

Previous analyses have investigated the event's drivers and its links to anthropogenic climate change, showing that it produced the largest terrestrial water storage deficit since 2002 across Central–Southern Europe, with human-induced warming amplifying drought intensity by more than 30% (Bevacqua et al., 2024). The drought was primarily driven by a persistent anticyclonic anomaly, which, together with other large-scale atmospheric circulation features —a blocking over Western Europe and a displaced jet stream— extreme heat, and elevated atmospheric evaporative demand, exacerbated its severity (Faranda et al., 2023; Garrido-Pérez et al., 2024). Easterly and southerly dry winds associated with the strengthened anticyclone further reinforced these conditions (Herrera-Lormendez et al., 2023). However, although this drought is extraordinary in the context of the current climate, soil droughts on a similar scale are projected to occur twice as often in West-Central Europe in a +2 °C warming (Schumacher et al., 2024).

While previous studies have elucidated the large-scale circulation and climate change influence, the specific role of anomalous moisture and temperature sources in shaping the drought's evolution remains unclear. Here, we addressed this gap by quantifying the anomalous sources of atmospheric moisture uptake and temperature during the 2022 European drought, providing new insights into the coupled thermodynamic and dynamic processes governing the origin and development of extreme droughts in Europe.

The 2022 drought affected extensive areas across both the Atlantic and Mediterranean climatic regions of Europe (Fig. S1, fourth column). To analyse the event, we defined the drought-affected area using the 6-month Standardized Precipitation Evapotranspiration Index (SPEI6) for June-August 2022 (≤ -1.28), capturing the core summer phase of maximum compound heat-drought impacts ("Supplementary Methods"). This area was then divided into two subregions based on their dominant oceanic moisture sources —the North Atlantic ocean (NATL) and the Mediterranean Sea (MED) (Fig. 1a) as indicated in Gimeno-Sotelo et al. (2024): the NATL-influenced region, covering northern and western Europe (hereafter NW_Europe), and the MED-influenced region, encompassing southern and eastern Europe (SE_Europe).

Monthly anomalies for key meteorological variables related to drought occurrence (Fig. 1b–h) illustrate the temporal evolution across both European subregions. 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. Suppression of vertical motion and persistence of high-pressure systems sustained these drought conditions. Vertical velocity anomalies at 500 hPa (Fig. 1f) indicate reduced upward motions except for September (the drought-breaking month) and November 2022. Persistent anticyclonic conditions and blocking activity (Faranda et al., 2023; Garrido-Pérez et al., 2024) are further evidenced by positive geopotential height anomalies at 850 hPa (Fig. 1g). This stable circulation favoured strong and widespread surface warming across both regions (Fig. 1h), more pronounced over NW_Europe during summer (~2.2 K), reflecting thermal persistence. These results highlight spatio-temporal differences between the subregions, driven by coupled land–atmosphere processes, evidenced by coherent anomalies in precipitation, soil moisture, evapotranspiration, temperature, and atmospheric stability (Figs. S1–S3).

At a large scale, and complementary to land–atmosphere interactions, the moisture flux patterns (measured as vertically integrated water vapour transport (IVT) anomalies, Fig. S4) also reveal circulation patterns modulating the event. While the subtropical Atlantic exhibited positive IVT anomalies, western Europe experienced moisture deficits before drought peak. The reduced inflow from the Mediterranean Sea limited replenishment of atmospheric moisture and intensified the drought (with partial recovery from September), acting as a drought-intensifying factor (Gimeno-Sotelo et al., 2024).

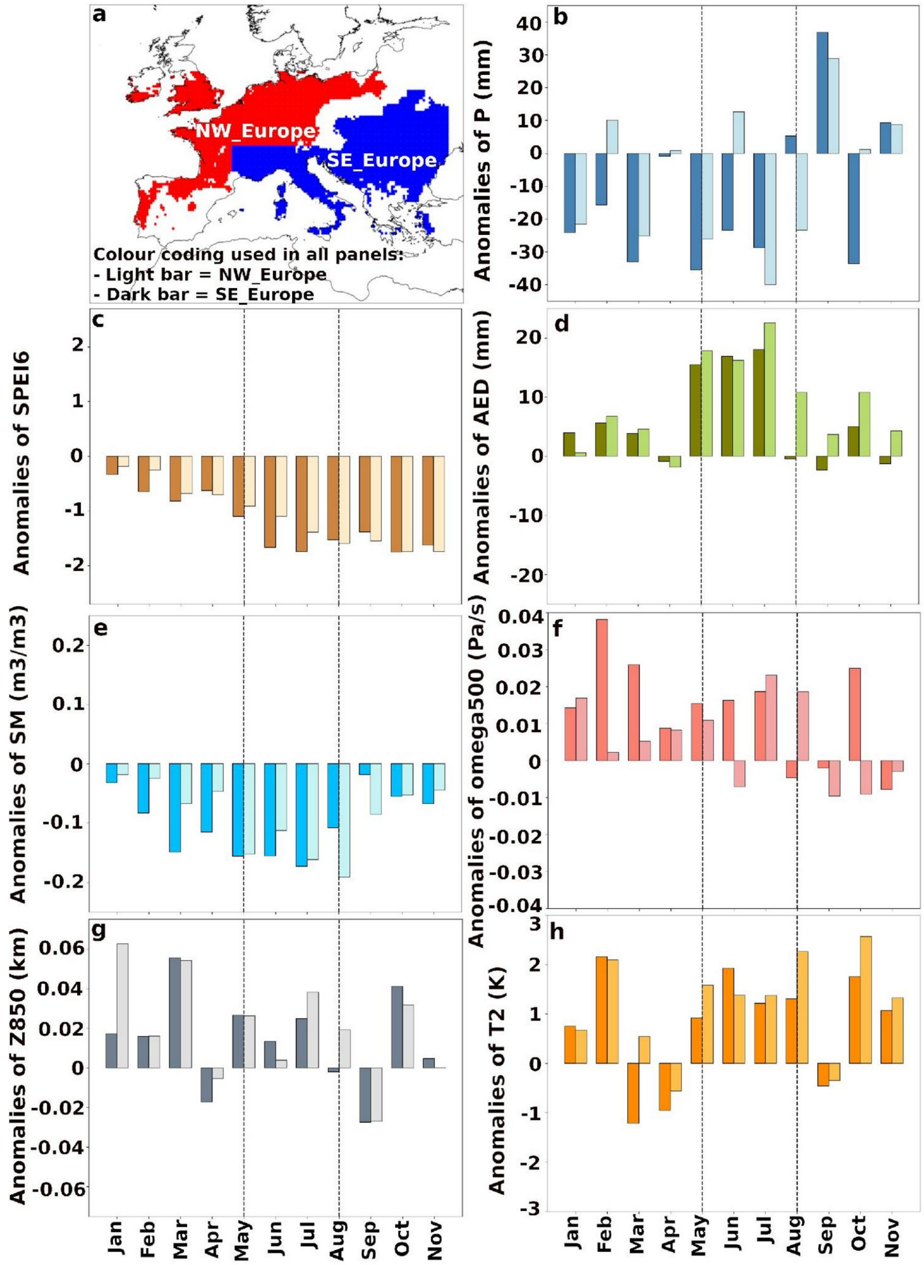

Fig. 1 Target regions and hydro-climatic monthly anomalies during the 2022 European drought | a Target regions considered in this study: northern-western Europe (NW_Europe, red) and southern-eastern Europe (SE_Europe, blue). **b–h** Monthly averaged anomalies of key hydro-climatic variables, calculated 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.

The role of changes in atmospheric moisture transport from source regions modulating droughts is recognized as a key factor in understanding their behaviour and intensity (Gimeno et al., 2012; Liu et al., 2020). To quantify this effect during the 2022 European drought, we applied a Lagrangian approach using the FLEXPART model (Pisso et al., 2019) and ERA5 reanalysis data (Hersbach et al., 2020) ("Supplementary Methods").

First, to evaluate moisture uptake (MU) feeding the study regions, backward trajectories were tracked to identify regions 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 Mediterranean Sea (MED), the broader North Atlantic ocean sector, and the remaining continental North Atlantic land area (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).

Marked temporal and spatial contrasts emerged between NW_Europe and SE_Europe in the evolution of MU and PC anomalies (Figs. 2a-h). From January to April, moisture availability preceding the peak drought was slightly enhanced, as both subregions exhibited positive MU anomalies mainly from local sources (Figs. 2a–d). In contrast, notable deficits in precipitation contributions (PC) occurred from MED and NATL sources, particularly from the latter, while PC values from the subregions themselves remained close to climatology (Figs. 2e-h). On average, anomalies during this period were markedly negative, ranging from –0.4 to –0.8 mm day^{-1} for both dominant oceanic sources (Fig. 2h).

From May to August (the hydro-climatic peak of drought), MU intensified from multiple sources, with a slight decrease from the Mediterranean during some months. This coincides with predominantly negative PC anomalies, particularly from NATL—although less pronounced than in preceding months (Fig. S3). During this period, mean moisture support anomalies from MED and NATL were about –0.2 mm day^{-1} (Fig. 2h). These patterns are coherent with reduced moisture flux and persistently stable atmospheric conditions associated with a sustained blocking pattern (Figs. 1f,g; Fig. S3) over the North Atlantic and Europe (Faranda et al., 2023; Garrido-Pérez et al., 2024).

During September to November, land-based sources became dominant for SE_Europe, while oceanic sources prevailed for NW_Europe (Figs. 2a-d). Positive PC anomalies, mainly from the two European subregions and the Mediterranean, indicate partial hydrological recovery, most evident in SE_Europe (Fig. 2h). In contrast, negative PC anomalies from the NATL were marked but weaker than those before the drought peak. Overall, MU increased, despite some declines south of 30°N (Fig. S6), reflecting the atmosphere’s greater capacity to retain moisture under higher temperatures (Soden and Held, 2006; Allen and Ingram; 2002) (Fig. 1h). However, PC behaviour associated with the MED and NATL oceanic sources and the two European subregions suggests that, although moisture availability increased, atmospheric instability required for convection and precipitation was largely absent until September, consistent with stable conditions driven by persistent high-pressure systems (Faranda et al., 2023; Garrido-Pérez et al., 2024), which inhibited upward motion and convection and diverted moisture fluxes away from the preferred sources (positive omega500 and Z850 anomalies, and reduced IVT; Figs. 1f,g; Fig. S4).

In general, weakening oceanic contributions to precipitation were key to sustaining the 2022 drought, which began to disappear by the late-season reactivation of regional moisture inputs (Figs. S7, S8). This behaviour reflects the decoupling identified in our analysis: despite enhanced regional moisture uptake, precipitation contributions from the NATL and MED sources remained strongly suppressed due to persistent anticyclonic circulation and divergent moisture transport patterns. Specifically, in September, drought across southern Europe ended abruptly as intense rainfall was triggered by a deep North Atlantic trough extending into central Europe and a strong subtropical high over North Africa (Figs. 2e,f; S3). This pattern advected warm, moist Mediterranean air toward southeastern Europe (Fig. S8), initiating severe convection under unstable conditions (Figs. 1f,g; Z850 and omega500 negative anomalies). This shift marked the end of the prolonged dry period.

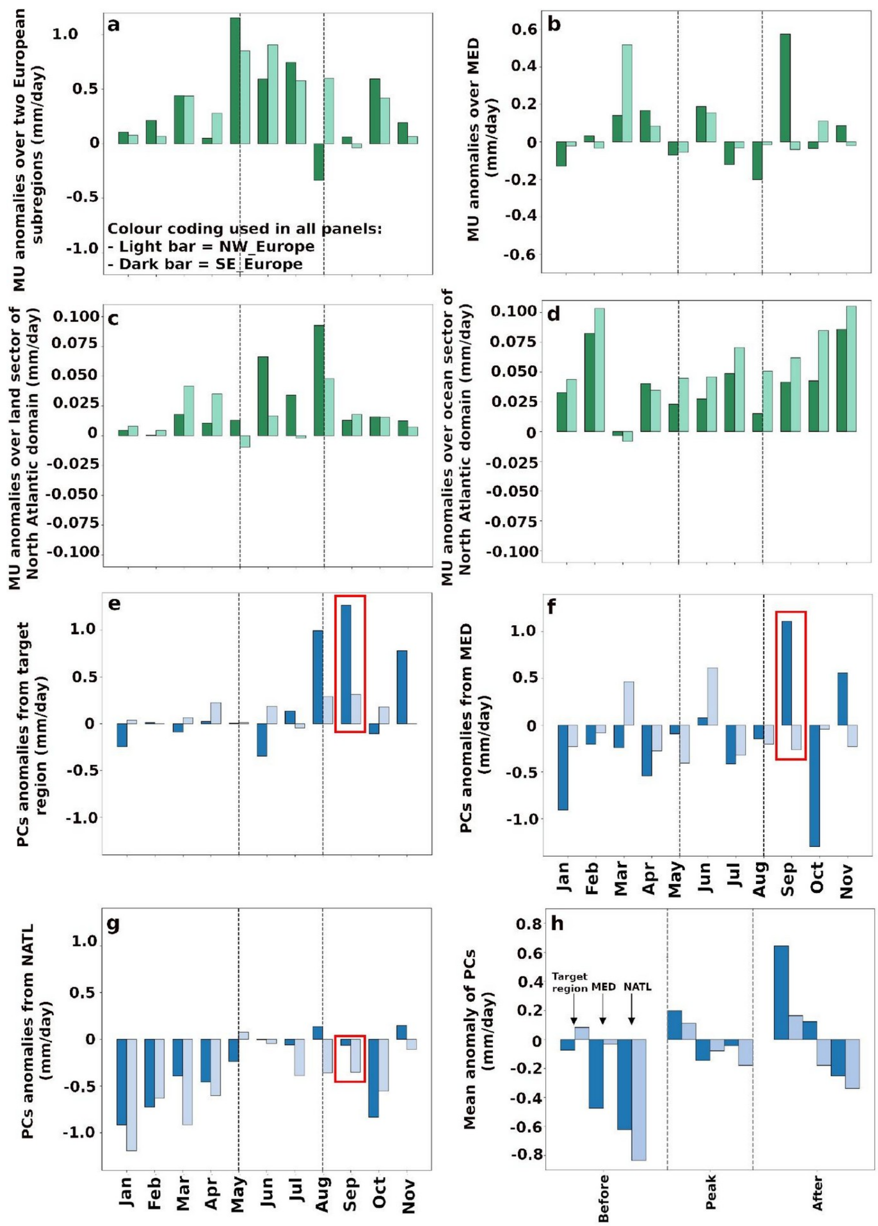

Fig. 2 Moisture uptake (MU) and precipitation contributions (PCs) associated with the 2022 European drought | Colour bar intensity indicates each European subregion: higher intensity for SE_Europe and lower intensity for NW_Europe. The framed period highlights the peak drought months (May–August 2022). **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.

The 2022 European drought was additionally characterized by a considerable near-surface temperature excess (Fig. 1h), accompanying several heatwaves (Schumacher et al., 2024). This thermal anomaly, linked to persistent stable atmospheric conditions (Faranda et al., 2023; Garrido-Pérez et al., 2024), was a key factor in exacerbating drought severity (Bevacqua et al., 2024). Using the Lagrangian framework (Papritz and Röthlisberger, 2023) (“Supplementary Methods”), temperature anomaly sources for the two drought-affected European regions were decomposed into adiabatic, diabatic, and advective components (Fig. 3), allowing identification of physical drivers arising from vertical motion, horizontal transport, and heat exchange.

Only months exhibiting positive near-surface temperature anomalies over the drought-affected regions were included in the Lagrangian temperature-source decomposition. 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 Mediterranean Sea, maintaining non-overlapping boundaries with the evaluated European subregions (Fig. S5a).

The two European subregions exhibit a dipolar pattern of total temperature anomaly sources, with positive anomalies over North Africa, the Mediterranean region, the North Atlantic Ocean, and central-eastern Europe, and negative anomalies north of 50° N. This pattern was strongest at the drought peak and expanded spatially during January–February and May (Figs. S9, S10). Averaged series for both subregions reveal a shared physical baseline dominated by adiabatic warming, with subtle quantitative variations across periods and domains (Fig. 3).

Over both subregions (Figs. 3 a–b), the adiabatic term dominates year-round, with pronounced positive values during the main drought period (May–August), indicating persistent warming driven by subsidence and adiabatic compression. The advective term generally exhibits negative anomalies during these same months, due to air flux from cooler higher latitudes, which partially offset the adiabatic warming. The diabatic term also remains negative. Over the North Atlantic land and oceanic source regions (Figs. 3c–f), anomalies are generally weaker than over the two European subregions, with modest positive adiabatic and slightly negative diabatic and advective components, indicating minor remote contributions to surface warming for the two European subregions. In contrast, over the Mediterranean Sea, strong positive adiabatic anomalies occur (Figs. 3g–h), particularly during May–August and autumn, reflecting intense subsidence. These periods correspond to the strongest total temperature anomalies, particularly in SE_Europe.

A percentage-based perspective (Fig. S11) indicates that temperature anomalies for both European regions are largely controlled by the continental regions themselves, explaining ~60–85% of the total signal, while the Mediterranean Sea accounts for only ~10–30%. For the adiabatic term, European subregions contribute ~40–60%, with Mediterranean influence near ~10-20%. A similar pattern is seen in the advective term, especially over NW_Europe, where the European subregions explain between 40–60% of the anomalies. The diabatic term is comparatively stronger over the Mediterranean (~20–40%), although the continental effects from the European subregions still dominate (~50–70%).

The dominant adiabatic term is the fingerprint of a persistent anticyclonic circulation pattern (Faranda et al., 2023; Garrido-Pérez et al., 2024), which results in descending air (Figs. S9, S10), confirming the major role of adiabatic processes in controlling European temperature anomalies driven by summer anticyclones and mid-tropospheric subsidence (Röthlisberger and Papritz, 2023; Hamal and Pfahl, 2024). The negative advective term over the two European subregions reflects anticyclonic circulation moving air from cooler northeastern Europe into the warmer European subregions (Figs. S9, S10).

The global cooling observed over the two subregions, linked to the diabatic term, is the result of the compensation of three processes with different net effects on the temperature: (i) the warming by enhanced evaporation (which occurs mainly over the ocean) resulting in enhanced condensation in the air with latent heat absorption during the liquid to vapour phase transition and the cooling for inhibited evaporative (Röthlisberger and Papritz, 2023) over central European land areas, due to reduced soil moisture (Bevacqua et al., 2024) (Figs. S12, S13), resulting in diminished condensation in the air (ii) the warming by upward transfer of sensible heat from the surface to the atmosphere, (Fig. S14), and (iii) the cooling by the imbalance in surface net longwave radiation, under predominantly clear-sky and stable atmospheric conditions —particularly during the summer drought peak— as indicated by positive anomalies in outgoing longwave radiation (Fig. S12, S14); being the cooling processes dominant over the warming ones.

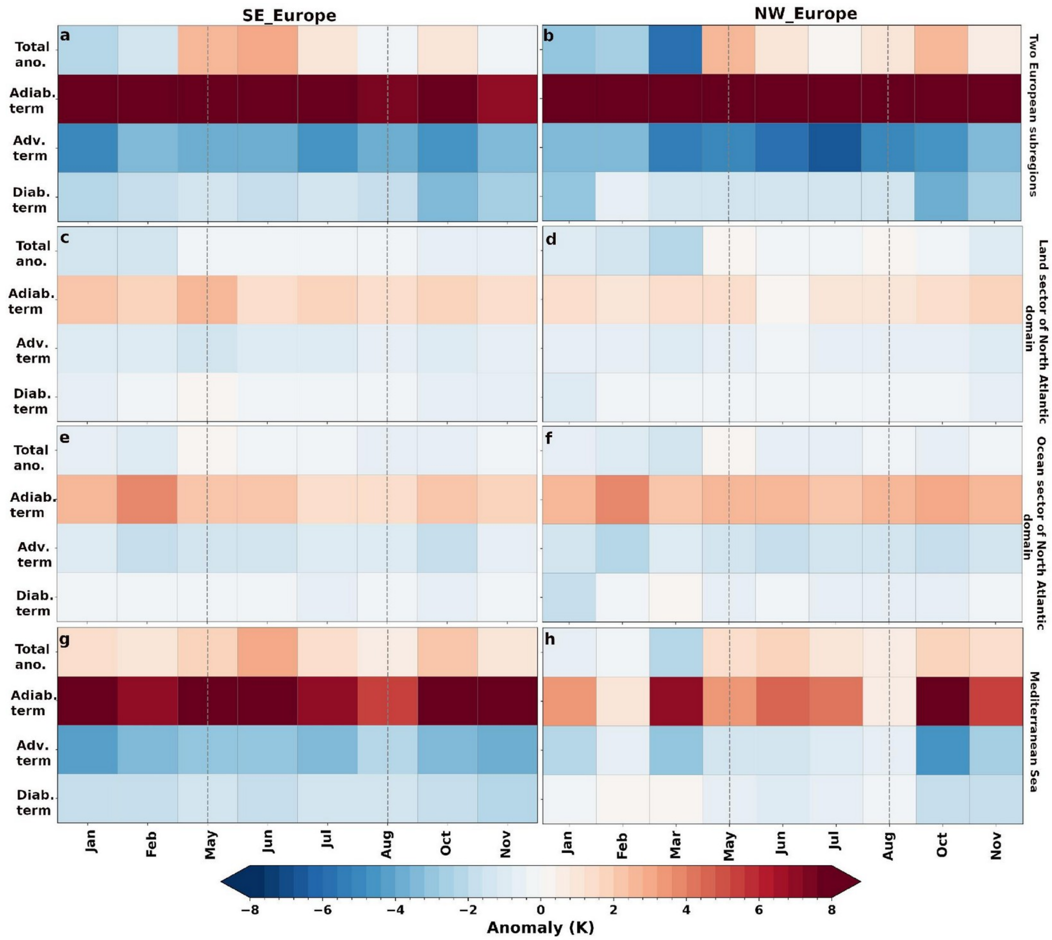

Fig. 3 Monthly series of temperature anomaly sources during the 2022 European drought | Heat maps show monthly anomalies of total temperature, and of the adiabatic, diabatic and advective components from January to November 2022. Left and right panels display anomalies for the SE_Europe and NW_Europe subregions, respectively. Panels show the anomaly values averaged over (a, b) each of the two European subregions, (c, d) the North Atlantic land sector, (e, f) the North Atlantic oceanic sector, and (g, h) the Mediterranean Sea. The framed period highlights the active hydro-climatic drought peak period (May–August 2022). Anomalies are computed relative to the 1994-2023 climatology. Data processed from FLEXPART outputs forced ERA5 data.

2 Summary and Conclusions

Our results show that a 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. 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.

By integrating Lagrangian moisture-uptake and precipitation contribution diagnostics with a temperature source decomposition, 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 decoupling, driven by the combined action of persistent anticyclonic circulation and large-scale subsidence, had not been previously quantified for the 2022 event.

Furthermore, applying a novel source-based regionalization (North-Western vs. South-Eastern Europe, tied to Atlantic and Mediterranean sources, respectively) reveals contrasting regional trajectories in moisture uptake and precipitation deficits. Tracking these dynamics across the three stages of the event (pre-onset, peak, and recovery) demonstrates how this decoupling evolved over time: it was sustained during the peak by descending air, adiabatic warming, and muted oceanic precipitation contributions to precipitation, until an abrupt synoptic shift toward unstable synoptic conditions reactivated regional moisture sources and broke the drought. Its abrupt termination highlighted the system's sensitivity: a shift toward unstable synoptic conditions was enough to reactivate regional moisture sources and break the drought.

These findings demonstrate that, in a warming climate, the severity of future European droughts will depend not only on atmospheric moisture availability but on the large-scale dynamics conditions controlling when and where rainfall can occur.

Data and code availability

ERA5 reanalysis is available via Copernicus Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form. FLEXPART simulations can be generated following Vázquez et al. (2024). TROVA package is openly hosted on GitHub (https://github.com/tramo-ephyslab/TROVA-master and the routines for decomposing temperature anomalies can be retrieved from ETH Zurich Research Collection (https://www.research-collection.ethz.ch/handle/20.500.11850/571107).

Author contributions

J.C.F-A, L.G. and R.N. designed the study; J.C.F-A. performed the computation processing and obtaining the results; J.C.F-A., L.G., R.N. S.V-S analysed the results; J.C.F-A., R.N., S.V-S., D.C. and L.G. wrote the paper; J.C.F-A., R.N., S.V-S., D.C. and L.G. review the paper.

Competing interests

The authors declare no competing interests.

Acknowledgements

J.C.F.-A. thanks the support from the Xunta de Galicia (Axencia Galega de Innovación) under the Postdoctoral grant no. IN606B2024/016. D.C. acknowledges the FCT (Portuguese Foundation for Science and Technology) and the Ministry of Science, Technology and Higher Education (MCTES) for his research contract (CEECINST/00013/2021/CP2779/CT0017). R.N. colaborates in DHEFEUS project (https://doi.org/10.54499/2022.09185.PTDC) supported by FCT, Portugal. This work has also been possible thanks to the computing resources and technical support provided by CESGA (Centro de Supercomputación de Galicia) and the Red Española de Supercomputación (RES) (DATA-2022-1-0001, DATA-2022-1-0003, DATA-2021-1-0005). The authors also acknowledge the computer resources at Storage5 and the technical support provided by BSC (RES-DATA-2024-1-0002 and AECT-2025-2-0048). Additional support was provided by the Unidad Asociada CSIC–Universidade de Vigo: Grupo de Física de la Atmósfera y del Océano.

Financial support

EPhysLab members are supported by the APALPADOR and ESMORGA projects (PID2024-155515NB-I00 and TED2021-129152B-C43) funded by the Ministerio de Ciencia, Innovación y Universidades, Spain (MCIN/10.13039/501100011033), the Xunta de Galicia (ED431C2025/37; Programa de Consolidación e Estructuración de Unidades de Investigación Competitivas, Grupos de Referencia Competitiva), and NextGenerationEU/PRTR. D.C. acknowledges FCT for the financial support to CESAM (UIDP/50017/2020, UIDB/50017/2020 & LA/P/0094/2020). CSIC members are also been supported by the research projects TED2021-129152B-C41 and PID2022-137244OB-I00, financed by the Spanish Ministry of Science

NextGenerationEU/PRTR, and by the MEHYDRO project (LINKB20080) funded by the i-LINK 2021 programme (CSIC), the CSIC Interdisciplinary Thematic Platform Clima (PTI-Clima), and the CSC2023-02-00 contract financed by MITECO and the European Commission NextGenerationEU (Regulation EU 2020/2094).

References

Baruth, B. et al. JRC MARS Bulletin - Crop monitoring in Europe - September 2022 Vol. 30 No 9, in Van Den Berg, M. *et al.* (eds.) Publications Office of the European Union, Luxembourg (2022). https://doi.org/10.2760/067974.

Toreti, A._et al. Drought in Europe July 2022, EUR 31147 EN, Publications Office of the European Union, Luxembourg (2022). ISBN 978-92-76-54953-6, https://doi.org/10.2760/014884.

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).

Copernicus Climate Change Service European State of the Climate 2022. Copernicus Climate Change Service (2022a). Available at: https://climate.copernicus.eu/esotc/2022 (Accessed: [March 16, 2025]).

Copernicus Climate Change Service European State of the Climate 2022: Drought (2022b). Available at: https://climate.copernicus.eu/esotc/2022 (Accessed: [March 16, 2025]).

Gharun, M., Shekhar, A., Xiao, J., Li, X., and Buchmann, N.: Effect of the 2022 summer drought across forest types in Europe. Biogeosciences, 21, 5481–5494 (2024).

Bevacqua, E., Rakovec, O., Schumacher, D.L. et al.: Direct and lagged climate change effects intensified the 2022 European drought. Nat. Geosci. 17, 1100–1107, https://doi.org/10.1038/s41561-024-01559-2. (2024)

Garrido-Pérez, J. M., Vicente-Serrano, S. M., Barriopedro, D., García-Herrera, R., Trigo, R., and Beguería, S.: Examining the outstanding Euro-Mediterranean drought of 2021–2022 and its historical context. J. of Hydrol. 630, 130653. https://doi.org/10.1016/j.jhydrol.2024.130653. (2024)

Herrera-Lormendez, P. et al.: European Summer Synoptic Circulations and Their Observed 2022 and Projected Influence on Hot Extremes and Dry Spells. Geophys. Res. Lett. 10, e2023GL104580. https://doi.org/10.1029/2023GL1. (2023)

Schumacher, D. L. et al.: Detecting the human fingerprint in the summer 2022 Western–Central European soil drought. *Earth Syst. Dyn.* **15**, 131–154 (2024).

Gimeno-Sotelo, L., Fernández-Alvarez, J.C., Nieto, R. *et al.:* The increasing influence of atmospheric moisture transport on hydrometeorological extremes in the Euromediterranean region with global warming. Commun Earth Environ 5, 604. https://doi.org/10.1038/s43247-024-01787-9. (2024)

Gimeno, L. et al.: Oceanic and Terrestrial Sources of Continental Precipitation. Rev. Geophysics 50, RG4003 (2012).

Liu, B. et al. Global atmospheric moisture transport associated with precipitation extremes: Mechanisms and climate change impacts. WIREs Water 7, e1412 (2020).

Pisso, I., et al.: The Lagrangian particle dispersion model FLEXPART version 10.4. Geosci. Model Dev. 12, 4955–4997 (2019).

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al.: The ERA5 global reanalysis. Q. J. R. Meteorol. Soc., 146, 1999–2049 (2020).

Soden, B. J., Held, I. M.: An assessment of climate feedbacks in coupled ocean-atmosphere models. J. Clim. 19, 6263–3360 (2006).

Allen, M. R., Ingram, W. J.: Constraints on future changes in climate and the hydrologic cycle. Nature 419, 228–232 (2002).

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).

Röthlisberger, M., Papritz, L.: Quantifying the physical processes leading to atmospheric hot extremes at a global scale. Nat. Geosci. 16, 210–216 (2023).

Hamal, K., Pfahl, S. (2024).: Physical Processes Leading to Extreme day-to-day Temperatures Changes, Part I: Present-day Climate. EGUsphere, 1-32 (2024).

Vázquez, M., Alvarez-Socorro, G., Fernández-Alvarez, J. C., Nieto, R., & Gimeno, L.: Global FLEXPART-ERA5 simulations using 30 million atmospheric parcels since 1980. *Zenodo*. https://doi.org/10.5281/zenodo.12204017 (2024).