

## **General overview**

The authors presented a valuable analysis focused on the influence of soil moisture on the land surface energy partitioning throughout Europe. They went a step further by providing an analysis of the consequences promoted by soil dry-out on the dynamics of the atmosphere, revealing a potential re-amplification of the LA feedbacks through the suppression of convection and further soil desiccation. In fact, there's a lack of studies performing an aggregation of several case studies, allowing for a detailed comparison of these LA feedbacks between different episodes characterized by the co-occurrence of extreme hot and dry conditions. This allows to get a time and spatial overview of the differences in the LA dynamics between episodes and I felt, particularly in the discussion chapter, that the authors missed the opportunity to underline and to explore more deeply the results in this context.

I think that a more detailed spatiotemporal integrated analysis under a climate change context is missing in the analysis (see major comments). It would be interesting to add some information about historical long-term changes in these LA feedbacks. The analysis was carried out using state of the art datasets and appropriate metrics. Thus, in terms of data/methods and the general conceptualization of the research problem I'm confident in the interest and robustness of the results presented here. As highlighted on the several following comments, my main concerns are focused on the poor quality of the English writing over some sections of the manuscript. The text has several typos and the English syntax is far from being ideal for a high-quality scientific publication. In addition, the author's argumentation is often poorly structured and presented in a confusing way. Therefore, a great effort should be made in order to improve the way authors expose their ideas and communicate with the reader. Moreover, the manuscript text often contains acronyms, abbreviations, scientific terms or metrics that are not properly defined in the data and methods sections. With this being said, I think the analysis has potential to be published, but only after authors have correctly addressed the following comments. This is my first round of reviews as I would like to check the manuscript once again to filter out other minor issues.

## **Major Comments**

- My first major comment concerns the way the manuscript is structured. The section n. ° 3 named as "Summer Season anomaly maps", presents the anomaly fields for several land surface and meteorological variables. These are, in fact, results that came from the analyses and they represent outcomes obtained by the authors. This section of the manuscript should therefore be included in the Results chapter. There's no reason to define a whole new chapter to present these findings.
- Throughout the manuscript, the argumentation, interpretation and discussion of the results is presented in a very vague and unclear way. An effort must be made in order to use a more appropriate scientific language and to adopt the correct scientific terms used in the literature to describe the processes and metrics under

consideration by the authors. More details about this aspect can be found in the minor comments below.

- Throughout the manuscript several abbreviations and acronyms used by the authors are not defined in the Material and Methods section (e.g. TCI  $\eta$ -LH; CTP-HI<sub>low</sub>; TLCI). In fact, this section of the manuscript needs some adjustments to define more clearly the several metrics adopted in the analysis. For example, the ACI was computed using two different approaches: one using CAPE and the other using HLCL. However, the way the authors distinguish both throughout the manuscript text is far from being the ideal and it brings some confusion to the narrative. I suggest similarly to TCI, to present the ACI in its mathematical equation form, defining two new abbreviations to the different approaches: ACI<sub>CAPE</sub> for the first, and ACI<sub>HLCL</sub> for the second.
- As I'm sure the authors know, the term LA feedbacks addresses several processes between the land surface and the atmosphere that describe the connection between soil moisture and precipitation, evaporation, temperature and even other meteorological parameters. The analysis is focused on the inter-link between soil moisture and temperature through perturbations in the turbulent fluxes of latent and sensible heat. Thus, I'm not entirely confident on the use of such a generic term to describe such a particular process. I suggest considering another term such as "soil moisture–temperature coupling" and keep land–atmosphere feedback for the link between soil moisture and CAPE or the link between soil moisture and HLCL.
- Have the authors considered using ERA5-Land or even GLEAM instead of ERA5 to obtain soil moisture data? ERA5-Land and GLEAM are forced by meteorological fields provided by ERA5 and so a potential problem associated with some inconsistency in the data source would be avoided. In addition, ERA5-Land and GLEAM incorporate land surface models capable to improve the representation of the water and energy cycles over land, contributing to a better simulation of land surface variables (Muñoz-Sabater et al. 2021). Beck et al. (2021) evaluated the temporal dynamics of 18 state-of-the-art (quasi-)global near-surface soil moisture products, and concluded the following: "The ERA5 reanalysis, which assimilates ASCAT soil moisture (Hersbach et al., 2020), obtained a lower overall performance (median R = 0.68) than the open-loop models ERA5-Land (median R = 0.72) and HBV-ERA5 (median R = 0.74), which were both forced with ERA5 precipitation (Fig. 2a). This suggests that assimilating satellite soil moisture estimates (ERA5) was less beneficial than either increasing the model resolution (ERA5-Land) or improving the model efficiency (HBV)."
- The Figures already present an overall good quality. However, some extra adjustments would be welcome. The size of the panels could be increased a bit

more by removing the latitude and longitude ticks that are repeated unnecessarily in all panels (I would only keep them in the first panel). A larger font size would also be a good idea, especially for the panel title.

- Finally, I'm not sure if the authors, with results here presented, have successfully achieved the main objectives stated for the study: “this study investigates interannual variability of LA coupling strength”; “In this study, we therefore assess the temporal variability of LA coupling of the European summer seasons 1991- 2022 on the interannual time scale”; “This paper describes the variability of the LA coupling strength of the warm summer seasons 1991-2022 which became the dominant situation over Europe since 2010”. Basically, the authors repeatedly stressed that the main goal of this study is to provide an interannual characterization of the LA coupling variability. However, in practice, what they presented here is an analysis focused on nine separated case study periods from a total of 32 years of data. This is not an interannual analysis even more when a time aggregation of these 9 years is lacking in the discussion. A narrative going, chronologically, throughout these 9 summer periods highlighting the effects of climate change, is not presented by the authors, which could be interesting. I think the authors have two options here: either they reformulate clearly the objectives of the analysis or they include a pure interannual analysis with a year-by-year evolution of the LA coupling and associated meteorological variables. The second option would be much more interesting, as it would also allow to get a temporal integrated overview of these parameters and see any possible trends in the soil moisture–temperature regimes throughout Europe and under a climate change context.

### **Minor Comments**

**Lines 23-24:** Please change accordingly: “In the last decades, Europe experienced severe drought periods and heatwaves (WMO, 2015; C3S, 2018; Markonis et al., 2021; WMO, 2022a) ~~where~~ with 2022 being the hottest summer ever recorded over Europe (WMO, 2022a).”

**Lines 29-30:** “(...) who suggest that these extreme conditions will be more likely under climate change conditions where two out of three summer seasons will experience hot and dry conditions.” This sounds a bit vague... This increase in hot and dry conditions under climate change conditions is estimated to occur for which period? Near future, far future? Is already happening? Authors should clarify.

**Line 30:** Please change accordingly: “(...) midlatitudes due to the occurrence of a double-jet stream **configuration associated to atmospheric blocking conditions** ~~situations~~ (Kornhuber et al., 2017).

**Line 56:** What is the CTP-HI<sub>low</sub> framework? More information should be given here.

**Line 63:** Change accordingly: “soil moisture-temperature feedback was, ~~among a wave train (Di Capua et al., 2021),~~ a key (...)”.

**Lines 76-78:** It reads weird: “The in the preceding paragraph described shifts in the hydrological conditions from energy- to moisture-limited conditions originating from droughts and heatwaves (Dirmeyer et al., 2021; Duan et al., 2020) or severe flooding (Lo et al., 2021) imply temporal variability in LA coupling at sub-seasonal to interannual time-scales.” Please rephrase it.

**Lines 82-84:** Please rephrase it to something like “However, a quantification of the temporal variability in different coupling relationships **and the associated impacts as well as understanding of the impact of the variability remain still lacking**, as LA coupling strength **on other times scales than climate period** was **has been** barely investigated over Europe, ~~and particularly on other time scales than climate periods, so far~~”.

**Lines 162-165:** The sentence is too long and confuse. Consider changing to something like: “As shown in Table 1 the warm and dry summer seasons **have become predominant the prevaileding situation** since 2015. **This has been** associated with a strong reduction in annual and seasonal precipitation, combined with a reduced atmospheric water availability that led to a constant decline of the root zone soil moisture and, thus, ~~to an agricultural drought which was the case, e.g., in 2018-2020 over Europe~~ (van der Wiel et al., 2022).”

**Lines 166-169:** It reads weird. Consider changing to: “The following sections **present an analysis of the anomaly fields of** ~~describe the characteristics of the summer seasons chosen for evaluation (Table 1) with respect to ERA5 500 hPa geopotential, 2-m temperature, root zone soil moisture  $\eta$ , and as well as observed and ERA5 simulated precipitation for the summer seasons chosen for evaluation (Table1).~~

**Line 175:** Change accordingly: “(...) However, the summer **seasons of 2015 and 2020 are exceptions** (...)”. However, Figure 1 clearly shows, in contrast with 2020, that most of Europe was covered by exceptional high values of 500hPa geopotential during 2015. Can you please clarify this? Authors also wrote the following: “In 2015, a pronounced north-south anomaly gradient is visible with negative values over the British Isles and Scandinavia while in 2020 the 500 hPa geopotential is only slightly above the average 1991-2020”. This is true, but a similar pattern is also observed during 2017... Why authors did not mention 2017 and highlight the similarities with 2015? Finally for both 2015 and 2017 summers, I’m not sure if a north-south anomaly gradient is the most accurate way to describe the geopotential anomalies... I would prefer to describe them as concentric nucleus of positive anomalies located over Central Europe associated to a strong meridional gradient of 500hPa Geopotential.

**Line 177:** “(...) while in 2020 the 500 hPa geopotential is only slightly above the average 1991-2020 (**bottom right panel in Fig. 1**)”. The bottom right panel in Fig.1 shows the anomaly pattern during 2021... In order to avoid this and to help establish a better link

between the text and the figure, I recommend the authors to label with letters (a,b,c,d...) the several panels. This works for all the other figures in the manuscript.

**Line 182-183:** Change accordingly: “~~†~~The highest 2-m temperature anomalies were present in observed during the summers of 2003, 2018, 2019, and 2022 (Fig. 2) which is and were spatially associated with strong positive geopotential anomalies over Central Europe. The summer of 2022 was the hottest ever recorded so far (C3S, 2023)”.

**Line 183 and 185:** This comment works for all the other sections of the manuscript where similar issues are observed. “2022 was the hottest summer ever recorded so far (C3S, 2023). During 2006, the 2-m temperature anomalies are highest north of 51°N 185 while in 2017, the highest temperature anomalies were observed south of 50°N as the maximum geopotential anomaly is shifted to the north and south, respectively”. It’s not correct to start a sentence with 4 numeric digits... It would be more proper to start with something like “The summer of 2022...”. Keep in mind that the analysis is focused only for the summer seasons, so make sure when analyzing and discussing the results that you’re referring to the summer periods. Also, two different verbal tenses are used in the same sentence, which is not correct. In fact, the authors should adopt, when describing the results, the same verbal tense.

**Lines 201-203:** This sounds too vague... More information about the way these correlations were obtained (time and space dimensions) and what they exactly mean should be provided by the authors.

**Lines 209-210:** It would be interesting to represent in an extra panel the time series of the daily spatially averaged values of soil moisture over Europe from the early spring until the late summer time for all the summer seasons. It would allow to better catch in the results this effect that the authors are mentioning here. This new panel could be included not just here in Figure 5, but also in all the other figures.

**Lines 212-214:** “By using the median of the soil moisture anomalies, 2006 largely is an average summer with moderate positive anomalies over East Europe while 2015 and 2017 on average show moderate dry soil anomalies”. Poor English syntax. Please rephrase it

**Lines 253-255:** Please change accordingly: “Apparently this ~~was is-related~~ explained by ~~to an already~~ a moist spring season (Fig. S2) and ~~the a~~ heavy precipitation event that occurred ~~occurring~~ in June 2021 (Mohr 255 et al., 2023), leading to a soil moisture content close to field capacity (top right middle panel of Fig. S1).”

**Lines 291-294:** “Coupling hot spots are observed over East and Southeast Europe with ACI values of more than 250 J kg<sup>-1</sup> occurring in connection with neutral or positive soil moisture anomalies in 2006, 2019, 2020, and 2021 (Fig. 8) which is connected to higher values of LH over these regions due to neutral or positive root zone soil moisture anomalies (Fig. 5)”. Sounds repetitive. Please rewrite the sentence more clearly.

**Line 295-296:** There’s a typo on the following sentence: “Over Germany and France, mostly only 14 weak coupling is seen with stronger signals during e2003 and 2019”

**Lines 305-306:** There's a typo on the following sentence: "Over Central Europe the LCL deficit is comparatively small with values of up to 300 m, unlike the years 2003 and 2022 which show strong positive values". Also, strong positive values are also observed for the summer of 2015...

**Lines 306-307:** Change accordingly: "These are the summers with a pronounced negative soil moisture anomaly and a strong positive temperature anomaly of more than 3°C (Fig. 2 and Fig. 5)"

**Line 319-320:** "At the same time, the high SH (not shown) leads to an increase of the PBL height and thus a higher LCL deficit as shown in Fig. 9" Considering that LCL deficit is defined as the difference between HLCL and PBLH and assuming that the HLCL was high during these summers and I'm not seeing how an increase in PBLH leads to an amplification of the LCL deficit. Can you please clarify this?

**Lines 321-324:** "During summer 2021, which showed record high temperatures over Europe, Central Europe shows a positive soil moisture anomaly (Fig. 5) connected to weak or negative coupling between  $\eta$  and LH (Fig. 6). This means that LH shows little variations and thus lowering HLCL (Wei et al., 2021) which is also reflected in a neutral LCL deficit Fig. 9)." This sentence is very confused, partially because it's written with a poor English syntax. An extra effort by the Authors is required in order to expose their ideas and the argumentation more clearly.

**Line 331:** TCI  $\eta$ -LH should be defined in the data and methods sections. See the major comment n. ° 3

**Line 334-335:** "These regions are usually water-limited thus leading to limited evapotranspiration further reducing LH." Once again poor English writing quality... Also what limited evaporation means in the context of a water-limited regime? A scenario with a limited evaporation could also be seen in an energy-limited regime. I'm not sure I fully understood what the authors mean to say here. This goes in line the major comment n. ° 2

**Line 356:** "(...) contrast to the cold and wet years 1997 and 2002 (Figs. S6, S7), the LCL deficit (not shown) is mostly positive" Not shown? The LCL deficit is represented in Figure 9, right?

**Line 364-365:** I understand what the authors are trying to say here, but they need to improve the writing quality... "A study of Denissen et al. (2020) found that LSMs tend to overestimate the critical soil moisture and thus evaporation becomes soil moisture limited too early."

**Line 380:** "This paper describes the variability of the LA coupling strength of the warm summer seasons 1991-2022 (...)" This is not entirely true. See the last major comment.

**Lines 389-394:** "According to Rousi et al. (2022) the frequency of the occurrence of heat waves has been accelerating over Europe 390 in the last 30-40 years where the large-scale

circulation pattern often features mid- and upper troposphere blocking situations leading to a split of the jet stream towards the Arctic and the Mediterranean. As the jet stream is an important feature for the European weather, it can also alter the near surface flow conditions in West and Central Europe (Laurila et al., 2021) while in other regions like the Mediterranean and East Europe, soil moisture preconditioning is more important as the impact of the jet stream becomes weaker (Prodhomme et al., 2022).” This text section looks a bit out of context in this summary chapter where the idea is to expose objectively and summarize the main outcomes from the analysis. Please consider to move it to the discussion chapter.

**Line 400-402:** An analysis based on 9 separate summer seasons is different from an interannual analysis. The authors need to reformulate this sentence. This goes in line with my last major comment

**Lines 401-404:** “Hot and dry conditions shift the terrestrial coupling to the moisture-limited regime, push the sensitivity of the HLCL on low LH, and through this switch gears to strongly positive LCL deficits which decreases the likelihood for locally triggered deep convection in this region”. Super confuse

**Line 404-405:** “The increasing frequency of warm and dry years toward the second half of the study period hints toward a trend of extended periods of **moisture-limitations for evapotranspiration**” I get what the authors want to say but what is “moisture-limitations for evapotranspiration”. Please rephrase it and try to adopt a more proper scientific language by using the right scientific terms to describe what you want to say. This goes in line with major comment n. ° 2.

## References

- Beck HE, Pan M, Miralles DG, et al (2021) Evaluation of 18 satellite- and model-based soil moisture products using in situ measurements from 826 sensors. Hydrol Earth Syst Sci 25:17–40. <https://doi.org/10.5194/hess-25-17-2021>
- Muñoz-Sabater J, Dutra E, Agustí-Panareda A, et al (2021) ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. Earth Syst Sci Data 13:4349–4383. <https://doi.org/10.5194/essd-13-4349-2021>