Soil moisture-atmosphere coupling strength over Central Europe in the recent warming climate

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Abstract

In the last decades~~,~~ Europe has experienced ~~increasing periods of~~ severe droughts and heatwaves~~ which have a major impact on~~. Notably, precipitation in Central Europe exhibited strong dry anomalies during the summers of 2003, 2018, and 2022. This phenomenon has significant implications for agriculture~~ and society. While soil moisture was found to be a crucial factor for enhancing the duration~~, ecosystems, and ~~intensity of~~human societies, highlighting the need to understand the underlying mechanisms driving these events~~, their influence is typically quantified for climate periods or single events. To provide an overview of how surface conditions shape~~. Despite significant advancements in understanding land-atmosphere (LA) coupling, ~~this study evaluates the~~ the temporal variability of LA coupling strength and its associated impacts remains poorly understood.

This study aims to quantify the variability of LA coupling strength over Central Europe during the summer seasons from 1991 to 2022, with a focus on the relationships between temperature, soil moisture, precipitation, and large-scale weather patterns. Our results reveal that interannual variability ~~of LA coupling strength for selected warm summer seasons between 1991-2022 over Central Europe by means of ERA5 data.~~ occurs in different coupling relationships throughout the summer seasons, with significant implications for climate extremes, agriculture, and ecosystems. The increasing frequency of warm and dry summers from 2015 onwards hints toward extended periods of reduced soil moisture available for evapotranspiration and the likelihood of locally triggered convection. This study provides new insights into the dynamics of LA coupling, highlighting the importance of considering the interannual variability of LA coupling strength in climate modeling and prediction, particularly in the context of a warming climate.

~~Especially the drought summer seasons 2003, 2018, and 2022 were particularly distinctive in respect to the changing soil moisture-atmosphere coupling pattern which in turn leads to an increased lifted condensation level height thereby inhibiting local deep convection triggering. Summer 2021 was a special case as spring precipitation was consistent with the climatological average and a heavy rain event occurred during July, resulting in high moisture availability and a change in the LA coupling strength. The results obtained with respect to LA coupling strength reflect a shift in the coupling relationships toward reinforced heating and drying by the land surface under heatwave and drought conditions, whose frequency is increasing with ongoing climate change.~~

1 Introduction

In ~~the last~~recent decades, Europe has experienced severe ~~drought periods~~ droughts and heatwaves, with 2022 being the hottest summer ~~ever recorded over Europe~~ on record (WMO, 2015; C3S, 2018; Markonis et al., 2021; WMO, 2022a)~~. Precipitation exhibited a strong dry anomaly during summer over~~. Notably, precipitation in Central Europe ~~in~~ exhibited strong dry anomalies during the summers of 2003, 2018, and 2022 (WMO, 2004, 2018; C3S, 2018; WMO, 2022b; Spensberger et al., 2020)~~. At the same time, the soil~~. Concurrently, soils experienced ~~an~~ exceptional dryness in the uppermost 25 cm ~~-as shown by the soil moisture index developed by~~ (Boeing et al., 2022; Rakovec et al., 2022). This phenomenon was also ~~shown~~observed by Rousi et al. (2023) and ~~for 2018, who suggest that these~~ Dirmeyer et al. (2021) in relation to the extreme conditions ~~will be more~~ of 2018, suggesting that such events are likely to become more frequent under climate change~~ conditions during 2020-2049 where two out of three summer seasons will experience hot and dry conditions in a +1.5°C warmer world which is already the case.~~. The underlying drivers of these events are complex and multifaceted, involving changes in atmospheric circulation patterns, sea surface temperatures, and land surface conditions (Barriopedro et al., 2023).

For instance, Rousi et al. (2022) identified Europe as a heatwave ~~hot spot~~hotspot, where the likelihood of heatwaves ~~are~~is three to four times ~~more likely~~greater than in other areas of the midlatitudes~~ due~~, attributed to ~~the occurrence of~~ a double-jet stream configuration associated with atmospheric blocking conditions (Kornhuber et al., 2017). One key factor influencing the development and persistence of heatwaves and droughts is the strength of land-atmosphere (LA) coupling (Yuan et al., 2023).~~Land-atmosphere (LA) coupling~~ . LA coupling refers to the interaction between the land surface and the atmosphere, wherein the terrestrial surface influences atmospheric conditions, and vice versa. This interaction is crucial for shaping the climate system as it affects the partitioning of energy between the land surface and the atmosphere, as well as the exchange of moisture and momentum. When the land surface is dry, it can lead to a reduction in evapotranspiration, which, in turn, may result in an increase in surface temperature. This can create a positive feedback loop, where a dry land surface amplifies the heatwave conditions, exacerbating the land surface dryness. Such feedback loops can lead to the rapid intensification of heatwaves and droughts, significantly impacting agriculture, ecosystems, and human societies.

LA coupling generally describes the co-variability of atmospheric conditions (e.g., planetary boundary layer (PBL) height, convective available potential energy (CAPE), lifted condensation level (LCL~~) and the~~)) with land surface characteristics ~~of the land surface~~ (e.g., vegetation, soil moisture) (Findell and Eltahir, 2003; Koster et al., 2004; Dirmeyer, 2011; Guo et al., 2006). In the context of extremes, LA coupling ~~was~~has been identified as a driver and intensifier ~~for~~of the duration and intensity of ~~heat waves~~heatwaves and droughts ~~.~~ (van Heerwaarden and Teuling, 2014; Ukkola et al., 2018; Schumacher et al., 2022). Miralles et al. (2019) and Schumacher et al. (2022)~~ showed the existence of~~ identified a self-propagating mechanism of droughts~~.~~, wherein meteorological droughts intensify due to increased water vapor deficit (VPD) ~~inside~~within the PBL~~ which feeds back into an intensified~~ , leading to further depletion of surface moisture reservoirs.

~~One of these reservoirs is~~ soil moisture~~, which plays a key role~~ is essential for ~~the~~ climate ~~due to its influence on~~dynamics, as it influences the partitioning between surface sensible and latent heat fluxes of ~~the~~ incoming solar energy (Seneviratne et al., 2010; Stephens et al., 2023). In vegetated areas~~ the~~, surface latent heat flux additionally depends on ~~the atmospheric water vapor deficit (VPD), air temperature, incoming radiation, and~~ vegetation ~~properties (~~characteristics such as stomatal resistance, leaf area index (LAI~~)~~), and rooting depth~~)~~ (Miralles et al., 2019; Warrach-Sagi et al., 2022)~~. In consequence of~~.

Due to the spatial and temporal variability ~~in~~of these influencing factors, LA coupling often ~~shows~~exhibits regional~~, but also~~ and temporal variations, especially under climate change conditions (Seneviratne et al., 2006; Denissen et al., 2022; Jach et al., 2022)~~.~~. According to Ossó et al. (2022) Europe has already experienced an increase in climate extremes since 2000 and is likely to remain a hotspot for severe droughts (Huebener et al., 2017; van der Wiel et al., 2022) impacting not only summer crop yields (Toreti et al., 2022) but also renewable energy generation. Regions exhibiting strong LA coupling coincide with those previously identified through various coupling metrics (e.g., Koster et al. (2004), Dirmeyer (2011), Guo and Dirmeyer (2013), Knist et al. (2017) and Jach et al. (2022)) Using water isotopes, precipitation, humidity, air temperature, and soil moisture data from 2006 to 2009, Yuan et al. (2023) identified the Central and Eastern Europe region in summer as one of 11 global hotspots for LA coupling, exhibiting varying pathways (e.g., soil moisture-precipitation, soil moisture-evapotranspiration, and soil moisture-temperature) and seasonality of LA coupling strength.

~~investigated~~Several studies have examined the ~~long-term average~~ relationship between ~~root zone~~ soil moisture and recent European heatwaves and droughts. Dirmeyer et al. (2021)~~surface fluxes by means of different regional climate model (RCM) simulations for the period 1989-2008 for the European summer seasons. They~~ and Orth et al. (2022) identified ~~a coupling hot spot region for the surface coupling of sensible and latent heat fluxes and latent heat flux and 2m temperature in South Europe while a transition zone is present over larger parts of Central Europe. performed a RCM LA coupling sensitivity experiment with respect to climate change signals of temperature and humidity for the period 1986-2015. Their results revealed a permanent coupling hot spot over Northeast and East Europe with the location being insensitive to changes in low level moisture and temperature. While there was only little sensitivity over the northern part of this area, Central Europe and the British Isles showed a change in the coupling regime based on the convective triggering potential and low-level humidity index (CTP-HI$_{low}$) framework . The combination of CTP and HI$_{low}$ allows for a determination whether convection is likely to occur (see Fig. 15 of). performed climate change sensitivity tests using the CTP-HI$_{low}$ framework. They found that Central Europe is in a transition zone where the development of convection is more likely to be solely controlled by a temperature increase.~~

~~evaluated the atmospheric coupling index (ACI;) using an RCM and found a strong sensitivity between sensible heat flux and CAPE during the growing season 2005 over South Germany while found a strong~~ soil moisture ~~– precipitation feedback over Central Europe during the summer seasons 1999-2008.~~

~~Several studies investigated the relation of soil moisture with recent European heat waves and droughts. found that a soil moisture-temperature feedback was~~as a key driver ~~for the severe heat wave over Siberia in 2010, while and found that it was a key driver for~~of the European heatwave in 2018. García-Herrera et al. (2010) ~~found~~similarly noted that a ~~strong~~significant soil moisture deficit was ~~also~~ one of the ~~key drivers for~~primary factors driving the 2003 European ~~heat wave. The study of~~ heatwave. Research by Miralles et al. (2014) ~~suggests~~ suggested that the heatwaves ~~over~~across Europe in 2003 and ~~over~~in Russia in 2010 were ~~enhanced~~intensified by a persistent large-scale weather pattern associated with ~~a strong~~substantial soil moisture decay. The analysis ~~of~~ conducted by Dirmeyer et al. (2021) for the 2018 European heatwave revealed enhanced soil moisture~~—near-surface~~ -maximum temperature coupling under drought conditions~~. The~~, where exceptionally low soil moisture limited evapotranspiration and ~~thus~~consequently amplified ~~the heat wave~~ heatwave conditions due to reduced evaporative cooling (Santanello et al., 2018)~~. This led to~~ , resulting in one of the most severe heatwaves ~~over~~recorded in Europe since 1979 ~~.~~(Becker et al., 2022). Wehrli et al. (2019) found that both soil moisture and ~~the~~ large -scale weather patterns are equally ~~important~~critical for the duration and intensity of heatwaves ~~around the globe. According to , Europe already faced an increase in climate extremes since 2000 and will remain a hot spot for severe droughts impacting not only summer's crop yields but also affecting the generation of renewable energy~~worldwide.

~~Shifts in the hydrological conditions from energy- to moisture-limited conditions originating from droughts and heatwaves or severe flooding imply temporal variability in LA coupling at sub-seasonal to interannual time scales.~~ Guo and Dirmeyer (2013)~~ also found~~ reported interannual variability in soil moisture-precipitation coupling~~ in~~

~~consequence of diverging~~, resulting from differing soil moisture availability. ~~Additionally,~~ The critical soil moisture ~~thresholds~~ threshold defines the boundary between energy-limited and water-limited regimes for evapotranspiration. Shifts from energy- to soil moisture-limited conditions due to droughts and heatwaves (Dirmeyer et al., 2021; Duan et al., 2020) or vice versa in the case of severe flooding (Lo et al., 2021) ~~suggest not only an intensification of the heat and drought conditions by~~ imply temporal variability in LA coupling over sub-seasonal to interannual timescales. Below these critical soil moisture thresholds, intensification of heat and drought conditions occurs through LA coupling over Europe ~~but also~~, alongside a strengthening of the coupling itself. Jach et al. (2022) identified Central Europe as a transition zone where the development of convection appears to be primarily influenced by temperature increases.

~~However, a quantification of~~Despite significant advancements in understanding land-atmosphere (LA) coupling, a crucial aspect of this complex phenomenon remains poorly understood: the temporal variability ~~in different coupling relationships and the associated impacts of the variability still lack, as~~ of LA coupling strength ~~on other time scales than~~and its associated impacts. Specifically, the investigation of LA coupling across timescales beyond climate periods has been ~~barely investigated over~~largely neglected in Central Europe ~~so far. The same applies to~~, and shifts between coupling regimes ~~due to~~driven by variability in ~~the~~ climatic conditions remain an ongoing research topic (Barriopedro et al., 2023)~~.~~

~~In~~. To address this knowledge gap, the current study~~, we therefore assess~~ aims to quantify the variability of LA coupling ~~of selected European~~strength over Central Europe during the summer seasons from 1991~~-~~ to 2022 ~~in dependence on~~, focusing on the relationships between temperature, soil moisture, precipitation, and large-scale weather ~~pattern by applying~~patterns. By leveraging high-resolution data from the fifth generation of the European Centre for Medium -Range Weather Forecasting (ECMWF) atmospheric reanalysis (ERA5; Hersbach et al., 2020~~).~~), this study seeks to provide new insights into the dynamics of LA coupling and its implications for climate extremes, agriculture, and ecosystems in the region. Ultimately, this research aims to enhance our understanding of the complex interactions between the land surface and the atmosphere and to inform the development of more effective strategies for mitigating the impacts of climate change in Central Europe. The paper is structured as follows: Section 2 describes the ~~applied~~ data sets and coupling indices~~.~~ utilized in the study. Section 3 ~~describes~~covers the interannual variability of meteorological variables~~,~~ and evaluates the meteorological ~~situation~~conditions of the summer seasons chosen ~~for evaluation~~, followed by the ~~LA coupling~~ analysis~~.~~ of LA coupling. Section 4 discusses ~~our~~the results, while section 5 summarizes ~~our work~~the findings and provides an outlook ~~on~~for potential future research.

2 Material and Methods

2.1 Datasets

For the analysis of the LA coupling, ERA5 was used. ERA5 is produced by the Copernicus Climate Change Service (C3S, http://climate.copernicus.eu/) at ECMWF. This data set provides hourly estimates of atmospheric, surface, and oceanic variables on a horizontal resolution of 0.25°. ERA5 clearly outperforms its predecessor ERA-Interim (Dee et al., 2011; Martens et al., 2020) and makes use of sophisticated atmospheric data assimilation including satellite derived soil moisture data (Albergel et al., 2012) to its land-surface model (LSM) HTESSEL (Balsamo et al., 2009).

ERA5 has been~~ recently~~ successfully applied in LA feedback studies over Europe (Rousi et al., 2023; Rousi et al., 2022) and other regions (Sun et al., 2021; Qi et al., 2023). Other reanalysis data sets like the Uncertainties in Ensembles of Regional ReAnalysis (UERRA), only available until 2019, are not recommended to use if surface fluxes are required for analysis (https://confluence.ecmwf.int/display/UER/Issues+with+data). The Consortium for Small-scale Modeling (COSMO) REA6 (Bollmeyer et al., 2015) data set is only available between 1995-2019 and does neither make use of a sophisticated data assimilation scheme nor of an ensemble approach. The Climate Forecast System Reanalysis (CFSR; Schneider et al., 2013) is only available until 2010 and thus does not cover the recent climate change period. Although a study of Beck et al. (2021) revealed that ERA5-Land (Muñoz-Sabater et al., 2021) outperformed ERA5 with respect to in-situ soil moisture measurements in the Carpathians and Southeast France during 2015-2019, data sets developed solely for land surface studies like ERA5-land and the Global Land Evaporation Amsterdam Model (GLEAM; Miralles et al., 2011) lack atmospheric boundary layer variables required for studying ~~land-atmosphere~~LA coupling and therefore were not considered in this study to avoid mixing different models for the investigation of the coupling chain.

~~To categorize the summer seasons during 1991-2022,seasonal mean anomalies of 2m temperatures and precipitation from ERA5 as well as precipitation from the ENSEMBLES daily gridded observational dataset for precipitation (E-OBS;) version V26.0e were calculated.~~

While ERA5 is a robust data set, it has some limitations. LH in ERA5 tend to be overestimated on average by about 9 Wm^{-2} (Muñoz-Sabater et al., 2021). ERA5 soil moisture shows reasonable correlations of up to 0.7 over Europe, but may be overestimated on wet days and underestimated on sub-daily precipitation rates. Despite its limitations, ERA5 is a reliable data set for studying LA coupling and has been successfully applied in various studies. Its hourly estimates and high horizontal resolution make it a valuable tool for understanding the complex interactions between the atmosphere and land surface.

2.2 LA coupling indices

In our study we apply a subset of the statistical LA coupling metrics~~ framework~~, namely the terrestrial coupling index (TCI) and atmospheric coupling index (ACI) (Guo et al., 2006; Dirmeyer, 2011; Santanello et al., 2018)., Additionally, the correlation $CORR_{SH\_LH}$ between surface sensible heat flux (SH) and surface latent heat flux (LH) is calculated. To derive the different indices, we used a combination of the NCAR Command Language (NCL, Brown et al., 2012) together with the FORTRAN programs provided by Tawfik (2015).

For our analysis, we used volumetric root zone soil moisture η, defined as weighted sum of the soil moisture in the top three soil layers of ERA5 ~~down to 1 m below~~(i.e. the ~~surface,~~top 1 meter), LH and SH, CAPE, and PBL height (PBLH). In addition, we used the height of the lifted condensation level (HLCL) and the lifted condensation level deficit (LCL deficit~~), ~~). The LCL deficit (m) is defined as height difference between HLCL and PBLH. ~~As~~Since HLCL was not directly available from ERA5, we ~~used~~applied the approach ~~from ~~proposed by Georgakakos and Bras (1984) and Bolton (1980), which ~~is ~~derive the HLCL based on surface pressure, 2m temperature, and 2m ~~dewpoint to derive HLCL which is~~dew point, a method also ~~applied in :~~employed by Dirmeyer et al. (2014):

$$\mathrm{HLCL} = \frac{R_d\, T_V}{g} * \log \frac{P_{SFC}}{P_{LCL}} \qquad (1)$$

R_d is the gas constant for dry air, T_v is the virtual temperature at 2 m above ground, g is the acceleration due to gravity, P_{SFC} is the surface pressure (hPa) and P_{LCL} denotes the pressure of the ~~lifted condensation level~~LCL (hPa). The strength of soil moisture-latent heat flux coupling ($TCI_{\eta\text{-}LH}$) between η and LH is defined as

~~The strength of soil moisture-latent heat flux coupling ($TCI_{\eta\text{-}LH}$) between η and LH is defined as~~

$$\cancel{TCI_{\eta-LH} = \sigma(\eta)\frac{dLH}{d\eta}} \qquad \text{~~(2)~~}$$

$$TCI_{\eta-LH} = \sigma(\eta)\frac{dLH}{d\eta} \qquad (2)$$

where $dLH/d\eta$ is the slope of the linear regression as described in Santanello et al. (2018) and σ(η) describes the standard deviation of root zone soil moisture. Equation (2) describes the sensitivity of LH with respect to changes in the root zone soil moisture.

~~Equation (2) describes the sensitivity of LH with respect to changes in the root zone soil moisture.~~

To derive the strength of the coupling between the land surface and the atmosphere (ACI), the standard deviation of η can, e.g., be substituted by surface fluxes in ~~Eq.~~equation 2 while LH in ~~Eq.~~equation 2 can be substituted by PBLH or CAPE (Dirmeyer et al., 2014)~~.~~

. ACIs are computed 1) between LH and CAPE ($ACI_{LH\text{-}CAPE}$), and 2) between LH and HLCL ($ACI_{LH\text{-}HLCL}$):

$$\cancel{ACI_{LH-CAPE} = \sigma(LH)\frac{dCAPE}{dLH}} \qquad \text{~~(3a)~~}$$

$$\cancel{ACI_{LH-LCL} = \sigma(LH)\frac{dHLCL}{dLH}} \qquad \text{~~(3b)~~}$$

$$ACI_{LH-CAPE} = \sigma(LH)\frac{dCAPE}{dLH} \qquad (3a)$$

$$ACI_{LH-HLCL} = \sigma(LH)\frac{dHLCL}{dLH} \qquad (3b)$$

σ(LH) denotes the standard deviation of LH. The daily mean values, required for the indices, are calculated between 06 UTC and 18 UTC (Yin et al., 2023)~~.~~

. Water grid cells are not considered in our evaluation.

2.3 Interannual variability of anomalies

Seasonal mean anomalies of 2m temperatures and precipitation from ERA5 as well as precipitation from the ENSEMBLES daily gridded observational dataset for precipitation (E-OBS; Cornes et al., 2018) version V26.0e were calculated to categorize the summer seasons in Central Europe between 1991 and 2022 into dry to wet and warm to cold or moderate years.

The investigation of interannual variability of anomalies in various variables and metrics, including their spatial distribution, involved the calculation of time series of the spatial variability of anomalies as follows. For each land grid cell, the average anomaly for the months of June to August was computed for each year. Box-whisker plots were then utilized to represent the data from all land grid cells, facilitating a comparison of the spatial variability of summer anomalies across different years.

3 Results

3.1 Interannual variability of summer seasons 1991-2022

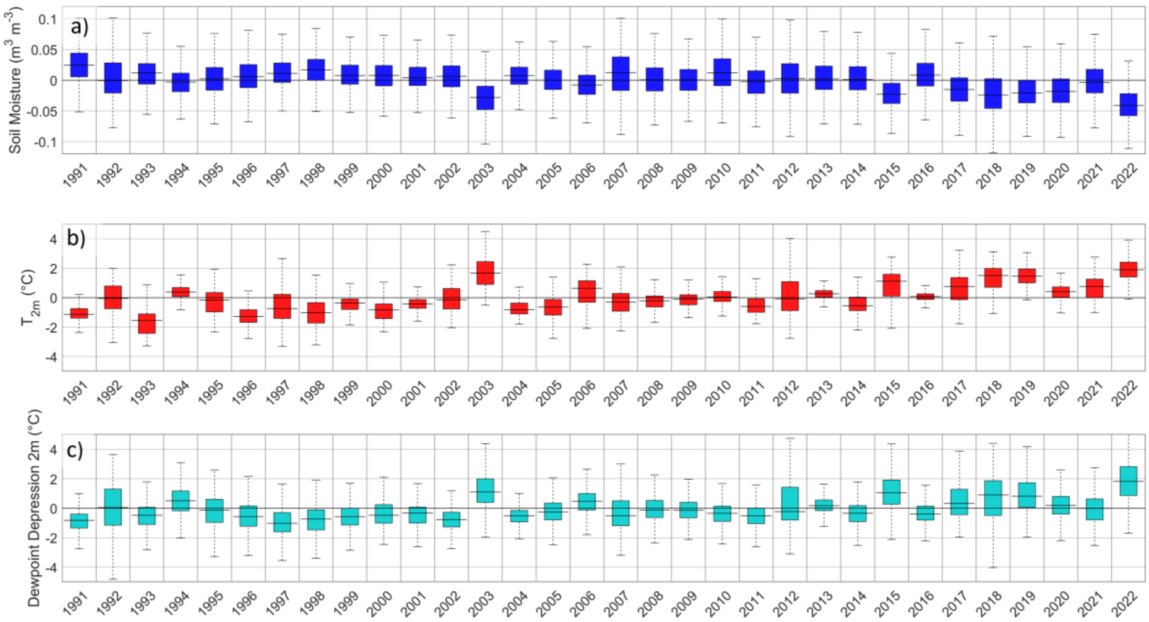
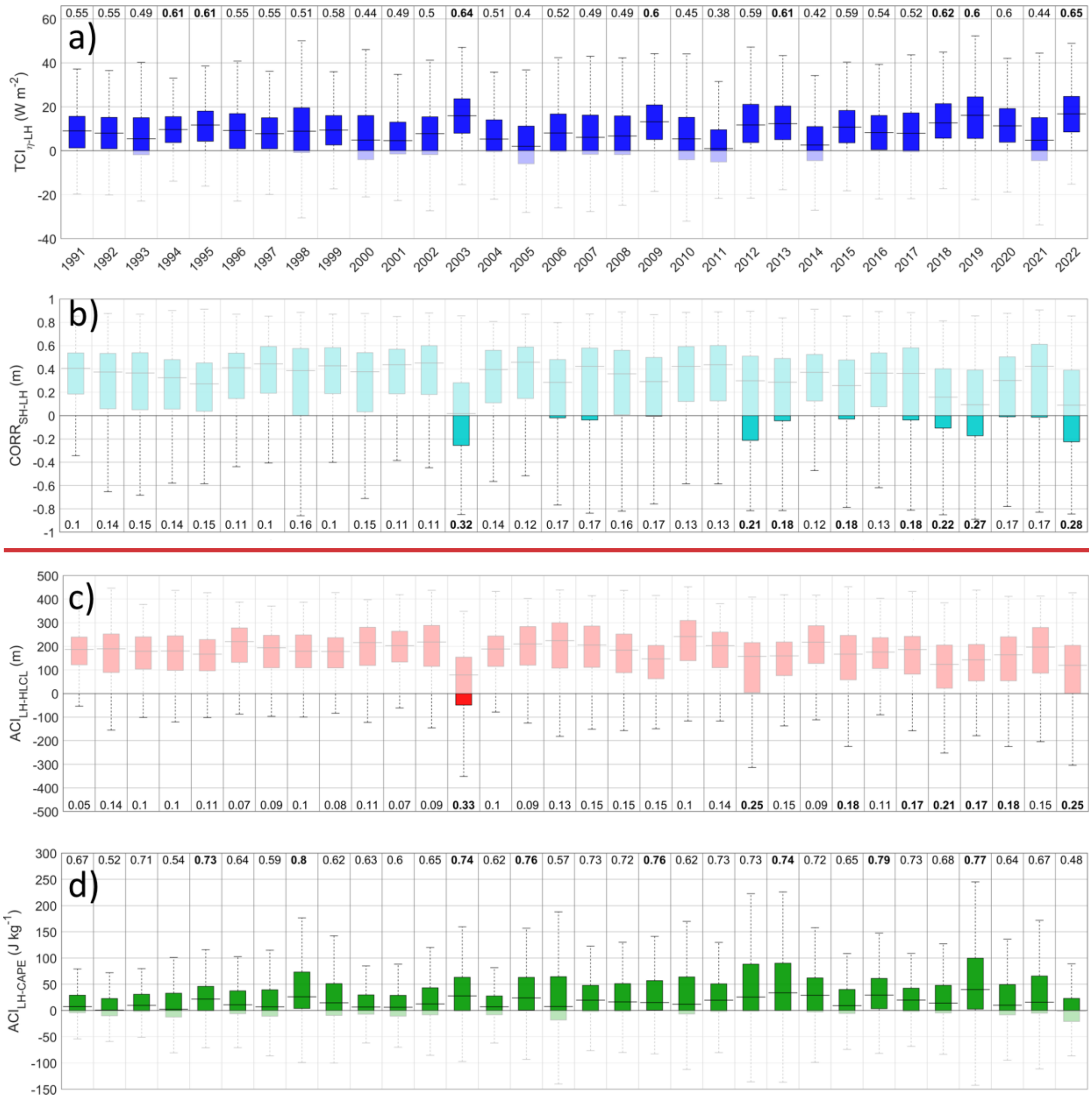


Figure 1. Interannual variability of anomalies of root zone soil moisture η (a), 2m temperature (b), and dewpoint depression (c) for the summer seasons between 1991~~-~~ and 2022. For each land grid cell, the average anomaly for the months of June to August was computed. Box-whisker plots were then utilized to represent the data ~~are averaged over~~from all land grid cells in the region between 40°N-60°N and 5°W-25°E.

~~From the anomaly timeseries in Fig. 1a it is seen that from 2015 onwards the soil moisture content shows a tendency to decrease during summer except for 2016. The summer seasons 2003 and 2022 are the driest summer seasons since 1991. At the same time, a trend for a temperature increase of 0.5-1°C is observed from Fig. 1b since 2015.~~

Figure 1 shows box-whisker plots of the summer mean values of soil moisture, 2m temperature and 2m dew point depression from 1991 to 2022 of the land grid cells in the study area between 40°N and 60°N and between 5°W and 25°E. The anomalies refer to the mean values of the respective grid cells from 1991-2020. Since 2015, apart from 2016 and 2021, more than 75% of the grid cells in the study area show negative soil moisture anomalies (Fig. 1a), in 2021 it is more than 50%. Previously, there was a stronger interannual variability with mostly more than 50% of the grid cells with positive soil moisture anomalies. The temperature anomaly (Fig. 1b) has been positive in more than 75% of the grid cells since 2015, in some cases more than 1 K. Before that, only 1994, 2003, 2006 and 2012 show more than 50% of the grid cells with a positive anomaly; in the other years, more than 75% of the grid cells are usually cooler than the mean value. There has also been a change in the dew point depression since 2015 (Fig. 1c). With the exception of 2016, the proportion of positive anomalies is more than 50%, while, as with the previous temperature, apart from 1994, 2003, 2006 and 2012, at least 50% of the grid cells show negative anomalies. It is also noticeable that the anomalies in at least 50% of the grid cells have spanned the same or a larger range of values since 2015, meaning that the spatial variability of the size of the anomalies is increasing. Dewpoint depression anomalies (Fig. 1c) can be used as an indicator for the inhibition of cloud formation. ~~A trend towards larger dewpoint depression is also observed here since 2015.~~ As higher temperatures increase the evaporative demand of the atmosphere, this results in a further reduction of soil moisture and thus an enhanced dewpoint depression which is seen among the summer seasons after 2015 in Fig. 1. The anomaly spread of η and 2m temperatures do not increase during these years pointing towards a general warming and drying over our region of interest~~ which will become more likely in the near future~~.



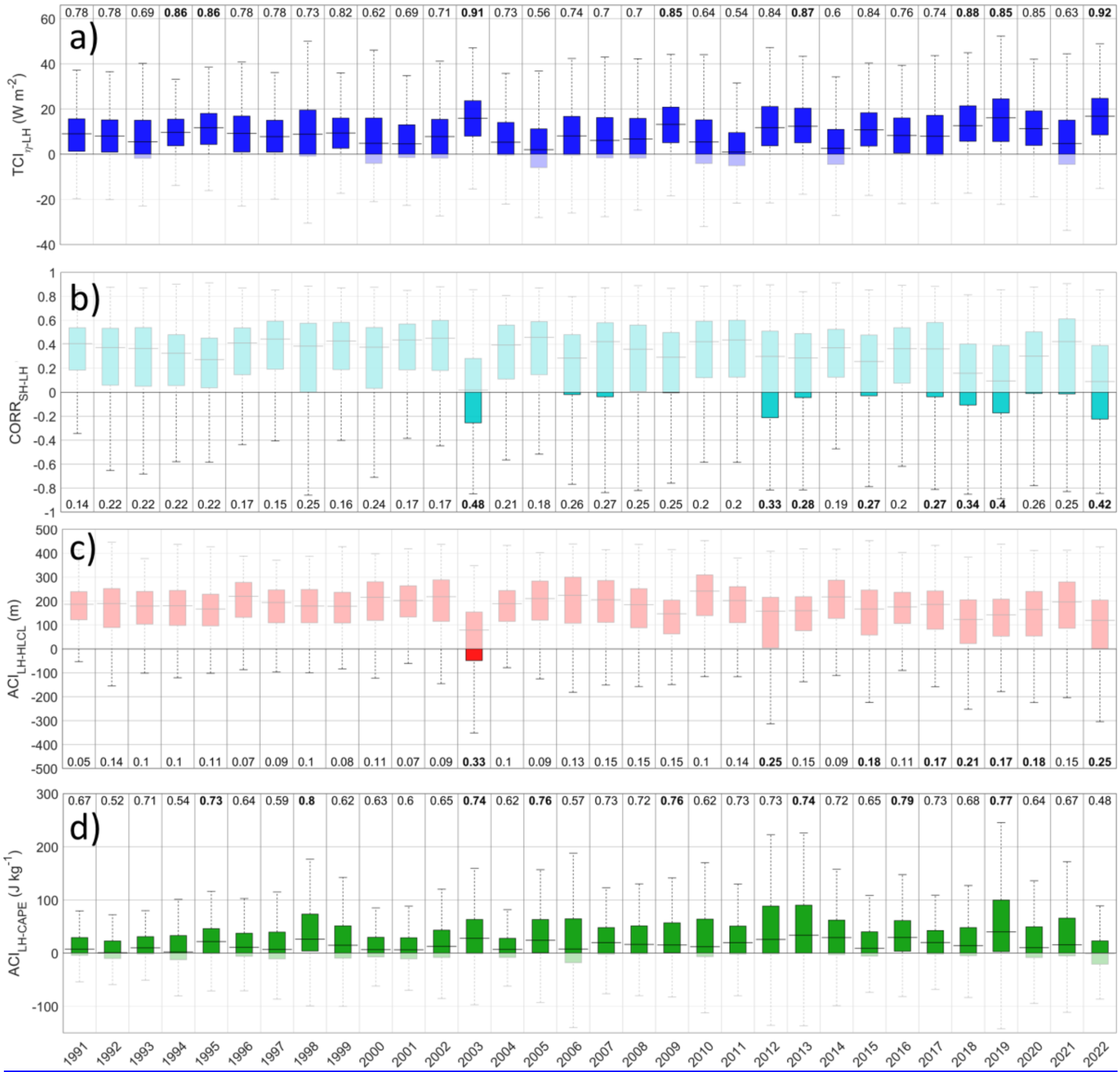


Figure 2. Interannual variability of the coupling indices ~~TCI η~~ TCI$_{\eta\text{-LH}}$ (a), ~~correlation SH~~ CORR$_{\text{SH}}$-LH (b), ACI$_{\text{LH-HLCL}}$ (c), and ACI$_{\text{LH-}}$~~HLCL~~CAPE (d) for the summer seasons 1991-2022. The ~~bold-faced~~ numbers indicate the fraction of ~~grid~~land cells ~~exceeding~~in the ~~75th percentile~~value range of the ~~respective~~ index potentially showing a physical relationship, i.e. TCI$_{\eta\text{-LH}} > 0$, CORR$_{\text{SH-LH}}$ and ACI$_{\text{LH-HLCL}} < 0$ and ACI$_{\text{LH-CAPE}} > 0$. Bold-faced numbers mark the 8 years (i.e. 25% of the examined years) with the highest share in the period. Full colors denote the sign, at which the first variable of the index (e.g., η) drives the second variable (e.g., LH). ~~The data are averaged over~~For each land grid cell, the average anomaly for the months of June to August was computed from all land grid cells in the region between 40°N-60°N and 5°W-25°E.

Figure 2 shows ~~the~~box-whisker plots of the summer mean values of LA coupling indices from 1991 to 2022 of all land grid cells in the study area between 40°N and 60°N and between 5°W and 25°E. They represent the value range across Europe for each index and summer. Variations between the years denote both interannual variability ~~of the correlation between SH and LH, and the coupling indices~~ in the number of grid cells (i.e. spatial extent) with potential for physical coupling, and differences in the strength of the coupling (higher or lower values for the index).

The distribution of TCI$_{\eta\text{-LH}}$ (Fig. 2a) displays strong interannual variability in the fraction of all grid cells with potential for physical coupling (see number in each box). The fraction of land cells with positive TCI$_{\eta\text{-LH}}$ fluctuates between 0.54 in 2011 and 0.92 in 2022, indicating a variability of up to 38% in the land area with potential for coupling. At the same time, the median of TCI$_{\eta\text{-LH}}$ (Fig. 2a) shows higher values for the warm summer seasons (see Fig. 1b). ~~, ACI$_{\text{LH-CAPE}}$, and ACI$_{\text{LH-HLCL}}$~~ Consequently, the strength of the coupling also increases during ~~the summer seasons 1991-2022. The correlation between SH and LH during the different summer seasons~~ these years. In contrast, CORR$_{\text{SH-LH}}$ is mostly positive across Europe (Fig. 2b), ~~however~~ which means that LH and SH co-vary. Negative correlations, where the limitation of LH causes an exaggeration of SH, mostly occur in the Mediterranean. However, there are few exceptions for the very warm and dry summer seasons of 2003, 2018, 2019, and 2022 where the median of ~~the~~CORR$_{\text{SH-LH}}$ drops below 0.2 due to reduced positive correlation ~~is less than 0.2~~ coefficients and ~~the number of grid cells~~a larger land area with negative correlations~~ is increased. The~~.

The interannual variability in ACI$_{\text{LH-HLCL}}$ (Fig. 2c) is less pronounced than that of TCI$_{\eta\text{-LH}}$ and CORR$_{\text{SH-LH}}$. The land area with potential for physical coupling ranges between 5% in the early 1990s and 33% in ~~median of TCI$_{\eta\text{-LH}}$ (Fig. 2a) shows higher values for the warm summer seasons (see Fig. 1b). Especially during the extremely warm and dry summer seasons~~ 2003 ~~and 2022 more than 90 % of the grid cells exceed the 75th percentile of the TCI$_{\eta\text{-LH}}$. The ACI$_{\text{LH-HLCL}}$ (Fig. 2c) does not show a clear trend for an increase or decrease while usually only a small fraction of the grid cells exceeds the 75th percentile. However, during~~, with the median TCI$_{\eta\text{-LH}}$ value also dropping below 100m in the latter year. However, with the exception of 2003, all summers with the largest expansion of the potential coupling region and the lowest median ACI$_{\text{LH-HCLC}}$ occur in the warm and dry years ~~a trend of ACI$_{\text{LH-HLCL}}$ approaching values around or below zero is evident. For the~~of the last decade (bold-numbers in Fig. 2c).

In contrast, ACI$_{\text{LH-CAPE}}$ (Fig. 2d) exhibits relatively weak interannual variability, with the median index showing little change over time. However, the land area fraction with positive ACI$_{\text{LH-CAPE}}$ ~~(Fig. 2d) no clear trend for an increase or decrease can be~~values varies between 0.48 and 0.8, suggesting larger spatial variability in some years. Notably, the years with the highest median index and the largest potential coupling regions do not correspond with the temperature and humidity conditions, as observed ~~which could give a hint that also the large-scale weather pattern can play a reasonable role in this case. It is worth noting that 2019 shows the largest variability of ACI$_{\text{LH-CAPE}}$ where 78 % of the grid cells exceed the 75th percentile.~~ for the other indices.

Based on the interannual variabilities shown in Figures 1 and 2, we ~~therefore~~ decided to focus on summer seasons which have a median 2m temperature anomaly of more than 0.5°C~~ which is proven to be a realistic estimate for changes of the maximum temperatures over land in the last decade . All anomalies were calculated using the Climate Data Operators (CDO) version 2.0.5 .~~.

Year	2003	2006	2015	2017	2018	2019	2020	2021	2022
E-OBS Precipitation anomaly [mm]	-60.4	-0.4	-34.3	-9.3	-37.8	-34.7	7.8	-3.7	-63.0
ERA5 Precipitation anomaly [mm]	-59.4	-8.7	-38.9	0.2	-36.1	-32.4	17.0	15.1	-37.9

Table 1. Selected summer seasons based on a positive summer temperature anomaly larger than 0.5°C with respect to the climatological summer mean of 1991-2020. The second row shows the median precipitation anomaly from E-OBS and the third row denotes the median precipitation anomaly from ERA5.

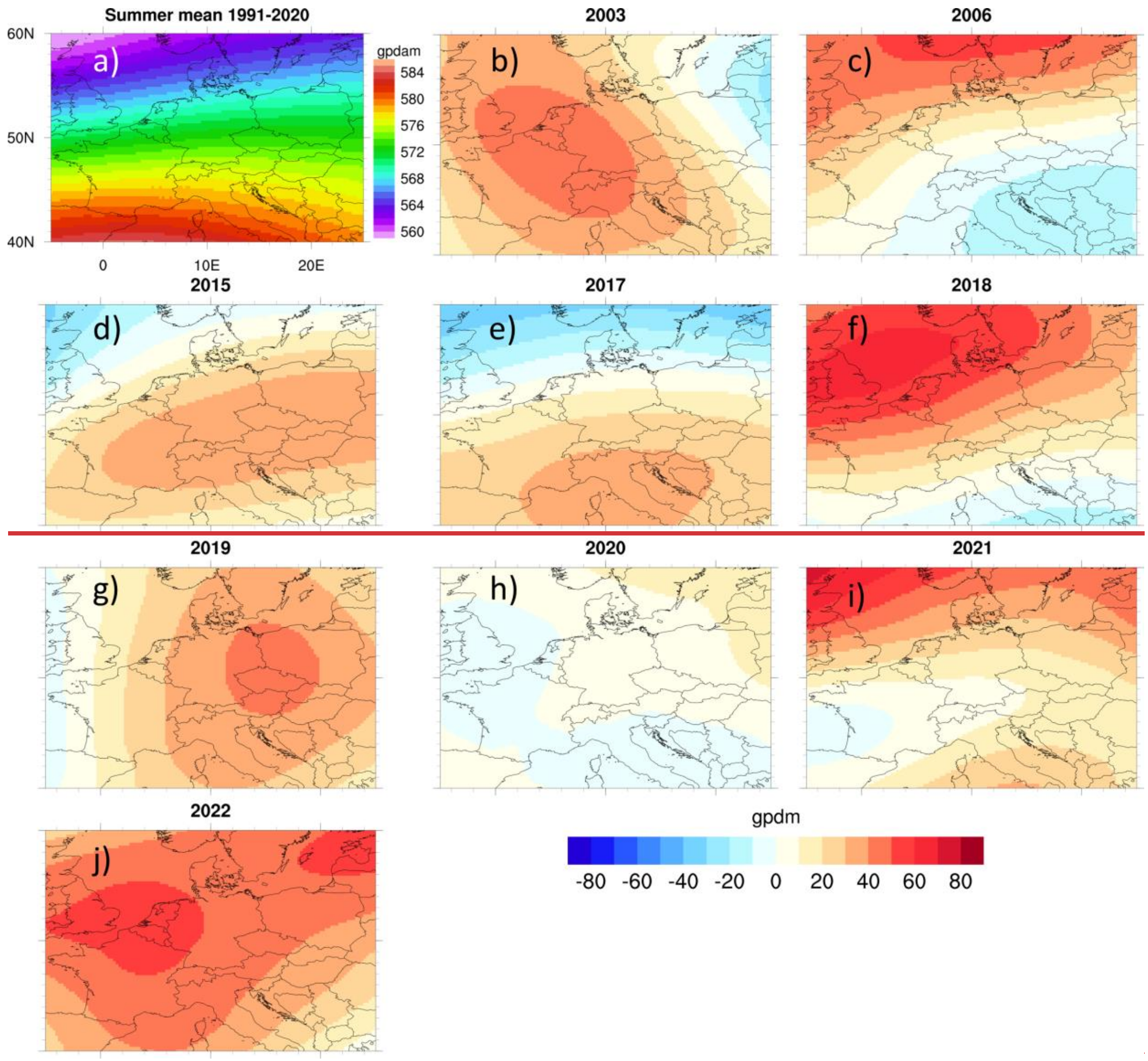
As seen from Fig. 1 and Table 1, the warm and dry summer seasons have become predominant since 2015. This has been associated with a strong reduction in annual and seasonal precipitation, combined with a reduced ~~atmospheric~~near-surface water availability as shown by an increased dewpoint depression (Fig. 1c) that led to a constant decline of the root zone soil moisture (Fig. 1a) and, thus, to an agricultural drought. Although the median 2m temperature anomaly for summer 2020 was only 0.4 °C, it ~~is~~was considered in our analysis ~~as~~considering that this was the only summer ~~with~~since 2015 witnessing a moderate observed positive precipitation ~~bias since 2015.~~anomaly according to both ERA5 and E-OBS datasets (Table 1).

3.2 Meteorological ~~situation~~characterization of the selected ~~summer seasons~~

~~This subchapter describes the synoptic conditions during each of the previously selected~~warm and dry summers~~. The conditions comprise the 500 hPa geopotential, which informs about the large-scale weather pattern, the 2m temperature anomaly, the precipitation anomaly and the root zone soil moisture anomaly. A more detailed characterization of the summers will be used for the interpretation of the coupling indices later.~~

3.2.1 ~~500 hPa geopotential~~

~~Figure 3 shows the 500 hPa geopotential height anomalies for the selected summer seasons. The 500 hPa geopotential height helps to determine mid-tropospheric troughs and ridges describing the large-scale weather pattern. Most of the investigated summer seasons are characterized by positive 500 hPa geopotential anomalies over large parts of Central Europe. The summer seasons 2003, 2019, and 2022 were characterized by a centric positive anomaly over central Europe with 2022 showing the highest positive anomalies of the investigated summer seasons. The summer seasons 2006 and 2017 were characterized by a meridional anomaly gradient around 50°N. In summer 2006, positive anomalies were present over the British Isles and South Scandinavia while in 2017, positive geopotential anomalies were observed over South Europe. Summer 2018 was characterized by strong positive anomalies north of 50°N and summer 2015 shows a moderate positive centric geopotential anomaly over Central Europe. During summer 2020, the 500 hPa geopotential shows a very weak zonal anomaly gradient so that it can be considered as an average summer compared with the climatology 1991-2020 (Fig. 3a). Summer 2021 was characterized by weak geopotential anomaly gradients while a higher anomaly was present over the British Isles.~~



~~**Figure 3.** ERA5 500hPa geopotential anomalies [gpdm] for the selected summer seasons. The top left panel shows the mean summer 500 hPa geopotential 1991-2020.~~

~~3.2.2~~ Near surface temperature

~~The positive 500 hPa geopotential anomalies shown in Fig. 3 are associated with positive 2m temperature anomalies.~~ The highest 2m temperature anomalies were observed during the summers 2003, 2018, 2019, and 2022 (Fig. ~~4b~~3b, f, g, j) and were spatially associated with strong positive geopotential anomalies over Central Europe~~.~~ (Fig. S1). During summer 2006, the 2m temperature anomalies are highest north of 51°N while during the summer seasons of 2015 and 2017, the highest temperature anomalies were observed south of 50°N. This coincides with the fact that maximum positive geopotential anomaly is observed south of 51°N (Fig. ~~3d~~S1d, e). Summer 2020 shows positive temperature anomalies over a wide area of our study domain. However, the 500 hPa anomalies were very moderate (Fig. S1h), indicating a constant flow of cooler and moist ~~airmasses~~air masses from the West to Central Europe. Summer 2021 showed a west-east anomaly gradient with temperatures slightly below the climatology over the western part of our investigation domain.

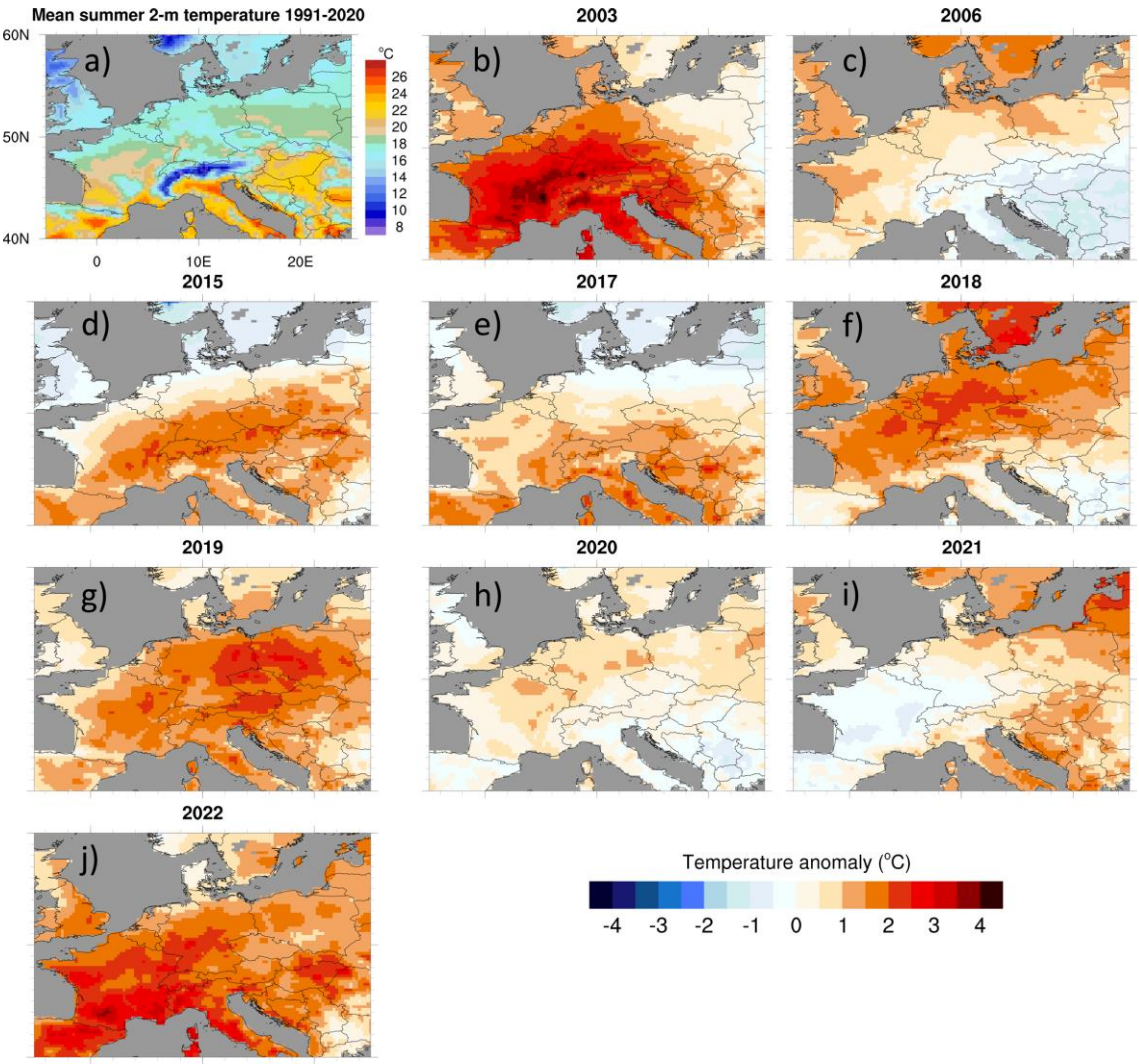
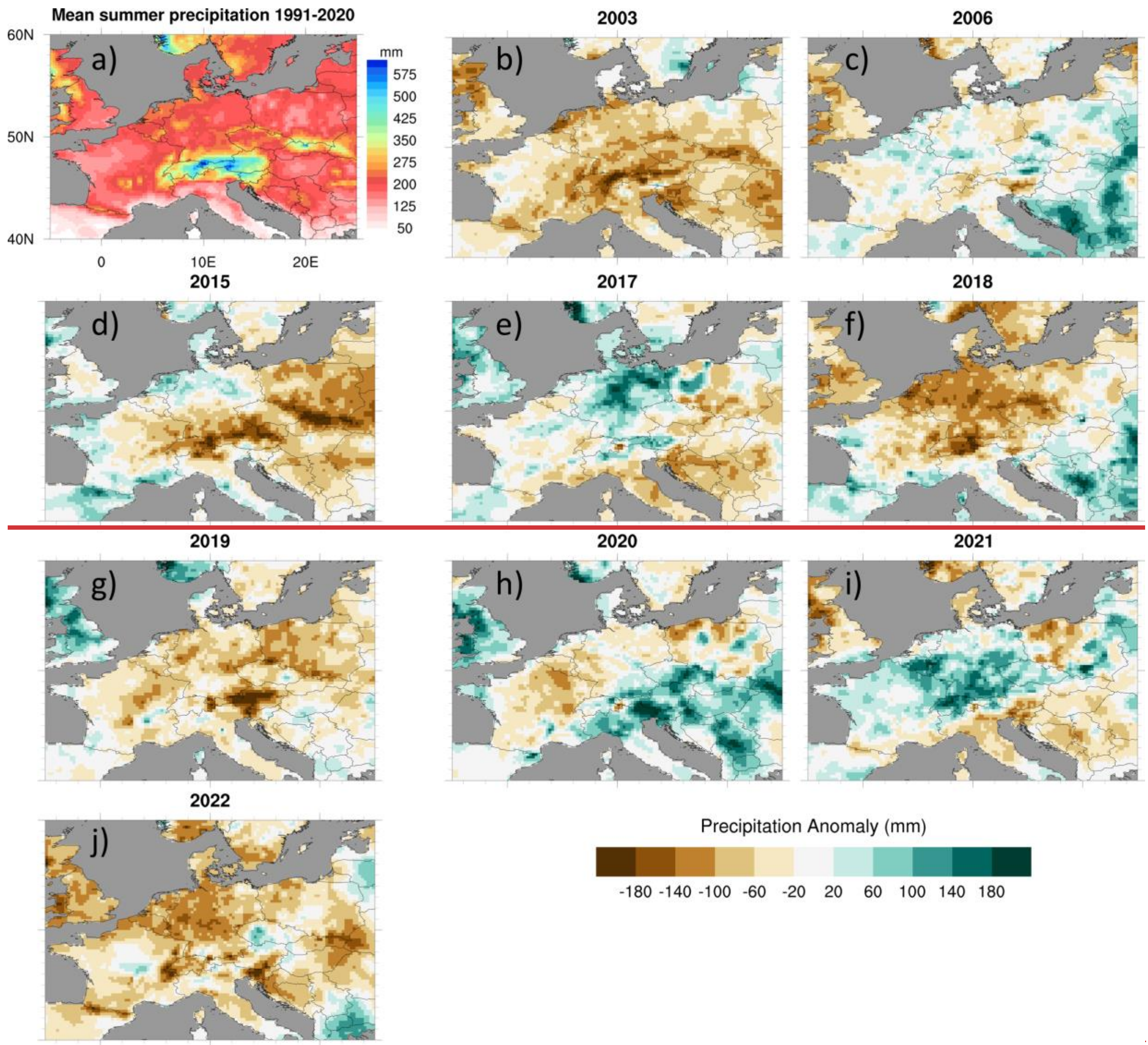


Figure ~~4~~3. ERA5 2m temperature anomalies [°C]. The top left panel shows the mean summer 2m temperature 1991-2020~~ from ERA5.~~.

3.2.~~3~~2 Precipitation

~~Observed~~ Precipitation (Fig. ~~5~~4 and Table 1) is often well below the climatological average 1991-2020. The summer seasons of 2003, 2015, 2018, 2019 and 2022 were exceptionally dry (Rousi et al., 2023; Rousi et al., 2022) with a spatial median precipitation anomaly between -~~34~~32.4 mm and -~~63~~59.4 mm. ~~These extreme anomalies are also seen in the precipitation anomalies derived from~~ ERA5~~ (Fig. 6) which~~ reasonably catches these dry periods (Lavers et al., 2022)~~. With respect to precipitation derived from E-OBS,~~, that are also evident in E-OBS (see Figure S2). 2006 can be seen as an average year with moderate precipitation anomalies over Central Europe. The summer season 2015 shows a strong dry anomaly associated with a warm temperature bias and positive 500 hPa geopotential anomalies~~.~~ (Fig. S1d). The summer season 2017 shows a strong wet bias over North Germany which is related to strong convective activity (e.g.,Caldas-Alvarez et al., 2022). Summer 2020 shows strong to moderate precipitation anomalies ~~both in E-OBS and ERA5~~ over Germany, France, Poland, and Benelux while precipitation over Southeast Europe is above the climatological average resulting in an overall positive precipitation anomaly in both data sets. During summer 2021, precipitation over France, Benelux, and Germany was above average due to a small scale low-pressure system which caused the Ahr flood event (Mohr et al., 2023) ~~. This event was also simulated by ERA5~~ as indicated by the dark teal colors in Fig. ~~6j~~4j.


Mean summer precipitation 1991-2020
a)
mm
575
500
425
350
275
200
125
50
60N
50N
40N
0
10E
20E
2003
b)
2006
c)
2015
d)
2017
e)
2018
f)
2019
g)
2020
h)
2021
i)
2022
j)
Precipitation Anomaly (mm)
-180 -140 -100 -60 -20 20 60 100 140 180

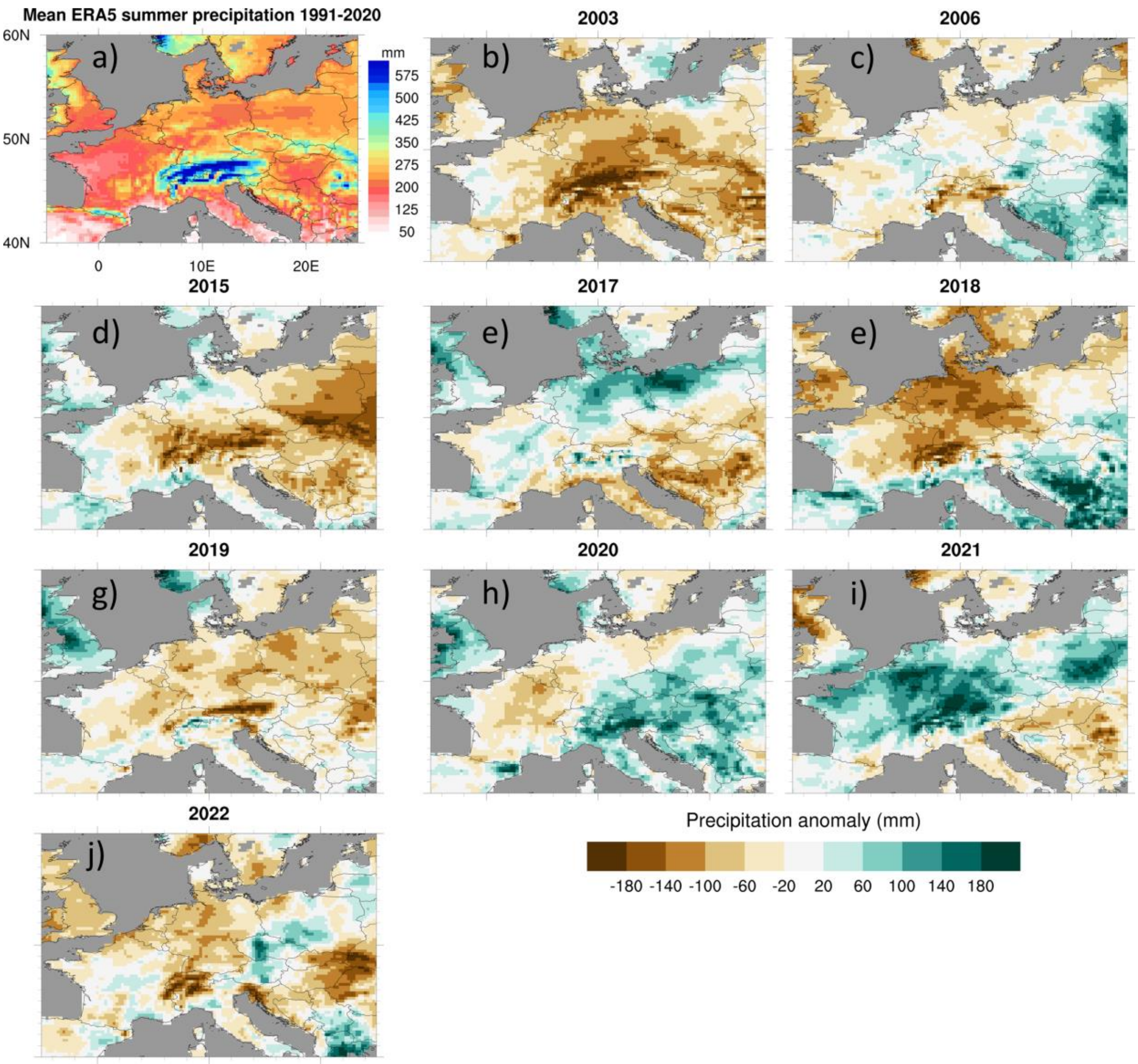
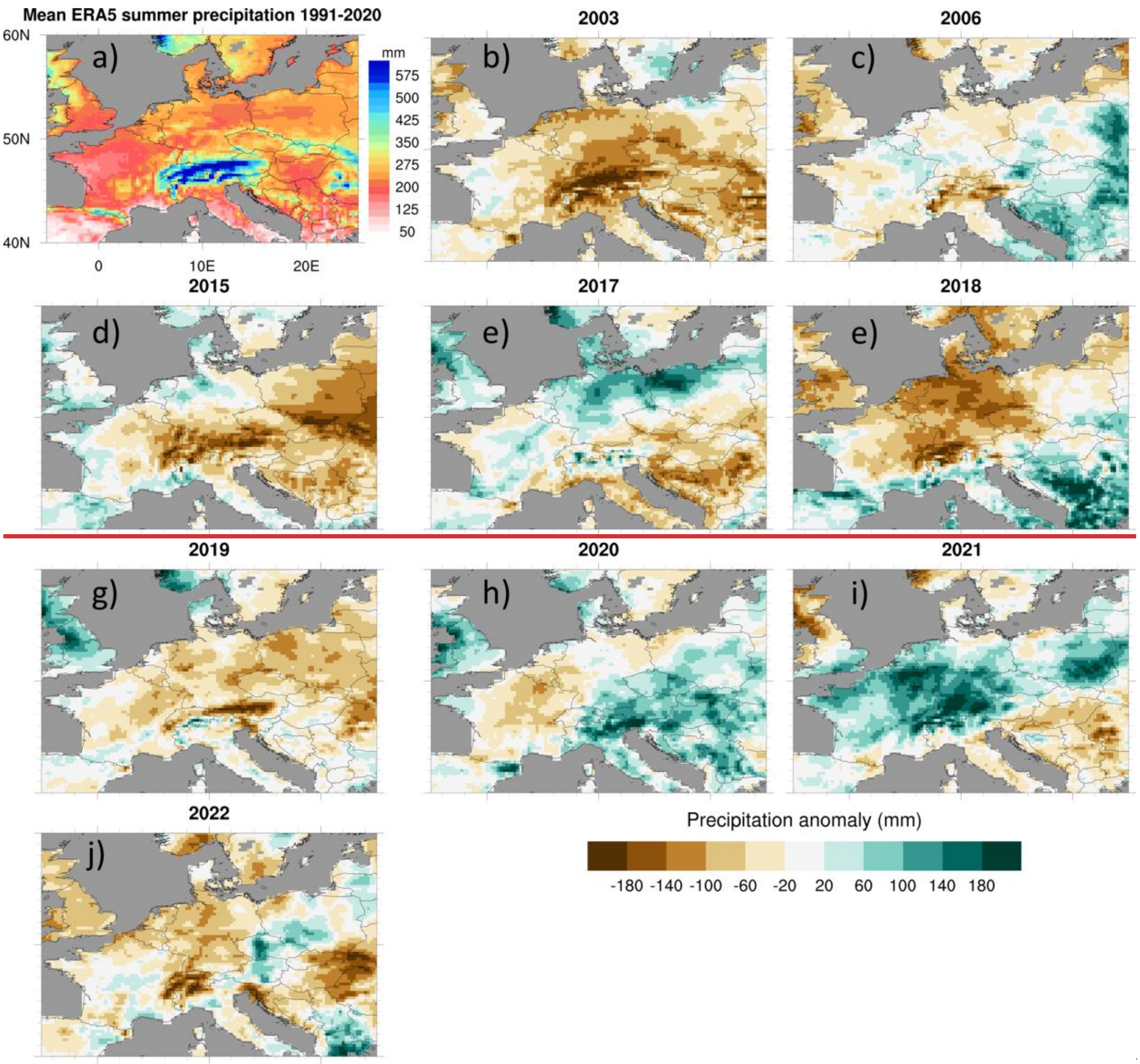


Figure ~~5. E-OBS~~4. ERA5 precipitation anomalies [mm] for the selected summer seasons. The top left panel denotes the mean summer precipitation from 1991~~-~~ to 2020.



~~**Figure 6.** Same as Fig. 5 but for ERA5.~~

3.2.~~4~~3 Soil moisture

Figure ~~7~~5 displays the ERA5 derived root zone soil moisture anomalies. The summer seasons of 2003, 2018, and 2022 show the lowest root zone soil moisture availability over Germany, Benelux, and France. This relates to the strong positive temperature bias and the precipitation dry bias ~~shown both by E-OBS and ERA5.~~. An evaluation of the median of the soil moisture anomalies over Central Europe revealed that summer 2006 is an average summer with moderate positive anomalies over East Europe. The negative soil moisture anomaly during summer 2015 is related to missing precipitation over large parts of Central Europe. Summer 2017 shows a strong positive soil moisture anomaly over North Germany and North Poland related to the higher-than-average rainfall ~~amount~~ (see ~~Figs. 5 and 6~~Fig. 4). Interestingly, although summer 2019 was among of the warmest and driest summers, the soil moisture dry ~~bias~~anomaly is less pronounced as in the other three hot and dry summer seasons of 2003, 2018, and 2022 ~~related to a~~. The reason is the higher soil moisture content during spring 2019 (Fig. ~~S2f).~~S4f), that was not used by the beginning of the summer. Summer 2020 shows drier than average soils over France and Germany while soil moisture in the other regions is around or even above the climatological average. The summer season

2021 shows strong positive soil moisture anomalies over Benelux and Germany which was related to colder than average April and May 2021 (C3S, 2022) as well as due to the Ahr flood event (Mohr et al., 2023).

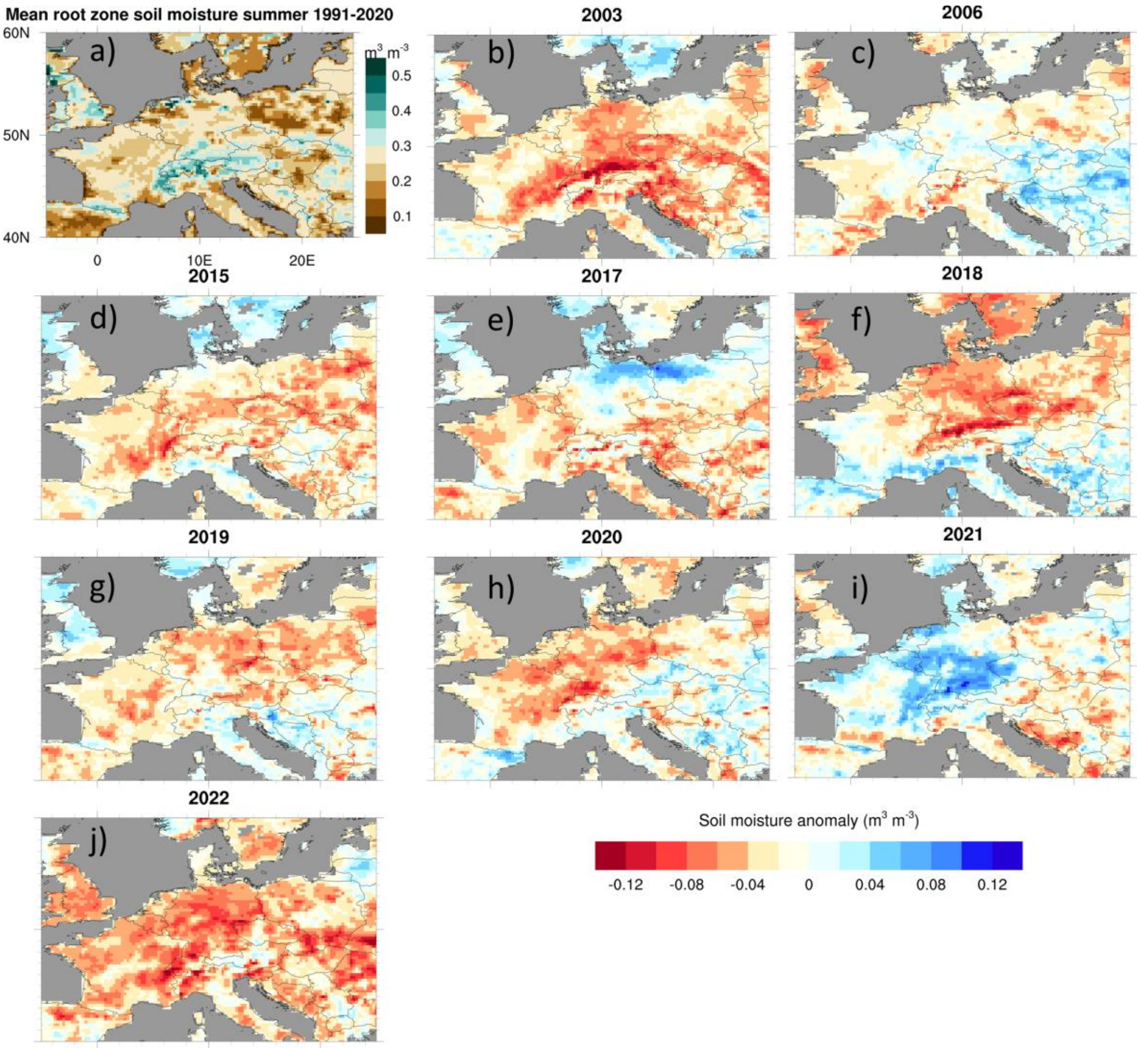


Figure ~~7~~5. ERA5 soil moisture anomalies [m^3 m^{-3}] for the selected summer seasons. The top left panel denotes the summer mean root zone soil moisture from 1991~~-~~ to 2020~~ from ERA5~~.

3.2.~~5~~4 Categorization of evaluated warm summer seasons

~~Although~~While all years ~~showed~~indicated that most of the cells ~~faced~~experienced a ~~considerable~~significant warm anomaly, the ~~years diverge in the~~ spatial patterns and the ~~spatial~~ extent of warm or cool, as well as moist or dry anomalies~~.~~ varied between the years. By visual examination it is possible to identify three groups within the hot years. Firstly, the years that stand out the most are 2003, 2015, 2018, 2019, and 2022~~ stand out the most.~~. They are characterized by ~~large~~warm temperature anomalies~~,~~ and dry anomalies in soil moisture and precipitation ~~extent over~~across most of the land areas in our study domain. Secondly, 2017 and 2021 were warm, but also comparatively wet years. Finally, 2006 and 2020 both exhibited moderate anomalies in all the meteorological fields shown before. In the following chapters, the groups will be referred to as "warm and dry", "warm and humid", and "moderate".

3.3 Terrestrial coupling

3.3.1 Soil moisture-latent heat flux coupling

In this section, we present the η-LH coupling based on the terrestrial coupling index ($TCI_{\eta\text{-}LH}$) for the selected summer seasons. The $TCI_{\eta\text{-}LH}$ describes how changes in soil moisture coincides with variations in LH. A positive $TCI_{\eta\text{-}LH}$ denotes that LH is limited by the root zone soil moisture and the soil moisture variation results in LH variation~~ while~~. A negative TCI $_{\eta\text{-}LH}$ indicates that the development of LH is energy limited, i.e., the incoming energy determines the LH development. In case the absolute $TCI_{\eta\text{-}LH}$ is low, either there is too little soil moisture available for evaporation, close to the wilting point, or the soil is too wet and a further increase does not lead to considerable changes in evaporation (Müller et al., 2021). Since the land surface influence on the convective and nocturnal boundary layer differs considerably due to the presence or absence of incoming shortwave radiation, ~~all analyses base~~the analysis was based on daytime means computed for the period 06 UTC and 18 UTC of each day (Yin et al., 2023)

Figure ~~8~~6 shows the ~~TCI $_{\eta}$~~mean spatial pattern of $TCI_{\eta\text{-}LH}$ ~~of all warm~~ observed for the previously selected warm and dry summer seasons~~ shown in Table 1 which became the dominant situation over Europe since 2015.~~. The very warm and dry seasons show a strong positive ~~TCI $_{\eta}$~~$TCI_{\eta\text{-}LH}$ over the regions affected by low soil moisture (Germany, France, and Benelux; Fig. ~~7~~5a, e, f, i). In summer 2015, which is overall very dry with respect to soil moisture and precipitation, $TCI_{\eta\text{-}LH}$ shows neutral values over North Germany while the rest of the investigation domain shows positive values. The warm and wet summers show the lowest values for the $TCI_{\eta\text{-}LH}$ of all warm years. In the wettest ~~areas of~~regions during both years~~ a switch in the sign of~~, the index ~~occurs.~~changes its sign. The now neutral to negative values indicate ~~the availability of sufficient~~that there is enough soil moisture ~~(Fig. 7), which~~available (see Fig. 5). This implies that in these areas and during these years, the variations in ~~turn suggests a decoupling of the~~ latent heat (LH) flux ~~variation from~~ are not directly linked to changes in soil moisture ~~variation in these regions and years (compare~~(refer to Fig. ~~6~~5 and ~~7~~Fig. 6).

During 2021, when a positive η anomaly is observed over Germany, Benelux, eastern France (Fig. ~~7h~~5h), the $TCI_{\eta\text{-}LH}$ becomes moderately negative in these regions with values of about -20 W m^{-2} (Fig. ~~8h~~6h). This can be explained by a moist spring season (Fig. S~~2~~3i) and the heavy precipitation event that occurred in June 2021 (Mohr et al., 2023) leading to a soil moisture content close to field capacity (Fig. ~~S1b~~S4). A similar behavior of the $TCI_{\eta\text{-}LH}$ is observed during the two cold and wet summer seasons (1997 and 2002, not shown).

During the moderate summers 2006 and 2020, the ~~TCI $_{\eta}$~~$TCI_{\eta\text{-}LH}$ shows a heterogenous pattern with neutral to slightly positive values of up to 20 W m^{-2} over most parts of Central Europe. The only exception is the alpine area and in 2006 the eastern part of our study domain where the ~~TCI $_{\eta}$~~$TCI_{\eta\text{-}LH}$ gets slightly negative.

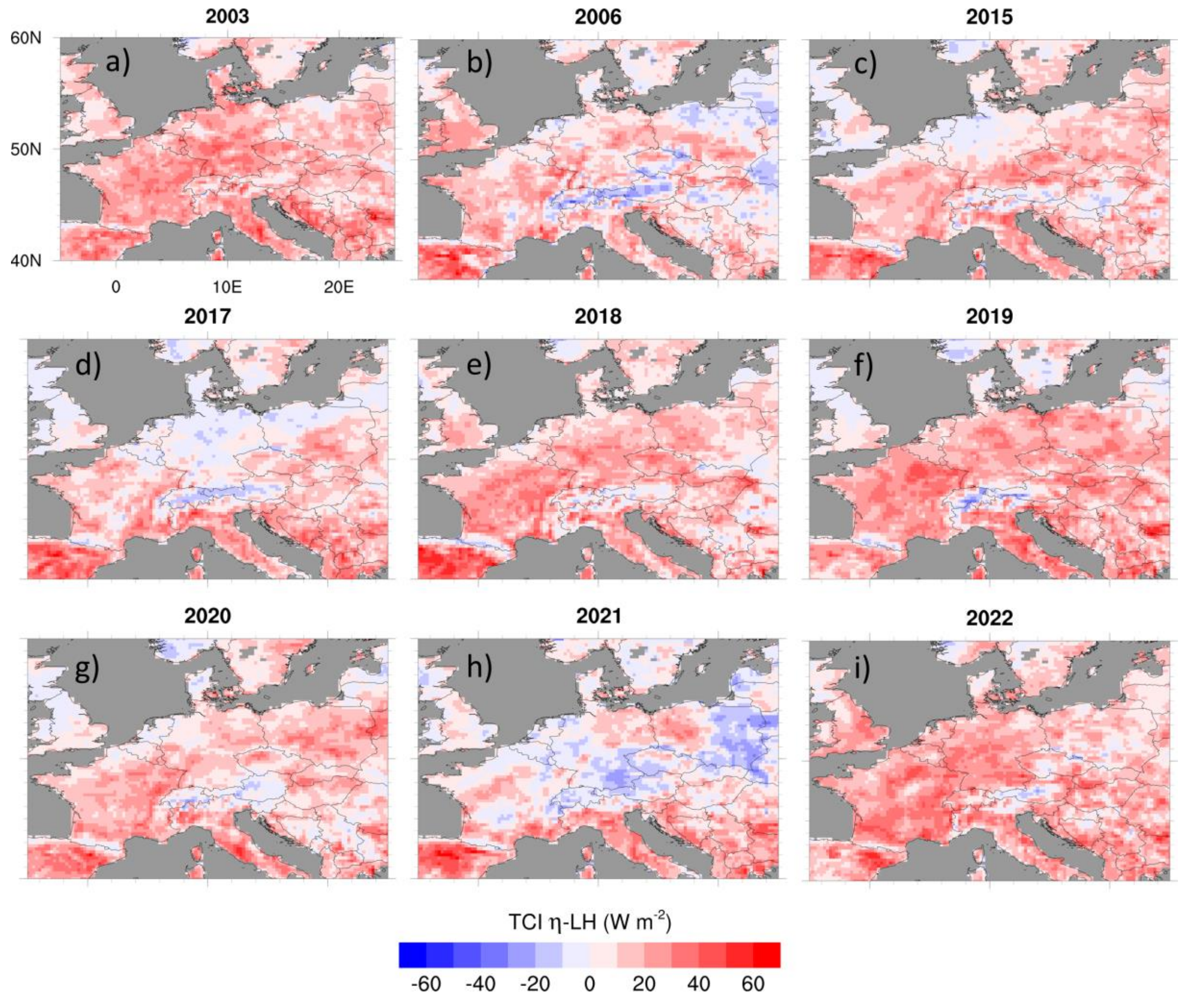


Figure ~~8~~6. ERA5 based Terrestrial Coupling Index ~~TCI η~~TCI$_{\eta\text{-LH}}$ between root zone soil moisture η and latent heat flux LH for the selected summer seasons.

3.3.2 Correlation SH-LH

The majority of correlation coefficients CORR$_{SH\text{-}LH}$ are negative over the Iberian Peninsula and the Mediterranean, which is related to very low absolute evapotranspiration (Seneviratne et al., 2006). Over the British Isles, Scandinavia and the Atlantic coasts, the heat fluxes usually demonstrate a positive correlation.

During the warm and dry summers 2003, 2018, 2019 and 2022, ~~the correlation~~ CORR$_{SH\text{-}LH}$~~-SH~~ (Fig. ~~9~~7) became negative over Germany, France, and Benelux. This is related to the anomalously warm and dry conditions in the atmosphere and a soil moisture deficit during these years. The soil moisture deficit limits LH ~~while SH is further increased. The SH increases~~ and due to ~~a~~the resulting reduction of ~~the~~ evaporative cooling ~~effect at the surface, and the consequent increase in~~SH is further increased. Consequently, the temperature gradient between land surface and atmosphere increases. During the warm and wet as well as the moderate years, the SH-LH correlations remain positive over Mid Europe and the patterns of ~~the correlation coefficients~~CORR$_{SH\text{-}LH}$ largely resemble those of the TCI$_{\eta\text{-LH}}$ (see Fig. ~~8~~6).

In 2017, the spring season showed a positive soil moisture anomaly over Germany, East Europe and the British Isles (Fig. S3) which is reflected in the strong ~~correlation~~ positive CORR$_{SH\text{-}LH}$ during the summer over these regions~~.~~ (Fig. 7d). The correlation pattern for summer 2021 is similar as during the cold and wet seasons of 1997 or 2002 (not shown) where enough soil moisture is available for evapotranspiration.

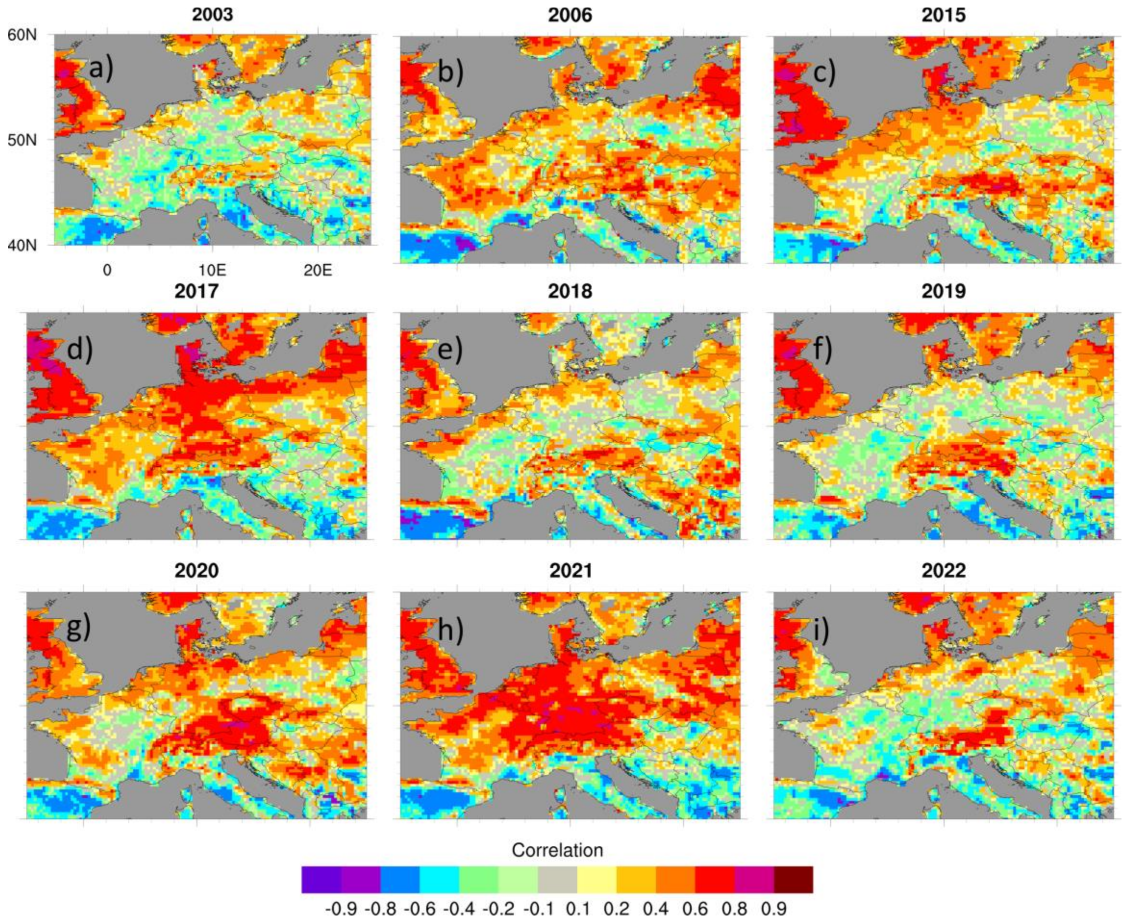


Figure ~~9~~7. Pearson correlation coefficient between SH and LH ($CORR_{SH-LH}$) for the selected summer seasons. Dark grey areas denote water grid cells.

3.4 Atmospheric coupling

3.4.1 Coupling LH-HLCL

This chapter explores the relationship between LH and HLCL and is complemented by an evaluation of the LCL deficit~~, building a bridge toward convective processes.~~.

For the $ACI_{LH-HLCL}$ negative values are associated with a potentially physical relationship. An increase in LH means stronger PBL moistening by the land surface. Stronger moistening in turn suggests that saturation is reached faster and at a lower altitude meaning a lower HLCL. The LCL deficit compares the heights of the PBL and the LCL (PBLH - HLCL). It can be employed as a proxy for the evolution of locally triggered deep convective processes. A positive LCL deficit means that the PBL top is above the LCL, when both heights are given in units of meters above ground. Hence, saturation occurs within the PBL, which is a prerequisite for locally triggered convective processes and cloud formation. Contrarily, a negative LCL deficit denotes an inhibition of convection developments (Santanello et al., 2011). Please note that Santanello et al. (2011) depict LCL and PBL on pressure levels, which leads to a switch in the sign in their interpretation.

The average pattern~~s~~ of the $ACI_{LH\text{-}HLCL}$ in the reference period indicate a physical influence of the LH on HLCL (negative values) over the South of the domain (Fig. ~~10~~8). The negative values are limited to the Iberian Peninsula and the Mediterranean, where summers are typically strongly moisture limited. Simultaneously, the LCL deficit is negative (Fig. ~~12~~9) leading to a strong inhibition of the local formation of clouds and deep moist convection. Over France, Germany and the Balkan~~ states~~, the $ACI_{LH\text{-}HLCL}$ patterns are patchy with negative or slightly positive values ~~in valleys~~at lower elevations and ~~strongly~~ positive ~~ones~~values over mountain ranges. The LCL deficit over these regions is comparatively ~~small~~low with values of up to -300 m. This is the area in the study domain facing considerable interannual variability, which is reflected ~~in~~by the sign changes~~, among other things.~~ of the $ACI_{LH\text{-}HLCL}$. Over the ~~rest of the domain, the values are primarily~~other regions, the $ACI_{LH\text{-}HLCL}$ is mostly positive, which suggests no considerable influence of the LH on HLCL, although the LCL deficit has ~~overall~~ negative values throughout all summer seasons. ~~This shows that saturation in~~Over the ~~PBL primarily occurs in the North~~northern regions of our ~~study~~investigation domain, the LCL deficit is often neutral or positive indicating favorable conditions for evolution of convection.

During the warm and dry summers 2003, 2015, 2018, 2019, and 2022, Mid Europe experiences a switch in the sign from averagely positive to slightly negative values ~~in~~of the $ACI_{LH\text{-}HLCL}$ (Fig ~~11a~~8a, e, f, i). These areas mostly ~~converge~~overlap with those where ~~the correlation between~~ $CORR_{SH\text{-}LH}$ ~~and SH~~ also switched the sign (Fig. ~~8~~7). At the same time, the ~~moderately~~ negative LCL deficit ~~intensifies to~~increases up to -600m over Mid Europe ~~to~~and over -900m over the Iberian Peninsula (Fig. ~~11~~9). This indicates that the very dry soil during these summers (Fig. 7) caused~~ the~~ low LH which in turn initiated a considerable increase of the HLCL (Fig. S5) and thus a higher LCL deficit as shown in Fig. ~~12. This is also shown by the negative values of the $TLCI_{\eta,LH\text{-}HLCL}$ (Fig. S3) showing feedback between η, LH and HLCL while only weak feedback between η, LH, and CAPE is present (Fig. S4). Please note that the SH is always positively correlated with the PBLH over land and doesn't experience strong interannual variability (not shown). This implies that a strong increase in the SH due to the LH limitation causes strong PBL heating and growth. This in turn pushes both the PBLH and the HLCL upward. Due to the combination of strengthened PBL heating and decreased PBL moistening the HLCL rises further, which leads to an intensification of the LCL deficit and thus inhibiting deep moist convection . The areas with the strongest changes in the signal converge with the regions experiencing the strongest warm and dry anomalies (compare Fig. 3j, Fig. 5j, and Fig. 7j).~~9.

During the warm and humid as well as the moderate summers, the $ACI_{LH\text{-}HLCL}$ is positive over large parts of Central Europe indicating that LH variations are not the primary driver of the HLCL evolution. Further, the SH is not influencing the HLCL (not shown), which suggests a stronger atmospheric influence in the ~~L-A~~LA system during moderate to humid periods.~~ The pattern of 2006 overly corresponds to the pattern of the climatological average. During summer 2021, the positive soil moisture anomaly (Fig. 7) is connected to weak or negative coupling between η and LH (Fig. 8).~~

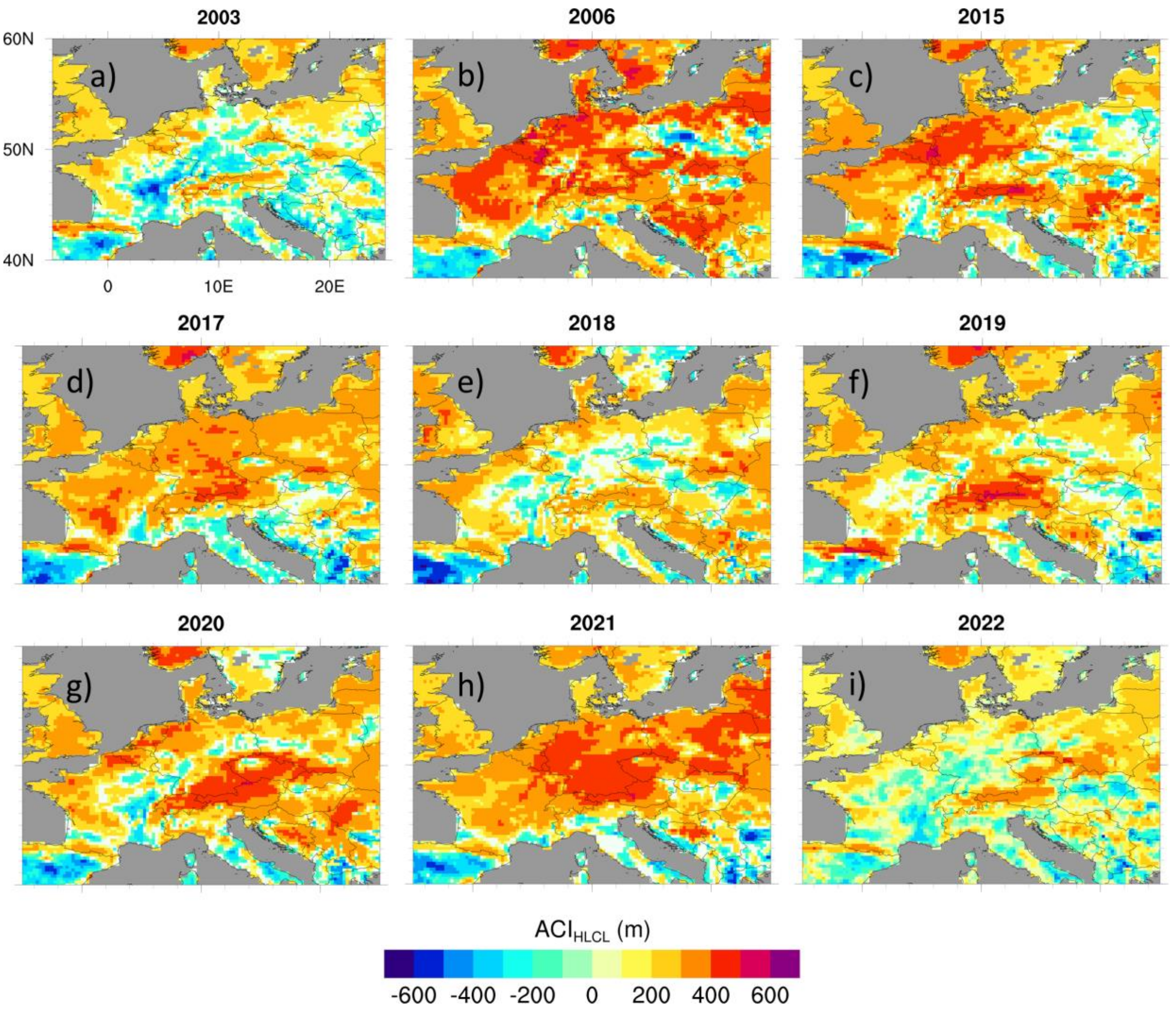


Figure ~~10~~8. Atmospheric coupling index between LH and HLCL (ACI$_{LH\text{-}HLCL}$) for the selected summer seasons.

Over Germany, France, and Benelux, the ACI$_{LH\text{-}HLCL}$ shows low or negative values during the extreme warm and dry summer seasons of 2003, 2018, and 2022 (Fig. ~~10a~~8a, e, i). This indicates that the very dry soil during these summers (Fig. ~~7~~5) caused ~~the~~ low LH which in turn initiated a considerable increase of the HLCL (Fig. S5) and thus a higher LCL deficit as shown in ~~Fig. 12. This is also reflected by the negative values of the TLCI~~$_{\eta\text{ LH HLCL}}$ ~~(Fig. S3) pointing towards feedback between η, SH and HLCL while only weak feedback between η, LH, and CAPE is present (Fig. S4).~~Figure 9.

In summer 2006, 2015, and 2017 the ACI$_{LH\text{-}HLCL}$ is positive over large parts of Central Europe indicating that LH variations drive the evolution of HLCL. During summer 2021, the positive soil moisture anomaly (Fig. ~~7~~5) is connected to weak or negative coupling between η and LH (Fig. ~~8~~6). This implies that LH either has little variations or is high compared to other summer seasons and thus lowering HLCL (not shown, e.g., Wei et al., 2021) which is also reflected in a mostly neutral LCL deficit over Central Europe as shown in ~~Fig. 11~~Figure 9.

As the TCI$_{\eta\text{-}LH}$ is mostly positive over these regions during these summers, while the ACI$_{LH\text{-}CAPE}$ is neutral to slightly positive, this indicates that soil moisture variation impacts LH variations but with weak feedback to the atmosphere ~~as indicated by the TLCI~~$_{\eta\text{ LH CAPE}}$ ~~(Fig. S4).~~.

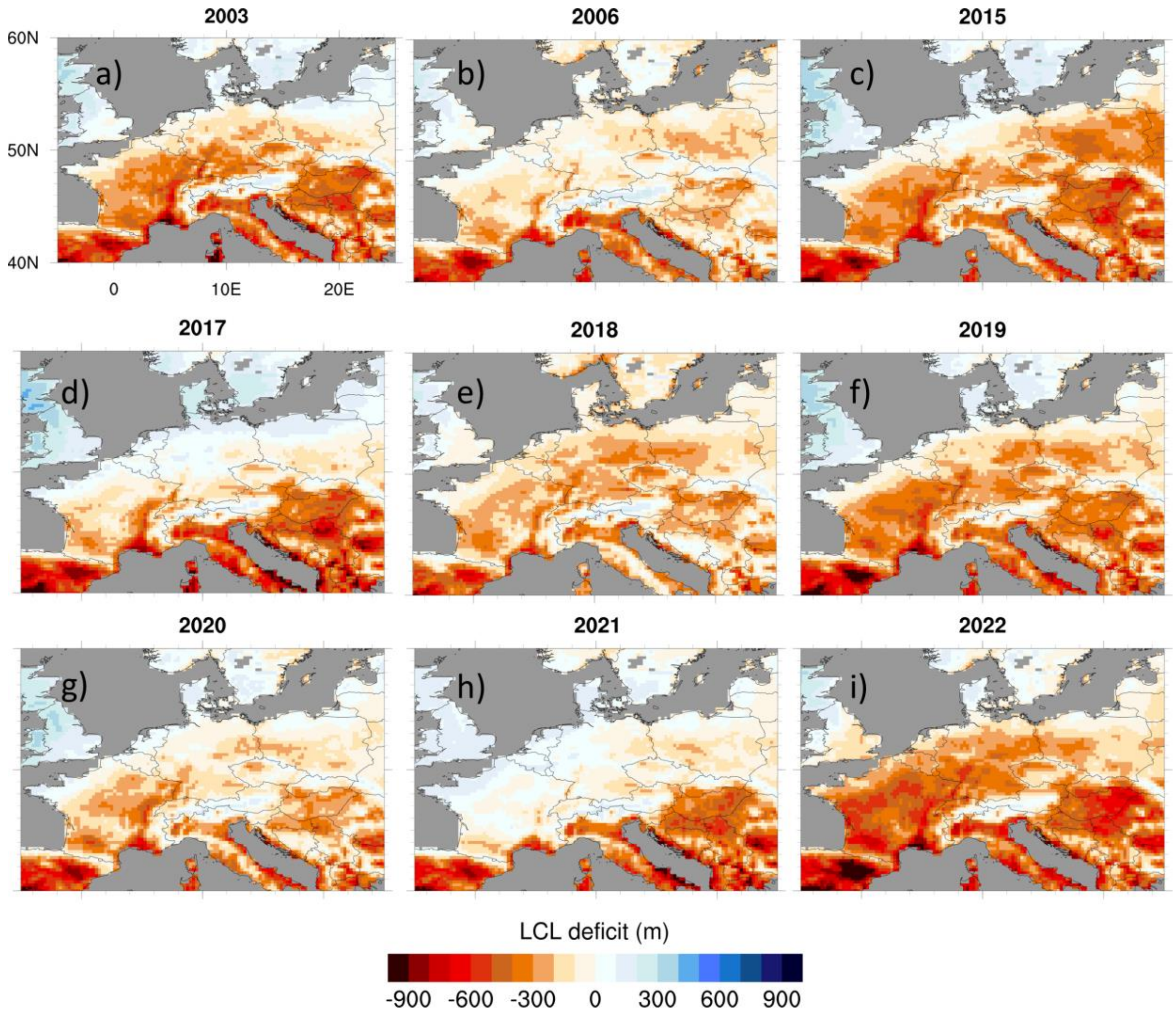


Figure ~~11~~9. Mean ERA5 LCL deficit. Orange and reddish colors denote less favorable conditions for convection.

3.4.2 Coupling LH-CAPE

This section explores the results of $ACI_{LH\text{-}CAPE}$ for the warm summer seasons. This index aims ~~at assessing~~to assess the relationship between surface moistening of the PBL represented by LH and the energy in the atmosphere, which is potentially available for the development of deep moist convection (CAPE). CAPE represents the deviation of the atmospheric virtual temperature profile from the moist adiabat between the level of free convection and the equilibrium level. This buoyant energy is typically stored a couple of hundred meters above the ground. It depends on both atmospheric humidity and the temperature gradient, which in turn are subject to surface influences through the surface heat fluxes. Through PBL moistening, an increase in LH can lead to an increase of CAPE which indicates the potential for convective developments and thus precipitation. In case evapotranspiration and therefore LH is not limited by soil moisture, the incoming radiation is allowing for potential evapotranspiration and surface LH and SH are partitioned accordingly. In case evapotranspiration is not limited by incoming radiation but by available soil moisture, evapotranspiration is below the potential rate leading to higher Bowen ratios and a further increase in temperature. This enhances evapotranspiration and therefore a gradual decrease in soil moisture towards wilting point. ~~CAPE depends on the atmospheric humidity which is, among others, related to LH while~~

~~LH is related to the atmospheric temperature, humidity, soil moisture and LAI~~According to Benson and Dirmeyer (2021) this ultimately leads to the situation that LH almost vanishes and the incoming radiation mainly transforms into sensible heat which can exacerbate heatwaves and droughts.

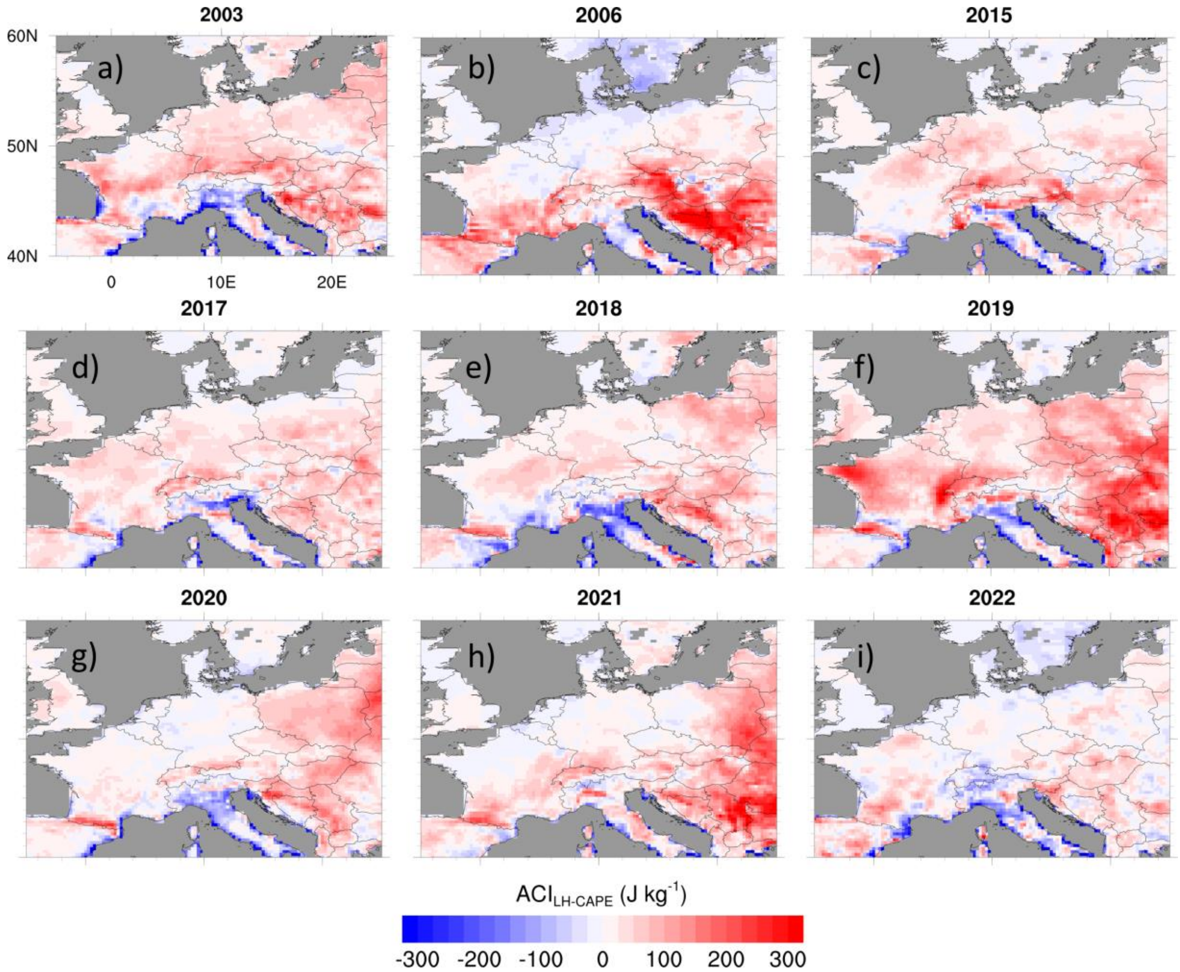


Figure ~~12~~10. ERA5 based atmospheric coupling index between LH and CAPE ($ACI_{LH\text{-}CAPE}$). Grey areas denote water grid points.

A common feature is the negative $ACI_{LH\text{-}CAPE}$ along the coast of the Mediterranean. As the sea surface temperatures in this region can reach up to 26°C (García-Monteiro et al., 2022), this leads to high evaporation over the sea and thus high precipitable water values. Together with a temperature gradient of up to 30 °C or more in the Mediterranean between 850 hPa and 500 hPa (not shown), this ~~leads~~can lead to ~~stronger~~a strong atmospheric instability in ERA5 and thus ~~reduced coupling~~ to ~~LH.~~ an overestimation of CAPE in the Mediterranean (Taszarek et al., 2018).

Coupling hot spots are observed over East and Southeast Europe with $ACI_{LH\text{-}CAPE}$ values of more than 250 J kg^{-1} in summer 2006, 2019, 2020, and 2021 (Fig. ~~12~~10). They are related to higher values of LH over these regions (not shown) due to neutral or positive root zone soil moisture anomalies (Fig. ~~7~~5). These coupling hot spots were also observed in a climate sensitivity study of Jach et al. ~~who added climate change perturbations of temperature and moisture to a RCM simulation. Over Germany and France, mostly only weak coupling is seen with stronger signals during 2003 and 2019. In case evapotranspiration is not limited by soil moisture, the incoming radiation is allowing for potential evapotranspiration and surface latent and sensible heat fluxes are partitioned accordingly.~~(2022). Over Germany and France, coupling is generally weak, although stronger signals were observed in 2003 and 2019.~~In case evapotranspiration is not limited by incoming radiation but by available soil moisture, evapotranspiration is below the potential rate leading to higher Bowen ratios and a further increase in temperature. This enhances evapotranspiration and therefore a gradual decrease in soil moisture towards wilting point.~~ ~~According to this ultimately leads to the situation that LH almost vanishes and the incoming radiation mainly transforms into sensible heat which can exacerbate heatwaves and droughts.~~ The low values of $ACI_{LH\text{-}CAPE}$ over the British Isles and South Scandinavia suggest that these regions are more frequently impacted by large scale synoptic systems with a more stable atmosphere rather than localized precipitation events (Jach et al., 2020). This is also reflected by the positive LCL deficit shown in ~~Fig. 11~~Figure 9.

4 Discussion

Our objectives were to evaluate interannual variability of coupling strength between soil moisture, surface fluxes, HLCL and CAPE over Central Europe (summer 1991-2022), and to further investigate the coupling during the warmest nine summer seasons in the context of the prevailing temperature and humidity anomalies. ~~We now discuss the key findings.~~

~~Our first finding is~~The results reveal that interannual variability occurs in different coupling relationships throughout the summer seasons from 1991~~-~~ to 2022. ~~A comparison of the~~ This variability is particularly evident in ~~the~~ indices ~~reveals~~associated with the hydrological cycle, such as the terrestrial coupling index ($TCI_{\eta\text{-}LH}$), the correlation between surface sensible heat flux and surface latent heat flux ($CORR_{SH\text{-}LH}$), and the atmospheric coupling index between LH and the lifted condensation level ($ACI_{LH\text{-}HLCL}$). These indices show a connection with temperature and moisture anomalies on the interannual scale, which ~~was also suggested for the climate time scale by . This connection is particularly shown in indices showing a relation associated with the hydrological cycle (~~$\sout{TCI_{\eta\text{-}LH}}$~~, correlation SH-LH,~~ $\sout{ACI_{LH\text{-}HLCL}}$~~). for instance also showed interannual variability in the coupling of soil moisture~~is consistent with ~~surface fluxes and temperature associated with soil moisture anomalies.~~ previous studies of Jach et al. (2022) and Guo and Dirmeyer (2013).

~~In this study,~~ The $TCI_{\eta\text{-}LH}$ shows ~~a year-to-year~~interannual variability during the full period of summer seasons from 1991~~-~~ to 2022~~. However, there is a trend of an increased~~, with the last decade exhibiting the largest spatial extent and highest coupling ~~during the warm and dry summers~~strengths (Fig. 2a). This indicates that variations ~~of~~ in soil moisture (η) drive LH as there is not enough soil moisture available for evapotranspiration. The average ~~correlation SH~~$CORR_{SH\text{-}LH}$ stays mainly positive, ~~however especially~~but becomes negative in the warm and dry summer seasons ~~the correlation became negative. This further suggests~~(Fig. 2b), suggesting a moisture-limited coupling regime. The interannual variability of $ACI_{LH\text{-}HLCL}$ shows ~~a trend towards~~ zero or even negative values during the warm and dry summer seasons ~~which~~ (Fig. 2c) namely in the last decade. This indicates less moistening of the planetary boundary layer (PBL) due to insufficient evaporation from the land surface and thus an increase of HLCL.

~~The average interannual variability of $ACI_{LH-CAPE}$ shows only little variations throughout the summer seasons. This could be related to a weaker direct connection between changes of LH impacting CAPE due to the present atmospheric stratification which is not only impacted by the surface conditions but also by the large-scale weather pattern and atmospheric stratification.~~

~~However,~~CAPE results from a complex interplay of atmospheric stratification, synoptic circulation and moistening and heating by the land surface. The $ACI_{LH-CAPE}$ shows coupling hot-spots over Southeast and East Europe as well as over the Baltic states which ~~were also observed in the study of who applied a climate temperature change signal to an existing 30 year simulation~~coincides with the hotspot observed in Jach et al. (2022) who studied surface fluxes influences on the potential for deep convection triggering. However, the interannual variability of $ACI_{LH-CAPE}$ shows little connection with the temperature and humidity conditions. Therefore, results suggest that rather the atmospheric factors drive the interannual variability.

From the interannual variability of the different variables shown in Figs. ~~2~~1 and ~~3~~2, it can be concluded that warm and dry summer seasons ~~show, on average,~~ are associated with a differing behavior of ~~the~~LA coupling strength~~.~~ across Europe. During summer seasons with enough moisture, despite higher temperatures strong LA coupling is largely limited to the European South as seen in the summer of 2021. This matches with the finding of Guo and Dirmeyer (2013), that areas with normally wet climate can experience a shift in coupling regimes under dry conditions. On the seasonal time-scale, Lo et al. (2021) also found regime shifts due to an extreme flood ~~or drought~~ in a semi-arid region. According to Rousi et al. (2022) the frequency of occurrence of heat waves is accelerating over Europe in the last 30-40 years where the large scale circulation pattern often features mid- and upper troposphere blocking situation leading to a split of the jet stream towards the Arctic and the Mediterranean. As the position of the jet stream has a decisive effect on 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). Dirmeyer et al. (2021) showed the causal connection between the hot and dry conditions during the 2018 extreme summer. The spring already started with a warm anomaly and slightly drier conditions over Germany (Xoplaki et al., 2023) turning into a severe drought due to a strong soil moisture depletion (Rousi et al., 2023). Dirmeyer et al. (2021) also showed that the drought conditions intensified the 2018 heatwave, because when the volumetric soil moisture content fell below a critical value, surface fluxes and temperatures became highly sensitive to the further declining soil moisture. The concept of drought-induced warming through evaporative controls was also found by Koster et al. (2009). The increased frequency of hot and dry extremes together with our findings suggests that stronger coupling can occur more often over a larger extent of Europe in the future.~~-~~ Despite the warmer temperatures variations in humidity can cause variability in coupling as seen in 2021 for instance ~~Rousi et al. (2022)conditions. As the current global warming trend reflects in more frequent hot and dry conditions over Central Europe, it was decided to focus only on nine hot summer seasons between 1991-2022 (sec, 3.2.5). suggest(Laurila et al., 2021)(Prodhomme et al., 2022)(Xoplaki et al., 2023)(Rousi et al., 2023)Dirmeyer et al. (2021) that precipitation dry bias is the result of strong positive temperature anomalies because of reduced evaporative cooling and Koster et al. (2009)increased SH. This is confirmed by an evaluation of summer temperature and precipitation anomalies over our region of interest which yield correlations ranging from -0.25 to -0.65 between temperature and precipitation anomalies. This suggests that hot and dry conditions will often coincide in the future and the regime shifts as discussed below, will occur with a higher frequency. During the warm and humid and moderate summer seasons a switch of the regime is rarely visible.~~

The coupling signals remain stable throughout the summer seasons over North Europe and the Mediterranean region (Seneviratne et al., 2006~~; ; ;). The correlation between SH and~~; Knist et al., 2017; Jach et al., 2020; Jach et al., 2022). The CORR$_{SH\text{-}LH}$ is mainly positive over the British Isles, indicating that evapotranspiration is limited by the incoming energy (Knist et al., 2017) which is also the case over France, Benelux, and Germany for summer 2021 (not shown). Over Central and East Europe changes in the coupling regimes occur between the individual summers which is indicated by switches in the sign of multiple indices. This area coincides with the transition zones which was also observed in the studies of Knist et al. (2017) and Jach et al. (2022).

The available net radiation energy is divided between LH and SH according to the energy required for evapotranspiration. LH and SH are correlated as long as evapotranspiration is not limited by the available soil moisture. LH in the regions south of 44 °N (Fig. 6) is usually water-limited. Therefore, a common feature of the warm and dry summer seasons is the anticorrelation of LH and SH~~ south of 44 °N (Fig. 8). These regions are usually water-limited leading to limited evapotranspiration thus further reducing LH~~. As enough incoming solar energy is present in these regions, this further enhances SH and thus could further intensify drought periods (positive coupling). Together with the positive ~~TCI $_{\eta}$~~TCI$_{\eta\text{-LH}}$ the anticorrelation of SH-LH points to a strong limitation of evapotranspiration by insufficient root zone soil moisture. ~~Though not yet represented in the model, in reality, this results in a low LAI which is often the case in South Europe (see Fig. S6c, d).~~ Moisture-limitation of the LH in the warm and dry summers leads to a shift in the energy flux partitioning towards reduced PBL moistening and amplified PBL heating because of increased SH. This shift causes a drying throughout the PBL, which is shown by an increased HLCL (Fig. S5) and an intensified negative LCL deficit. Thus, the dry and warm conditions at the land surface propagate through the atmosphere and feed back in less favorable conditions for local convection.

~~As an example~~During warm and humid or moderate summer seasons, the ~~year 2018 started with an already warmer than average and slightly drier spring season over Germany turning into a severe drought due to a strong soil moisture depletion resulting in an exceptionally low LAI (Fig. S6c). found that when the volumetric soil moisture content falls below a critical value, surface heating becomes extremely more sensitive to further surface drying amplifying the intensity of heatwaves.~~

~~According to the frequency of the occurrence of heat waves is accelerating over Europe in the last 30-40 years where the large scale circulation pattern often features mid- and upper troposphere blocking situation 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 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 .~~

~~If enough moisture is in the~~ local ~~L-A~~LA system~~, (warm humid and moderate years) variations in the moisture at the land surface do not play a strong role locally. This is shown by~~ is characterized by sufficient moisture, which leads to a decoupling in several links along the local coupling (LoCo; Santanello et al., 2018~~)~~) chain. Specifically, the terrestrial coupling ~~chain:~~index TCI$_{\eta\text{-LH}}$ is negative, indicating that variations in η do not drive LH. Additionally, LH and SH co-vary, suggesting that evapotranspiration is not limited by soil moisture availability. Furthermore, the atmospheric coupling index between LH and HLCL (ACI$_{LH\text{-}HLCL}$) is positive~~.~~, indicating that LH variations drive the evolution of HLCL. However, during these humid or moderate summers, the LCL deficit ~~gets~~becomes positive~~ and~~, which can lead to the development of locally triggered deep convection~~ can occur~~.

As an example, in the warm and humid summer 2021 a strong SW-NE temperature anomaly gradient associated with a strong 500 hPa geopotential anomaly gradient around 55°N was evident. This led to a stronger westerly flow air which allows for more humid air masses from the Atlantic. A major event during this summer was the flood event mid of July 2021 which affected larger areas of West and Central Europe and lead to extreme precipitation of more than 150 mm d^{-1} (Ludwig et al., 2023; Mohr et al., 2023). This heavy precipitation event, which was also captured by ERA5 (Fig. ~~6h~~4i), was caused by a slow moving small-scale low-pressure system over France and Benelux and led to a longer lasting positive soil moisture anomaly from mid of July onwards. The anomaly is directly reflected in negative ~~TCI_{η}~~ $TCI_{\eta\text{-LH}}$ values and a strong positive ~~correlation between LH and SH~~ $CORR_{SH\text{-LH}}$ as enough surface moisture was available for evaporation. The pattern of ~~the correlation SH~~ $CORR_{SH\text{-LH}}$ and the pattern of $ACI_{LH\text{-HLCL}}$ largely resembles each other, which is also observed in the cold and wet summer seasons (not shown). The LCL deficit shown in ~~Fig. 10~~Figure 9 is mainly positive over Central and South Europe which is associated with a negative precipitation anomaly over the respective areas. On the other hand, the negative LCL deficit over the British Isles is directly connected with a positive precipitation anomaly (especially during summer 2019 and 2020) indicating that LA feedback processes were driven by low pressure systems. ~~Although ERA5 is the most comprehensive reanalysis data set currently available , some limitations have to be acknowledged. Like many other numerical weather prediction (NWP) models, ERA5 applies a static LAI climatology (Fig. S6b) which was derived from the period 2000-2008 . However, under a changing climate the interannual variability of LAI is enhanced as shown by the satellite derived data from the Copernicus Global Land Service (CGLS) project (Fig. S6c,d). Data such as these could help to further improve, e.g., the simulated evapotranspiration. Vegetation-climate dynamics are presumed to intensify the response in the regimes, as dry conditions e.g. cause less vegetation growth or vegetation dying, which potentially further reduces the LH and exacerbate the effects described above.~~

~~On the other hand, found that LSMs tend to overestimate the critical soil moisture . A recent study of using the LSM NOAH-MP showed that, even on a convection permitting (CP) horizontal resolution, LA feedback strength tends to be underestimated when using a LAI climatology in numerical weather prediction (NWP) models as compared to including the dynamic vegetation model GECROS . Since, this is in contrast to the results of indicating the need for further enhancements of the applied LSMs and the need to investigate the role of dynamic vegetation in the LA system.~~

~~However, evaluated LH from ERA5 against FLUXNET stations for the period 1991-2014. Their analysis revealed that ERA5 surface fluxes perform well in a moderate temperature climate. ERA5 soil moisture shows reasonable correlations of up to 0.7 over Europe while LH in ERA5 tend to be overestimated on average by about 9 W m^{-2}. This could be related to an overestimation of wet days in combination with underestimated sub-daily precipitation rates . Hence, although limitations are present in the reanalyses data set, they suggest that the exact values of coupling indices can vary but the sign and magnitude of the indices are robust~~

5 Summary

This study provides an assessment of ~~temporal~~ interannual variability in ~~three~~ four coupling relationships during the summer seasons between 1991 and 2022 for Central Europe. The relationships under investigation are soil moisture-LH coupling at the terrestrial leg of the local coupling chain, LH-SH, LH-CAPE as well as LH-HLCL coupling comprising two relationships of the atmospheric leg. The analysis of the LA coupling strength was performed by means of different coupling indices like TCI, ACI (Dirmeyer, 2011; Santanello et al., 2018) as well as $CORR_{SH-LH}$ (Knist et al., 2017) by applying the coupling metrics framework provided by Tawfik (2015). Firstly, the interannual variability ~~between~~of these relationships was examined across all ~~years~~ summers of the period ~~was examined in~~taking into account the ~~context of~~ prevailing temperature and moisture anomalies. ~~in the light of a warming climate and a projected increase in hot and dry periods until 2100 (Huebener et al., 2017).~~ The second part of the analyses focused on the coupling during the nine warmest summers of the period to address the context of a warming climate and a projected increase in hot and dry periods until 2100 (Huebener et al., 2017).~~.~~ All indices were calculated from ERA5 data using daytime values between 06 UTC and 18 UTC for each day (Yin et al., 2023). To enhance our analysis, anomalies of the 500 hPa geopotential, volumetric root zone soil moisture, and precipitation anomalies derived from ERA5 and E-OBS (Cornes et al., 2018), were considered for the interpretation of the results. Reanalyses can be used as a reference for a further analysies and evaluation of climate simulations. However, these investigations requires high-frequency and high spatial resolution model output from NWP models (Findell et al., 2024) which is still a challenging task.

Soil moisture availability during the summer seasons of 1991~~-~~ to 2022 show a decreasing trend while average 2m temperatures shows an increase of about 0.5°C since 2015. At the same time, the dewpoint depression anomalies show strong positive signals during the very warm and dry summer seasons of 2003, 2015, 2018, 2019, and 2022 ~~indicating a drier PBL and potentially leading to a suppression of the development of convection~~. These summer seasons are characterized by positive 500hPa geopotential anomalies throughout Europe, which are linked to considerable positive 2m temperature anomalies, strong soil moisture decline and larger dewpoint depressions. The warm and dry conditions lead to an intensification or even the onset of statistically measurable coupling in the various processes along the LoCo process chain. In Central Europe, they caused a shift from energy- to moisture-limitation for evapotranspiration. This ultimately contributes to a drier PBL potentially leading to a suppression of deep convection. In wet years, LH does not depend on the soil moisture availability as sufficient transpiration of the leaves is possible and the HLCL is not primarily controlled by the lack of moisture at the surface.

The interannual variability of the ~~correlation SH~~$CORR_{SH-LH}$ as well the $TCI_{\eta-LH}$ also reflected the exceptional warm and dry summer seasons. Therefore, it was decided to further investigate the summer seasons exceeding a median temperature anomaly of +0.5°C based on the ERA5 summer mean value of 1991-2020 (WMO, 2017).

~~To enhance our analysis, anomalies of the 500 hPa geopotential, volumetric root zone soil moisture, and precipitation anomalies derived from ERA5 and E-OBS (Cornes et al., 2018), were considered for the interpretation of the results.~~ ~~Our results revealed that the investigated summer seasons are characterized by positive geopotential anomalies throughout Europe. Strong geopotential anomalies are linked to considerable positive 2m temperature anomalies strong dry soil moisture anomaly.~~

~~The analysis of the LA coupling strength was performed by means of different coupling indices like TCI, ACI (Dirmeyer, 2011; Santanello et al., 2018) as well as the correlation between SH and LH (Knist et al., 2017) by applying the coupling metrics framework provided by Tawfik (2015). All indices were calculated from ERA5 data using daytime values between 06 UTC and 18 UTC for each day (Yin et al., 2023). Reanalyses can be used as a reference for a further analyses and evaluation of climate simulations. However, these investigations requires high-frequency and high spatial resolution model output from NWP models (Findell et al., 2024) which is still a challenging task.~~

~~The interannual variability of the summer seasons revealed a temperature increase which is accompanied by a decline in soil moisture and an increase in the dewpoint depression which is most prominent in the especially warm and dry summers 2003, 2015, 2018, 2019, and 2022.~~

~~The warm and dry conditions lead to an intensification or even the onset of statistically measurable coupling in the various processes along the LoCo process chain. In wet years, LH does not depend on the soil moisture availability as sufficient transpiration of the leaves is possible (see Fig. S5d) and the HLCL is not primarily controlled by the lack of moisture at the surface.~~

The increasing frequency of warm and dry summers from 2015 onwards hints toward a trend of extended periods of reduced soil moisture available~~-~~ for evapotranspiration and the likelihood of locally triggered convection. This leads to a growing influence of soil moisture variability on the meteorological conditions which was not as pronounced before 2003 due to cooler and moister conditions. Markonis et al. (2021) found a considerable increase in drought events over Central Europe since 2010 which they relate to increasing temperature and a lack of rainfall which together cause a soil moisture depletion due to excessive evapotranspiration.

The switches in the sign of the coupling indices imply that on the seasonal time scale local soil moisture and temperature anomalies can cause an exceedance of thresholds along the LoCo process chain. This has the potential to changes the role of the land surface as the driver for the local LA-system on the interannual time scale, and thus needs to be considered ~~for~~ in sub-seasonal to seasonal (S2S) forecasts~~-~~ which are used, e.g., for risk assessment of natural hazards.

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Code availability

The code used in this study to calculate the coupling indices is obtained from https://github.com/abtawfik/coupling-metrics. The NCL software package can be downloaded from https://www.ncl.ucar.edu/current_release.shtml.

Data availability

E-OBS data were downloaded from https://surfobs.climate.copernicus.eu/dataaccess/access_E-OBS.php and the ERA5 data are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview.

Author contributions

TS, LJ, VW, and KWS conceived the idea for the LA feedback study presented here. TS processed the data and graphics and performed the analyses together with LJ and KWS. The paper was written by TS with support of all coauthors.

Competing interests

The authors declare that they have no competing interests.

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