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 ~~more often experiences~~ periods of severe drought and heatwaves which have a major impact on agriculture and society. While soil moisture was found to be a crucial

10   factor for enhancing the duration and intensity of these events, their influence is typically quantified for climate periods or single events. To provide an overview of how surface conditions shape land-atmosphere (LA) coupling, this study ~~investigates~~ evaluates the interannual variability of LA coupling strength for selected warm summer seasons~~s~~ between ~~2003~~1991-2022 over Central Europe~~-~~ by means of ERA5 data.

Especially the drought summer seasons 2003, 2018, and 2022 were particularly distinctive in respect to ~~can be~~

15   ~~identified by~~ the changing soil moisture-atmosphere coupling pattern which ~~in turn~~ leads~~ing~~ 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 ~~on~~average and a heavy rain event occurred during July, resulting in high moisture availability ~~leading to~~and a change in the LA ~~feedback~~ coupling strength. The results obtained with respect to LA coupling strength reflect a shift in the coupling relationships toward reinforced heating

20   and drying by the land surface under heatwave and drought conditions, whose frequency is increasing with ongoing climate change.

1 Introduction

In the last decades, Europe experienced severe drought periods and heatwaves (WMO, 2015; C3S, 2018; Markonis et al., 2021; WMO, 2022a) ~~where~~ with 2022 ~~was~~ being the hottest summer ever recorded over Europe (WMO,

25   2022a). Precipitation exhibited a strong dry anomaly during summer over Central Europe in 2003, 2018 and 2022 (WMO, 2004, 2018; C3S, 2018; WMO, 2022b; Spensberger et al., 2020). At the same time, the soil experienced an exceptional dryness in the uppermost 25 cm (Boeing et al., 2022; Rakovec et al., 2022) as shown by the soil moisture index developed by Zink et al. (2016). This was also shown by Rousi et al. (2023) ~~-~~and Dirmeyer et al. (2021) for 2018, who suggest that these extreme conditions will be more likely under climate change conditions

30   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. Rousi et al. (2022) identified Europe as a heatwave hot spot where heat waves are three to four times more likely than in other areas of the midlatitudes due to the occurrence of a double-jet stream configuration associated with atmospheric blocking conditions ~~situations~~ (Kornhuber et al., 2017). ~~According to~~ Rousi et al. (2022) ~~the frequency of the occurrence of heat waves is accelerating over Europe in the~~

35   ~~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 (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)~~.~~

Land-atmosphere (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 characteristics ~~condition~~ of the land surface (e.g., vegetation, soil moisture) (Findell and Eltahir, 2003b; Koster et al., 2004; Dirmeyer, 2011; Guo et al., 2006). In the context of extremes, LA coupling ~~it~~ was identified as a driver

45   and intensifier for the duration and intensity of heat waves 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 a self-propagating mechanism of droughts. Meteorological droughts intensify due to increased water vapor deficit (VPD) inside the PBL which feeds back into an intensified depletion of surface moisture reservoirs. One of these reservoirs is soil moisture, which plays a key role for the climate due to its influence on the

50   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 (stomatal resistance, leaf area index (LAI) and rooting depth) (Miralles et al., 2019; Warrach-Sagi et al., 2022). In consequence of spatial and temporal variability in these influencing factors, LA ~~feedback~~ coupling often shows regional, but also temporal

55   variations, especially under climate change conditions (Seneviratne et al., 2006; Denissen et al., 2022; Jach et al., 2022).

Knist et al. (2017) investigated the long-term average relationship between root zone soil moisture and surface fluxes by means of different regional climate model (RCM) simulations for the period 1989-2008 for the European summer seasons. They identified a coupling hot spot region for the surface coupling of sensible and latent heat

60   fluxes and latent heat flux and ~~2-m~~2m temperature in South Europe while a transition zone is present over larger parts of Central Europe. Jach et al. (2022) 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

65   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 (Findell and Eltahir, 2003a, 2003b). The combination of CTP and HI$_{low}$ allows for a determination whether convection is likely to occur (see Fig. 15 of Findell and Eltahir, 2003a). Jach et al. (2022) 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

70   by a temperature increase.

Warrach-Sagi et al. (2022) evaluated the atmospheric coupling index (ACI; Guo et al., 2006; Dirmeyer, 2011) using an RCM and found a strong sensitivity between sensible heat flux and CAPE during the growing season 2005 over South Germany while Leutwyler et al. (2021) found a strong soil moisture – precipitation feedback over Central Europe during the summer seasons 1999-2008.

75   Several studies investigated the relation of soil moisture with recent European heat waves and droughts. Hauser et al. (2016) found that a soil moisture-temperature feedback was~~, among a wave train~~ (Di Capua et al., 2021)~~,~~ a key driver for the severe heat wave over Siberia in 2010, while Dirmeyer et al. (2021) and Orth (2021) found that it was a key driver for the European heatwave in 2018. García-Herrera et al. (2010) found that a strong soil moisture

deficit was also one of the key drivers for the 2003 European heat wave. The study of Miralles et al. (2014) suggests
that the heatwaves over Europe in 2003 and over Russia in 2010 were enhanced by a persistent large scale weather
pattern associated with a strong soil moisture decay. The analysis of Dirmeyer et al. (2021) for the 2018 European
heatwave revealed enhanced soil moisture – near-surface ~~feedback~~ coupling under drought conditions. The
exceptionally low soil moisture limited evapotranspiration and thus amplified the heat wave due to reduced
evaporative cooling (Santanello et al., 2018). This led to one of the most severe heatwaves over Europe since 1979
(Becker et al., 2022). Wehrli et al. (2019) found that soil moisture and the large scale weather pattern are equally
important for the duration and intensity of heatwaves around the globe. According to Ossó et al. (2022), Europe
already faced an increase in climate extremes since 2000 and will remain a hot spot for severe droughts (Huebener
et al., 2017; van der Wiel et al., 2022) impacting not only summer's crop yields (Toreti et al., 2022) but also
affecting the generation of renewable energy.

~~The preceding paragraph describes s~~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. Guo and
Dirmeyer (2013) also found interannual variability in soil moisture-precipitation coupling in consequence of
~~different~~ diverging soil moisture availability. Additionally, the critical soil moisture thresholds (Dirmeyer et al.,
2021; Rousi et al., 2023) suggest not only an intensification of the heat and drought conditions by LA coupling
over Europe but also a strengthening of the coupling itself. ~~However, a quantification of temporal variability in
different coupling relationships, as well as understanding of the impact of the variability remain lacking, as LA
coupling strength was barely investigated over Europe, and particularly on other time scales than climate periods,
so far.~~

However, a quantification of the temporal variability in different coupling relationships and the associated impacts
of the variability still lack, as LA coupling strength on other time scales than climate periods has been barely
investigated over Central Europe so far. The same applies to shifts between coupling regimes due to variability in
the climatic conditions.

In this study, we therefore assess the ~~temporal~~ variability of LA coupling of selected European summer seasons
~~2003~~1991-2022 ~~on the interannual time scale~~ in dependence on temperature, soil moisture, precipitation and large-
scale weather pattern by applying data from the fifth generation European Centre for Medium Range Weather
Forecasting (ECMWF) atmospheric reanalysis (ERA5; Hersbach et al., 2020).

The paper is structured as follows: Section 2 describes the applied data sets, ~~selected~~and -coupling indices. ~~and the
classification of the summer seasons .~~ Section 3 describes the interannual variability of meteorological variables,
the meteorological situation of the summer seasons chosen for evaluation ~~large-scale weather pattern and
anomalies of 500 hPa geopotential, 2 m temperatures, precipitation, and soil moisture~~ followed by the LA
coupling analysis ~~in section 4~~. Section 4~~5~~ discusses our results while section 5~~6~~ summarizes our work and provides
an outlook on potential future research.

2 Material and Methods

2.1 Datasets

For the analysis of the LA ~~feedback~~ coupling~~regions~~, ~~the fifth generation European Centre for Medium Range
Weather Forecasting (ECMWF) atmospheric reanalysis (~~ERA5~~;~~ Hersbach et al., 2020~~)~~ 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° ~

120 ~~30 km and includes the assimilation of observations~~. 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.,

125 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 ~~from~~ between 1995-

2019 and does neither make use of a sophisticated data assimilation scheme nor of an ensemble approach. The

130 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

135 variables required for studying land-atmosphere coupling and therefore were not considered in this study to avoid

mixing different models for the investigation of the coupling chain. ~~To summarize, ERA5 data deliver the required~~

~~3D data to apply LA feedback metrics that combine the variables of our study.~~

~~Following the World Meteorological Organization's (WMO) recommendation to adjust the climate normal period~~

(WMO, 2017)~~, the summer seasons of 1991-2020 serve as reference period for the calculation of anomalies. The~~

140 ~~investigation period covers the summer seasons between 1991-2022 over an area between 5°W-25°E and 40°N-~~

~~60°N (see Fig. 1). Reasons to choose very recent summers were, among others, that the first half of summer 2021~~

~~was very warm and dry while an extreme precipitation event~~ (Mohr et al., 2023) ~~led to a sudden increase in soil~~

~~moisture over France, Benelux, and West Germany. Summer 2022 was the hottest summer seasons ever recorded~~

~~over Europe associated with a west-east soil moisture anomaly pattern~~ (C3S, 2023). ~~Overall, both recent summers~~

145 ~~reflect the climate change trend over Europe.~~

To categorize the summer seasons during 1991-2022, ~~this period into warm and wet, warm and dry, and cold~~

~~summer seasons,~~ seasonal mean anomalies of ~~2 m~~ 2m temperatures and precipitation from ERA5 ~~and~~ as well as

precipitation from the ENSEMBLES daily gridded observational dataset for precipitation (E-OBS; Cornes et al.,

2018) version V26.0e were calculated.

150 ~~To complement our analysis, seasonal mean anomalies of 500 hPa geopotential~~ (Lhotka and Kyselý, 2022) ~~and~~

~~volumetric root zone soil moisture were calculated from ERA5.~~

~~All anomalies were calculated using the Climate Data Operators (CDO) version 2.0.5~~ (Schulzweida, 2022).

2.2 LA coupling indices

In our study we apply a subset of the statistical LA ~~feedback~~ coupling metrics framework, namely the terrestrial

155 coupling index (TCI) and atmospheric coupling index (ACI) (Guo et al., 2006; Dirmeyer, 2011; Santanello et al.,

2018). ~~, described in~~ Guo et al. (2006)~~,~~ Dirmeyer (2011)~~, and~~ Santanello et al. (2018). Additionally, the correlation

between surface sensible heat flux (SH) and surface latent heat flux (LH) is calculated. To ~~calculate~~ 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).

160 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 the surface, ~~surface latent and sensible heat fluxes (~~LH and SH~~)~~, CAPE, and PBL height (PBLH). In addition, we used the height of the lifted condensation level ~~height~~ (HLCL) and the lifted condensation ~~height~~ level deficit (LCL deficit), defined as difference between HLCL and PBLH. As HLCL was not available from ERA5, we used the approach from Georgakakos and Bras (1984) and

165 Bolton (1980) which is based on surface pressure, ~~2 m~~2m temperature, and ~~2 m~~2m dewpoint to derive HLCL which is also applied in Dirmeyer et al. (2014):

$$\text{HLCL} = \frac{R_d \, T_V}{g} * \log \frac{P_{SFC}}{P_{LCL}} \tag{1}$$

~~.~~

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 (hPa).

170 The strength of soil moisture-latent heat flux coupling (TCI $_{\eta\text{-LH}}$)~~the TCI~~ between η and LH ~~(Eq. 1)~~ is defined as

$$\sout{TCI}TCI_{\eta-LH} = \sigma(\eta) \frac{dLH}{d\eta} \tag{\sout{1}2}$$

where $dLH/d\eta$ is the slope of the linear regression ~~between the surface latent heat flux (LH) and the root zone soil moisture η~~ as described in Santanello et al. (2018)~~),~~ and σ(η) describes the standard deviation of root zone soil

175 moisture~~.~~ Equation (2~~1~~) ~~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~~soil moisture~~ can, e.g., be substituted by surface fluxes in Eq. 2~~1~~ while LH in Eq. 2 can be substituted by PBLH~~the planetary boundary layer height,~~ 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$_{LH\text{-HLCL}}$):

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

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

180

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). ~~as e.g., the surface latent heat fluxes during night-time becomes close to zero with very little variations during this time. Also, during night-time, PBLH collapses to small values and stays often constant which has a detrimental~~

185 ~~impact on the LA-feedback analysis.~~ Water grid cells are not considered in our evaluation.

~~2.3 Classification of summer seasons. Summer 2022 was the hottest summer seasons ever recorded over Europe associated with a west-east soil moisture anomaly pattern~~ (C3S, 2023)~~.~~

~~For the classification of the summer seasons with respect to temperature (Table 1), we calculated the spatial median~~

190 ~~of the 2 m temperature anomalies from ERA5 with respect to the summer mean 1991-2020 over Europe. If the 2 m temperature anomaly is larger than 0.5°C, the corresponding summer season is used for our analysis. For the~~

classification only land grid cells between 40°N-60°N and 5°W-25°E were considered. All anomalies were calculated using the Climate Data Operators (CDO) version 2.0.5 (Schulzweida, 2022).

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 temperature anomaly larger than 0.5°C with respect to the climatological mean 1991-2020. As a reference, the median precipitation anomaly from E-OBS (2ⁿᵈ row) and ERA5 (3ʳᵈ row) is given.

Although the median 2-m temperature anomaly for 2020 was only 0.4 K, it is considered in our analysis as this was the only summer with a moderate positive precipitation bias in the last decade. The warm and dry summer seasons became the prevailing situation since 2015. A strong reduction in annual and seasonal precipitation, combined with a reduced atmospheric water availability led to a constant decline of the root zone soil moisture and thus an agricultural drought which was the case, e.g., in 2018-2020 over. **3 Results**

3 Summer season anomaly maps

The following section describes 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 η ,as well as observed and ERA5 simulated precipitation. **3.1 Interannual variability of summer seasons 1991-2022**

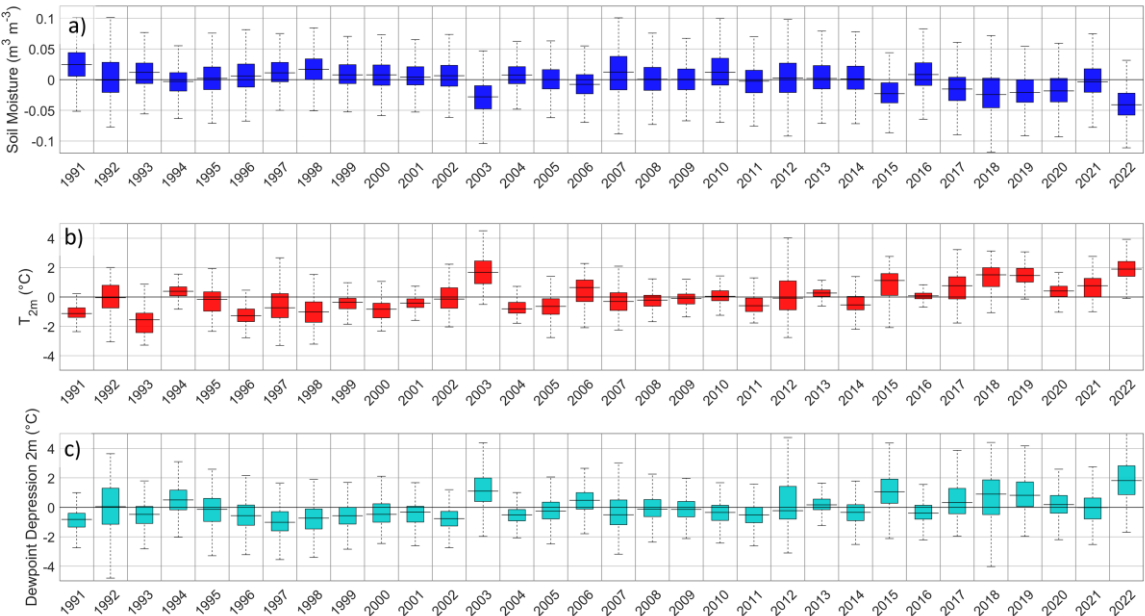



Figure 1. Interannual variability of anomalies of root zone soil moisture η (a), 2m temperature (b), and dewpoint depression (c) for the summer seasons between 1991-2022. The data are averaged over land grid cells in the region between 40°N-60°N and 5°W-25°E.

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.

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 (Huebener et al., 2017; Rousi et al., 2022).

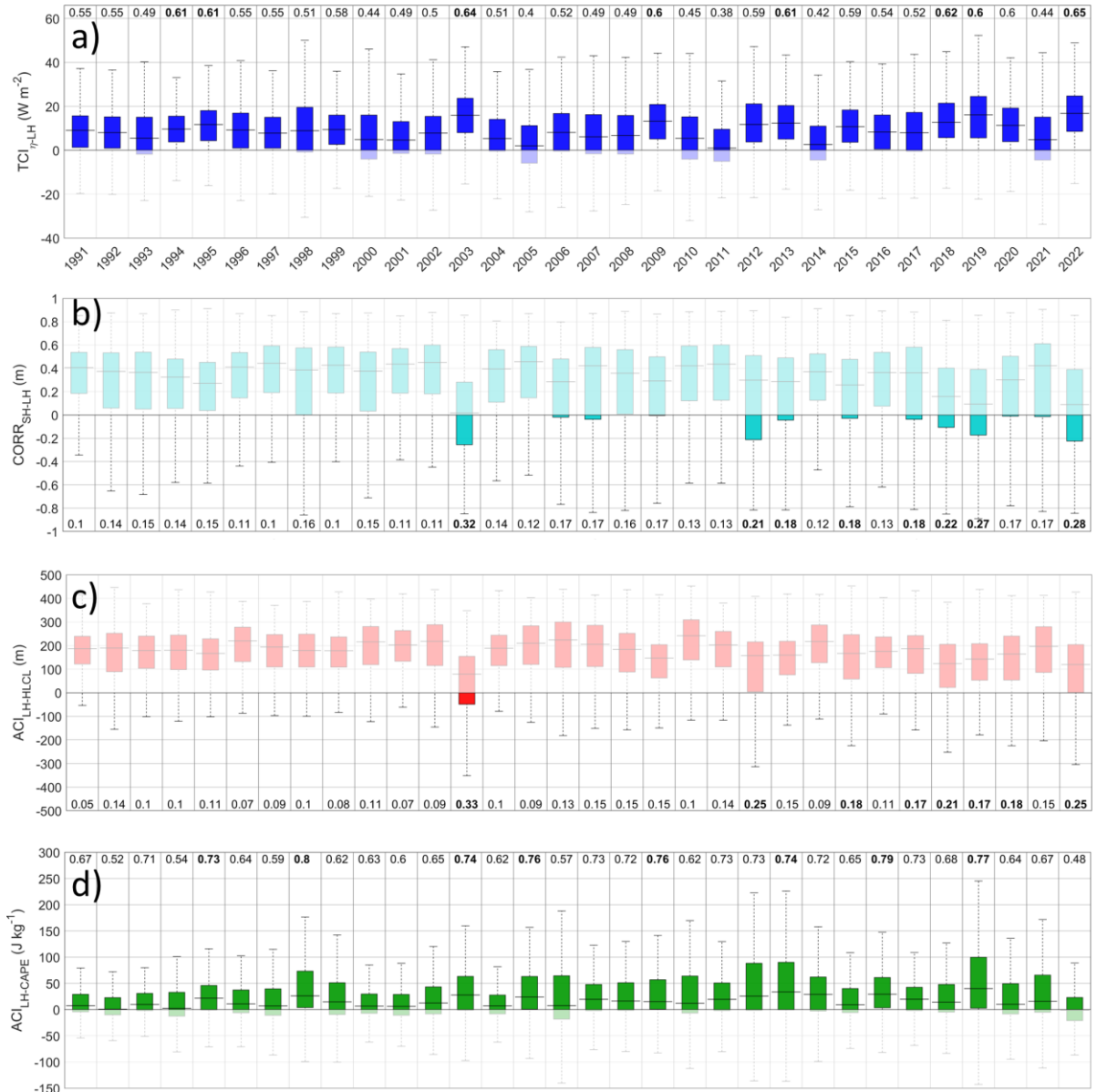



Figure 2. Interannual variability of the coupling indices $TCI_{\eta\text{-}LH}$ (a), correlation SH-LH (b), $ACI_{LH\text{-}HLCL}$ (c), and $ACI_{LH\text{-}HLCL}$ (d) for the summer seasons 1991-2022. The bold-faced numbers indicate the fraction of grid cells exceeding the 75th percentile of the respective index. 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 land grid cells in the region between 40°N-60°N and 5°W-25°E.

Figure 2 shows the interannual variability of the correlation between SH and LH, and the coupling indices $TCI_{\eta\text{-}LH}$, $ACI_{LH\text{-}CAPE}$, and $ACI_{LH\text{-}HLCL}$ during the summer seasons 1991-2022. The correlation between SH and LH during the different summer seasons is mostly positive (Fig. 2b), however there are few exceptions for the very warm summer seasons 2003, 2018, 2019, and 2022 where the median of the correlation is less than 0.2 and the number of grid cells with negative correlations is increased. The 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 $ACI_{LH\text{-}HLCL}$ (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 the warm and dry years a trend of $ACI_{LH\text{-}HLCL}$ approaching values around or below zero is evident. For the $ACI_{LH\text{-}CAPE}$ (Fig. 2d) no clear trend for an increase or decrease can be 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 $ACI_{LH\text{-}CAPE}$ where 78 % of the grid cells exceed the 75th percentile.

Based on the interannual variabilities shown in Figs 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 (Forster et al., 2023). All anomalies were calculated using the Climate Data Operators (CDO) version 2.0.5 (Schulzweida, 2022).

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 temperature anomaly larger than 0.5°C with respect to the climatological summer mean 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 water availability that led to a constant decline of the root zone soil moisture and, thus, to an agricultural drought. Although the median 2m temperature anomaly for summer 2020 was only 0.4 °C, it is considered in our analysis as this was the only summer with a moderate observed positive precipitation bias since 2015.

3.2 Meteorological situation of the selected summer seasons

This subchapter describes the synoptic conditions during each of the previously selected 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.

3.1 500 hPa geopotential3.2.1 500 hPa geopotential

Figure 31 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 Thethe investigated summer seasons are in general characterized by strong positive 500 hPa geopotential anomalies over major 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.

However, summer 2015 and 2020 are exceptions. 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 (bottom right panel in Fig. 1).

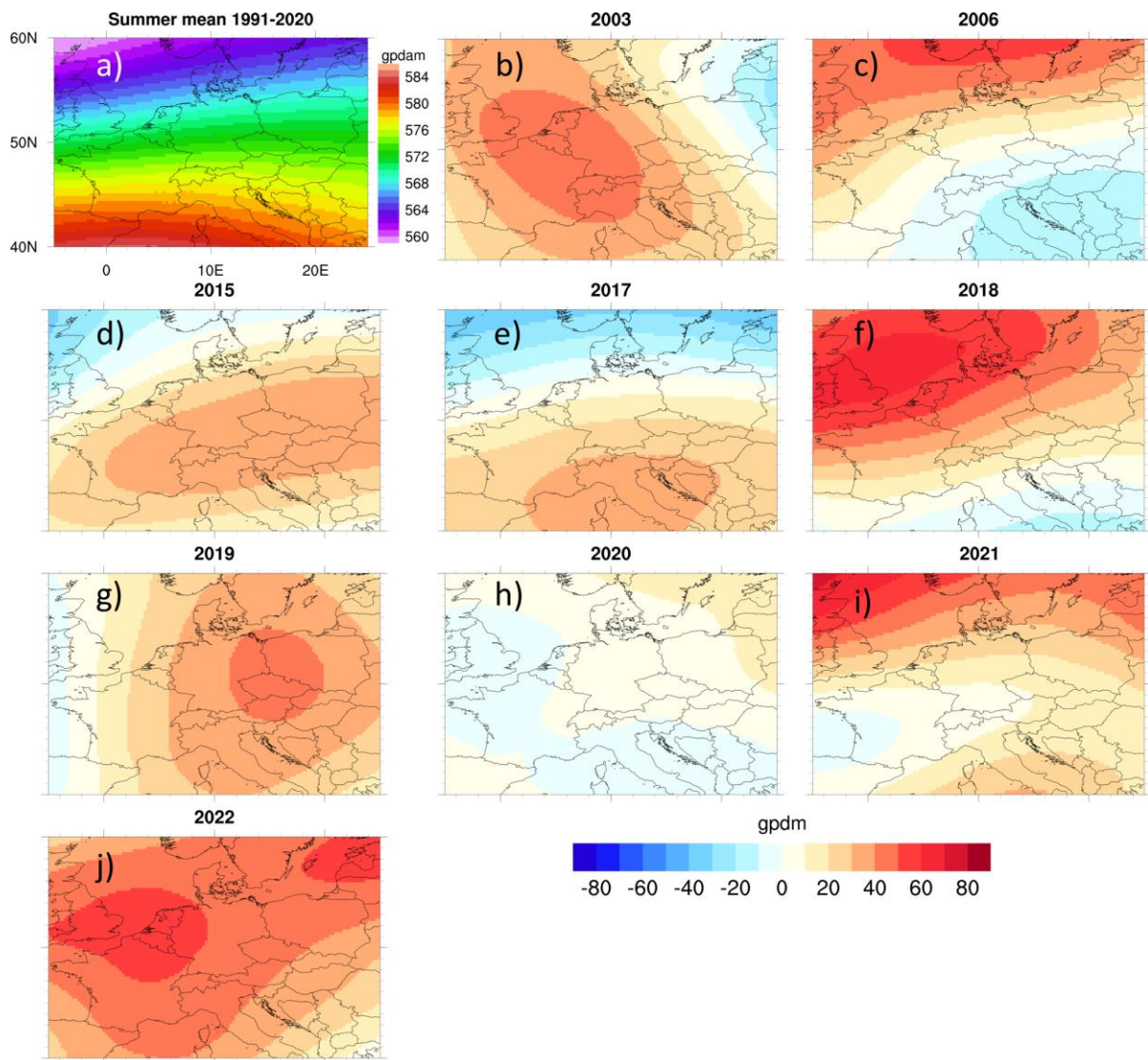
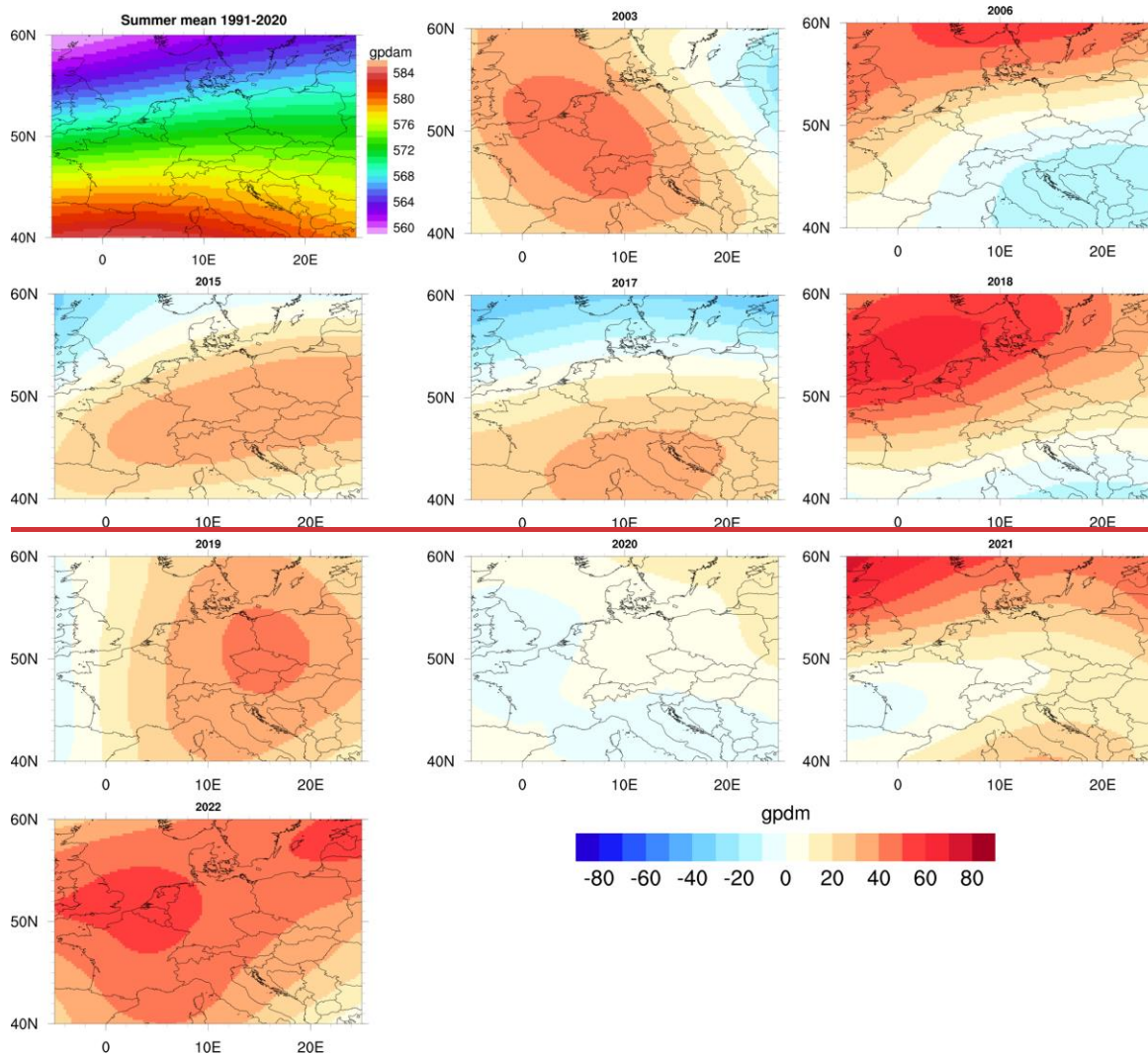



Figure 3~~1~~. ERA5 500hPa geopotential anomalies [gpdm] for the selected summer seasons. ~~(Table 1).~~ The top left panel shows the mean summer 500 hPa geopotential 1991-2020 ~~from ERA5~~.

265   ~~3.2 Surface temperature~~**3.2.2 Near surface temperature**

The positive 500 hPa geopotential anomalies shown in Fig. 3~~1~~ are ~~generally~~ associated with positive ~~2 m~~2m temperature anomalies. ~~T~~the highest ~~2 m~~2m temperature anomalies were observed~~present in~~ during the summers 2003, 2018, 2019, and 2022 (Fig. 4~~2~~b, f, g, j) and were spatially associated ~~which is associated~~ with strong positive geopotential anomalies over Central Europe. ~~2022 was the hottest summer ever recorded so far~~ (C3S, 2023)~~.~~

270   During summer 2006, the ~~2 m~~2m temperature anomalies are highest north of 51°N while ~~in~~during the summer seasons 2015 and 2017, the highest temperature anomalies were observed south of 50°N. ~~as~~ This coincides with the fact that maximum positive geopotential anomaly is ~~shifted~~ observed south of 51°N ~~to the north and south, respectively~~(Fig. 3d, e). Summer 2020 shows positive temperature anomalies over a wide area of our ~~investigation~~ study domain~~.,~~ ~~H~~however, the 500 hPa anomalies were very moderate indicating ~~pointing towards~~ a constant flow

275   of cooler ~~warm~~ and moist airmasses from the West ~~towards~~ 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.

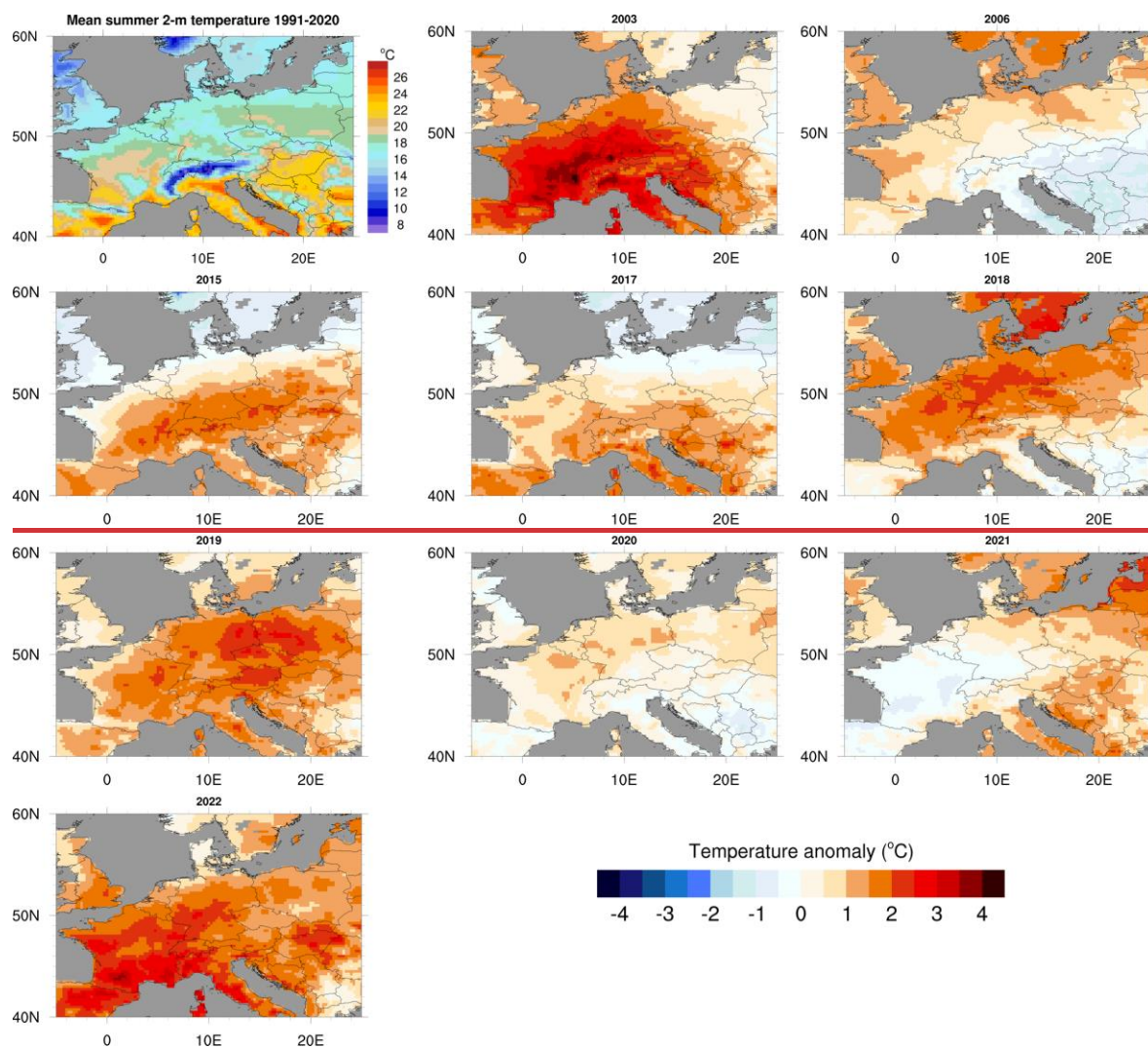
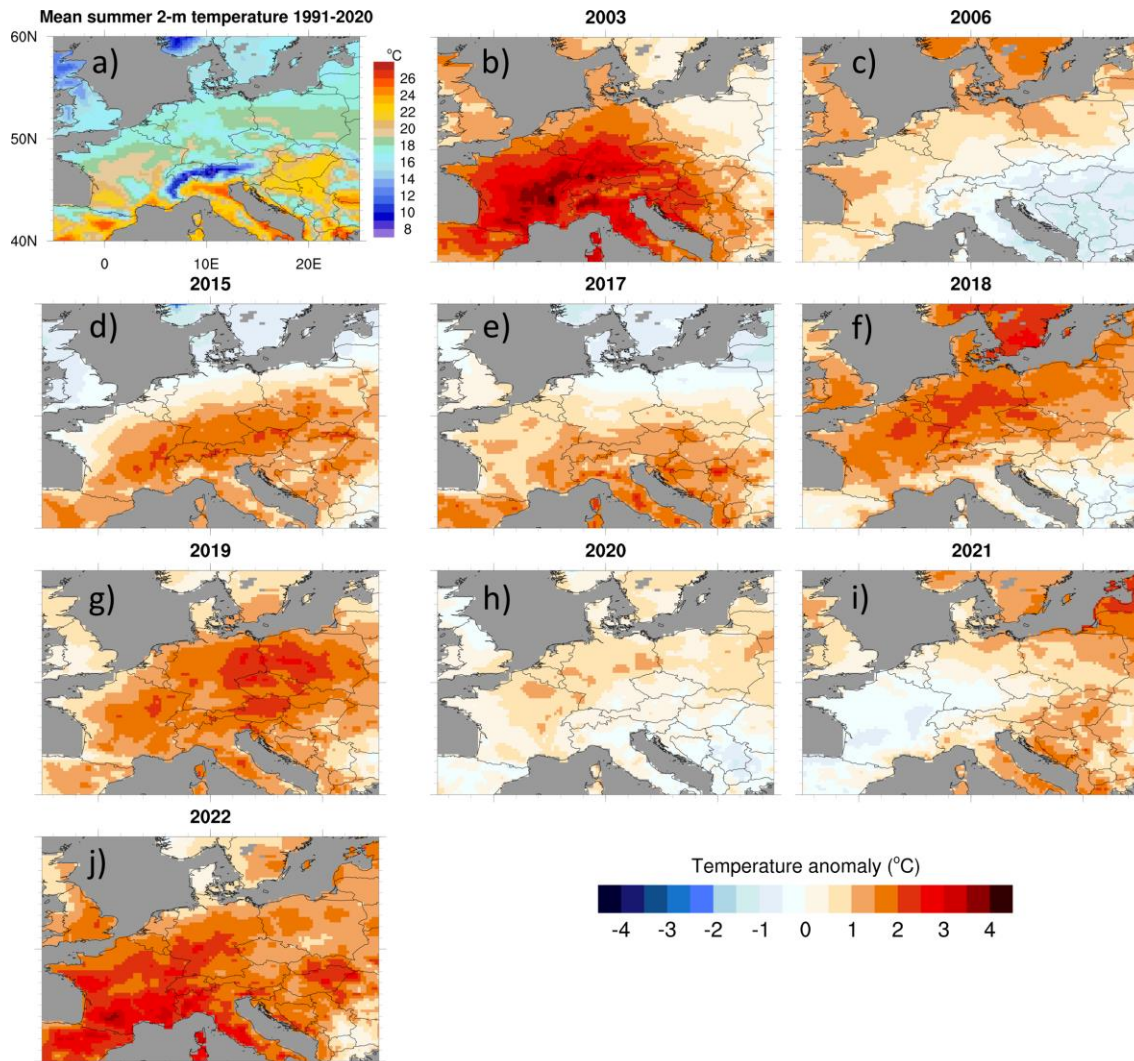



Figure 42. ERA5 2 m2m temperature anomalies [°C]. The top left panel shows the mean summer 2 m2m temperatures 1991-2020 from ERA5.

3.2.3 Precipitation

3.3 Precipitation

Observed pPrecipitation (Fig. 53 and Table 1) is often well below the climatological average 1991-2020except for 2006 and 2021. The summer seasons 2003, 2018, 2019 and 2022 were exceptionally dry (Rousi et al., 2023; Rousi et al., 2022) with a median precipitation anomaly between -34 mm and -63 mm. These extreme anomalies are also seen in the precipitation anomalies derived from ERA5 (Fig. 64) which reasonably catches these dry periods (Lavers et al., 2022). With respect to precipitation derived from E-OBS, 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. 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. Although temperatures in 2021 were well above the climatological average 1991-2020.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) (Fig 3). This event was also simulated by ERA5 as indicated by the dark teal colors in Fig. 64j.

295 ~~A statistical evaluation revealed correlations between -0.25 and -0.65 between precipitation and temperature during the summer seasons presented here indicating a precipitation dry bias in case of strong positive temperature anomalies.~~

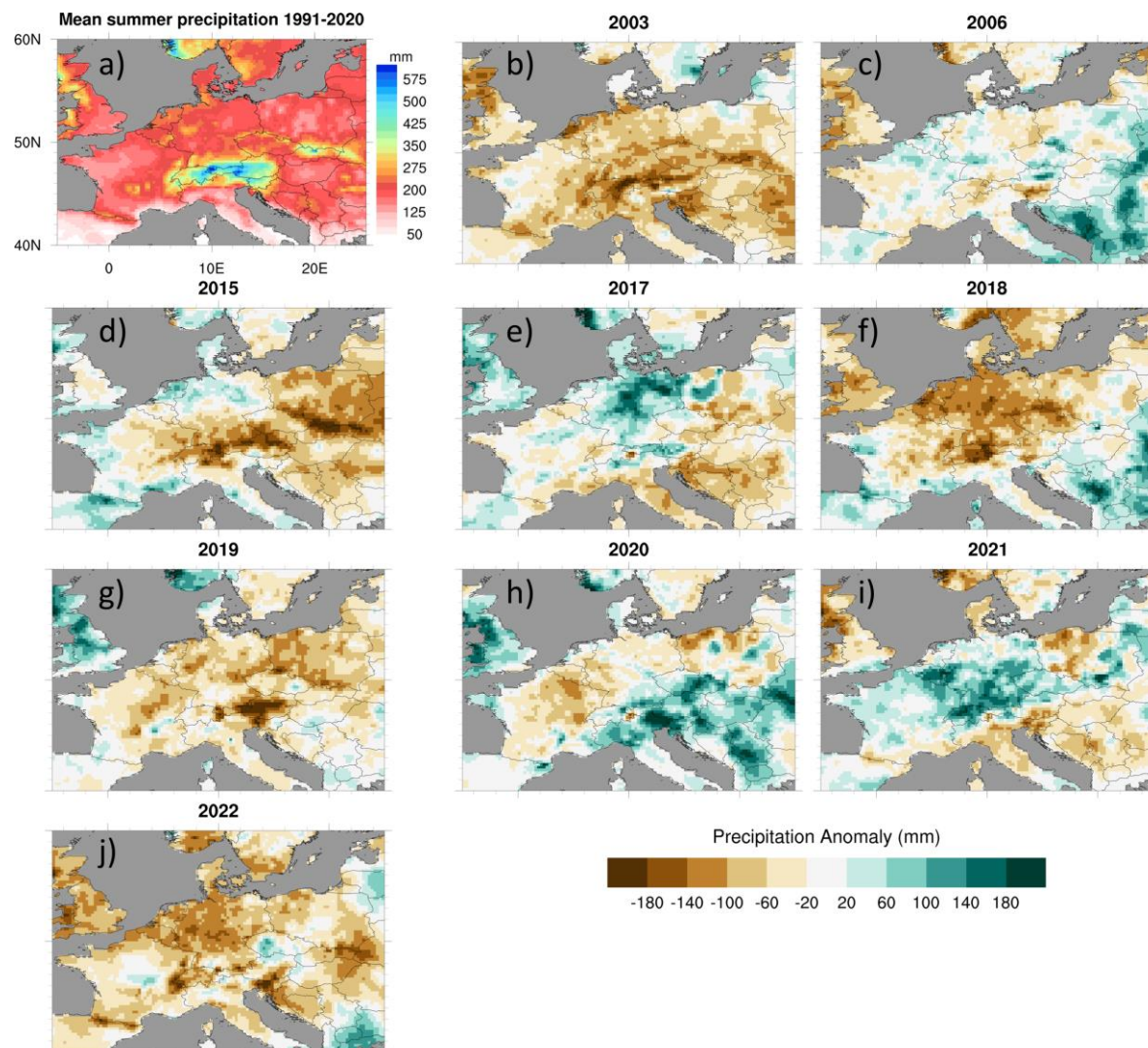



Figure 5. E-OBS precipitation anomalies [mm] for the selected summer seasons. The top left panel denotes the mean summer precipitation 1991-2020.

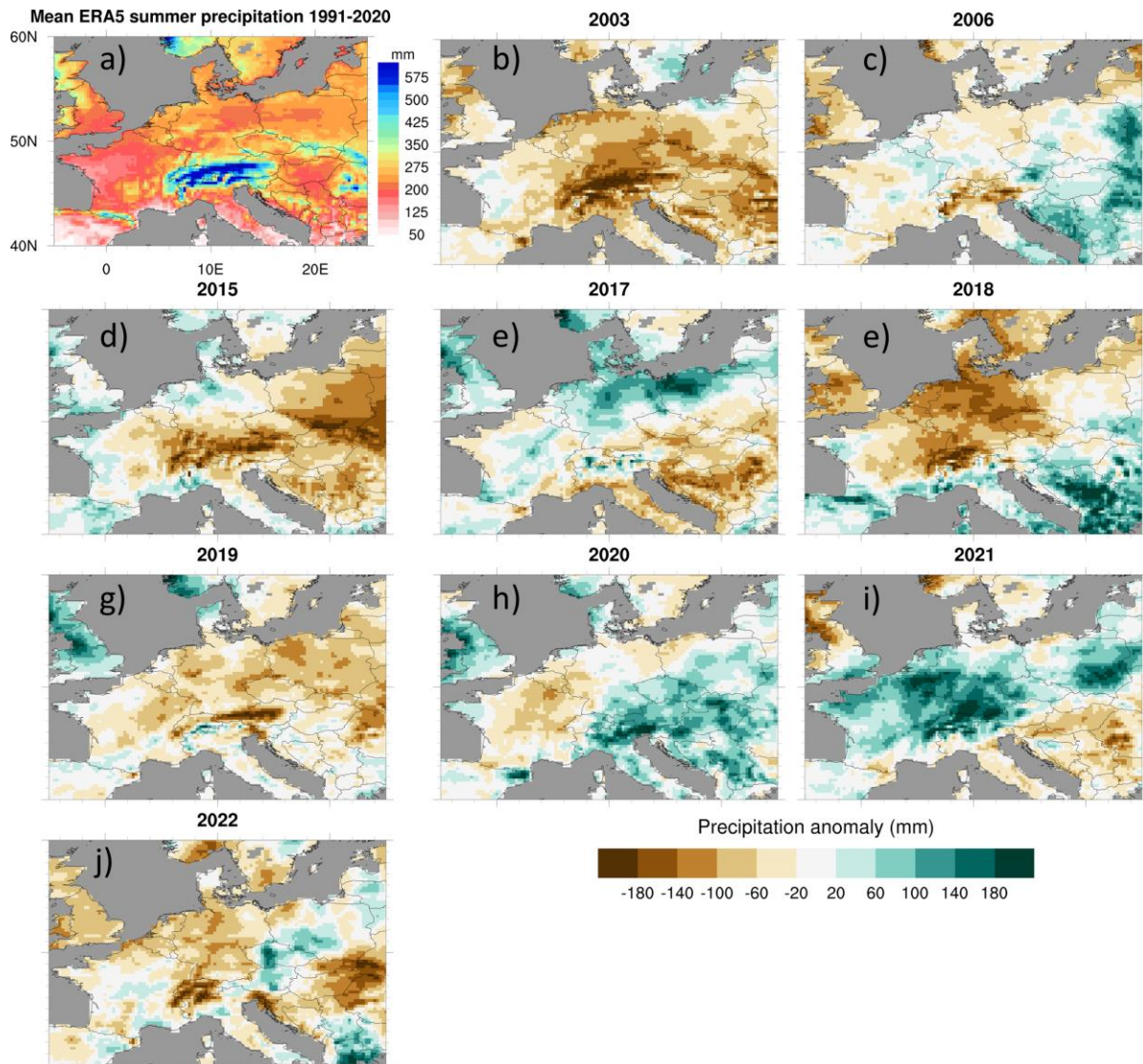



Figure 6. Same as Fig. 5 but for ERA5.

3.2.4 Soil moisture

~~3.4 Root zone soil moisture~~

Figure 7~~5~~ displays the ERA5 derived root zone soil moisture anomalies. The summer seasons ~~Here~~ 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 ~~(see. 3.2)~~ and the precipitation dry bias shown both by E-OBS and ERA5 ~~(see. 3.1). Interestingly, although 2019 was also among of the warmest and driest summers, the soil moisture dry bias is less pronounced as in the other three years pointing towards a higher soil moisture content during spring (Fig. S2). 2021 shows strong positive soil moisture anomaly over Benelux and Germany which was related to colder than average April and May 2021~~ (C3S, 2022)~~.~~ An evaluation of ~~By using~~ the median of the soil moisture anomalies over Central Europe revealed~~,~~ that summer 2006 ~~largely~~ 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 ~~while 2015 and~~ 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).on average show moderate dry soil anomalies. Interestingly, although summer 2019 was also among of the warmest and driest summers, the soil moisture dry bias is less pronounced as in the other three yearshot and
315   dry summer seasons 2003, 2018, and 2022 pointingrelated towards a higher soil moisture content during spring (Fig. S2f). 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 anomaliesy 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).

320

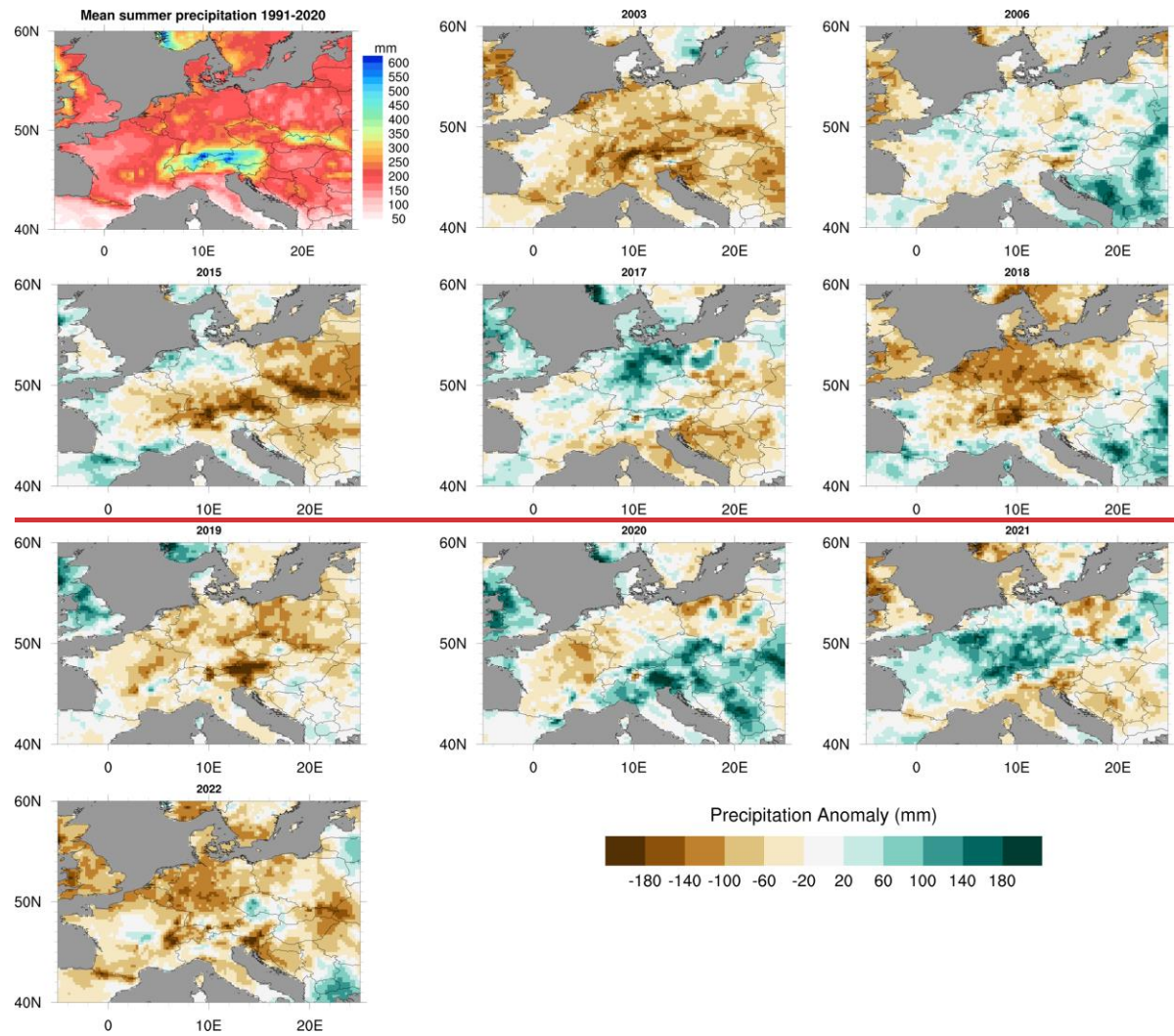



Figure 3. E-OBS precipitation anomalies for the selected summer seasons. The top left panel denotes the mean summer precipitation 1991-2020.

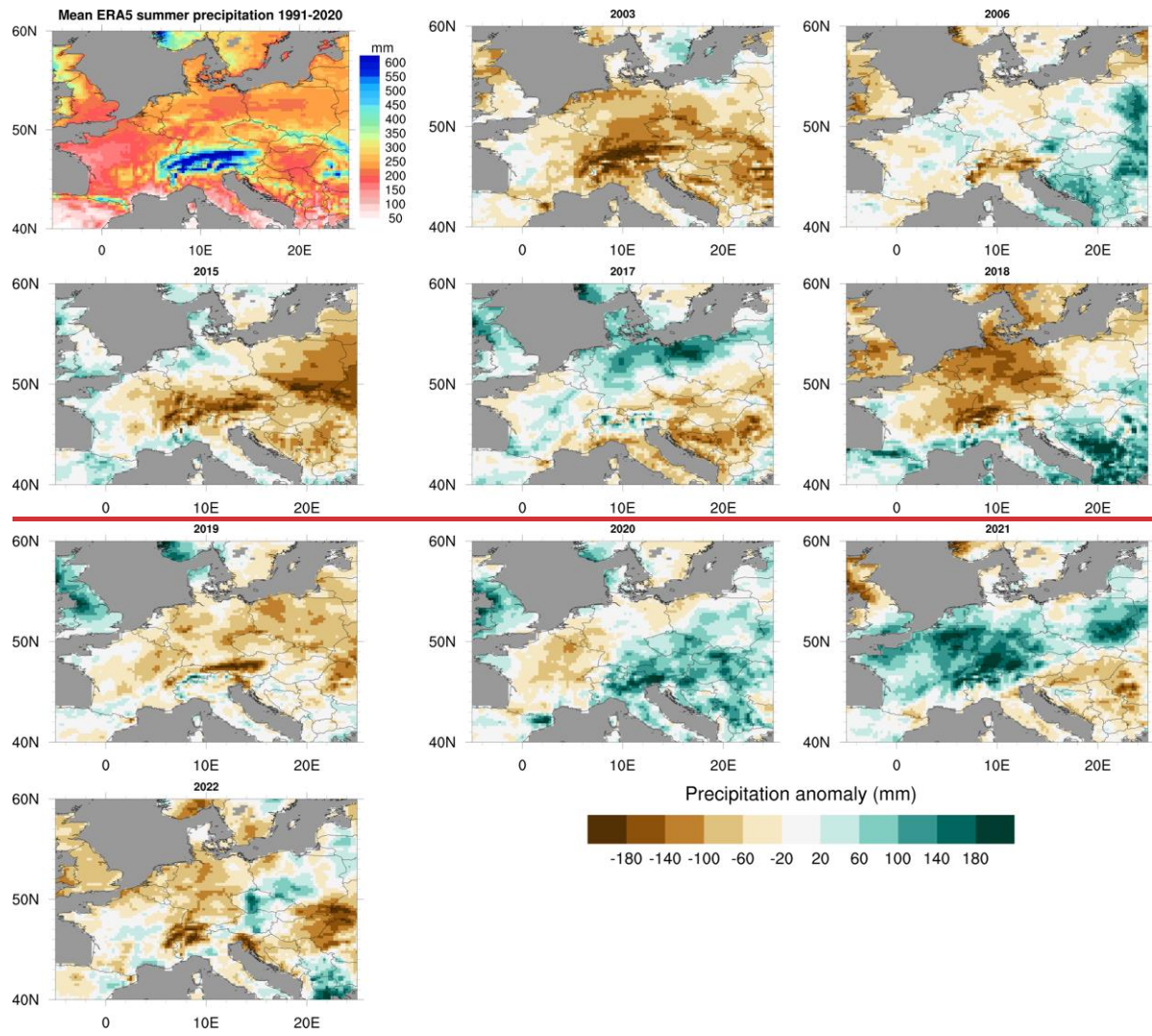



Figure 4. Same as Fig. 3 but for ERA5.

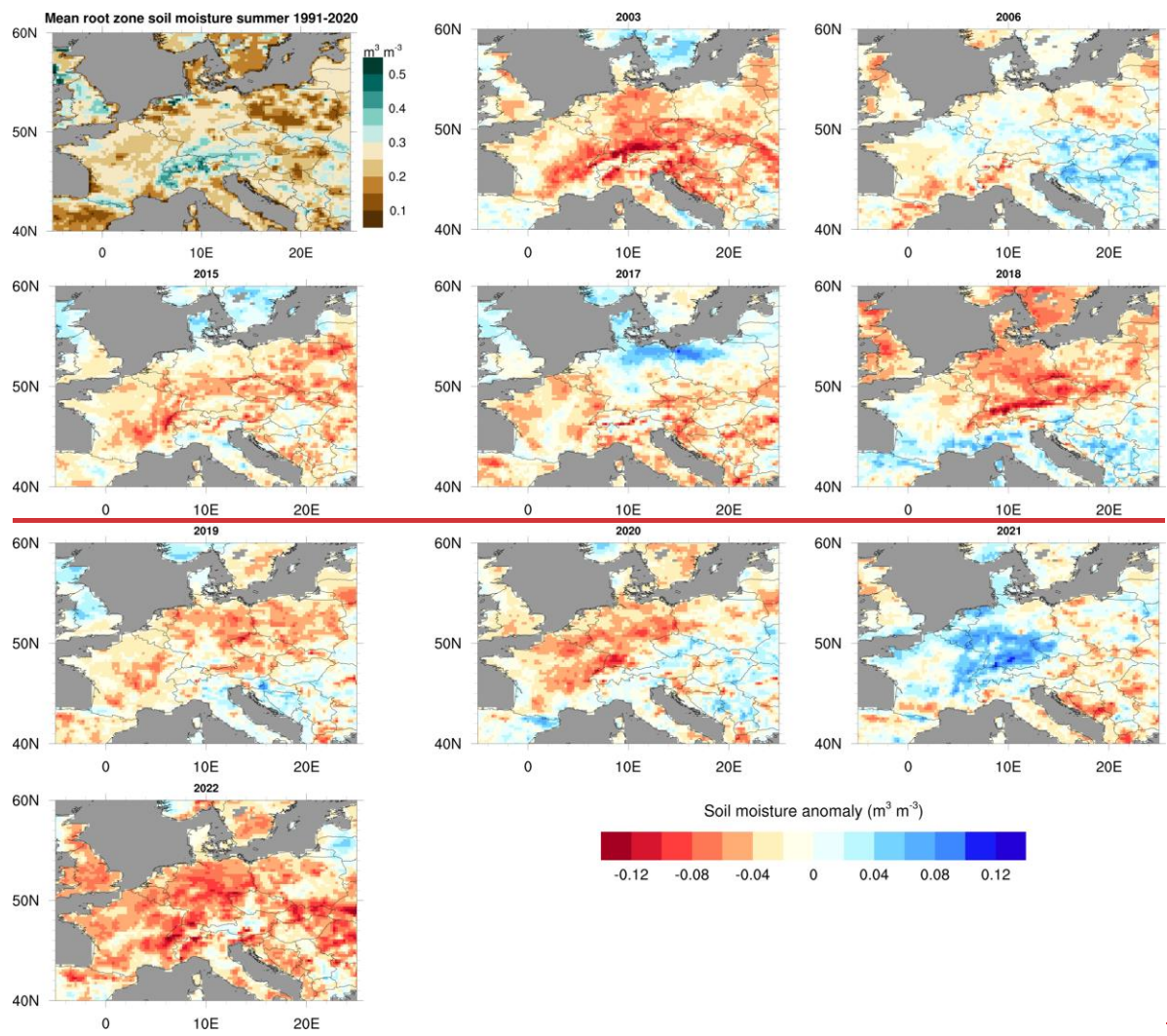
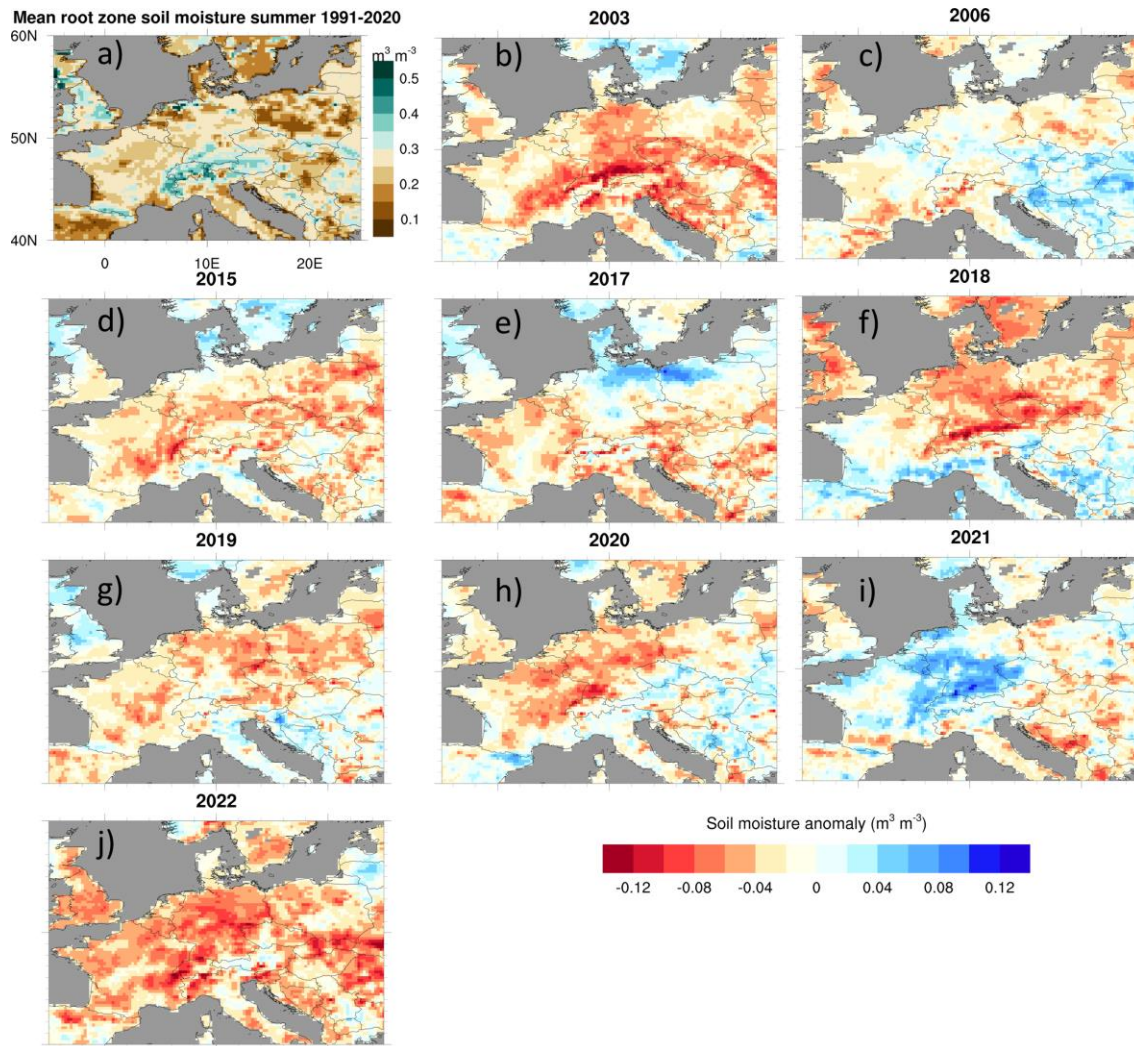



Figure 7~~5~~. ERA5 soil moisture anomalies [m³ m⁻³] ~~with respect to 1991-2020~~ for the selected summer seasons. The top left panel denotes the summer mean root zone soil moisture 1991-2020 from ERA5.

3.2.5 Categorization of evaluated warm summer seasons

Although all years showed that most of the cells faced a considerable warm anomaly, the years diverge in the spatial patterns and the spatial extent of warm or cool as well as moist or dry anomalies. By visual examination it is possible to identify three groups within the hot years. Firstly, 2003, 2015, 2018, 2019, and 2022 stand out the most. They are characterized by large temperature anomalies, dry anomalies in soil moisture and precipitation extent over 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 on daytime means computed for the period 06 UTC and 18 UTC of each day (Yin et al., 2023)

Figure 8 shows the $TCI_{\eta\text{-}LH}$ of all warm 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 $TCI_{\eta\text{-}LH}$ over the regions affected by low soil moisture (Germany, France, and Benelux; Fig. 7a,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 both years a switch in the sign of the index occurs. The neutral to negative values indicate the availability of sufficient soil moisture (Fig. 7), which in turn suggests a decoupling of the LH flux variation from soil moisture variation in these regions and years (compare Fig. 6 and 7).

During 2021, when a positive η anomaly is observed over Germany, Benelux, eastern France (Fig. 7h), the $TCI_{\eta\text{-}LH}$ becomes moderately negative in these regions with values of about -20 W m^{-2} (Fig. 8h). This can be explained by a moist spring season (Fig. S2i) 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). A similar behavior of the $TCI_{\eta\text{-}LH}$ is observed during the two cold and wet summer seasons (not shown).

During the moderate summers 2006 and 2020, the $TCI_{\eta\text{-}LH}$ 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 $TCI_{\eta\text{-}LH}$ gets slightly negative.

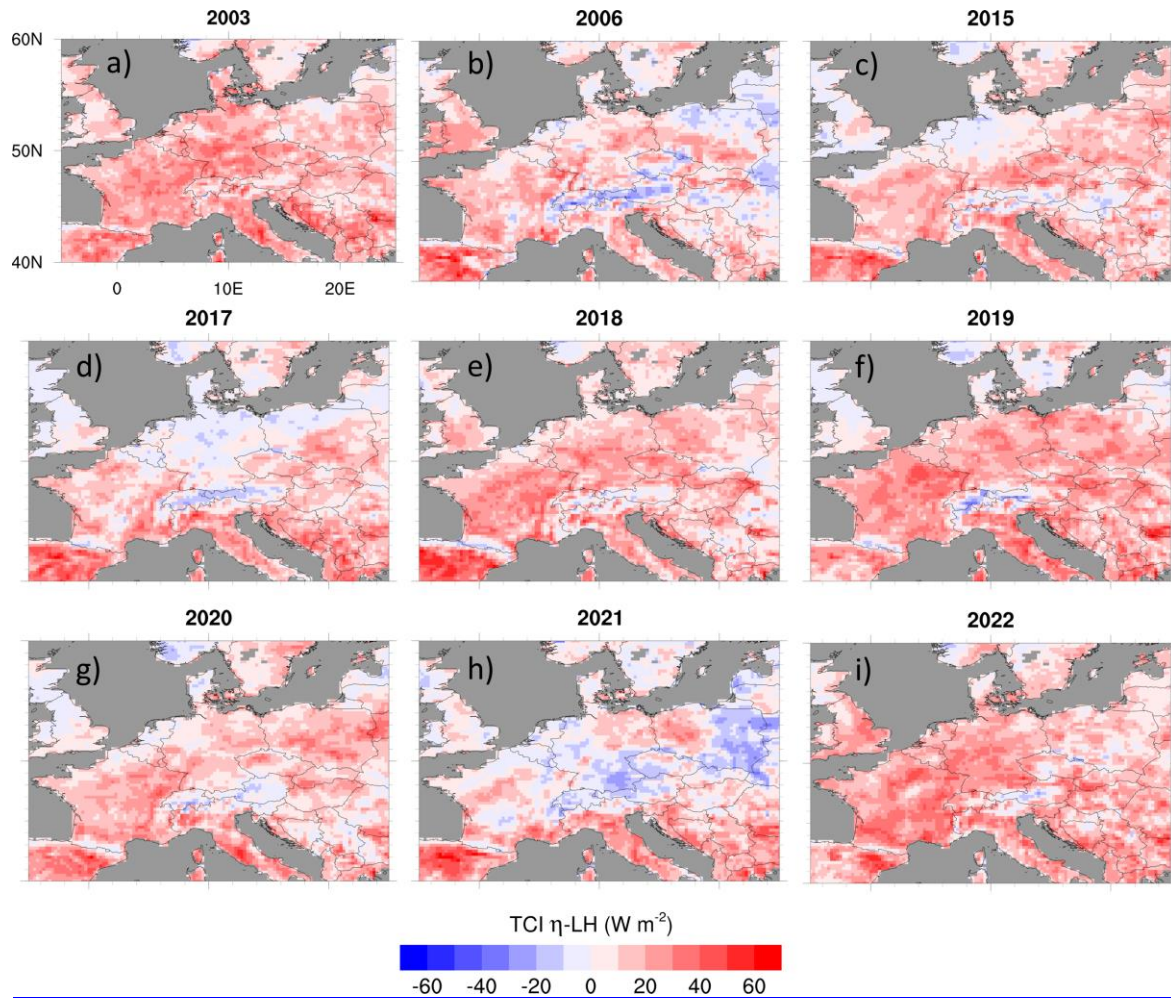



Figure 8. ERA5 based Terrestrial Coupling Index TCI $_{\eta\text{-LH}}$ between root zone soil moisture η and LH for the selected summer seasons.

3.3.2 Correlation SH-LH

The majority of correlation coefficients 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 LH-SH (Fig. 9) 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. The soil moisture deficit limits LH while SH is further increased. The SH increases due to a reduction of the evaporative cooling effect at the surface, and the consequent increase in the temperature gradient between land surface and atmosphere. 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 largely resemble those of the TCI $_{\eta\text{-LH}}$ (see Fig. 8).

In 2017, the spring season showed a positive soil moisture anomaly over Germany, East Europe and the British Isles which is reflected in the strong correlation over these regions. The correlation pattern for summer 2021 is similar as during the cold and wet seasons 1997 or 2002 (not shown) where enough soil moisture is available for evapotranspiration.

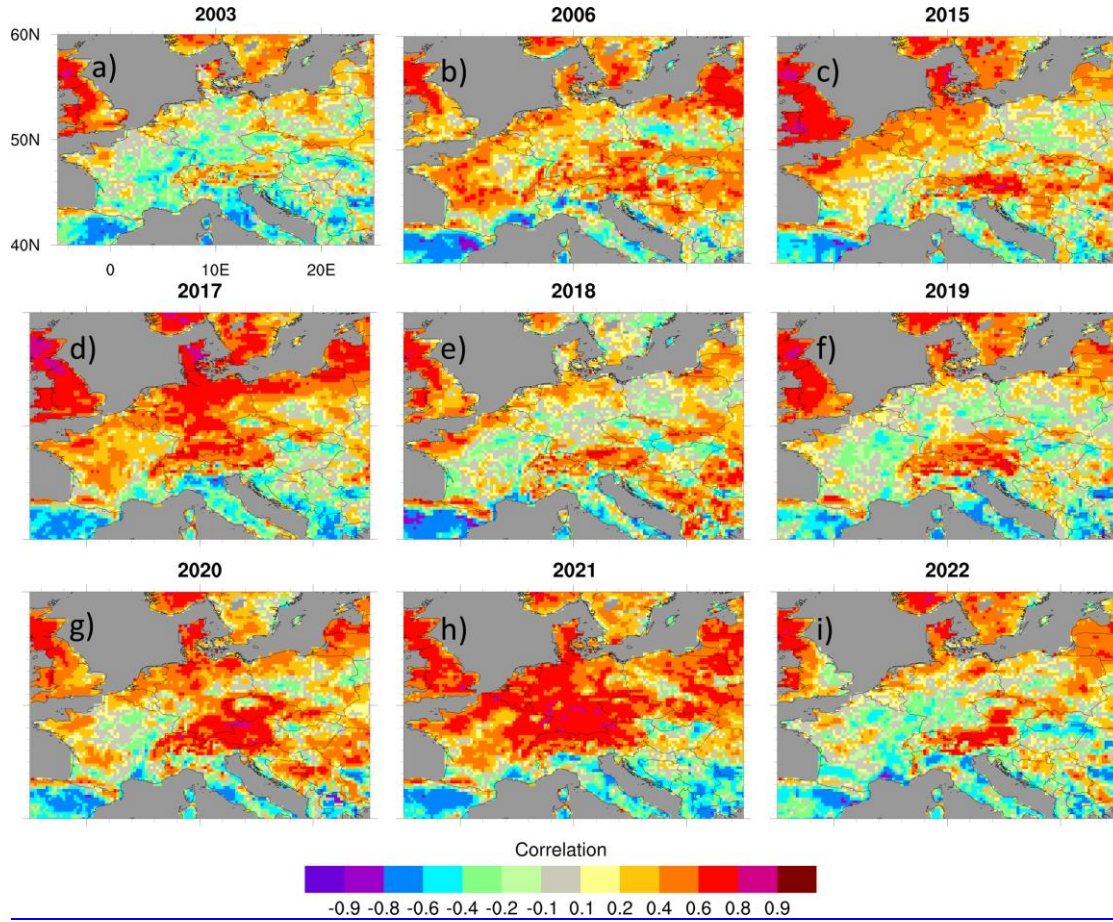



Figure 9. Pearson correlation coefficient between SH and LH for the selected summer seasons. Dark grey areas denote water grid cells.

380 ~~4 Results~~

~~4.1 Terrestrial coupling strength~~

~~In this section, we will present the terrestrial coupling index following~~ Dirmeyer; Dirmeyer, 2011 ~~(2011)for the~~ ~~selected summer seasons. As we are interested in daytime properties, we only used data between 06 UTC and 18~~ ~~UTC to derive daily mean values from ERA5. According to~~ Findell et al. ~~(2015), a 92 day period is sufficient for~~

385 ~~LA feedback analysis on individual data sets.~~

~~In addition, the Pearson correlation coefficient between surface sensible (SH) and latent heat flux (LH) is shown~~ ~~which can also be used as an indicator for LA coupling~~ ~~(Knist et al., 2017). Water grid cells are not considered for~~ ~~the analysis.~~

~~Fig. 6 shows the TCIs of the summer seasons categorized as warm and dry which became the dominant situation~~

390 ~~over Europe since 2015. The TCI between η and LH describes how changes in soil moisture drives variations in~~ ~~the surface latent heat flux. A positive TCI denotes that LH is limited by the root zone soil moisture and the soil~~ ~~moisture variation results in LH variation while a negative TCI indicates that the development of LH is energy~~ ~~limited, i.e., the incoming energy determines the LH development. In case the absolute TCI 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~~

395   ~~increase does not lead to considerable changes in evaporation~~ (Müller et al., 2021). ~~The very warm and dry seasons 2003, 2018, 2019 and 2022 show a strong positive TCI over the regions affected by low soil moisture (Germany, France, and Benelux; Fig. 5). During 2006, which is considered as an average summer with respect to temperature, soil moisture and precipitation, the TCI 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 the most far eastern part~~

400   ~~of our validation domain where the TCI is slightly negative. In 2015, which overall is a very dry year with respect to soil moisture and precipitation, shows neutral values over North Germany while the rest of the investigation domain shows positive values. During 2017, TCI over Germany shows neutral values as apparently enough soil moisture is available (Fig. 5) while it is mostly negative south of 48°N. During 2020, TCI shows a heterogenous pattern as a moderate NW-SE precipitation and soil moisture anomaly gradient is present while at the same time~~

405   ~~temperature anomalies are in the range of less than ± 1.5 K.~~

~~During 2021, when a positive η anomaly is observed over Germany, Benelux, eastern France (Fig. 5) (C3S, 2022), the TCI becomes moderately negative in these region with values of about -20 W m⁻² (Fig. 6). Apparently this is related to an already moist spring season (Fig. S2) and the heavy precipitation event occurring in June 2021 (Mohr et al., 2023) leading to a soil moisture content close to field capacity (middle panel of Fig. S1). A similar behavior~~

410   ~~of the TCI is observed during the two cold and wet summer seasons 1997 and 2002 (Fig. S7).~~

Figure 6. ~~ERA5 based Terrestrial coupling indices (TCI) between root zone soil moisture η and surface latent heat flux (LH) for the selected summer seasons presented in Fig. 1.~~

Correlation

3~~4~~.4~~3~~ Atmospheric c~~C~~oupling ~~strength and LCL deficit~~

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 patterns of the $ACI_{LH-HLCL}$ in the reference period indicate a physical influence of the LH on HLCL (negative values) over the South of the domain (Fig. 10). 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) leading to a strong inhibition of the local formation of clouds and deep moist convection. Over France, Germany and the Balkan states, the patterns are patchy with negative or slightly positive values in valleys and strongly positive ones over mountain ranges. The LCL deficit is comparatively small with values of up to -300 m. This is the area in the study domain facing considerable interannual variability, which is reflected in sign changes, among other things. Over the rest of the domain, the values are primarily 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 the PBL primarily occurs in the North of our study domain.

During the warm and dry summers, Mid Europe experiences a switch in the sign from averagely positive to slightly negative values in the $ACI_{LH-HLCL}$ (Fig 11a, e, f, i). These areas mostly converge with those where the correlation between LH and SH also switched the sign (Fig. 8). At the same time, the moderately negative LCL deficit intensifies to up to -600m over Mid Europe to over -900m over the Iberian Peninsula (Fig. 11). 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 $TLCI_{\eta-LH-HLCL}$ (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 (Santanello et al., 2011). 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).

During the warm and humid as well as the moderate summers, the $ACI_{LH-HLCL}$ 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 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).

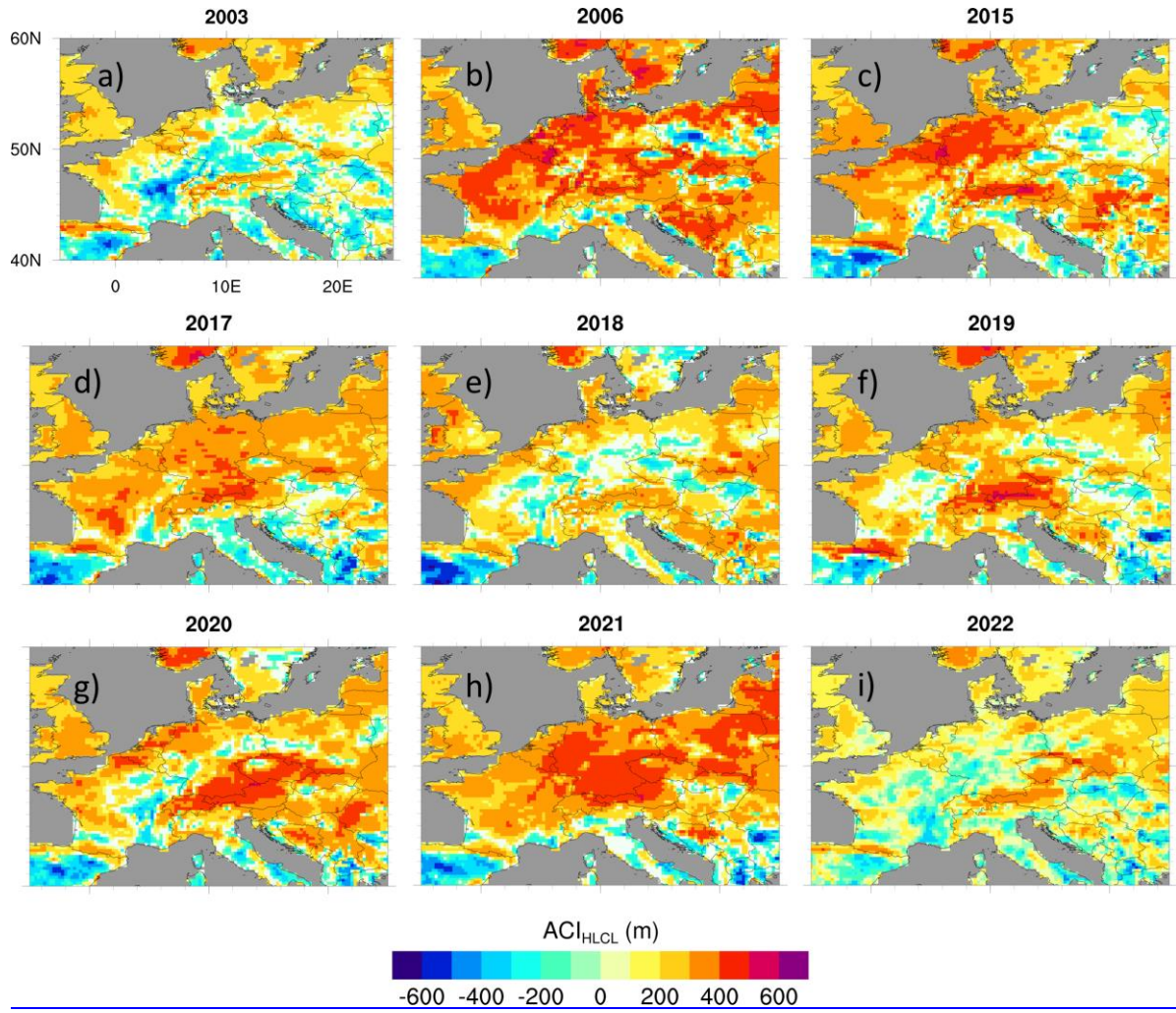



Figure 10. Atmospheric coupling index between LH and HLCL (ACI$_{LH-HLCL}$) for the selected summer seasons.

Over Germany, France, and Benelux, the ACI$_{LH-HLCL}$ shows low or negative values during the extreme warm and dry summer seasons 2003, 2018, and 2022 (Fig. 10a, e, i).

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 reflected by the negative values of the TLCI$_{η-LH-HLCL}$ (Fig. S3) pointing towards feedback between η, SH and HLCL while only weak feedback between η, LH, and CAPE is present (Fig. S4).

In summer 2006, 2015, and 2017 the ACI$_{LH-HLCL}$ 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) is connected to weak or negative coupling between η and LH (Fig. 8). 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.

As the TCI$_{η-LH}$ is mostly positive over these regions during these summers, while the ACI$_{LH-CAPE}$ 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$_{η-LH-CAPE}$ (Fig. S4).

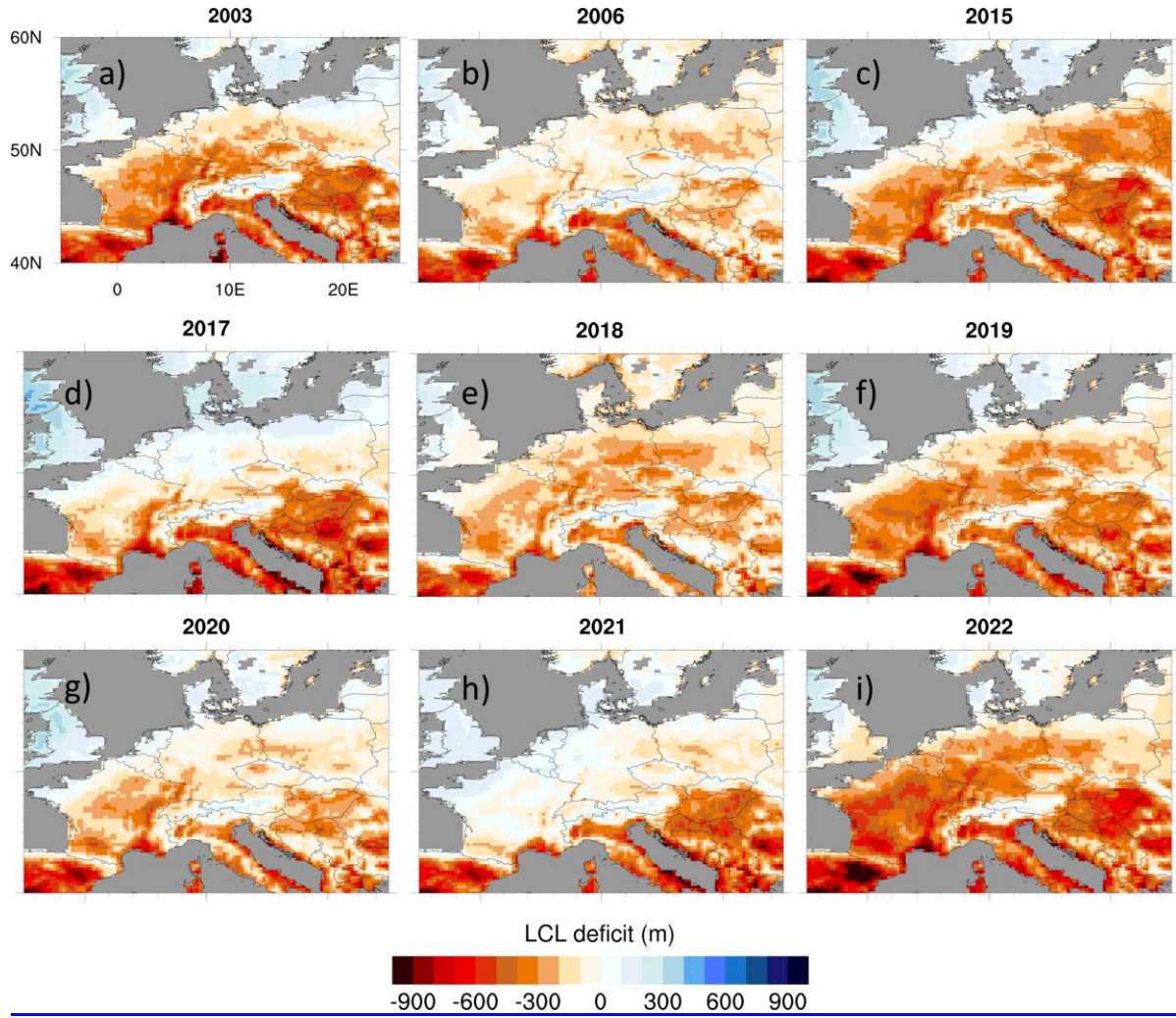



Figure 11. Mean ERA5 LCL deficit. Orange and reddish colors denote less favorable conditions for convection.

3.4.2 Coupling LH-CAPE

This section ~~presents~~ explores the results of ~~two ACIs~~ACI$_{LH-CAPE}$ ~~for~~of the warm summer seasons. This index aims at assessing 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. ~~different summer seasons 1991-2022. ACIs are computed 1) between LH and convective available potential energy (CAPE) (Eq. 2), and 2) between LH and height of the lifted condensation level (HLCL) (Eq. 3):.~~

$$ACI = \sigma(LH)\frac{dCAPE}{dLH} \tag{2}$$

$$ACI = \sigma(LH)\frac{dHLCL}{dLH} \tag{3}$$

495 ~~σ(LH) denotes the standard deviation of surface latent heat flux.~~ 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. ~~Thus, an increase in LH leads to an increase of CAPE which indicates the potential for convective developments and thus precipitation.~~

~~Positive ACI values denote a dependence of the diurnal evolution of CAPE on the LH evolution while negative~~
500 ~~values show that CAPE is independent of the LH evolution but dependent on the atmospheric stratification. The lifted condensation level is the level above which saturation occurs and it sinks with increasing atmospheric humidity. Hence, negative ACI values denote a physical relationship between LH and HLCL, whereas a positive index signifies no coupling.~~

~~To complement the analysis, the LCL deficit is shown in addition. The LCL deficit can be seen as a proxy for the~~
505 ~~evolution of the convective atmosphere as a positive LCL deficit inhibits convection developments~~ (Santanello et al., 2009)~~.~~

~~Figure 8 shows the ACI between LH and CAPE using daytime data between 06 UTC and 18 UTC.~~

ACI (J kg⁻¹)

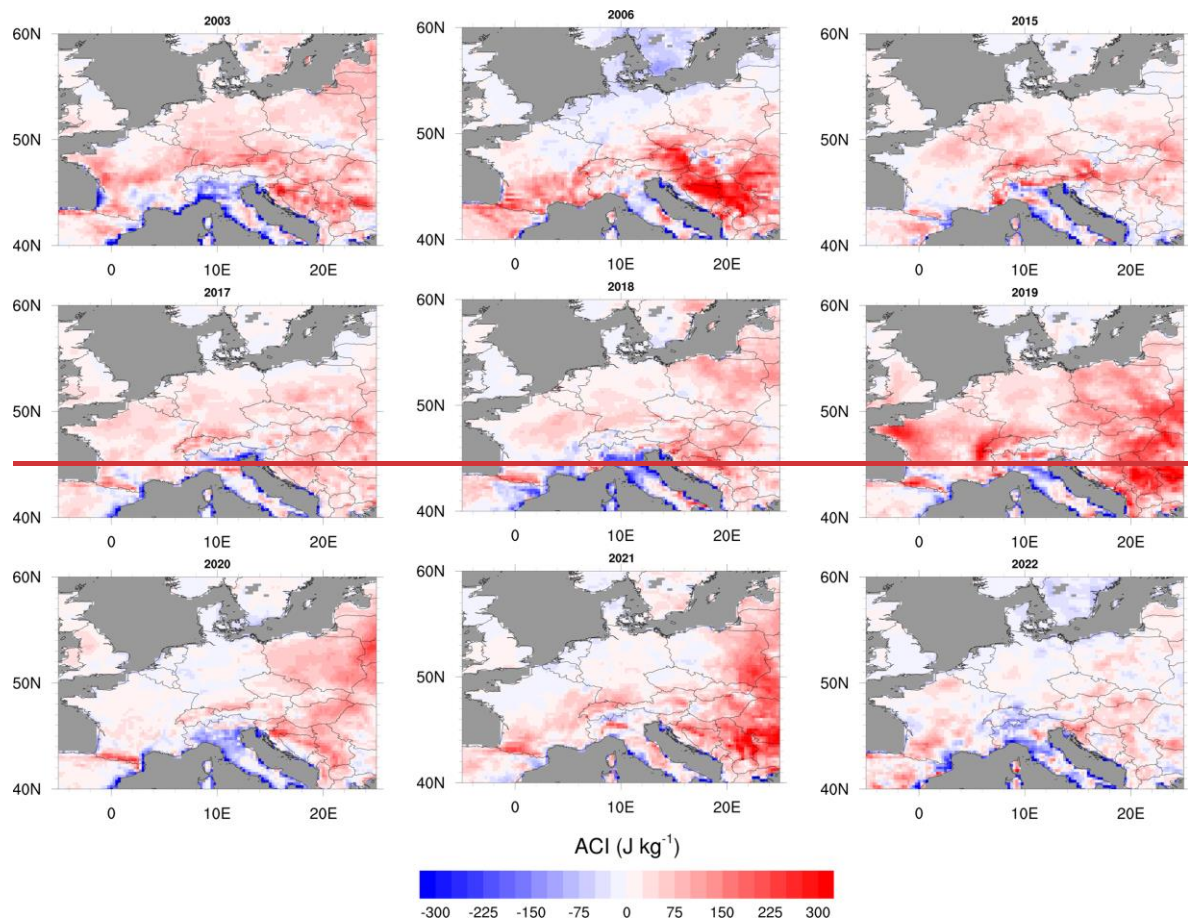
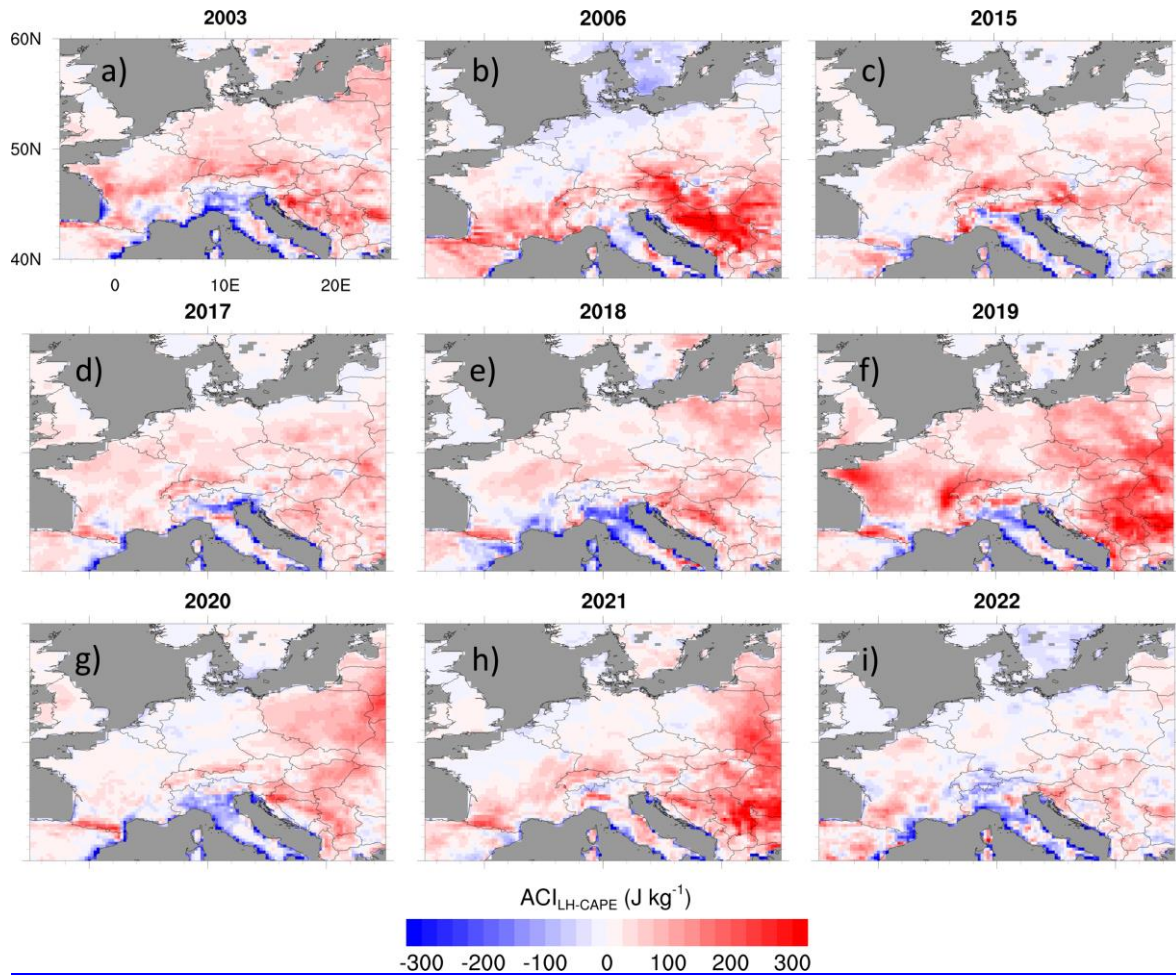
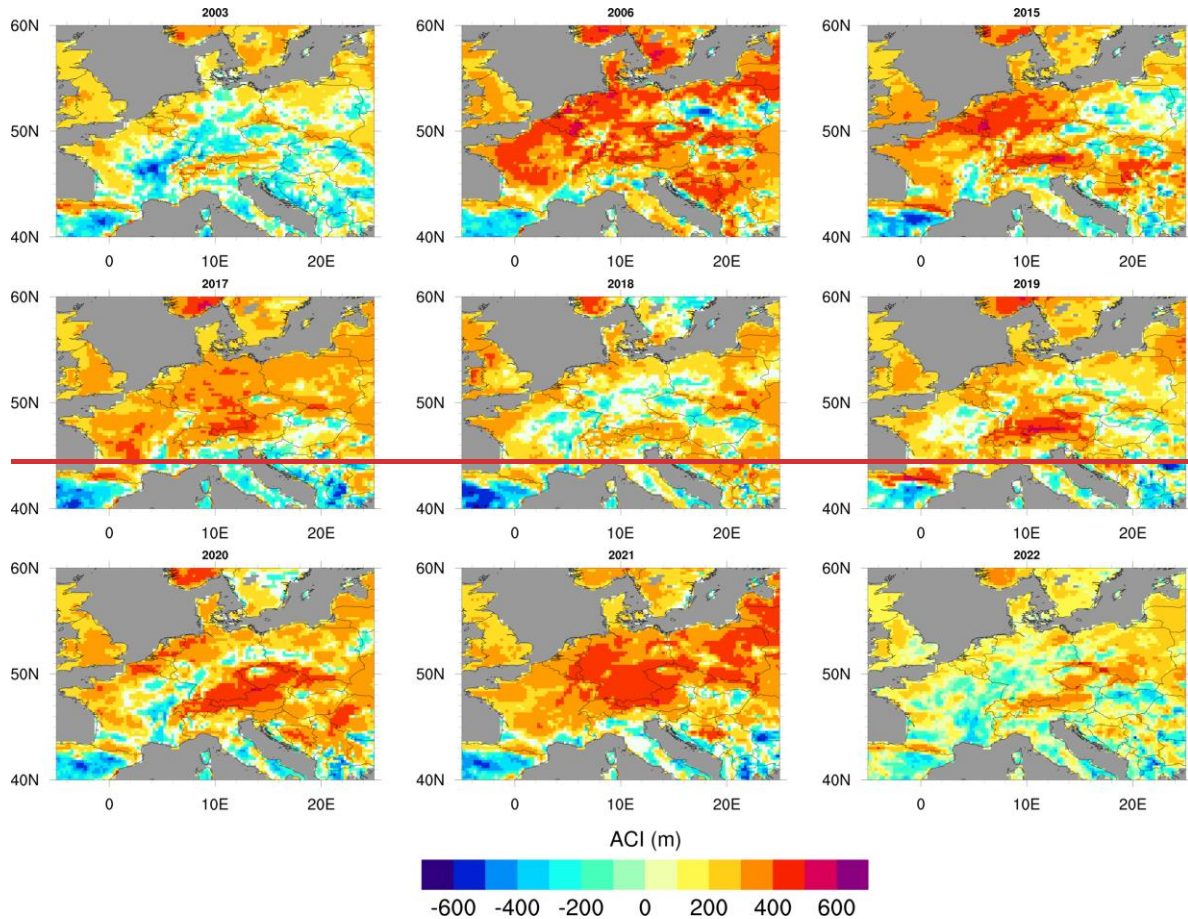



Figure 12~~8~~. ERA5 based atmospheric coupling index~~ACI~~ between LH and CAPE (ACI$_{LH-CAPE}$). Grey areas denote water grid points.

A common feature is the negative ACI$_{LH-CAPE}$ 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 °CK̶ or more in the Mediterranean between 850 hPa and 500 hPa (not shown), this leads to stronger atmospheric instability and thus reduced coupling to LH.

Coupling hot spots are observed over East and Southeast Europe with ACI$_{LH-CAPE}$ values of more than 250 J kg^{-1} o̶c̶c̶u̶r̶r̶i̶n̶g̶ ̶i̶n̶ ̶c̶o̶n̶n̶e̶c̶t̶i̶o̶n̶ ̶w̶i̶t̶h̶ ̶n̶e̶u̶t̶r̶a̶l̶ ̶o̶r̶ ̶p̶o̶s̶i̶t̶i̶v̶e̶ ̶s̶o̶i̶l̶ ̶m̶o̶i̶s̶t̶u̶r̶e̶ ̶a̶n̶o̶m̶a̶l̶i̶e̶s̶ in summer 2006, 2019, 2020, and 2021 (Fig. 12̶8). w̶h̶i̶c̶h̶ ̶i̶s̶ They are c̶o̶n̶n̶e̶c̶t̶e̶d̶related to higher values of LH over these regions (not shown) due to neutral or positive root zone soil moisture anomalies (Fig. 7̶5). These coupling hot spots were also observed in a climate sensitivity study of̶ Jach et al. (2022) who added climate change s̶i̶g̶n̶a̶l̶s̶ perturbations of temperature and moisture to a RCM simulation. Over Germany and France, mostly only weak coupling is seen with stronger signals during e̶2003 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. 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 . T̶h̶e̶ ̶i̶n̶c̶r̶e̶a̶s̶i̶n̶g̶ ̶B̶o̶w̶e̶n̶ ̶r̶a̶t̶i̶o̶ ̶l̶e̶a̶d̶s̶ ̶t̶o̶ ̶a̶n̶ increase in temperature. This enhances evapotranspiration and therefore a gradual decrease in soil moisture towards wilting point. According to Benson and Dirmeyer (2021) this ultimately leads to the situation that LH l̶a̶t̶e̶n̶t̶ ̶h̶e̶a̶t̶ ̶f̶l̶u̶x̶e̶s̶ almost vanishes and the incoming radiation mainly transforms into sensible heat which can exacerbate heatwaves and droughts. The low values of ACI$_{LH-CAPE}$ 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.

530   ~~be as a proxy for the evolution convective~~

~~The LCL deficit (Fig. 9) is usually positive over South Europe leading to a strong inhibition of the formation of clouds and precipitation. Over Central Europe the LCL deficit is comparatively small with values of up to 300 m, unlike the years 2003and 2022 which show strong positive values. These are the summers with a pronounced~~

535   ~~negative soil moisture anomaly and a strong positive temperature anomaly of more than 3°C (Fig. 2). Hence, HLCL is higher than the planetary boundary layer height potentially leading to clear sky conditions and thus inhibiting convection~~ (Santanello et al., 2011)~~. As the TCI is mostly positive over these regions during these summers, while the ACI 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~~ (Dirmeyer et al., 2014~~, Fig. S3).~~

540   ~~The LCL deficit over the British Isles and South Scandinavia, stays negative throughout all summer seasons. As at the same time the ACI between LH and CAPE shows also only small values, this suggests that the British Isles and South Scandinavia are more frequently impacted by large scale synoptic systems with a more stable atmosphere rather than localized precipitation events~~ (Jach et al., 2020)~~.~~

~~To complement our analysis, Fig. 10 shows the ACI between LH and HLCL. Over Germany, France, and Benelux,~~

545   ~~the ACI shows low or negative values during the extreme warm and dry years 2003, 2018, and 2022.~~

~~This indicates that the very dry soil during these summers (Fig. 5) caused the low LH which in turn initiated a considerable increase of the HLCL (Fig. S4). 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. In 2006, 2015, and 2017 the ACI is positive over large parts of Central Europe indicating that LH variations drive the development of HLCL, During summer 2021,~~

550   ~~which showed record high temperatures over Europe, Central Europe shows a positive soil moisture anomaly (Fig. 5) connected to weak or negative coupling between η 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).~~

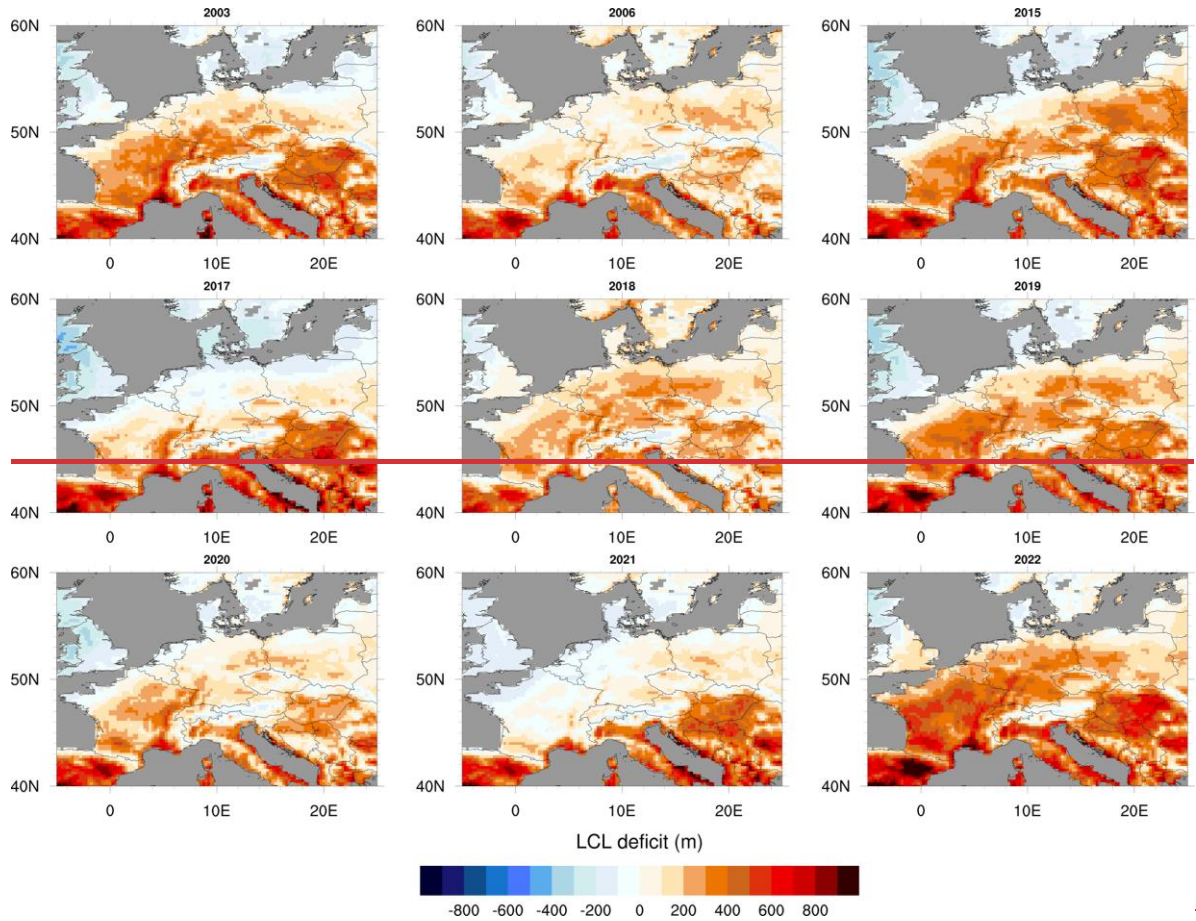



Figure 9. ~~Mean ERA5 LCL deficit. Orange and reddish colors denote less favorable conditions for convection.~~

4~~5~~ Discussion

Our objectives were to evaluate interannual variability of coupling strength over Central Europe (summer 1991-2022), and to further investigate 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 that interannual variability occurs in different coupling relationships throughout the summer seasons 1991-2022. A comparison of the variability in the indices reveals a connection with temperature and moisture anomalies on the interannual scale, which was also suggested for the climate time scale by Jach et al. (2022). This connection is particularly shown in indices showing a relation associated with the hydrological cycle (TCI$_{\eta\text{-}LH}$, correlation SH-LH, ACI$_{LH\text{-}HLCL}$). Guo and Dirmeyer (2013) for instance also showed interannual variability in the coupling of soil moisture with surface fluxes and temperature associated with soil moisture anomalies.

In this study, the TCI$_{\eta\text{-}LH}$ shows a year-to-year variability during the full period of summer seasons 1991-2022. However, there is a trend of an increased coupling during the warm and dry summers (Fig. 2a). This indicates that variations of η drive LH as there is not enough soil moisture available for evapotranspiration. The average correlation SH-LH stays mainly positive, however especially in the warm and dry summer seasons the correlation became negative. This further suggests 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 indicates less moistening of the 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, 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 Jach et al. (2022) who applied a climate temperature change signal to an existing 30 year simulation.

From the interannual variability of the different variables shown in Figs. 2 and 3, it can be concluded that warm and dry summer seasons show, on average, a differing behavior of the coupling strength. 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 flood or drought 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). Koster et al. (2009) suggest that precipitation dry bias is the result of strong positive temperature anomalies because of reduced evaporative cooling and 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; Knist et al., 2017; Jach et al., 2020; Jach et al., 2022). The correlation between SH and 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).

~~During the warm summer seasons shown in this study, the TCI η-LH shows a strong coupling throughout major parts of Europe (Fig. 6) indicating that variations of η drive LH which was also observed in a study of~~ Warrach-Sagi et al. (2022). A common feature of ~~all~~ the warm and dry~~evaluated~~ summer seasons is the anticorrelation of LH and SH south of 44 °N (Fig. 8~~7~~). These regions are usually water-limited ~~thus~~ 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)~~in these regions~~. Together with the positive TCI$_{η-LH}$ ~~this~~ 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 ~~-~~result~~sing~~ in a low LAI which is ~~usually~~ often the case in South Europe (see Fig. S5~~6~~c, 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. ~~At the~~

~~same time, the correlation between SH and LH is shows a heterogenous pattern. The correlation between SH and LH is mainly positive over the British Isles, pointing s towards 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.~~

As an example, ~~T~~the year 2018 started with an already warmer than average and slightly drier spring season over Germany (Xoplaki et al., 2023) ~~leading~~ turning in~~t~~o a severe drought due to a strong soil moisture depletion (Rousi et al., 2023) resulting in an exceptionally low LAI (Fig. S6~~5~~c). Dirmeyer et al. (2021) 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 Rousi et al. (2022) 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 (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).

If enough moisture is in the local L-A 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 a decoupling in several links along the local coupling (LoCo; Santanello et al., 2018) coupling chain: $TCI_{\eta-LH}$ negative, LH and SH co-vary, $ACI_{LH-HLCL}$ positive. However, during the humid or moderate summers the LCL deficit gets positive and locally triggered deep convection can occur.

As an example, in the warm and humid summer 2021 ~~A~~a strong SW-NE temperature anomaly gradient associated with a strong ~~positive~~ 500 hPa geopotential anomaly ~~north~~ gradient around~~of~~ 55°N ~~was evident in 2021~~. 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~~4~~), 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 ~~low~~ negative $TCI_{\eta-LH}$ values and a strong positive correlation between LH and SH as enough surface moisture was available for evaporation. The pattern of the correlation SH-LH and the pattern of $ACI_{LH-HLCL}$ largely resembles each other

~~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~~ Jach et al. (2022) ~~who applied a climate temperature change signal to an existing 30 year simulation and evaluated the CTP-HI$_{low}$ feedback metric~~ (Findell and Eltahir, 2003b, 2003a). ~~In contrast to~~ which is also observed in the cold and wet ~~years~~ summer seasons~~1997 and 2002~~ (~~Figs. S6,S7~~not shown). ~~, t~~The LCL deficit in ~~(not shown~~Fig. 10) is ~~mostly~~ 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 (Hersbach et al., 2020), some limitations have to be acknowledged. Like many other numerical weather prediction (NWP) models~~Currently~~, ERA5 applies a static LAI climatology (Fig. S6~~5~~b) which was derived from the period 2000-2008 (Boussetta et al., 2013; ECMWF, 2016). However, under a changing climate the interannual variability of LAI is ~~increasing~~

enhanced as shown by the satellite derived data from observed by satellites in the Copernicus Global Land Service (CGLS) project (Fuster et al., 2020) (Fig. S65c,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,

A study of Denissen et al. (2020) found that LSMs tend to overestimate the critical soil moisture (Hsu and Dirmeyer, 2023). and thus evaporation becomes soil moisture limited too early. A recent study of Warrach-Sagi et al. (2022) using the LSM NOAH-MP (Niu et al., 2011) 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 (Yin and van Laar, 2005). Since, Tthis is in contrast to the results of Denissen et al. (2020) indicating the need for further enhancements of the applied LSMs (Hersbach and Bell, 2022; He et al., 2023). and the need to investigate the role of dynamic vegetation in the LA system.

However, Martens et al. (2020) evaluated LH surface latent heat fluxes from ERA5 against FLUXNET stations (Pastorello et al., 2020) for the period 1991-2014. Their analysis revealed that ERA5 surface fluxes perform well in a moderate temperature climate which is the case over Europe. ERA5 soil moisture over Europe shows a reasonable correlations of up to 0.7 over Europe (Muñoz-Sabater et al., 2021) while LH in ERA5 tend to be overestimated on average by about 9 W m^{-2} when compared to all stations. This could be related to an overestimation of wet days in combination with underestimated sub-daily precipitation rates (Beck et al., 2019). Hence, although limitations are present in the reanalyses data set, they The tendency to overestimate precipitation resulting suggest that the exact values of coupling indices can vary but the sign and magnitude of the indices are robust in higher LH estimates could lead to an increased atmospheric instability and thus affecting the TCI, ACI and the LCL deficit. In case LH is overestimated, this also raises near surface moisture lowering the LCL which results in a decreased LCL deficit. This has the potential to initiate atmospheric convection thus increasing the ACI between LH and CAPE.

56 Summary

This study provides an assessment of temporal variability in three 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-CAPE as well as LH-HLCL coupling comprising two relationships of the atmospheric leg. Firstly, the interannual variability between all years of the period was examined in 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.

Soil moisture availability during the summer seasons 1991-2022 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 2003, 2015, 2018, 2019, and 2022 indicating a drier PBL and potentially leading to a suppression of the development of convection. The interannual

variability of the correlation SH-LH as well the TCI_{n-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).

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. The summer seasons were classified according to 2 m temperature anomalies based on ERA5 (Hersbach et al., 2020) exceeding a threshold of +0.5 K. The reference period for the calculation of the anomalies was 1991-2020 (WMO, 2017). To further enhance support 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. In addition, we also used the E-OBS precipitation data set (Cornes et al., 2018) for the interpretation of our results.

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) and 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.

Our results revealed that warm and dry summer are characterized by positive geopotential anomalies throughout Europe (Kueh and Lin, 2020; Rousi et al., 2023) while the two warm and wet summers exhibit a negative geopotential anomaly over Central Europe (not shown). Strong geopotential anomalies are linked to considerable positive 2 m temperature anomalies and the warm and dry summer seasons are usually characterized by a strong dry soil moisture anomaly.

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.

Our results show that the interannual temperature and soil moisture variability during the different summers considerably drive the interannual variability in LA coupling over Central Europe. 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.

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. The increasing frequency of warm and dry years summers from 2015 onwards toward the second half of the study period hints toward a trend of extended periods of reduced soil moisture availablemoisture limitations for evapotranspiration and the likelihood of locally triggered convection. This suggests leads to a growing influence of soil moisture variability on the meteorological conditions which was not as pronounced before 2003 experiencing 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
735   increasing temperature and a, lack of rainfall ~~resulting~~ which together cause~~in~~ a soil moisture depletion due to
excessive evapotranspiration.

~~From our study we conclude that applying reanalysis data for the derivation of the feedback metrics could be used~~
~~as a reference for a further analyses and evaluation of climate simulations. However, this requires high-frequency~~
~~model output from (high-resolution) climate models~~ (Findell et al., 2024)~~ which is still a challenging task.~~The
740   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 sub-seasonal to seasonal (S2S) forecasts.

~~Though it requires more research to deepen the understanding of how different surface wind patterns, horizontal~~
745   ~~moisture transport~~ (Findell et al., 2024)~~, the location of the center of a high- or low-pressure system influence the~~
~~coupling or how dynamic vegetation-climate feedback do~~ (Nogueira et al., 2021; Warrach-Sagi et al., 2022)~~, we~~
~~consider this work a valuable contribution to further understanding land surface influences on extreme events over~~
~~Central Europe.~~

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https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview.   The   results
contain modified Copernicus Climate Change Service information 2020. Neither the European Commission nor
755   ECMWF is responsible for any use that may be made of the Copernicus information or data it contains. We thank
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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
760   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.

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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.

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Competing interests

The authors declare that they have no competing interests.

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