

Abstract

Hot temperature extremes are changing in intensity and frequency. Quantifying these changes is key for developing adaptation and mitigation strategies. The conventional approach to study changes in hot extremes is based on air temperatures. However, soil processes are triggered by soil temperature and it remains unclear whether it changes as does air temperature. Here, we demonstrate that hot extremes based on soil temperatures (soil hot extremes) are intensifying and becoming more frequent faster than air hot extremes over central eastern and western Europe. Based on existing model simulations, we also show that the increase in hot soil extremes could amplify or spread future heat waves by releasing sensible heat during hot days. In light of these results, future research on the impact of hot extremes on agriculture should be complemented with the analysis of soil hot extremes, since the fast intensification of soil hot extremes could pose high risk for crop failure.

Data and Methods

The evolution of soil and air hot extremes are analyzed from several data sources:

- **Maximum daily soil and air temperatures** at meteorological stations over Europe from the FLUXNET2015 dataset, ICOS, ARPAV, DWD and Météo France.
- **Earth observations**, including the E-OBS daily gridded land-only observational dataset and the CM SAF Land Surface Temperature dataset from Meteosat First and Second Generation Edition 1.
- **Reanalysis data** from the land component of the ECMWF ERA5 climate reanalysis - ERA5Land at hourly resolution.
- **Climate model simulations** from the five Coupled Model Inter-comparison Project Phase 6 - CMIP6 models (MIROC-ES2L, MIROC6, MPI-ESM2-LR, MPI-ESM2-MR and EC-Earth3). Outputs from the historical and SSP5-8.5 simulations were employed.

Based on soil and air daily maximum temperatures from the datasets listed above, we calculated two extreme indices for the period 1996–2021: an intensity index (TX7d) defined as the mean maximum temperature of the hottest week in a year and a frequency index (TX90p) defined as the number of hot days in a year. We define hot day as the day with maximum temperature reaching the 90th percentile of a reference period. The reference period was set to the first 10 years of the data overlapping period.

Trend significance and magnitude in the two extreme indices for all datasets were computed on the basis of the Mann–Kendall trend test and the non-parametric Sen's slope estimator to reduce the effect of out-layers on our results. The study of soil temperature as heat contributor to future hot days developed near the surface was performed comparing daily maximum soil and air temperatures during hot days above the surface in summer. Thus, we estimated the percentage of hot days when maximum soil temperatures are higher than maximum air temperatures.

Soil hot extremes in the recent past

Trend in TX7d based on air (TX7dAir) and soil temperatures (TX7dSoil) show an increase during the last decades based on different source of evidence. The difference between absolute values of trends in soil and air (Abs. TX7dSoil - TX7dAir) and the difference between trends where both trends are positive (Incr. TX7dSoil - TX7dAir) indicate a faster increase in the intensity of soil hot extremes than in air hot extremes in central Europe.

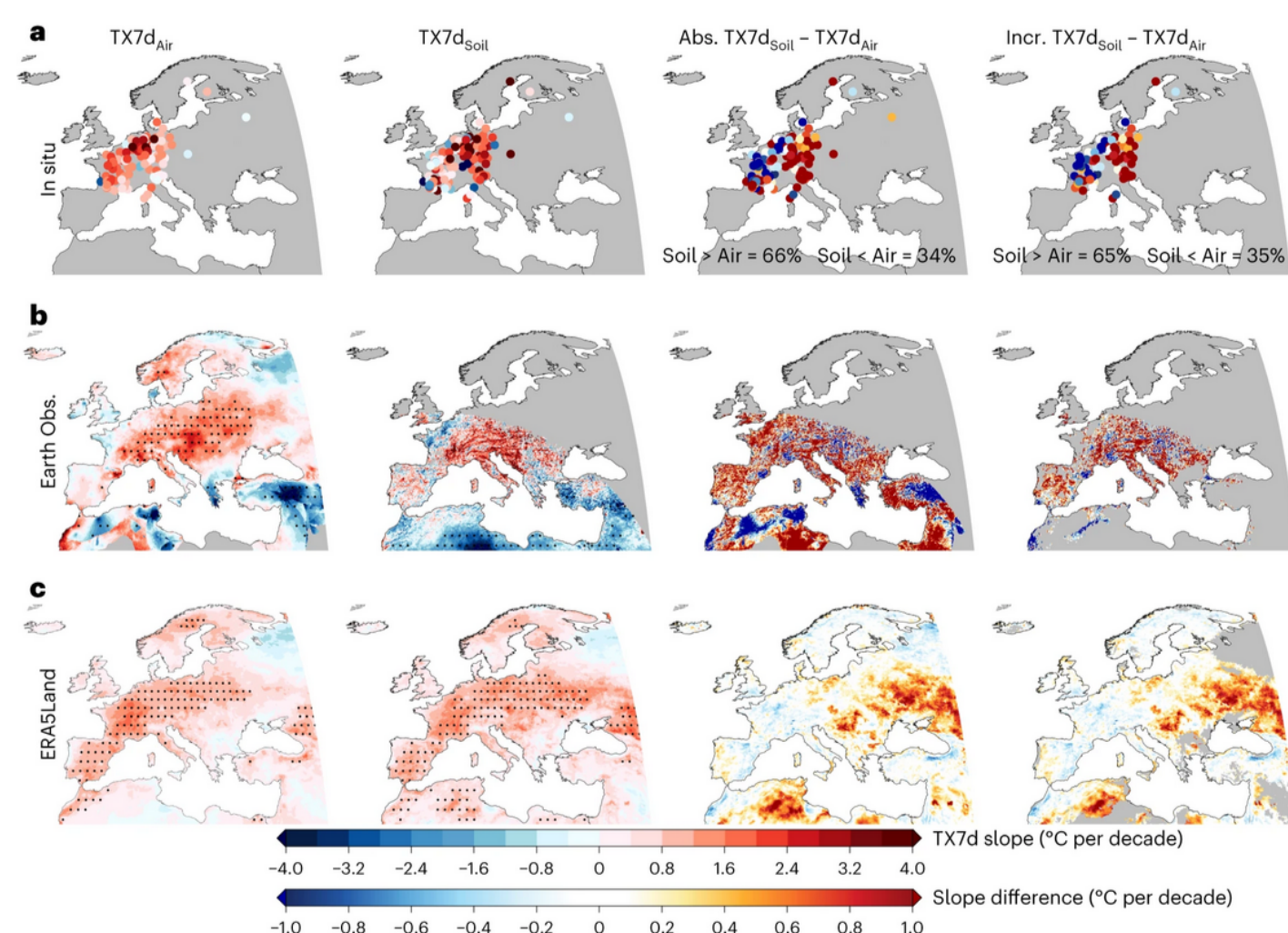


Figure 1. Trends in the intensity of air and soil hot extremes and their differences over Europe based on different sources of information. Dots indicate areas with significant trends above the 90% confidence level.

Soil temperature in the soil moisture – temperature feedback

During wet and warm conditions, net radiation is mainly released from the soil as latent heat (LE). This process decreases soil temperatures (T_{Soil}) and increases cloud fraction (CF), leading to higher precipitations (P), which may further increase soil moisture (SM). During dry and warm conditions, net radiation is mainly used to raise T_{Soil}, increasing sensible (H) and ground (G) heat fluxes, while LE is constrained by SM. The release of H into the atmosphere increases local and/or remote air temperatures (T_{Air}), leading to vapour pressure deficits (VPDs). High VPD increases the demand for LE, further drying out and warming the soil.

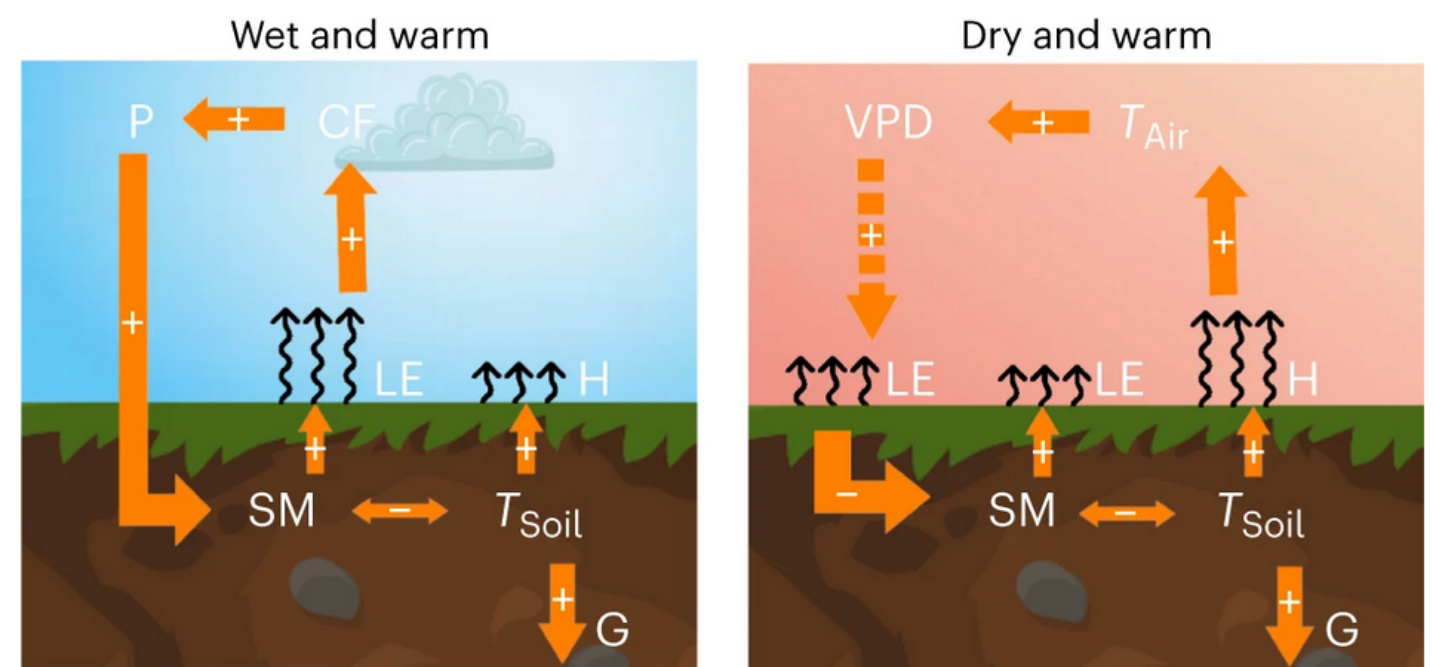


Figure 2. The role of soil temperature in the soil moisture - temperature feedback. + (–) symbols indicate a direct (inverse) relationship, while arrows indicate the direction of the feedback.

The role of soil temperatures in a warming climate

The percentage of days with maximum soil temperatures (T_{Soil}) higher than maximum air temperatures (T_{Air}) during air hot extremes show a fast increase during this century as represented by the multimodel mean of the CMIP6 models under the 1.5°C warming level and its difference with warming levels of 2.0°C and 3.0°C.

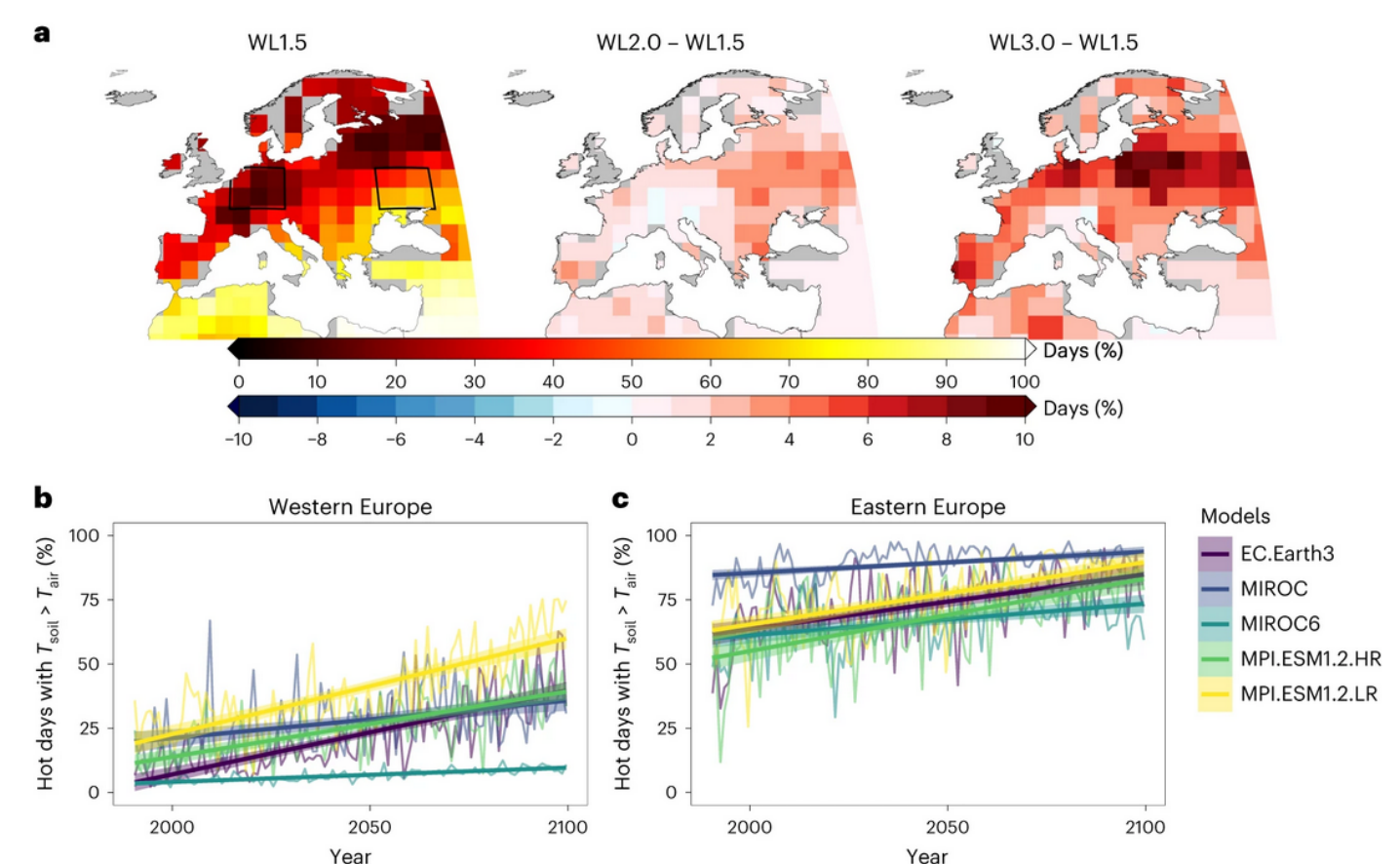


Figure 3. Percentage of days with maximum soil temperatures (T_{Soil}) higher than maximum air temperatures (T_{Air}) during air hot extremes as represented by the multimodel mean of the CMIP6 models.

Conclusions and implications

Soil hot extremes are increasing faster than air hot extremes by 0.7°C/Decade in intensity and twice as fast in frequency over some areas of central Europe as demonstrated by different sources of information.

Soil temperatures play a crucial role in the soil moisture - temperature feedback. The lack of water in soil lead to a soil warming, increasing the probability of a release of heat from the soil to the atmosphere affecting this feedback.

These results provide further **support to the importance of the soil moisture–temperature feedback for the evolution of hot spells in a warming climate**, indicating that soil temperatures are becoming an important contributor to atmospheric heat waves in the 21st century.

The fast increase in soil hot extremes could pose high risk for the health of crops above and below the land surface. Thus, **future research on the impact of heat extremes on agriculture should complement their analysis with soil temperatures.**