EGU24-10748, updated on 20 May 2024
https://doi.org/10.5194/egusphere-egu24-10748
EGU General Assembly 2024

Changes in the causal effect networks of single and compound extreme hot and dry events in Central Europe

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Hot and dry extreme events in Europe have become more frequent and pose serious threats to human health, agriculture, infrastructure, and ecology. Single and compound hot and dry extremes in Europe have been attributed to synoptic atmospheric circulation variations and land-atmosphere interactions. However, the exact causal pathways and their strength, as well as their historical trends, have not been quantified. An accurate understanding of the mechanisms behind these land-atmosphere extremes is crucial to improving S2S forecasts and implementing appropriate adaptation measures. Here, we use the Peter and Clark momentary conditional independence (PCMCI) based Causal Effect Networks (CENs) to detect and quantify dynamic and thermodynamic causal precursors of extremely high 2m temperature (T2m) and extremely low soil water deficit and surplus (WSD) in central Europe (CEU).

Our analysis reveals that the single hot events are driven mainly by anomalous atmospheric patterns and soil water deficiency, while single dry events are mainly driven by the soil moisture memory, and anomalous atmospheric patterns, and only marginally by temperature changes. The atmospheric circulation patterns preceding both single hot and dry events show a high-pressure system over central Europe, with a low-pressure system over the Atlantic Ocean, and partly explain the occurrence of the compound events. This atmospheric pattern is also linked to an anomalous zonal cold-warm-cold SST pattern over the Atlantic Ocean and a warmer eastern Pacific Ocean.

The identified causal links vary with temperature and humidity conditions, that is, the impact of soil moisture memory on the WSD variation is sensitive to T2m and WSD, while the influence of

soil moisture condition on T2m changes is strengthened by reduced WSD. Moreover, during compound hot and dry extremes, the effect of reduced soil moisture on temperature is significantly higher than during single events, reaching twice the magnitude under moderate conditions. When historical trends are analyzed, we show that the impact of dry soil on temperature is amplified by 42% (46%) for single (compound) extremes during 1979-2020, while the influence of atmospheric drivers on soil moisture is intensified by 28% (43%).

This work emphasizes (i) the intensification of the strength of the thermodynamic causal pathways for warmer and dryer CEU over time and (ii) the stress on the varying forcing strength of the drivers, which can lead to non-linear variations of weather stressors under climate changes and thus add extra challenges to extreme adaptations.