



Storyline attribution of flash drought-heatwave compound extreme to global warming

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Flash droughts (FD) are characterised by rapid depletion of soil moisture conditions. A heatwave (HW) is a period of abnormally hot weather (typically defined as lasting for three or more consecutive days). While HWs intensify through ongoing atmospheric heating, FDs result from a sudden drop in soil moisture brought on by increased evaporative demand and precipitation deficiencies. When combined, FD–HW compound occurrences can cause ecosystem disruption, hydrological stress, and significant agricultural losses. In Europe, flash droughts (FD) and heatwaves (HW) are becoming more dangerous due to changes in land-atmosphere coupling and increased warming. However, because conventional free-running climate model simulations are not the best solution to replicate the observed dynamic circumstances that drive actual events, their evolution under future warming requires a different approach.

Here, we employ a storyline-based method that imposes counterfactual warming levels (Pre-Industrial (PI), Present-Day (PD), +2 K, and +3 K worlds) while reconstructing the synoptic conditions of recent European extremes (2018–2024) using spectrally nudged simulations of AWI-CM-1-1-MR, which are constrained toward ERA5 circulation. This approach avoids the sampling constraints of historical analogues, maintains the physical structure of the observed FD–HW sequences, and produces dynamically consistent representations of warm worlds. The mesoscale Hydrologic Model (mHM), which measures soil moisture anomalies, spatial drought extent, and compound FD–HW features throughout Europe, is driven by these climate forcings.

Our findings demonstrate intensification in the FD and HW separately as well as when they occur simultaneously. FD events are expected to approximately double in the same time frame, while heatwaves are expected to occur 5 times more frequently and have an average magnitude more than 12 times greater in a 4K world compared to pre-industrial levels. When they happen together in a difference of less than or equal to three pentads, such events are expected to become more

than 7 times more common. This work offers a solid foundation for climate-risk assessment and drought preparedness throughout Europe.