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Different Roles of Land-atmosphere Coupling in Compound Drought-heatwave Events

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Droughts and heatwaves are inherently linked through land-atmosphere (L-A) coupling, where the interactions between surface energy and water availability play critical roles in their evolution. In energy-limited regimes, anomalously high surface air temperature (T) intensifies evapotranspiration (ET), leading to rapid depletion of soil moisture (SM). Conversely, in water-limited regimes, reduced SM suppresses ET, exacerbating surface warming. The transition between these two regimes, characterized by critical soil moisture thresholds, governs the progression of compound drought-heatwave events.

This study analyzed the spatiotemporal variability of L-A coupling mechanisms during six extreme compound drought-heatwave events. In all cases, SM exhibited a consistent negative temporal correlation with T, declining from the onset to the peak of the heatwave and recovering during the decay phase. However, the behavior of ET varied, with SM-ET coupling dominating in some cases and T-ET coupling prevailing in others. These distinctions in coupling regimes demonstrated regional heterogeneity, even within individual events. As regimes shifted from T-ET to SM-ET coupling, evaporative fraction (EF) on heatwave peak days significantly decreased, underscoring that the drivers of drought-heatwave interactions differ spatially. Furthermore, correlation analysis between SM and EF revealed that critical soil moisture thresholds are key determinants of these coupling behaviors. This highlights the role of critical soil moisture in modulating L-A feedbacks and controlling the transition between coupling regimes.

Using the GFDL SHIELD global 13-km model configuration, we evaluated the predictability of two prominent events in 2022 and 2023, which displayed contrasting dominant regimes. SHIELD effectively captured the spatial distribution and temporal evolution of L-A coupling regimes in both cases. Notably, the SM-ET coupling-dominated 2023 event demonstrated superior forecast skill for SM and TMAX compared to the T-ET coupling-dominated 2022 event. This result emphasizes the importance of soil moisture memory in water-limited regions for enhancing predictability in compound drought-heatwave scenarios.