# Distinct Energy Partitioning and Hydro-Thermal Coupling Regimes Shape Three Types of Global Compound Drought and Heatwave Events


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## ✦ Abstract


**Compound Drought and Heatwave Events (CDHEs)** are intensifying under global warming, yet existing identification frameworks often **conflate atmospheric and soil extreme signals**, obscuring their spatial patterns and physical mechanisms. Using **global ERA5 and GLDAS data from 1965 to 2024**, we developed a **Mutually Exclusive Identification Scheme (MEIS)** based on four hydro-thermal state variables, **VPD, Tair, SM, and Tsoil**, to classify CDHEs into **Single-Atmosphere (SA-CDHEs), Single-Soil (SS-CDHEs), and Coupled Atmosphere–Soil (CAS-CDHEs)**. We then combined **HFC hotspot mapping**, **nonlinear trend analysis**, **full-lifecycle event evolution**, **Copula dependence modelling**, and **SEM-inferred causal pathways** to diagnose their spatiotemporal characteristics and governing mechanisms. Results reveal three distinct regimes. **SA-CDHEs** are the most frequent but short-lived, reflecting a radiative-pulse regime with downstream atmospheric stress and soil thermal loading. **SS-CDHEs** persist the longest and develop through a moisture-memory regime, where precipitation deficits and antecedent soil drying reshape fluxes and transmit soil thermal anomalies into atmospheric stress. **CAS-CDHEs** are the most intense and emerge from radiation–moisture convergence, upper-tail thermal–flux dependence, and event-period soil-moisture limitation, revealing a shift toward strongly coupled atmosphere–soil extremes.


## ✦ Background

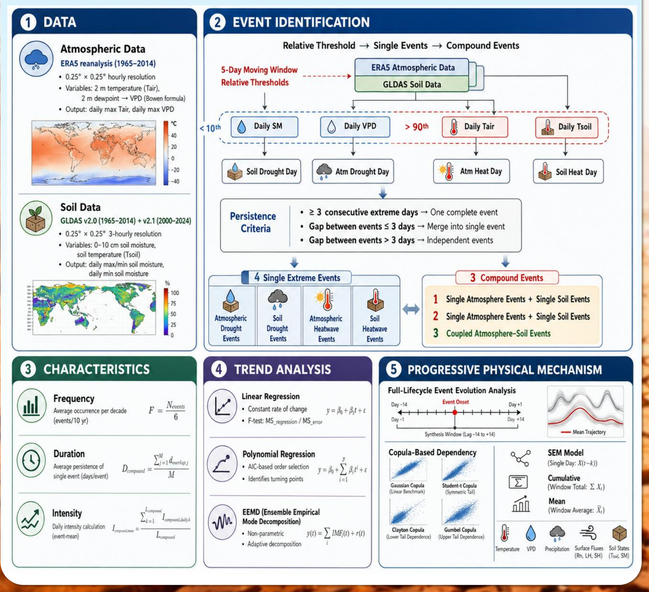
- **Core problem: atmospheric and soil dry–hot signals are often mixed in current CDHE studies.**
- **Atmosphere bias:** many definitions emphasize air temperature, VPD, or precipitation, while soil heat and moisture are underrepresented.
- **Signal confounding:** cross-interface indicators can mix atmospheric and soil extremes, causing events to be assigned to the wrong physical source.
- **Fragmented mechanisms:** most mechanism studies focus on individual cases or isolated feedbacks, rather than tracking large samples through the full event lifecycle.

**How do distinct land–atmosphere regimes shape global CDHEs?**

## ✦ Highlights

- MEIS separates atmospheric and soil dry–hot signals, **reduces spatial and mechanistic misclassification**.
- Three CDHE types reveal **divergent hotspot patterns**.
- **All three CDHE types intensify nonlinearly**, with CAS-CDHEs accelerating fastest in the late period.
- Progressive mechanism analysis uses **million-event samples** to trace type-specific causal pathways.

## ✦ Methods




## ✦ Mechanism

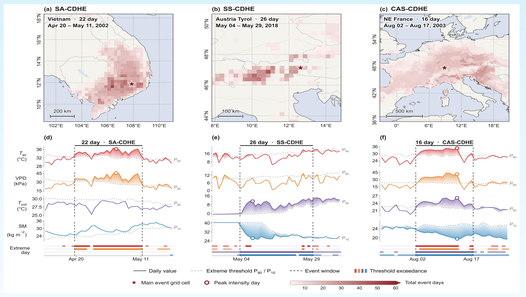



Fig. 7. Identification of three CDHE types and representative events.

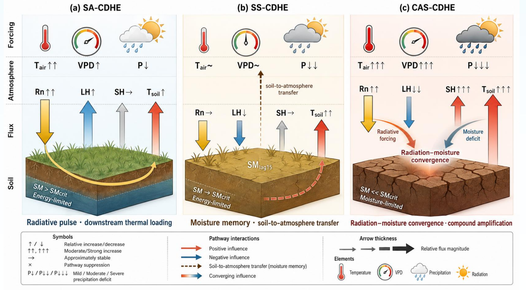



Fig. 8. Physical mechanisms of SA-CDHEs, SS-CDHEs, and CAS-CDHEs.

## ✦ Results

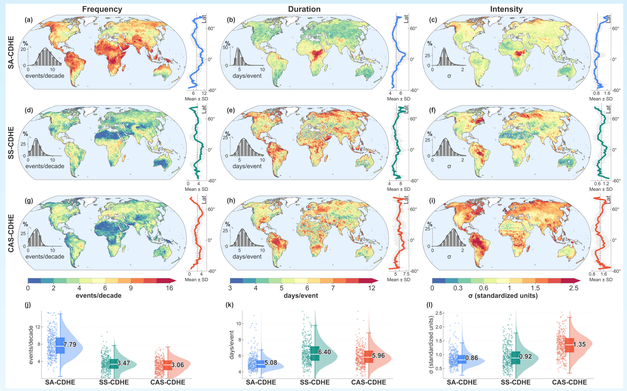



Fig. 1. Global patterns of frequency, duration, and intensity across three CDHE types.

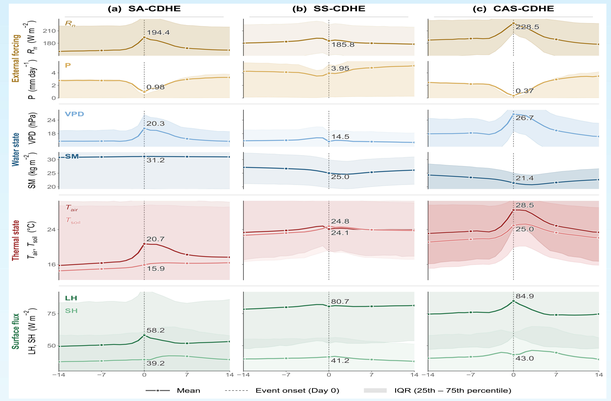



Fig. 4. Event evolution analysis of eight land–atmosphere variables.

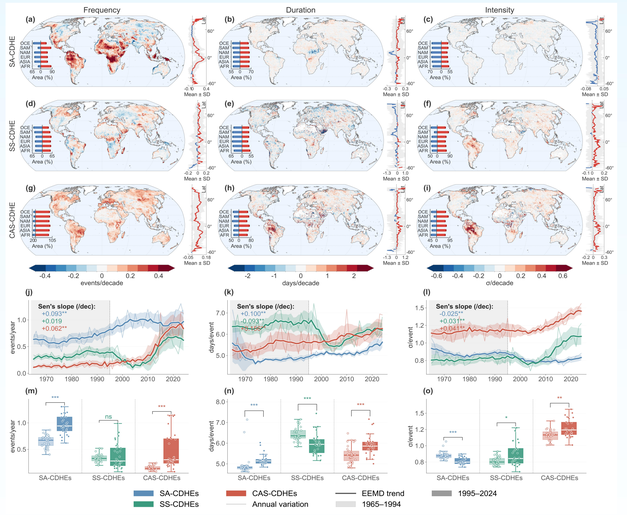



Fig. 3. Spatial trends and temporal changes in three CDHE types during 1965-2024.

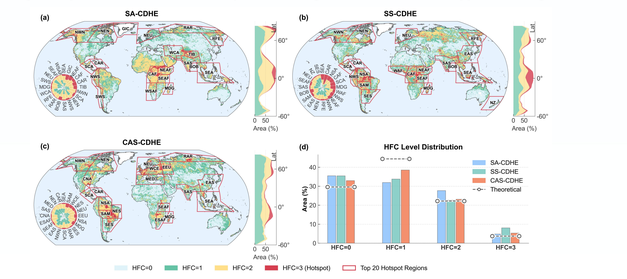



Fig. 2. CDHE hotspot classification and regional distribution.

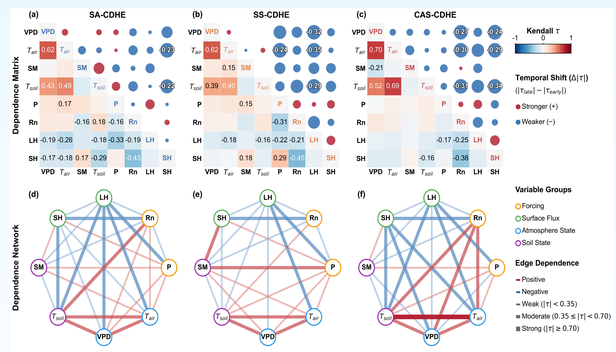



Fig. 5. Same-day and lagged dependence structures among CDHE variables.

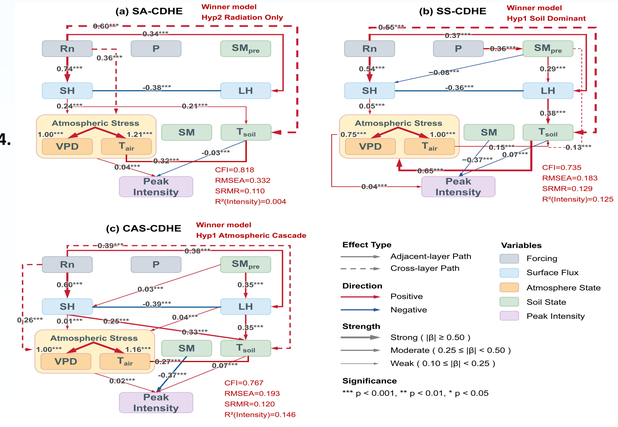



Fig. 6 . Selected SEM-inferred causal pathways for CDHE development.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