Climate Warming Favors the Early Emergence of Rapid Flash Drought

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Motivation

Under climate change, rising evaporative demand accelerates drought development, raising the risk of "Flash Drought" (FD). These rapid-onset events cause severe agro-economic damage within weeks. However, the physical mechanisms, specifically land–atmosphere interactions, and the precise timescales of intensification remain poorly understood.

Research Questions

-When do flash droughts emerge or disappear relative to their onset timescales?
- After their disappearance, do these events dissipate or transition into different droughts regime?
- What physical mechanisms control their rapid development?

Detection of Soil Moisture-based Flash Drought

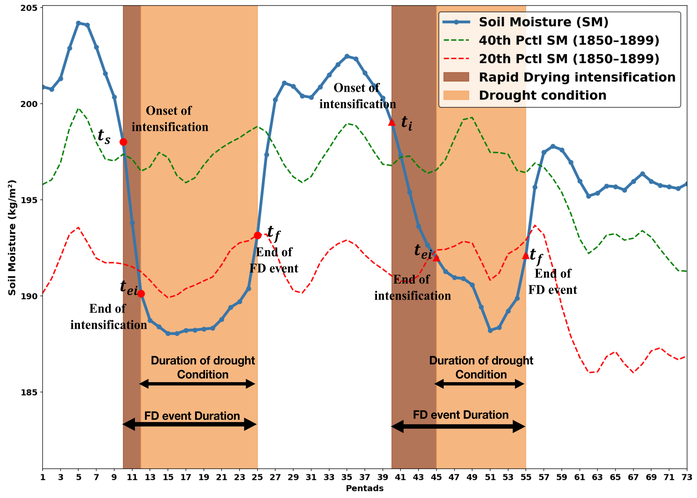

Fig. 1: Schematic representation of the definition and detection of the flash drought. The onset duration is between 1 to 5 pentads, and the drought condition is between 3 to 12 pentads.

$$\text{Onset: } \begin{cases} \dfrac{\mathrm{SM}(t_{i+1}) - \mathrm{SM}(t_i)}{t_{i+1} - t_i} \geq 5\%\text{ percentile (rapid decline)} \\ 1 \leq t_{ei} - t_s \leq 5 \text{ (Intensification Rate Duration; IRD)} \end{cases}$$

$$\text{drought condition: } \{3 \leq t_f - t_{ei} \leq 12 \text{ (pentads)}$$

Data: Community Earth System Model version 2 Large Ensemble simulation under SSP3-7.0 (90 ensemble members spanning 1850–2100).

Sharing not permitted

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Cumulative Area of Flash Droughts

✳**Affected land area expands, particularly for the intensification rate duration (IRD) of 1-2 pentads, peaking at 34 ± 3 million km² in CESM2-LE, while decreasing for longer IRDs (3-5 pentads).**

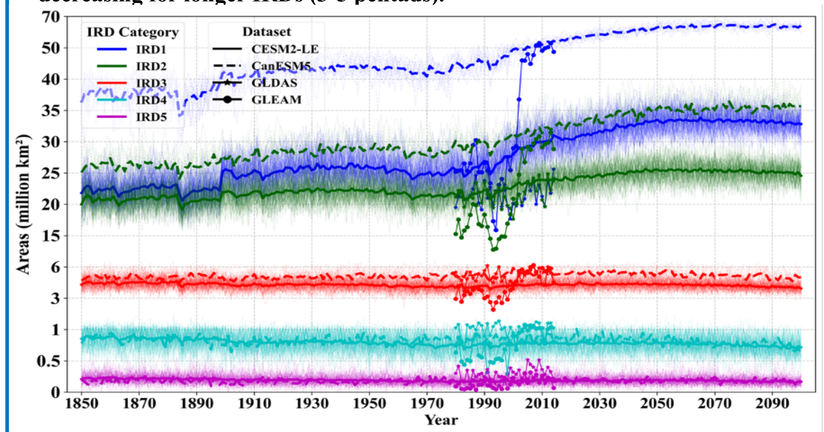
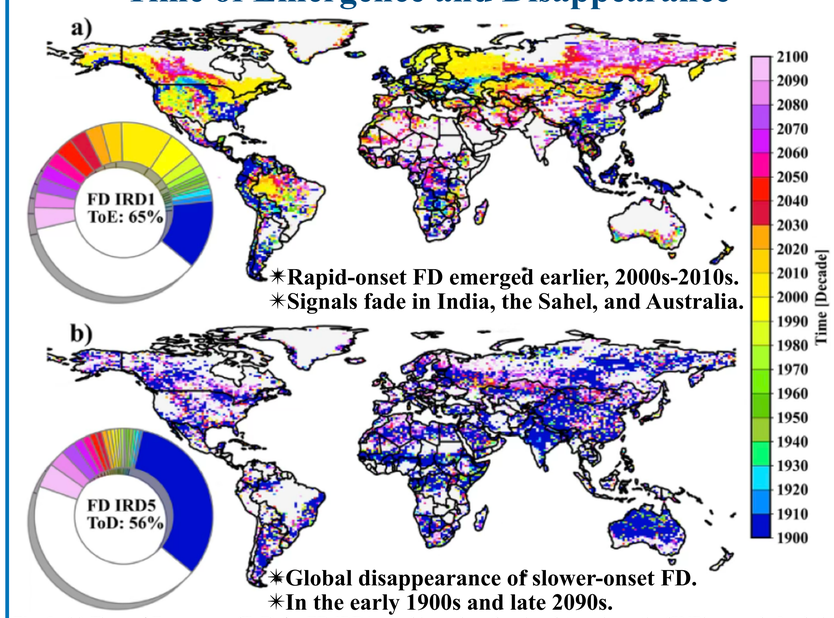


Fig. 2: Temporal evolution of global land area affected by flash droughts in a given year across intensification rate duration (IRD) of one to five pentads (IRD1 to IRD5).

Time of Emergence and Disappearance



✳**Rapid-onset FD emerged earlier, 2000s-2010s.**
✳**Signals fade in India, the Sahel, and Australia.**
✳**Global disappearance of slower-onset FD.**
✳**In the early 1900s and late 2090s.**

Fig. 3: (a) Time of Emergence (ToE) for FD IRD1, marking when the signal-to-noise ratio (SNR) exceeds 2 relative to pre-industrial variability. (b) Time of Disappearance (ToD) for FD IRD5, marking when SNR falls below 0.5. Insets show the global land fraction affected for each case. Timeline: 1900–2100.

Summary

✳ Warming drives faster-onset flash droughts by the mid-20th century, with increasing persistence in regions like the Sahel, India, and Australia.
✳ Slow-onset flash droughts decline, transitioning into conventional droughts.
✳ Even wetter mean-states regions experience intensified flash droughts due to ~30% drops in precipitation/runoff and ~10% increases in evapotranspiration.

Transition Pathways of Flash Droughts Under Warming

✳**Rapid-onset FDs transition toward flash-persistent droughts in the future.**

✳**Slower-onset FDs shift toward gradual, longer-lasting soil moisture drought conditions.**

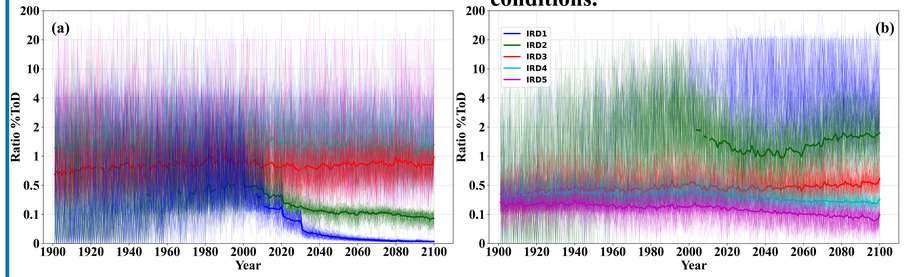
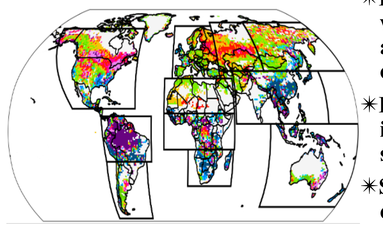


Fig. 4: Global temporal distribution of the ratio of flash drought occurrences relative to flash-persistent droughts (a) and conventional soil moisture drought (b) from Time of Disappearance to 2100, stratified by intensification rate duration (IRD1-IRD5). Thin lines represent individual 90 members, while the thick lines denote the ensemble mean for each IRD..

What Drives Flash Drought Onset?



✳**Increased evapotranspiration, which extends the warm season, reduces surface runoff and accelerates the onset of flash droughts, regardless of precipitation levels.**

✳**Rapid-onset, FD IRD1, becomes the new normal in Europe, with a strong clustering during spring–summer.**

✳**Slower-developing, FD IRD5, remains seasonally constrained, centered on May–June.**

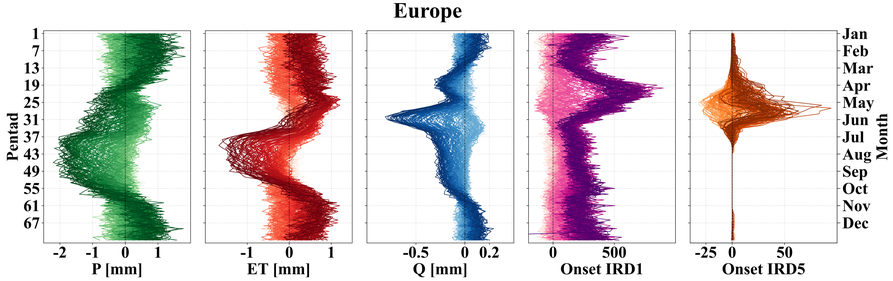


Fig. 5: Regional hydroclimatic anomalies and flash-drought onset dynamics in FD-prone regions. Pentad-scale anomalies in precipitation (P), evapotranspiration (ET), and runoff (Q), along with changes in the cumulative occurrence of FD onset based on intensification rate durations of one and five pentads (IRD1 and IRD5), relative to the pre-industrial baseline (1850–1899). Each thin line denotes an individual year spanning 1850–2100; lighter shades correspond to earlier years and darker shades to later years.