Soil Moisture Dominates the Land Surface Feedback in Compound Drought-Heat Extremes in Tropical South America

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Abstract

South America has experienced increasingly frequent extreme drought events. In Amazonia, all ten droughts recorded during 1979-2018 coincided with heatwaves; similarly, heatwaves over central and southeast Brazil were always accompanied by soil droughts. Despite the growing body of observational evidence highlighting the co-occurrence of drought and heat extremes in tropical South America, the mechanisms driving their simultaneous occurrence remain largely unexplored. In this study, we employ numerical experiments using CESM2 with prescribed oceanic forcing to assess how extreme soil temperature and soil moisture affect subsequent hydrometeorological conditions in tropical South America, with a focus on the pre-monsoon season when land-atmosphere coupling is strong. The results reveal a different diurnal pattern in the strength of the surface air temperature response, with a stronger nighttime response to soil temperature anomalies and a stronger daytime response to soil moisture anomalies. Elevated initial soil temperature or reduced initial soil moisture tends to yield warmer and drier conditions and increase the occurrence of both drought and heat extremes, with stronger and longer-lasting responses to soil moisture anomalies (than soil temperature anomalies). The simulated responses to initial soil moisture anomalies alone closely resemble those in the experiment with combined soil temperature and moisture anomalies. These findings underscore the dominant role of soil moisture feedback in shaping compound drought-heat extremes, highlighting its importance in the modeling and prediction of hydrometeorological extremes.

Methodology

"Slope" approach to soil initializations: Constructing the initial soil conditions making use of the slopes of linear regression between a variable over a target area and its surrounding region (Jiang & Wang, 2023).

Experimental Design:

- **Control**: CESM2 with prescribed SST and Sea Ice, *f09* resolution, 34-year continuous run (1980-2018)
- **Multiple 1-month 10-member ensemble experiments (Sept.1 & Nov. 1):**
  - With extreme anomalies of initial soil moisture, initial soil temperature, or their combinations (Table 1)
  - With initial atmospheric conditions from Sept. 1st or Nov. 1st of each year during 2006-2015 of the Control

TABLE 1. List of sensitivity tests

Test Name	Ensemble Experiments (10 members each)	Initial soil temperature in the target area	Initial soil moisture in the target area
Tsoi test (Hot minus Cool)	Hot ensemble	99th percentile Tsoi	Soilliq from each of the 10 years in the long control
	Cool ensemble	1st percentile Tsoi	Soilliq from each of the 10 years in the long control
Soilliq test (Dry minus Wet)	Wet ensemble	Tsoi from each of the 10 years in the long control	99th percentile Soilliq
	Dry ensemble	Tsoi from each of the 10 years in the long control	1st percentile Soilliq
Combined test (HotDry minus CoolWet)	HotDry ensemble	99th percentile Tsoi	1st percentile Soilliq
	CoolWet ensemble	1st percentile Tsoi	99th percentile Soilliq

Differences in Initial Anomalies

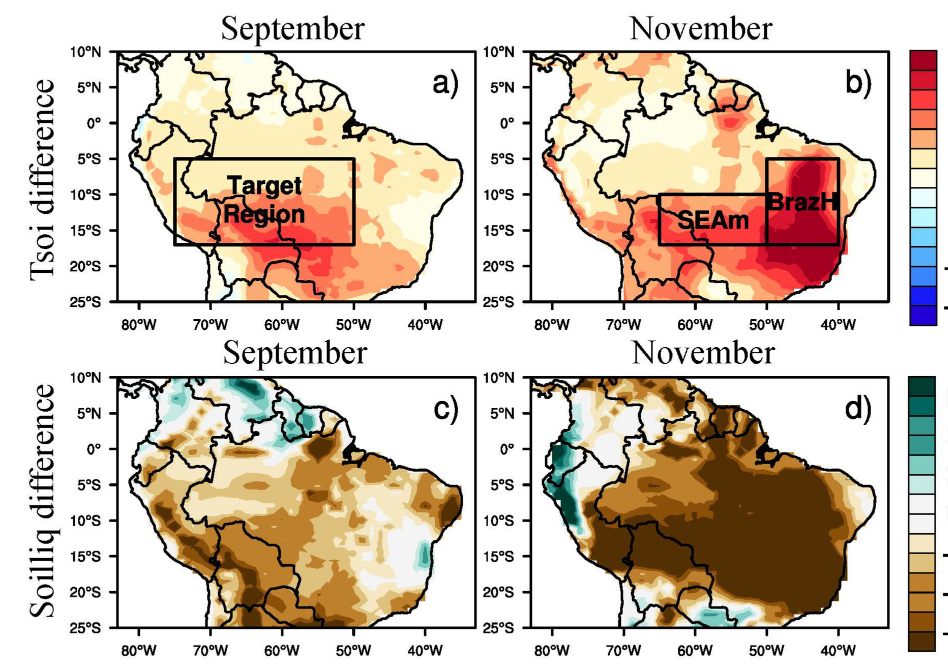

Fig. 1 Differences in the constructed initial soil temperature (a-b; in K) between the Hot and Cool experiments and in the constructed initial soil moisture (c-d; in mm) between the Dry and Wet experiments in the top 10 cm of soil for September and November. Rectangular box in 1a) indicates the target region of extreme soil anomalies (1st or 99th percentile).

Results Analyses

Focus on two subregions:

- Southeast Amazon (SEAm, box in Fig 1b)
- Brazil Highland (BrazilH, box in Fig.1b)

Response to Initial Soil Anomalies:

- Tsoi test (impact of initial soil moisture): Hot - Cool
- Soilliq test (impact of initial soi moisture): Dry - Wet
- Combined test (impact of both factors): HotDry - CoolWet

Soil Memory and Impact

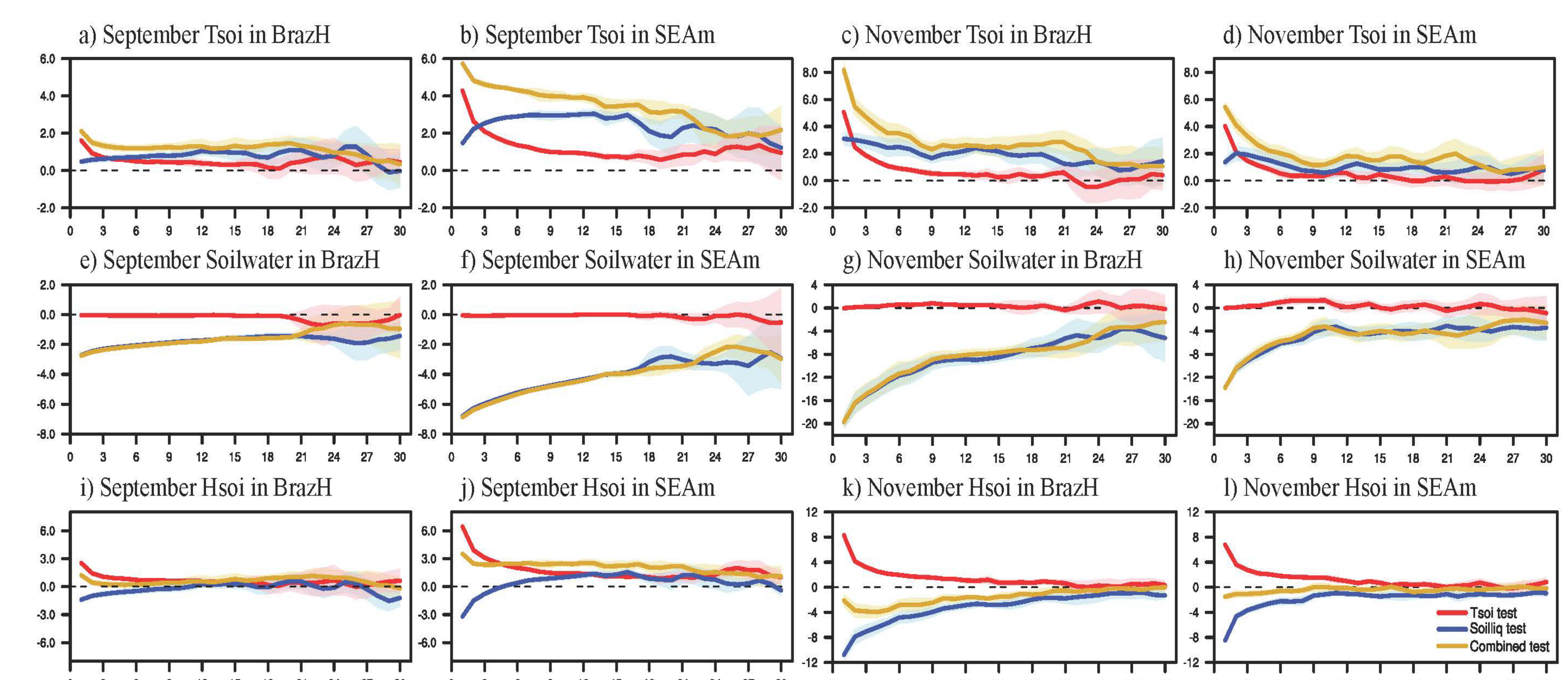

Fig. 2 Daily time series of differences in the ensemble mean of soil temperature (K), soil water (mm), and soil enthalpy (MJ/m^3) averaged over SEAm and BrazilH in September and November, in top 10cm of soil.

Summary

- Soil temperature anomalies in the absence of soil moisture anomalies *dissipate* rapidly;
- Soil temperature anomalies can *develop* rapidly in response to soil moisture anomalies through latent heat flux responses;
- Soil moisture anomalies influence daytime temperature (T_{max}) more than nighttime (T_{min});
- Soil enthalpy does not provide a coherent indication on the impact of initial anomalies of soil conditions (temperature and/or moisture).

Mechanisms

- **Stronger impact of soil moisture anomalies than soil temperature anomalies**
  - The latent heat needed to eliminate a soil moisture anomaly of 0.1 m^3/m^3 through ET is enough to change the soil temperature by 88K!
- **Stronger responses to initial soil temperature anomalies at night and stronger response to initial soil moisture anomalies during the day**
  - Night time: heat transport relying on LW emission (function of soil temperature)
  - Daytime: Latent heat flux (ET) response to soil moisture differences is strong during the day when turbulence is strong and is negligible at night due to the stable boundary layer.

Impacts on the Temperature & Extremes

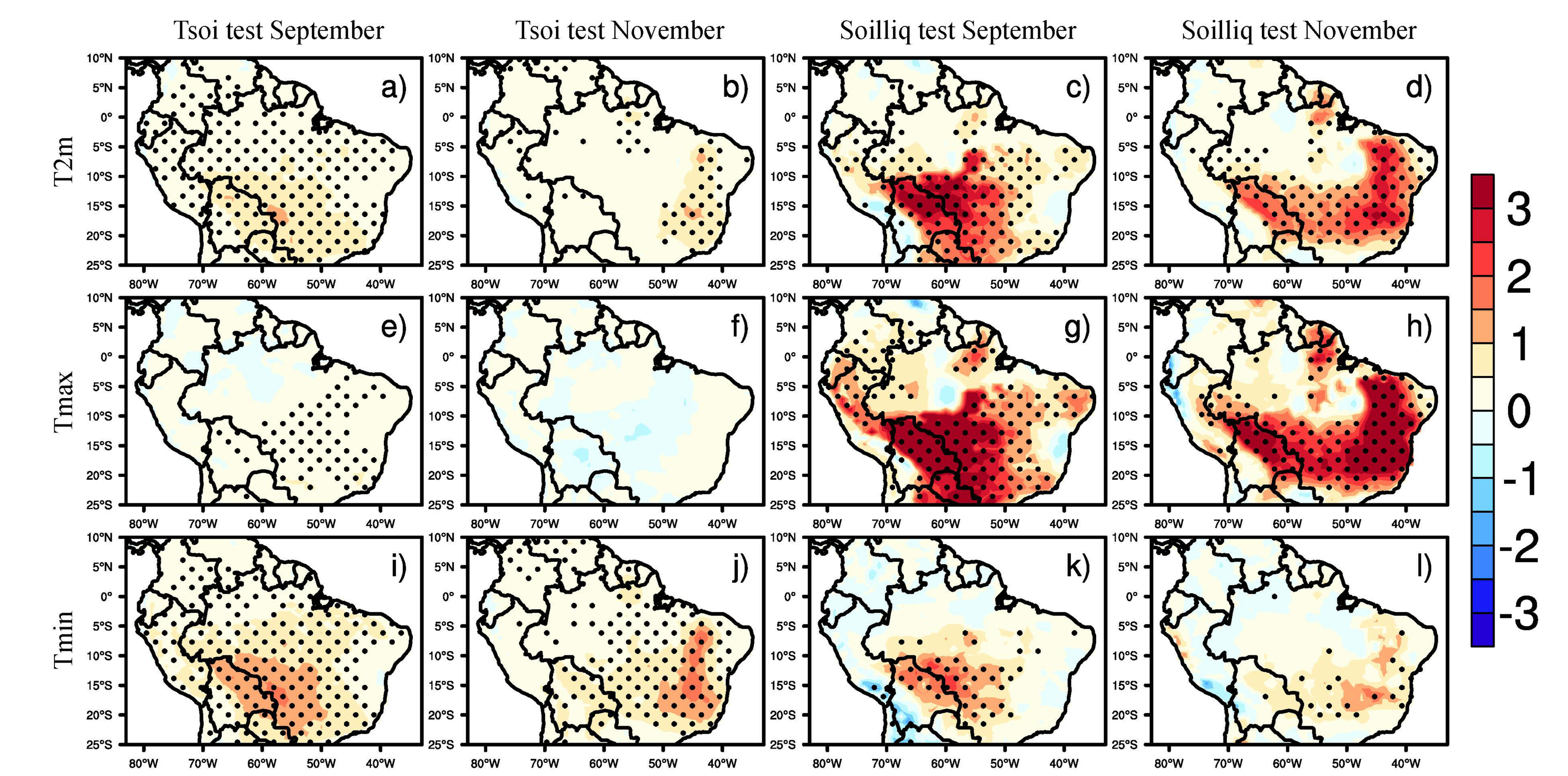

Fig. 3 Ensemble mean of daily average (a-d), maximum (e-h), and minimum (i-l) 2m air temperature responses in the Tsoi and Soilliq tests, averaged during the first 10-day of the simulations. Stippling indicates areas where the signal-to-noise ratio is larger than 1. Unit: in K.

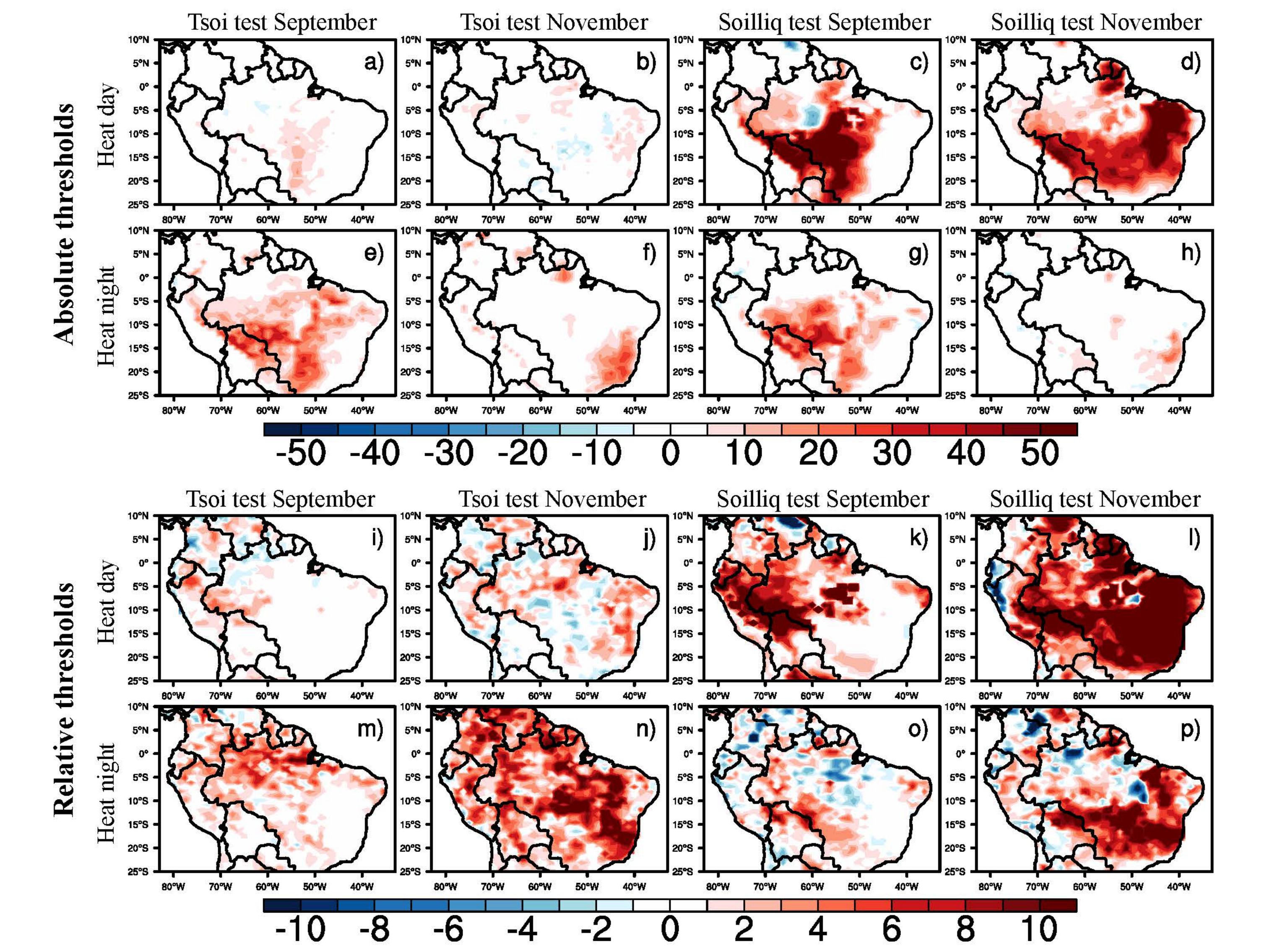

Fig.4: Ensemble mean of difference in the probability (in %) of heat day (1st and 3rd rows) and heat night (2nd and 4th rows) in the Tsoi and Soilliq tests. The first 10 days of each ensemble are selected for estimating the extreme heat statistics. The absolute thresholds are set at 93F (for heat day) and 68F (for heat night), and the relative thresholds are the 95th percentile.

Acknowledgment:
Funding from NSF (AGS-1659953); computational support from NCAR CISL (UCNN0012).

References

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