A Multivariate Conditional Probability Framework to Estimate Compound Sub-daily Rainfall Extremes Preconditioned by Humid Heatwaves

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WISER PG/47/2022-23/514

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Heatwaves are becoming near norm in Summer & Spring Seasons in India

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Reuters, 2023

Winter heat stress impacts grain filling, causes early senescence, reducing crop yields … especially for wheat

IMD Statement on Climate, 2022

Summer heat stress impacts human health, energy production; extended warm spell leads to changes in precipitation.

Severe Summer heatwaves in May 1998 resulted in over 2500 fatalities (GSDMA, 2023)

Extreme humid heat in South Asia in April 2023, largely driven by climate change, detrimental to vulnerable and disadvantaged communities

17 May, 2023

HEATWAVE

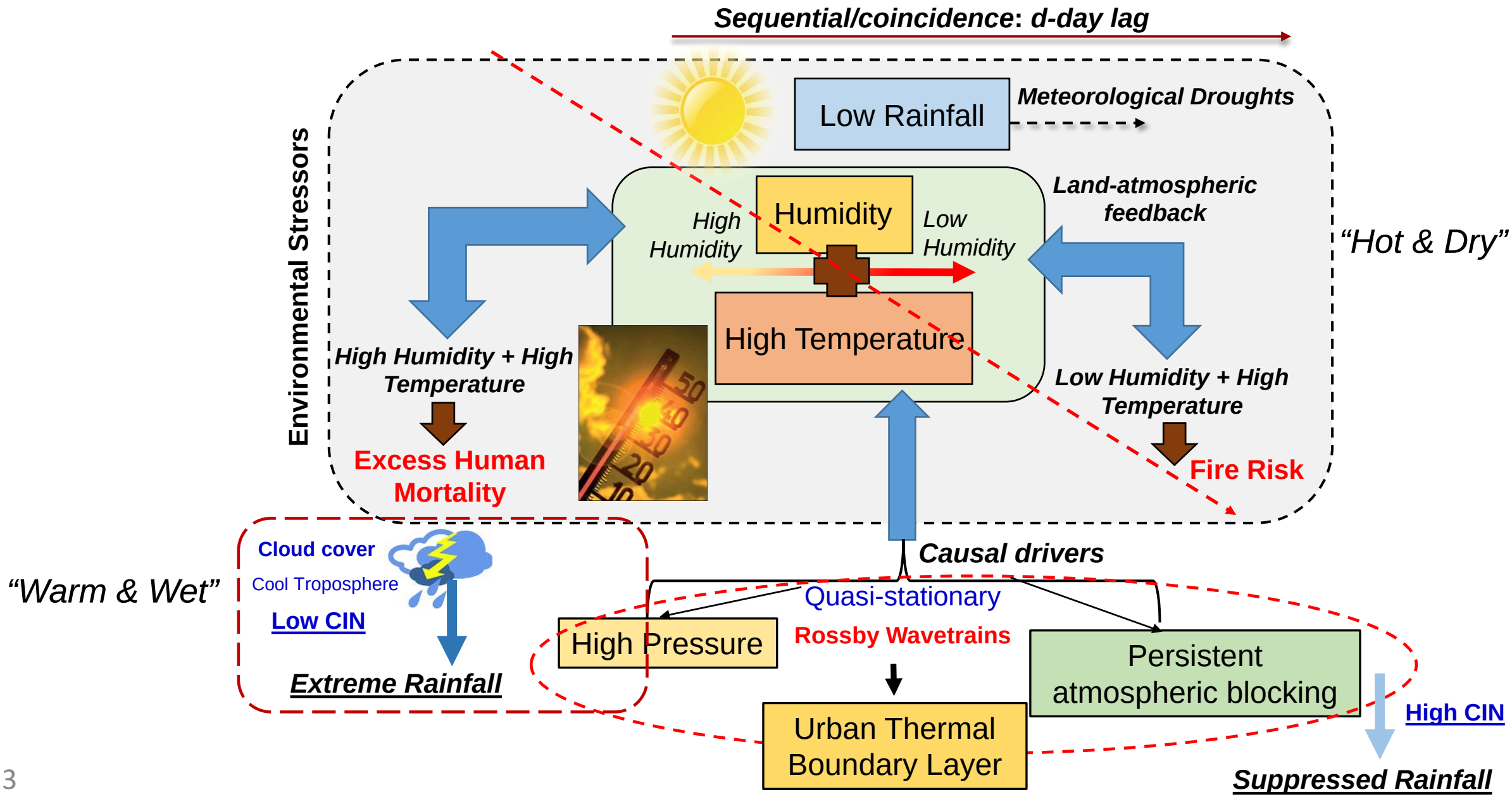
ASIA

For the last two weeks of April 2023, many parts of Bangladesh, India, Thailand and Lao PDR experienced record high temperatures.

In Bangladesh, Dhaka observed the highest maximum temperature recorded in decades of 40.6°C on 15th April. In India, several northern and eastern cities recorded maximum temperatures above 44°C on 18th of April. Thailand recorded its highest ever temperature of 45.4°C on 15th April in the city of Tak.

World weather Attribution, 2023

Hot-Dry versus Warm-Wet Compound Hazard



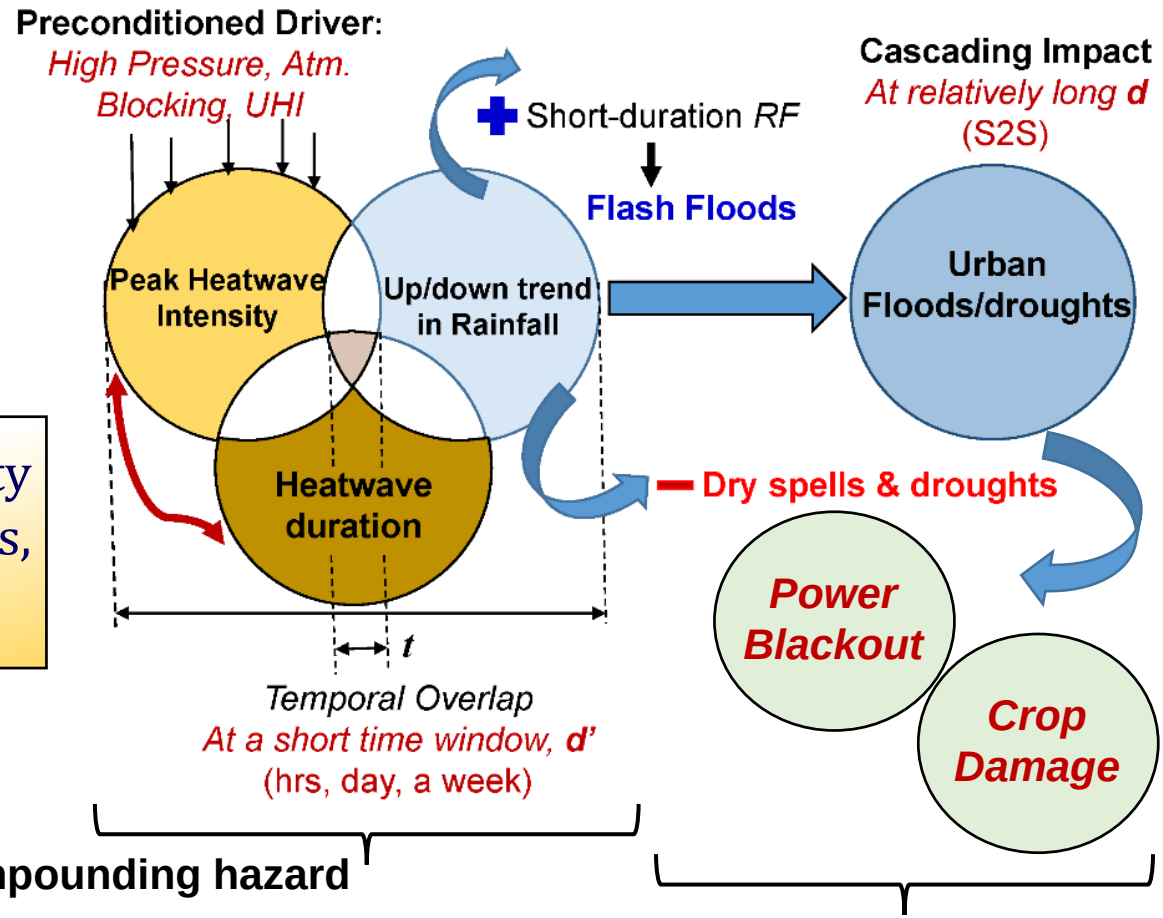
Research Gaps & Questions

- Studies have implemented different definition of compound 'warm-wet/dry' events considering *different datasets with varying* spatiotemporal resolutions.
  - Assessments have mostly focused on bivariate framework at global (Gu et al. 2022) & regional (Chen et al. 2021; Kumar et al. 2022) domain.

✓ Any approach to quantify exceedance rainfall probability conditioned on preceding humid heatwave characteristics, *duration* and *heatwave amplitude/peak intensity*?

Lengthening of dry spells intensify heat stress → *duration* is a crucial metrics (He et al., 2022)

Compound & Cascade Hazards from Heatwave & Rainfall

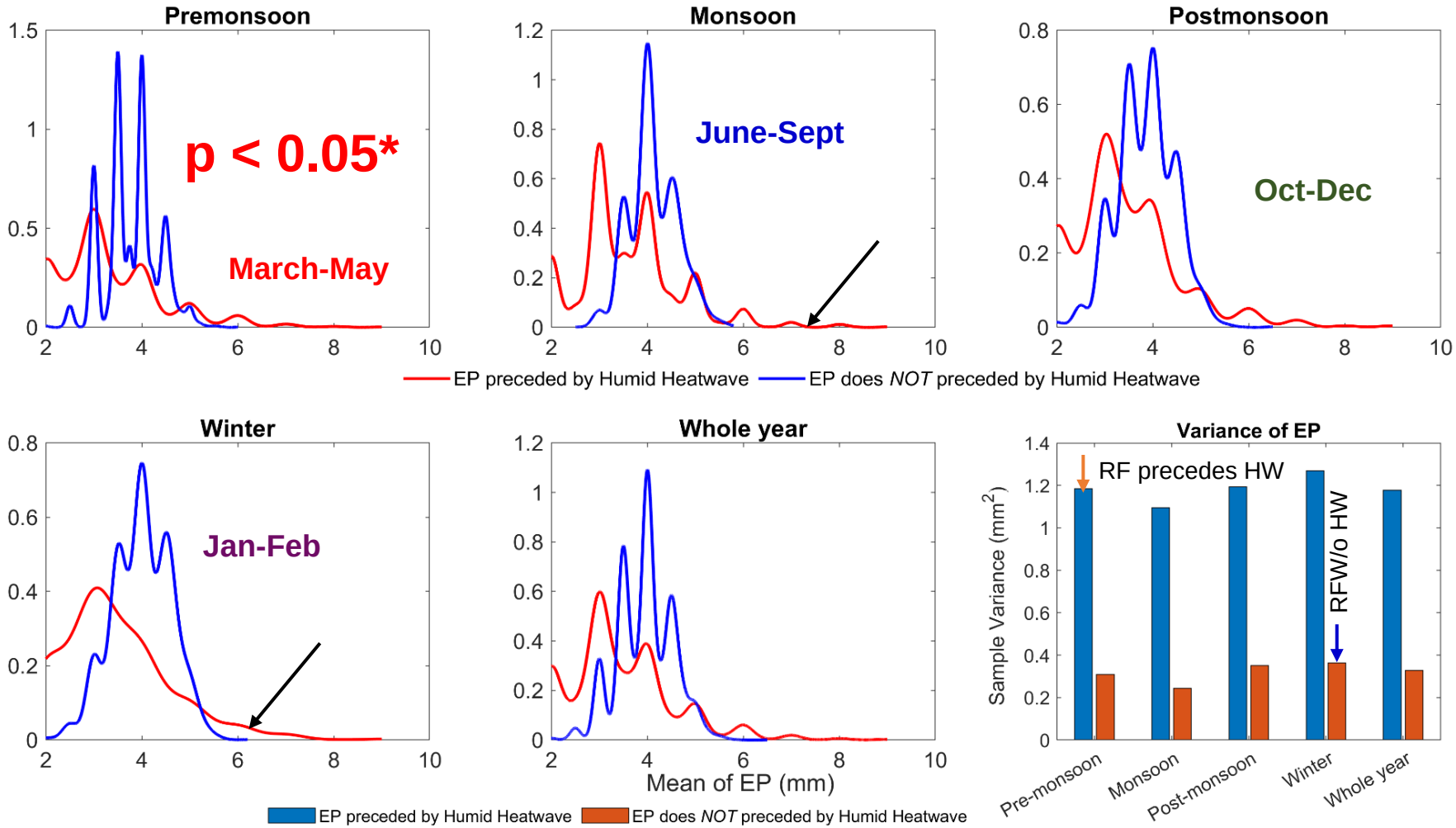


Link between Preceding Heat Stress & Following Extreme Precipitation

- Rain events preceded by humid heatwave episodes show a heavier tail with multiple peaks for larger magnitudes.
  - The variability of rain preceded by heatwaves show larger variance.

- Humid heatwave is detected when daily maximum T_w (from 3-hourly observation) *exceeds* temperature thre (> 90th percentile) > 3 days or longer.
- EP is the sub-daily maximum rainfall, which is > 50th percentile of rainfall sampled at a 3-hourly scale.

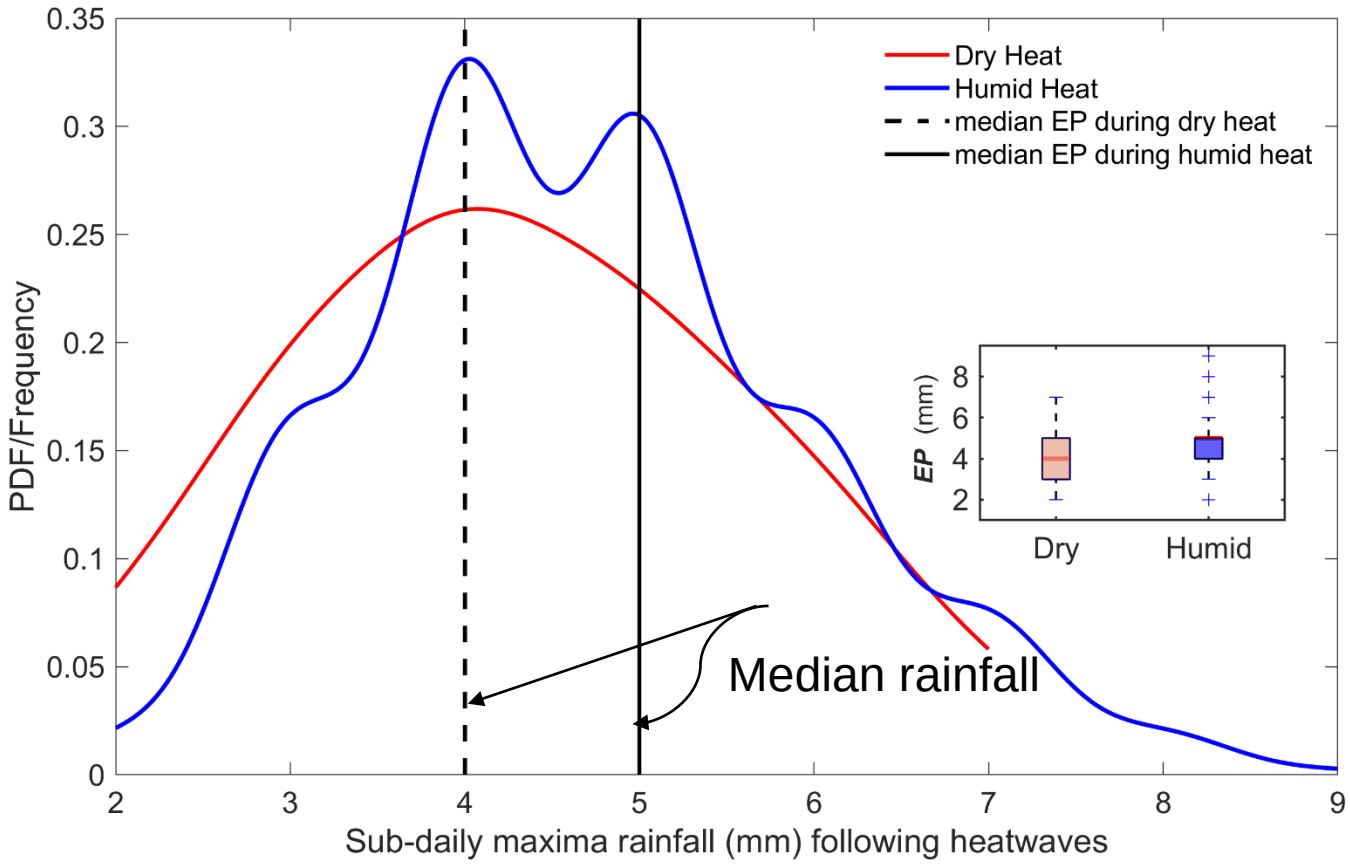
Sub-daily Meteorological records: IMD Data Supply Portal (3:00–12:00 hr UTC)



*Two-sample KS Test

Humidity Dictates Tail Properties of Extreme Precipitation

- Dry heat: $T_w < 33\%$ Rh
- Humid heat: $T_w > 67\%$ Rh



p < 0.05: Two-sample KS Test

Increasing Trends in Compound Warm-Wet Compound Extremes across Seasons

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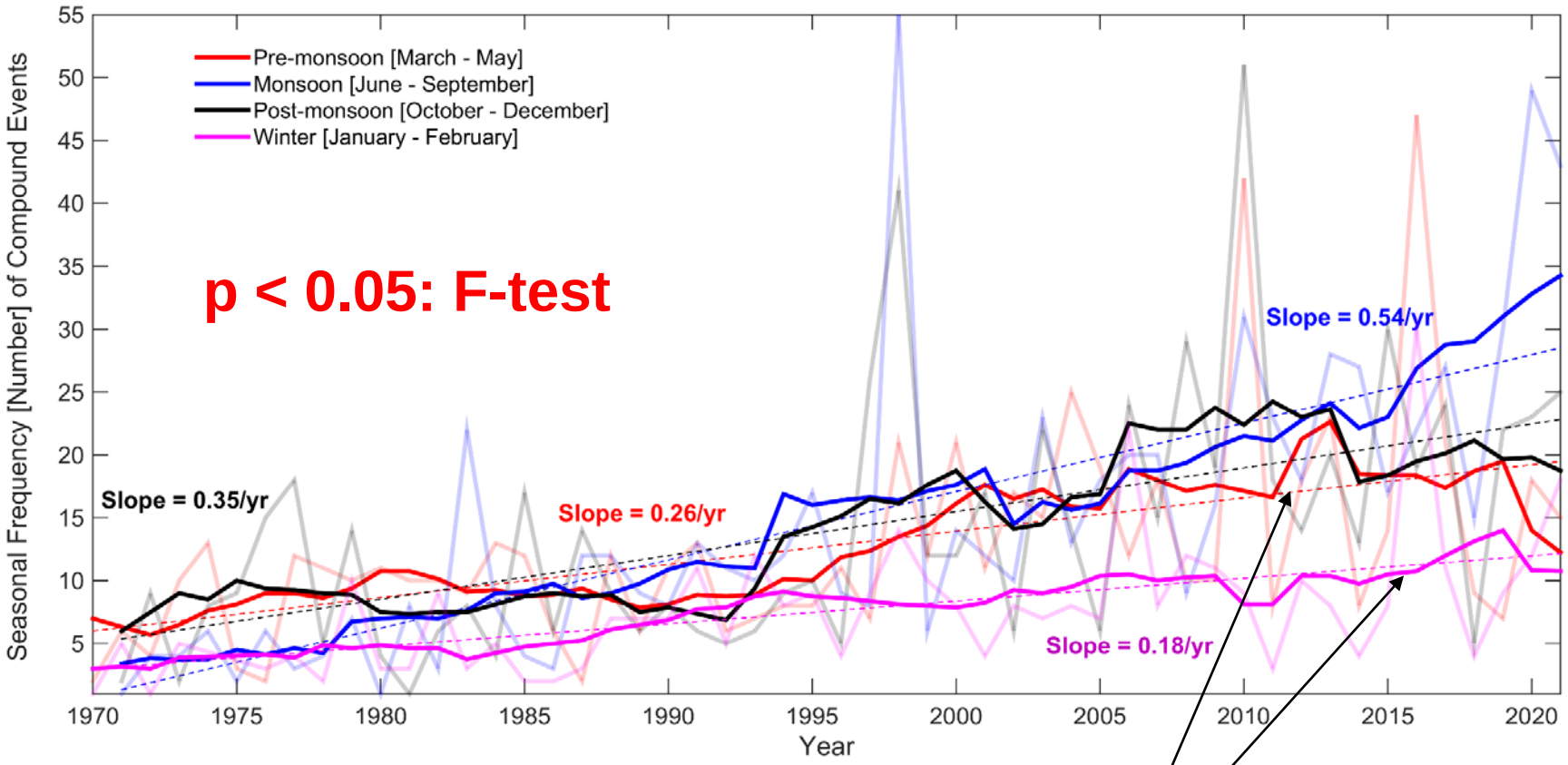
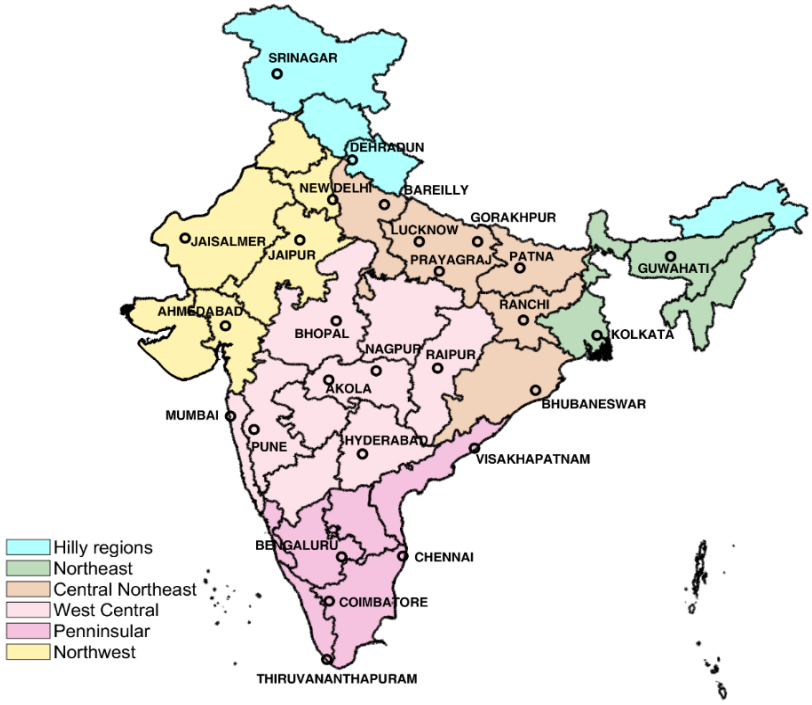
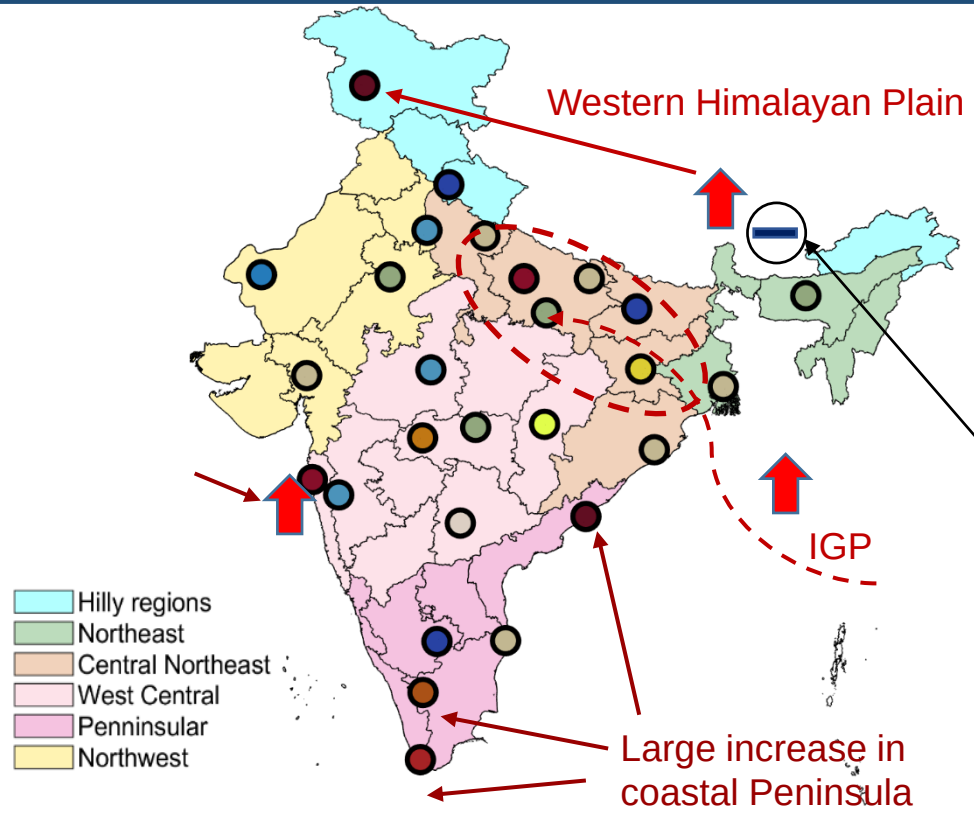


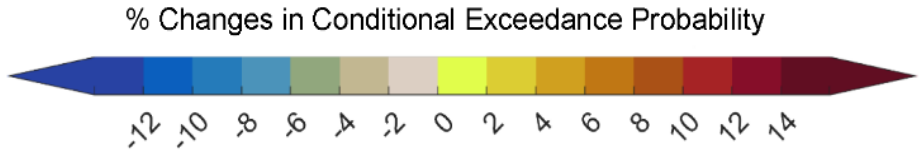


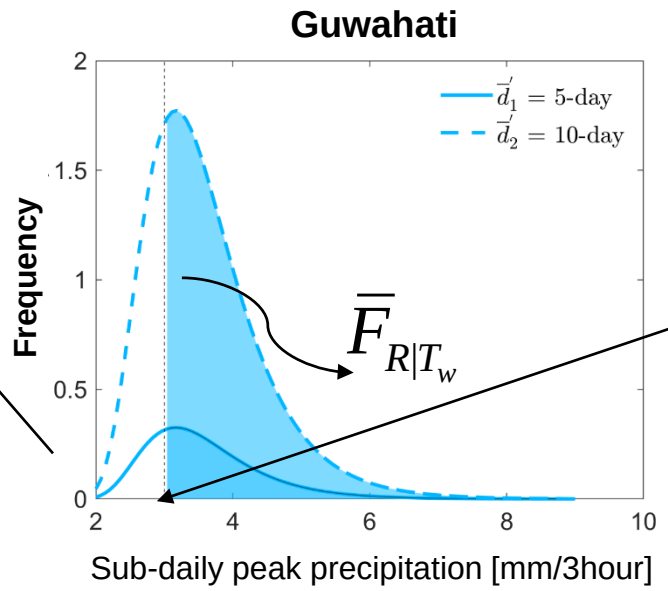
Smoothed using 8-year moving average

Compound "Warm-Wet" events are detected when humid heat stress precedes peak rainfall of a heavy rainfall event (> 50th percentile threshold) within $t \epsilon$ [-1, 7] window.

More Land Areas Show Decline in Sub-daily Peak rainfall, while a Localized Increase is Apparent







$$\bar{F}_{R|T_W}\left(R>r\,|\,T_w=10-yr,d'\right)=1-F_{R|T_W}\left(R\le r\,|\,T_w=10-yr\right)$$

Avg. of sub-daily rainfall maximum

Trivariate copula-based framework

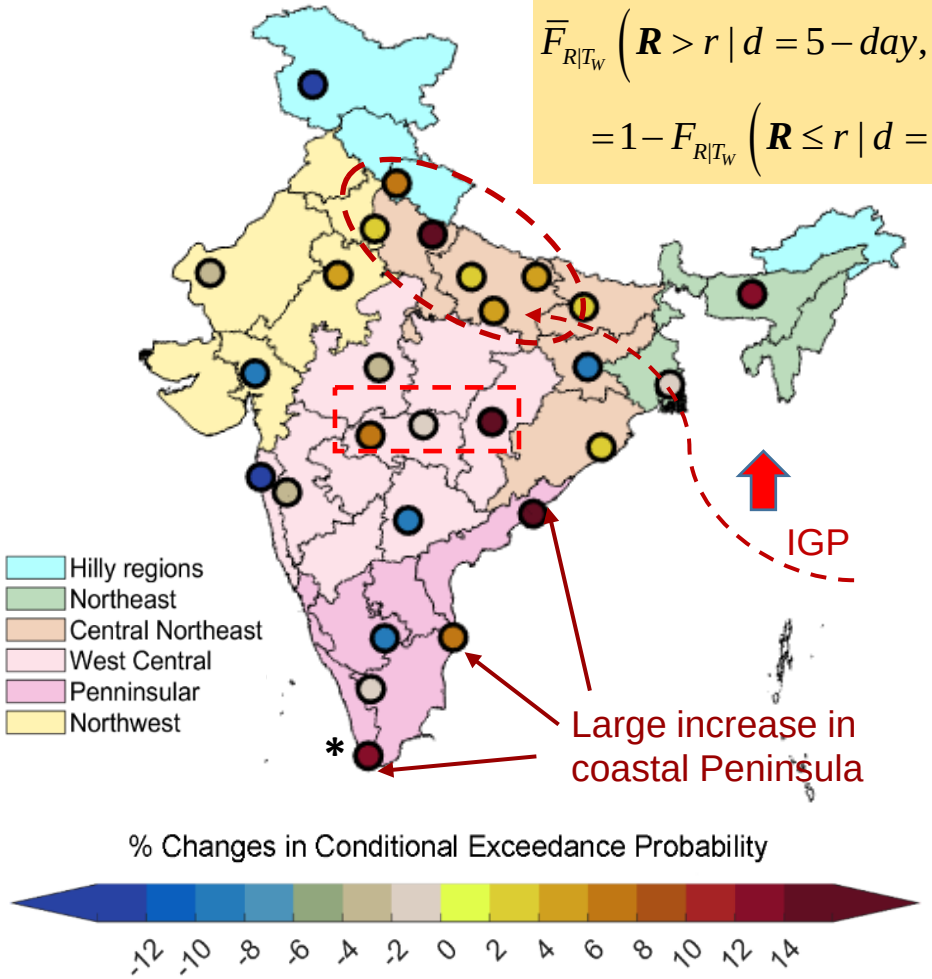
$$C\left(u_1,\ldots,u_d;\vartheta,\Sigma\right)=t^d_{\vartheta,\Sigma}\left(t^{-1}_{\vartheta}\left(u_1\right),\ldots,t^{-1}_{\vartheta}\left(u_d\right)\right),\qquad \vartheta\in(2,10]$$

$$t^d_{\vartheta,\Sigma}\left(x\right)=\int_{-\infty}^{x}\frac{\Gamma\left(\left(\vartheta+d\right)/2\right)}{\Gamma\left(\vartheta/2\right)\left(\vartheta\pi\right)^{d/2}\sqrt{|\Sigma|}}\left(1+y^T\Sigma^{-1}\,y/\vartheta\right)^{-(\vartheta+d)/2}dy$$

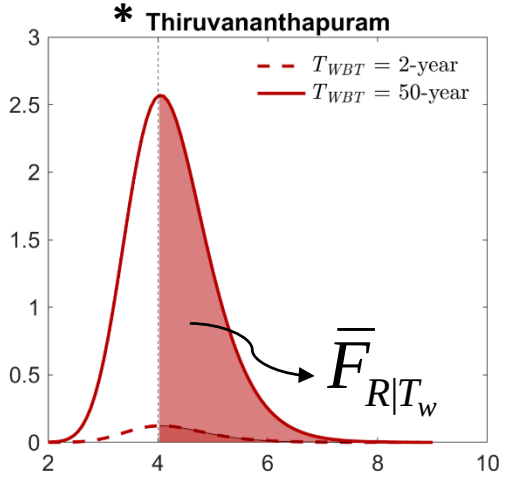
With increase in durations from 5-day to 10-day & with T_w = 10-year peak heatwave amplitude, ~67% sites show **decline** in peak precipitation

More Land Areas Show Increase in Sub-daily Peak Rainfall, with Increase in Peak Heatwave Intensity

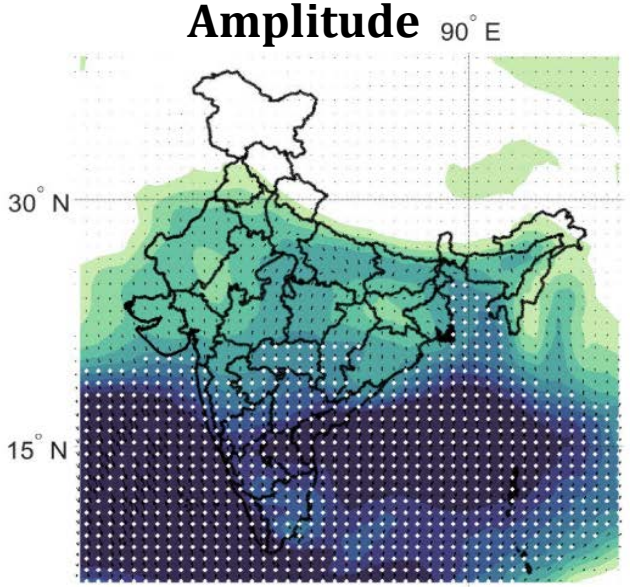
$$\bar{F}_{R|T_w}\left(\boldsymbol{R} > r \mid d = 5-day, T_w'\right)$$
$$= 1 - F_{R|T_w}\left(\boldsymbol{R} \le r \mid d = 5-day, T_w'\right)$$



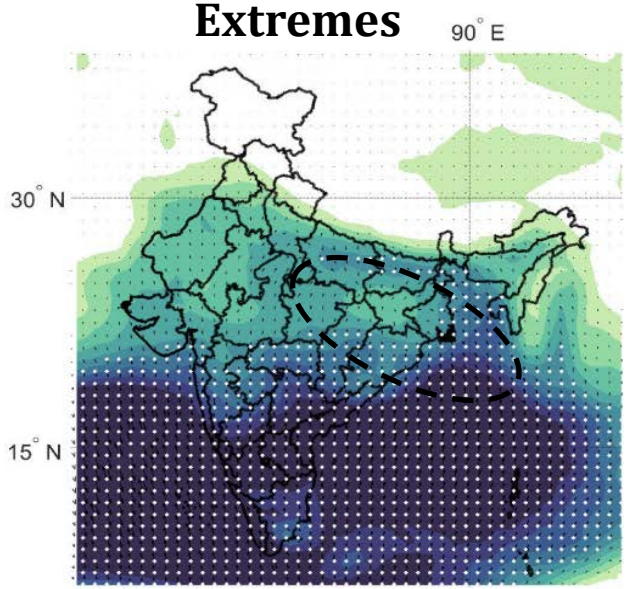
With increase in T_w = 2-year to T_w = 50-year peak heatwave amplitude for 5-day long events, > 50% sites show **increase** in peak precipitation

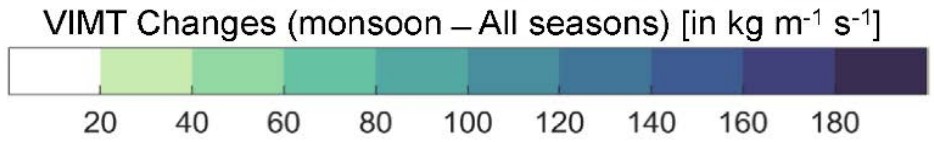


Day of Peak Heatwave Amplitude



Day of Sub-daily Rainfall Extremes





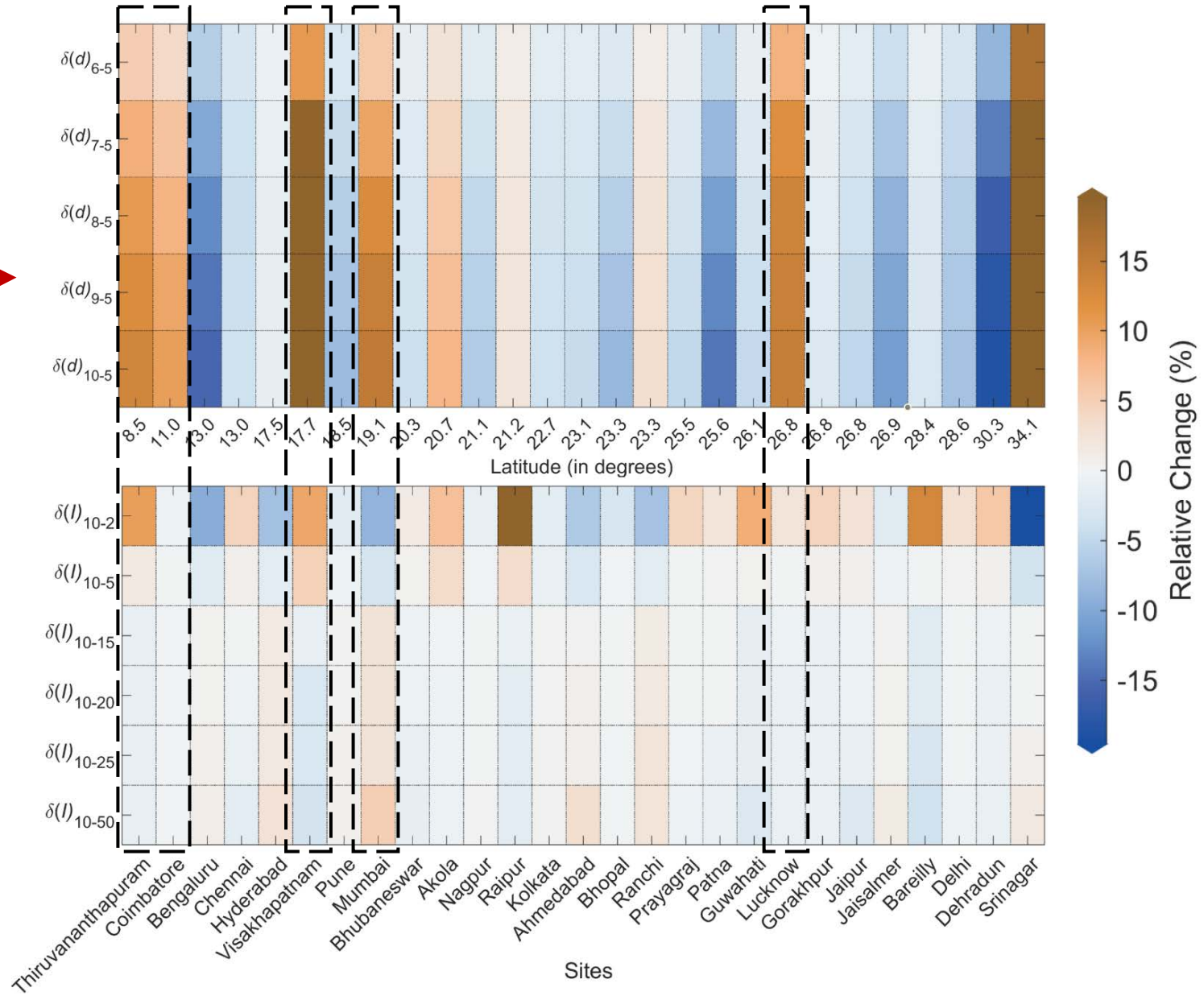
*≥100 kgm^{-1}s^{-1} with p < 0.01

Vertical Integrated Moisture Transport (VIMT) during heatwave and following peak precipitation days

Sensitivity of Extreme Precipitation to Heatwave Characteristics

$$\frac{\bar{F}_{\boldsymbol{R}>r|d',T_w=10-yr} - \bar{F}_{\boldsymbol{R}>r|d,T_w=10-yr}}{\bar{F}_{\boldsymbol{R}>r|d',T_w=10-yr}} \times 100$$

$$\frac{\bar{F}_{\boldsymbol{R}>r|d=5-day,T_w'} - \bar{F}_{\boldsymbol{R}>r|d=5-day,T_w}}{\bar{F}_{\boldsymbol{R}>r|d=5-day,T_w'}} \times 100$$



Key Highlights

- Robust **upward trend** in frequency of warm-wet compound events across all seasons.

- Their Extremes show **Contrasting** space-time *trends*

  - Sub-daily rainfall maximum shows notable changes in exceedance probability in response to changing humid heatwave properties.

  - Rainfall extremes increase with an increase in preceding heatwave intensity over 50% of sites
  - Rainfall peaks decrease with increasing heatwave durations over 60% of sites.

    - The decrease in rainfall peaks is possibly due to moisture limitations – heat-induced suppression of rainfall over *land* & storm-induced temperature variations over ocean (Fowler et al., 2021; Sun and Wang, 2022).

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Q&A; Thanks!