ICRC-CORDEX 2023
International Conference on Regional Climate-CORDEX 2023

Soil moisture revamps the temperature extremes in a warming climate over India

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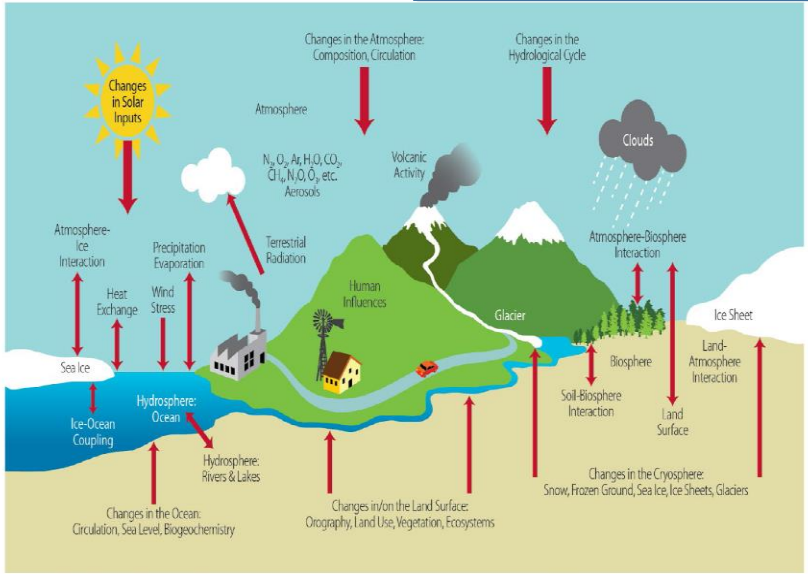
npj Clim Atmos Sci **6**, 12 (2023). https://doi.org/10.1038/s41612-023-00334-1

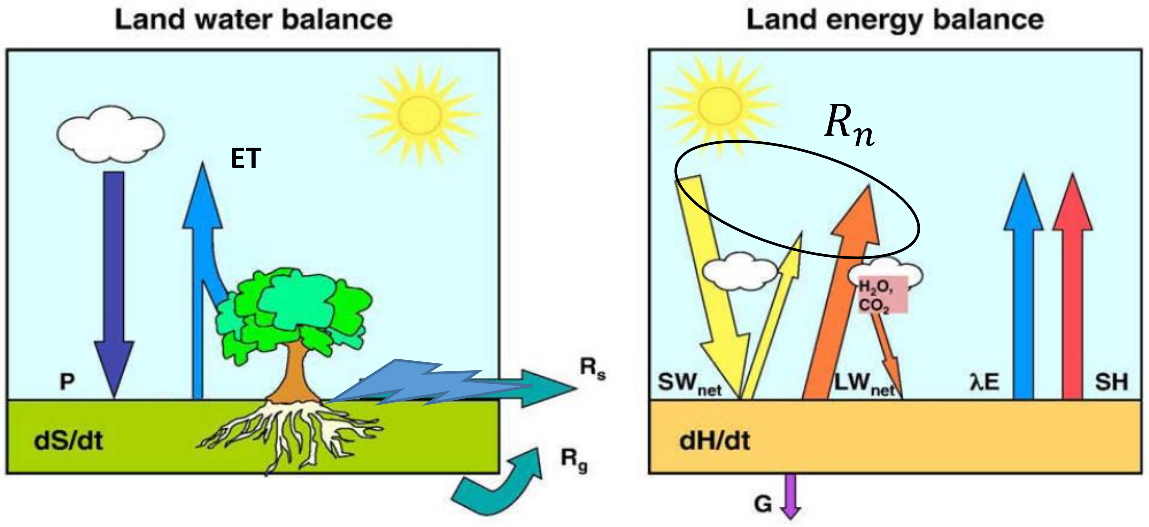
Introduction



An illustration of the main components of the climate system (the **Atmosphere, Hydrosphere** [liquid water components], **Cryosphere** [frozen water components], **Biosphere** [living things]) and **lithosphere** [land surface] and the interactions between them.

- **The water stored on land (soil moisture) is a key variable controlling numerous processes and feedback loops within the climate system.**
- **Soil moisture (SM) plays an important role in the earths hydrological cycle and surface energy balance.**
- **Soil moisture not only regulates partitioning of net radiation into sensible, latent, ground heat flux and surface heat change but also it will help in partitioning of precipitation into Evapotranspiration, infiltration, changes in soil moisture and runoff.**

Schematic of the land water balance (left) and land energy balance (right) for a given surface soil layer.



P=ET + R_s+ R_g + dS/dt

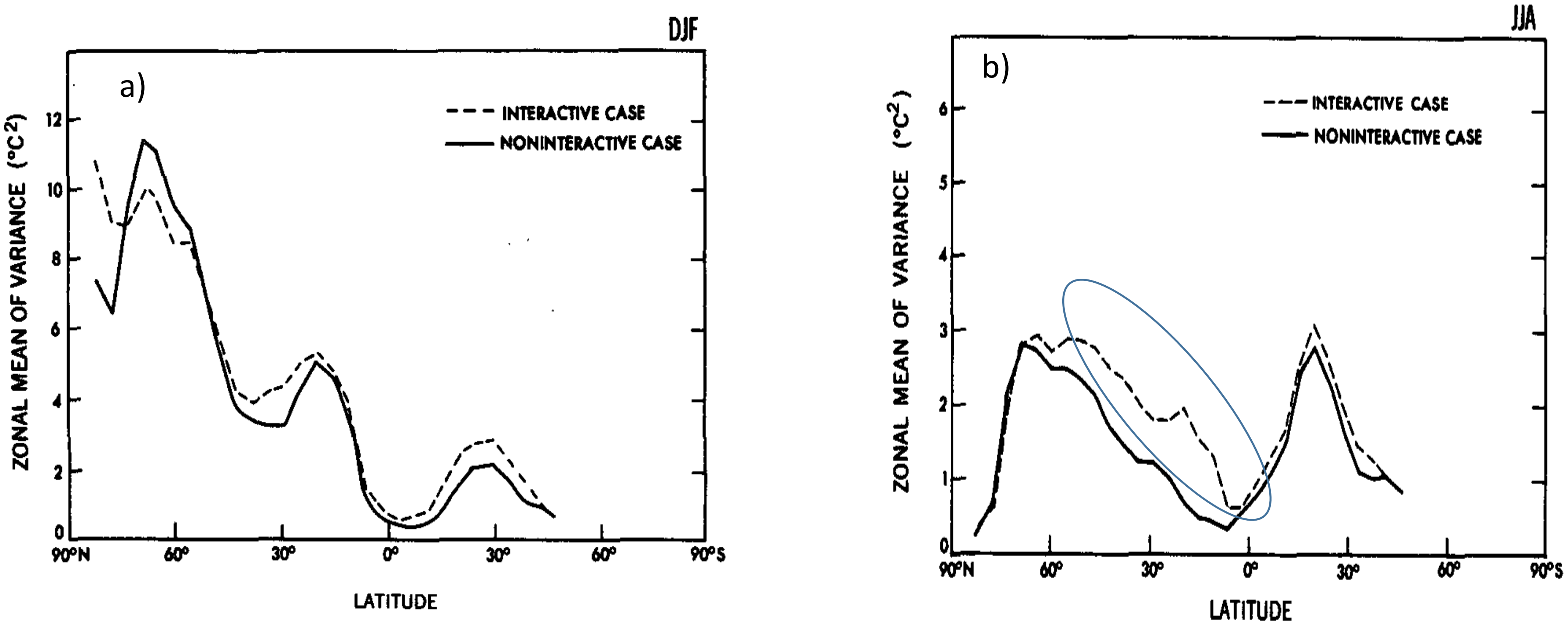
R_n= SH + λE+ dH/dt+G

P- Precipitation
ET- Evapotranspiration
R_s- Runoff
R_g- Infiltration
dS/dt - Soil moisture change

R_n - Net radiation
G - Ground heat flux
λE - Latent heat flux
SH- Sensible heat flux
dH/dt- surface heat change

IPCC AR4, Seneviratne 2010, Earth-Science Review

Soil moisture-temperature interaction



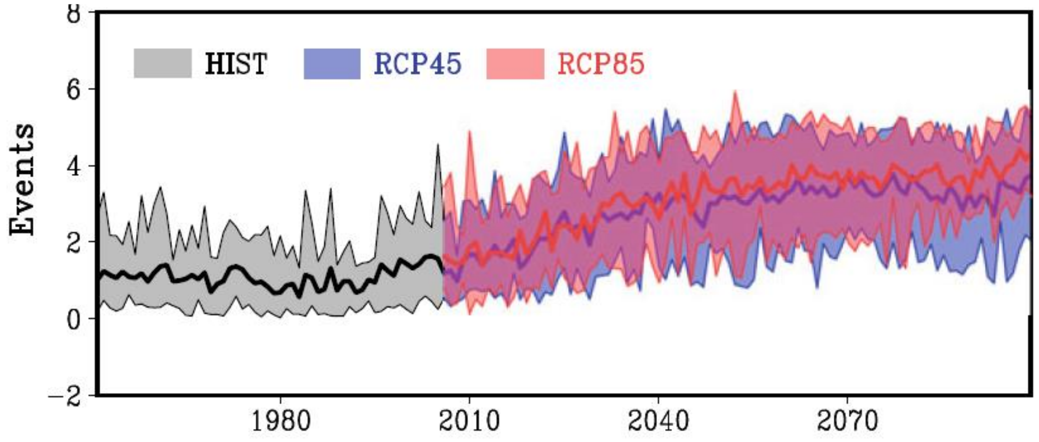
Zonal mean surface air temperature variance

Interaction between soil moisture and atmosphere have potential to make substantial contribution to temperature variability.

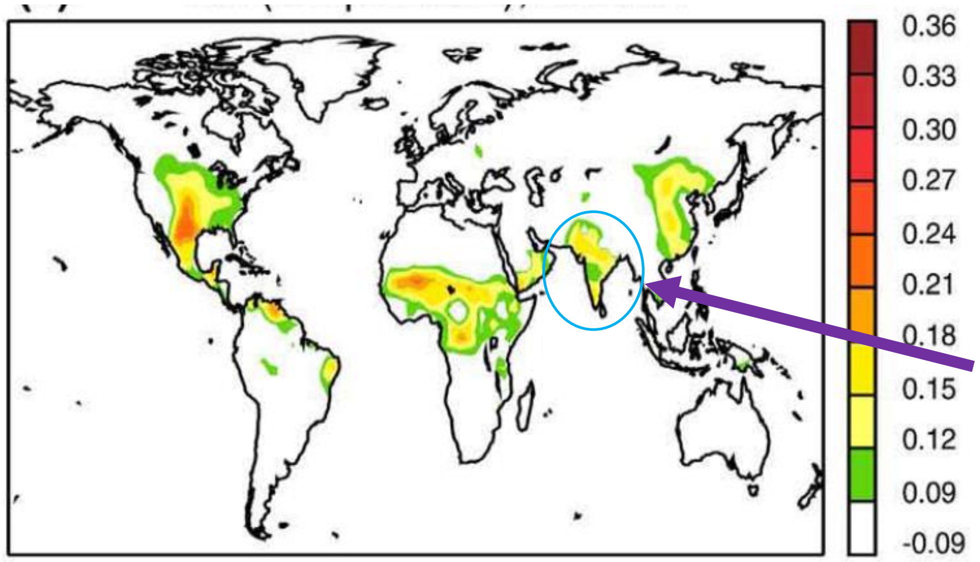
Delworth and Manabe (1988)

Temperature extremes over the Indian region

Time series of all India averaged CORDEX South Asia multi-RCM projections of the summer (April–June) heatwave a frequency.



Global hot-spots of soil moisture-temperature coupling in boreal summer



- **Observations shows an strong increase of number of hot days during the recent period over the Indian region.**

  Kothawale et al (2010)

- **Model projection shows an increase of about 5.5 and 6.5 heatwave events per season by the end-twenty-first century under the RCP4.5 and RCP8.5 emission scenario, respectively.**

  Krishnan et al., 2020 (MoES climate change Assessment report)

- **Heat wave events over India during pre-monsoon season associated with persistence high, depleted soil moisture and clear sky conditions.**

  Rohini et al., 2016

- **Heat waves over north central India are linked to blocking events over the North Atlantic, while heat waves over the coastal eastern part of India have atmospheric teleconnections with anomalous cooling in the Pacific.**

  Ratnam et al., 2016

- **Importantly higher land-atmosphere coupling over the Indian region indicates the dominant control of soil moisture on temperature variability.**

  Seneviratne et al 2010

What is the role of soil moisture on temperature extremes over the Indian region?

Observations analysis

Model diagnosis

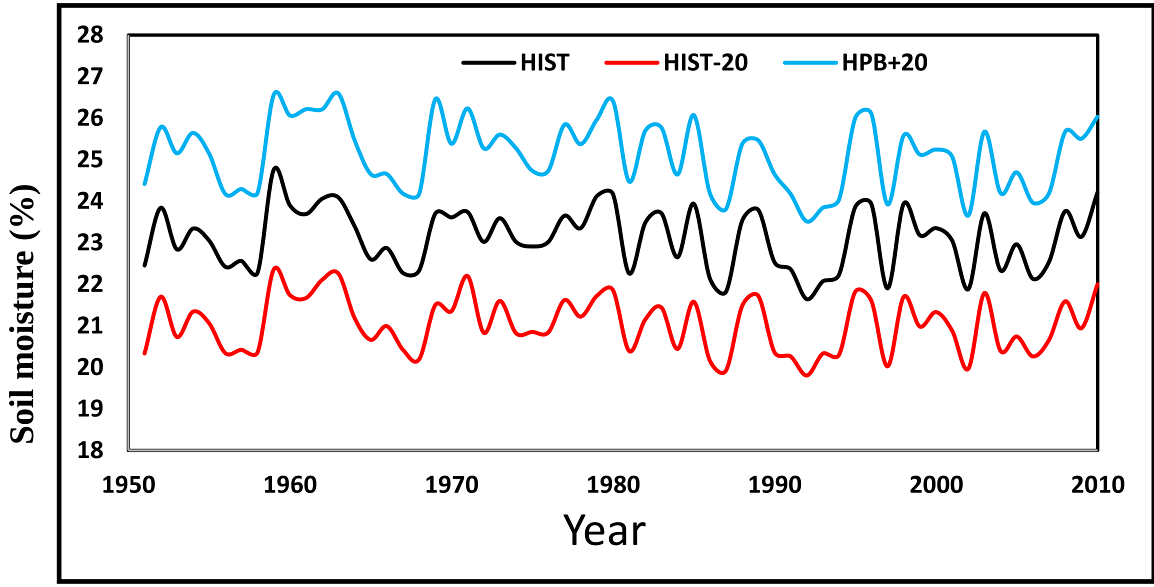
Objectives

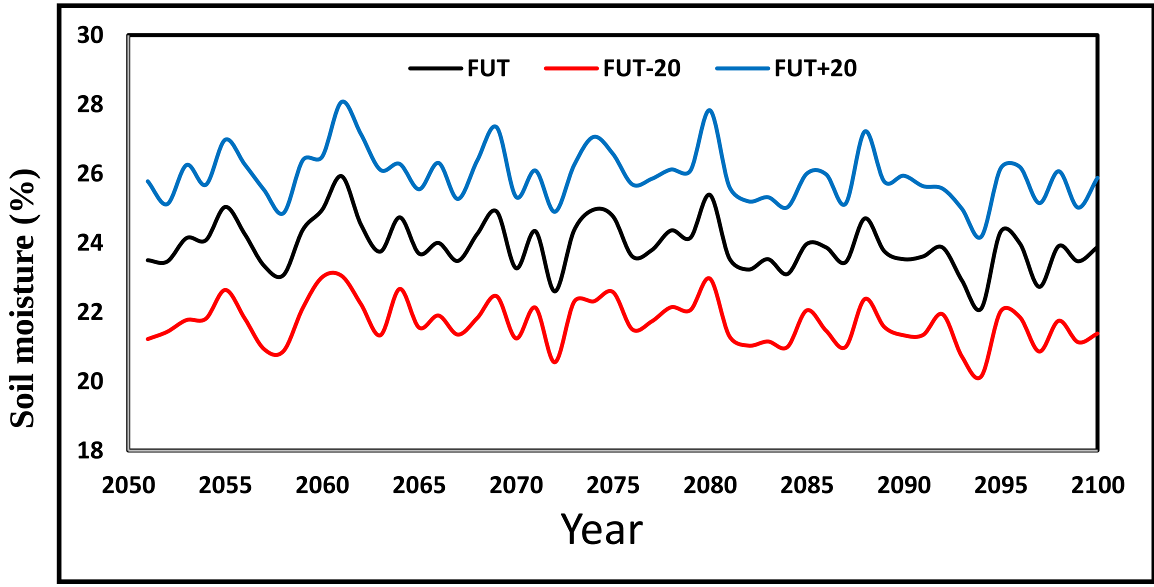
- Understanding the extreme temperature changes over the Indian region in historical and future climate
- To study the impact of soil moisture-temperature coupling on temperature extremes over the Indian region using the soil moisture sensitivity experiments

Model simulation experiments

We investigated the impact of soil moisture and temperature (SM-T) coupling on extreme temperature (ExT) using the MRI-AGCM (3.2) high-resolution (~60 km) climate model. We have analyzed a suite of model experiments (HIST, FUT, DRY-SM (HIST), WET-SM (HIST), DRY-SM (FUT) and WET-SM (FUT)) for the historical period (HIST: 1951-2010) and future (FUT: 2051-2100). The DRY-SM and WET-SM simulations are sensitivity experiments in which the SM initial conditions are perturbed on 1st day of each month. In DRY-SM, the SM is decreased by 20% of the HIST and FUT simulations, respectively. Conversely, in the WET-SM experiments the SM is increased by 20% of the HIST and FUT simulations, respectively.

Experiment	Forcing used	Period
HIST	Natural (e.g. volcanoes and solar variability) and anthropogenic forcing (e.g. greenhouse gases (GHG), aerosols etc.).	1951-2010 (60 years)
FUT	Future climate in which global mean temperature becomes 4K warmer than pre-industrial climate.	2051-2100 (50 years)
DRY-SM (HIST-20)	The sensitivity experiment initialized by decreasing the soil moisture on 1st day of each month by 20% in HIST.	1951-2010 (60 years)
DRY-SM (FUT-20)	The sensitivity experiment initialized by decreasing the soil moisture on 1st day of each month by 20% in FUT.	2051-2100 (50 years)
WET-SM (HIST+20)	The sensitivity experiment initialized by increasing the soil moisture on 1st of each month by 20% in HIST and FUT.	1951-2010 (60 years)
WET-SM (FUT+20)	The sensitivity experiment initialized by increasing the soil moisture on 1st of each month by 20% in FUT.	2051-2100 (50 years)

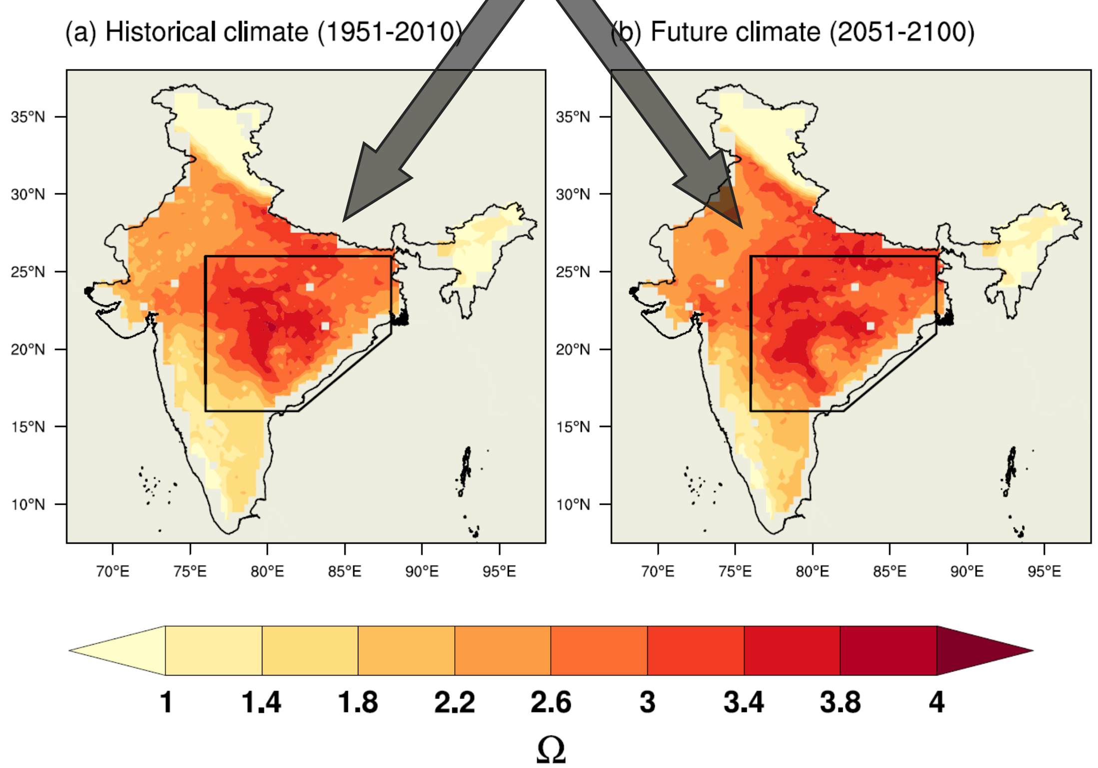




Soil moisture-temperature coupling (Ω)

Spatial distribution of soil moisture-temperature coupling (Ω) over the Indian region for HIST (1951-2010) and FUT (2051-2100) model experiments.

North-central India (NCI)



Experimental model: MRI-AGCM 3.2 (Mizuta et al., 2017)

The study uses the method developed by Dirmeyer (2011) to estimate the Soil moisture-temperature coupling

$$\text{Coupling strength } (\Omega) = -\mathcal{R}_c * \sigma_{SM}$$

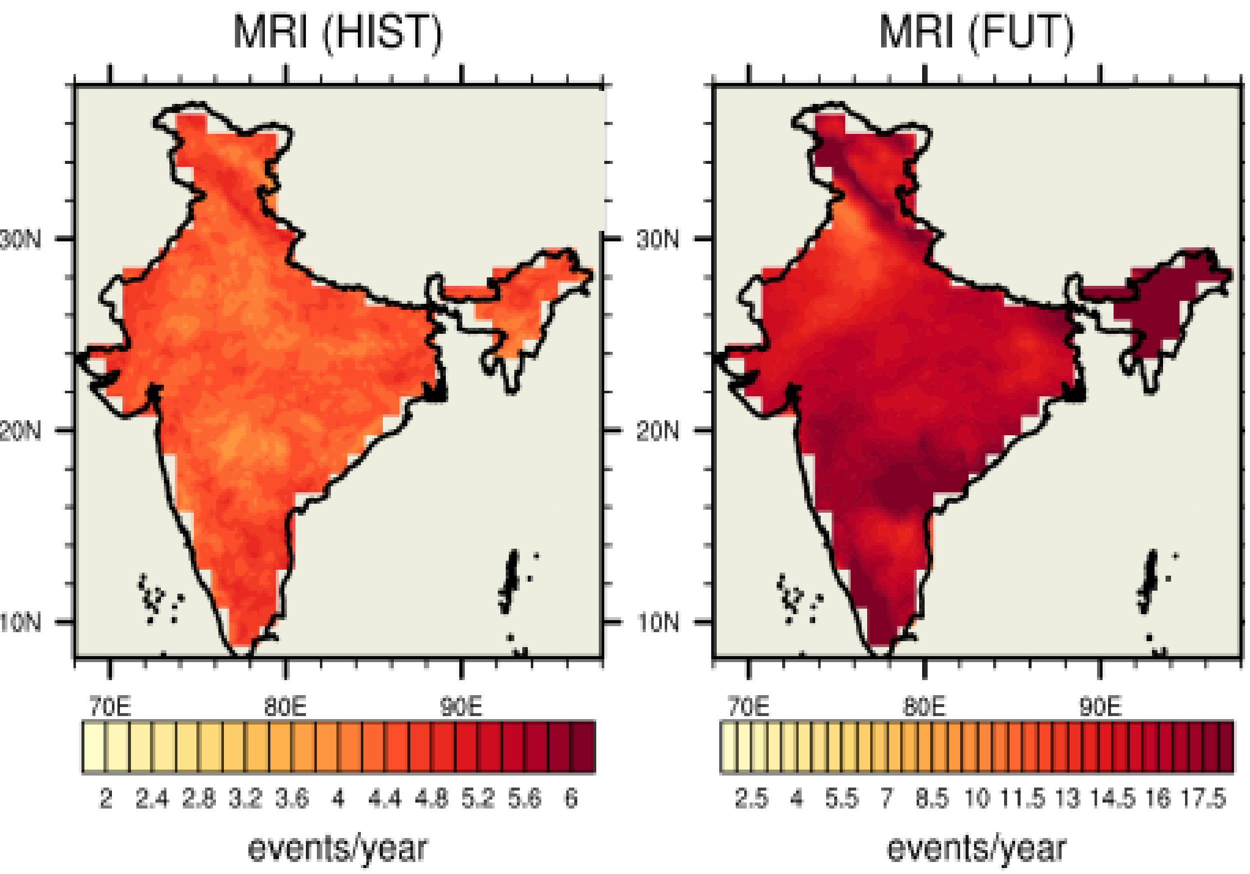
Whereas, $\mathcal{R}_c$ denotes the slope of linear regression of temperature anomaly on SM anomaly and σ_{SM} indicates the standard deviation of soil moisture.

Hot-spots of strong land-atmosphere coupling located across north-central India (NCI)

- Intermediate SM regions are more sensitive to near-surface temperature variability than wet and dry regimes.
- The regions such as the Western Ghats and north-east India (with wet SM conditions) are mainly energy control evaporation regime.
- Whereas region like north-west India (with very dry SM conditions) mainly have weak evaporation variability.

Simulations of temperature extremes

Spatial maps of frequency of extreme temperatures from HIST and FUT simulations



Extreme temperature indices

Extreme temperature event is defined if the daily T_{max} value at each grid point is greater than the 90th percentile T_{max} of the corresponding day and persists at least for three consecutive days.

For the historical period, it is noted that at least four extreme temperature events occur per year over the Indian landmass.

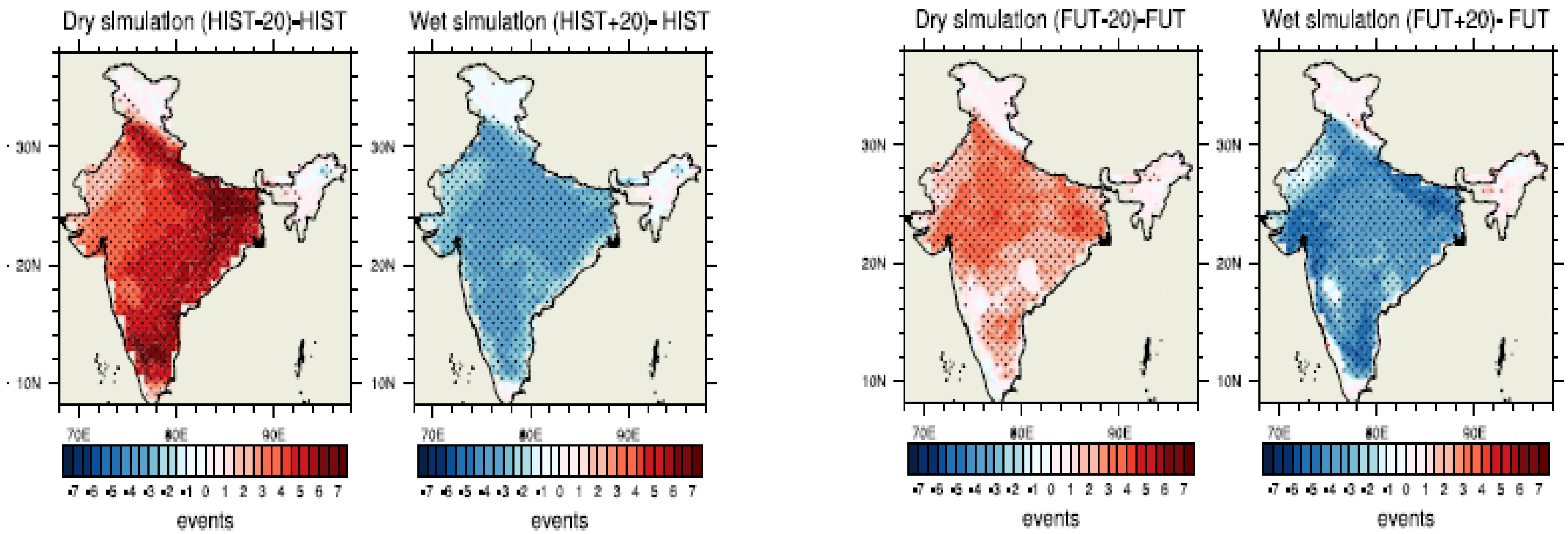
Future climate shows that high intensity extreme temperature events are more likely to occur every 25-30 days over India under the 4K warming scenario.

Result shows the significant impact of climate change of temperature extremes over the Indian region.

Impact of soil moisture on temperature extremes

Changes in the extreme temperatures for the DRY-SM and WET-SM simulations relative to the HIST and FUT experiments

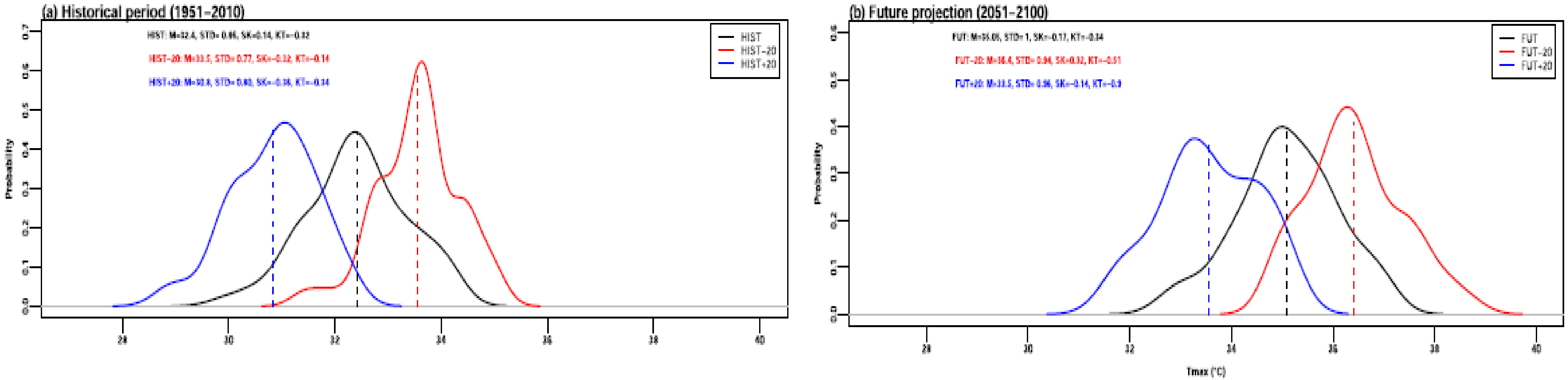
HIST FUT



It can be seen that drier SM conditions significantly enhance the extreme temperature characteristics over the Indian region, whereas, wet SM conditions significantly reduce the extreme temperature characteristics.

Impact of soil moisture on temperature extremes over NCI

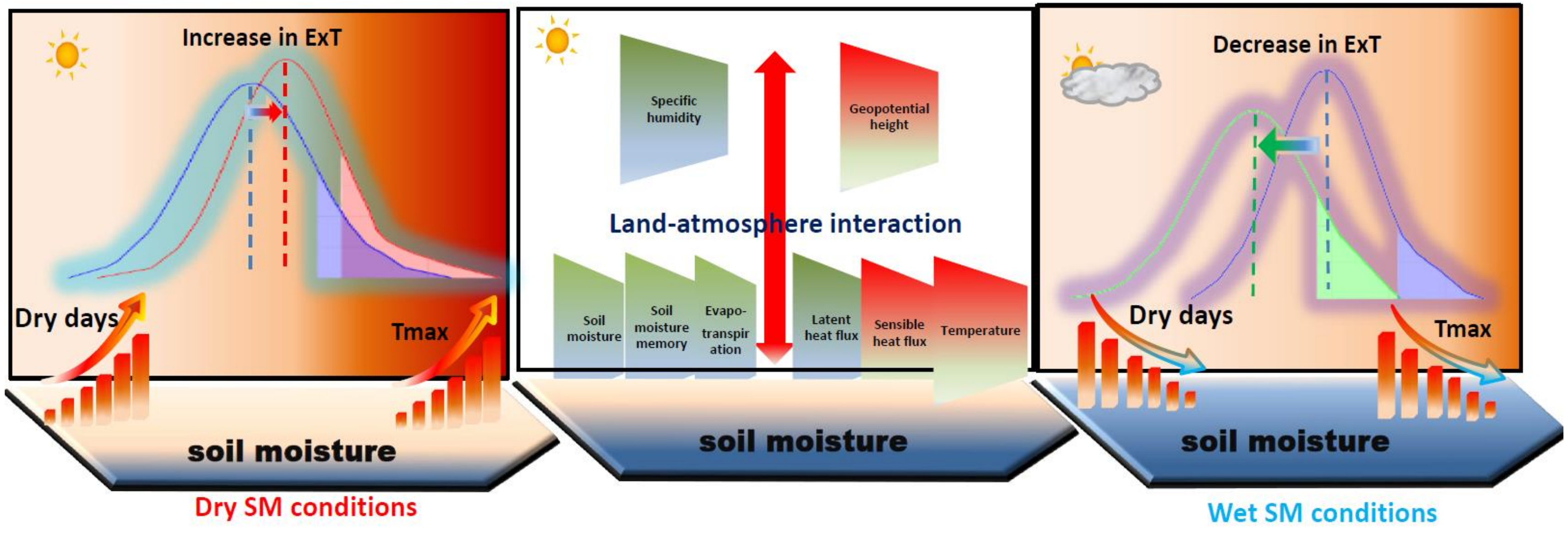
Probability distribution of extreme temperature intensity (ExTI) over NCI for HIST and DRY-SM simulations (Figure a). The lower panel is for corresponding FUT simulations (Figure b).



A 20% decrease of SM in HIST-20 over NCI shifts the 90th percentile probability limit of ExTI by 0.5°C. It is further noted that a 20% decrease of SM in FUT-20 shifts the 90th percentile probability limit of ExTI by 0.74°C.

Mechanism: Factors governing the impact of soil moisture on temperature extremes

Schematic explains the impact of soil moisture-temperature coupling on temperature extremes using the DRY-SM and WET-SM sensitivity experiments



In case of dry sensitivity run, below normal SM conditions cause the sensible heating process to entrain more energy back into the environment by reducing the evapotranspiration (ET) and soil moisture memory (SMM), leading to increase of temperature extremes.

On the other hand, in wet conditions the amount of energy available at the surface is used to cool the near-surface atmosphere by increasing the LHF through the ET process. As a result, the near-surface air temperature is remains below normal and high temperature occurrences are gradually slowed.

Ganeshi et al 2023, npj clim and atm. Sci. https://doi.org/10.1038/s41612-023-00334-1

Summary and conclusion

- Findings shows that more than 70% area of the Indian landmass has experienced significant changes in characteristics of ExT due to SM perturbations.
- In particular, we see larger impact of SM perturbations on ExT over the north-central India (NCI), which is a hotspot of strong SM-temperature coupling.
- Our findings suggest that a 20% increase of SM perturbation applied on the HIST and FUT experiments, tends to decrease the frequency and duration of ExT events over NCI by nearly 60–70% and 20–30%, respectively.
- Conversely, a 20% decrease of SM perturbation applied on the HIST and FUT experiments, tends to increase the frequency and duration of ExT events over NCI by nearly 60–100% and 15–40%, respectively.
- Over NCI, a 20% departure in SM significantly revamps frequency, duration and intensity of ExT by 2–5 events/year, 1-2 days/event and 0.5–2.1 °C, respectively, through modulating surface energy partitioning, evapotranspiration and SM memory.
- Importantly, the impact of SM perturbations on frequency and duration of ExT events becomes less prominent with intensification of global warming.

Thank you