Soil moisture induced land-atmosphere interactions in the evolution of extreme temperature over India

[Exploring the role of soil moisture in regulating land-atmosphere interactions over India]

Credits: **Naresh Ganeshi[1,2], Milind Mujumdar[1], Takaya Yuhei[2], Mangesh Goswami[1], Madhusudan Ingale[1], R Krishnan[1], Toru Terao[3], Trenton E Franz[4]**

[1]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune | [2]Meteorological Research Institute, Climate Research Department, Ibaraki, Japan | [3]Faculty of Education, Kagawa University, Kagawa, Japan | [4]The University of Texas at Austin, Department of Geological Sciences, Department of Civil, Architectural and Environmental Engineering, Austin, TX, United States of America

Bhupendra Bahadur Singh

Scientist E
Centre for Climate Change Research
Indian Institute of Tropical Meteorology, Pune
Ministry of Earth Sciences (MoES), Government of India

Email ID: bhupendra.cat@tropmet.res.in

Outline

- Introduction
- Effect of soil moisture on temperature variations
- The regional context: Temperature extremes over India
- Impact of soil moisture on temperature extremes
- Summary and Conclusion

Introduction

- Soil moisture (SM) a key variable of the climate system, generally refers to the amount of water stored in the unsaturated soil zone (or vadose zone), although its exact definition can vary depending on the context, i.e. whether it is defined in relative, absolute or indirect terms, and depending on the reference storage.

- It constrains plant transpiration and photosynthesis in several regions of the world, with consequent impacts on the water, energy and biogeochemical cycles.

- Also, as **a storage component for precipitation & radiation anomalies**, it induces **persistence in the climate system**.

- It is also *involved in a number of feedbacks* at the local, regional and global scales, and plays a major role in climate-change projections.

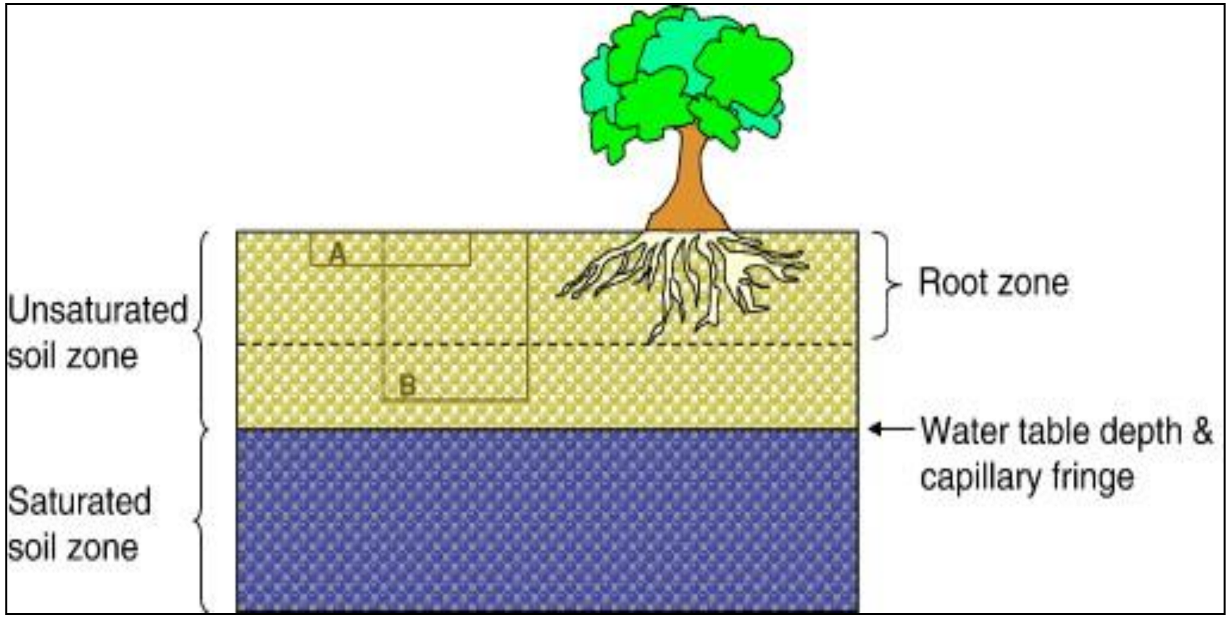


Figure. The saturated and unsaturated soil zones. A and B denote two distinct soil moisture volumes (Seneviratne et al. 2010, *Earth-Science Review*)

Introduction

Role in the context of the land energy and water balances

- **Land water balance**: $P = E + R_s + R_g + dS/dt$
  - **P** is the precipitation,
  - **E** is the evapotranspiration;
  - R_s is the surface runoff;
  - R_g is the drainage;
  - **d*S*/dt** refers to the change in water content within the layer;

- **Land energy balance**: $R_n = \lambda E + SH + G + dH/dt$
  - R_n is the net radiation at the surface ($R_n = SW_{in} - SW_{out} + LW_{in} - LW_{out}$)
  - **λE** is the latent heat flux;
  - **SH** is the sensible heat flux;
  - **G** is the ground heat flux to deeper layers;
  - **d*H*/dt** refers to the change of energy within the same layer;
  - SW_{net} refers to the net shortwave radiation ($SW_{in} - SW_{out}$);
  - LW_{net} refers to the net longwave radiation ($LW_{in} - LW_{out}$);
  - *For an infinitesimally small layer, **dH/dt** tends to zero and **G** becomes the ground heat flux at the surface*).

$P = E + R_s + R_g + dS/dt$ $\qquad$ $R_n = \lambda E + SH + G + dH/dt$

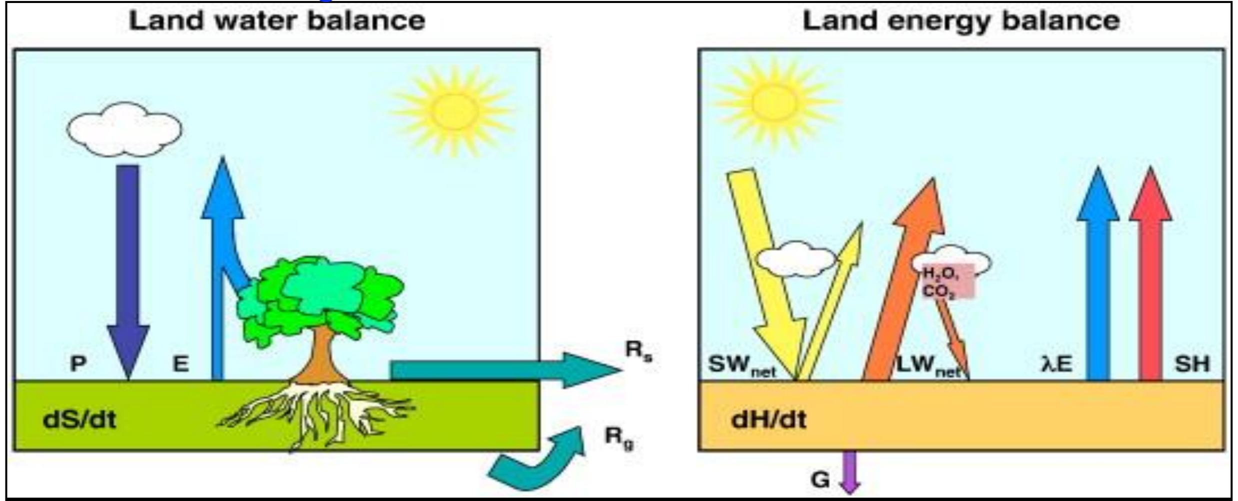


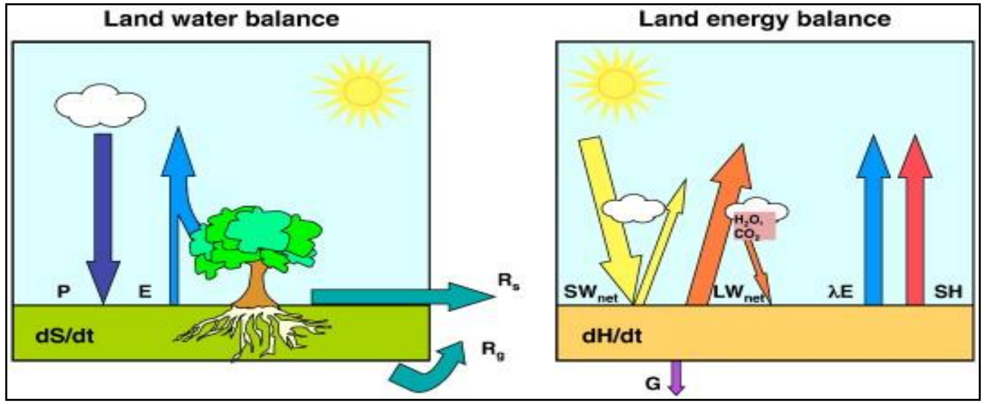
Figure. Schematic of the land water balance (**left**) and land energy balance (**right**) for a given surface soil layer.

(Seneviratne et al. 2010)

- SW_{net} refers to the net shortwave radiation ($SW_{in} - SW_{out}$);
- LW_{net} refers to the net longwave radiation ($LW_{in} - LW_{out}$);

Introduction

Role in the context of the land energy and water balances



- The land energy and water balances are coupled through the evapotranspiration term (**E, λE**).

- Thus soil moisture plays a key role both for the water and energy cycles through regulating:

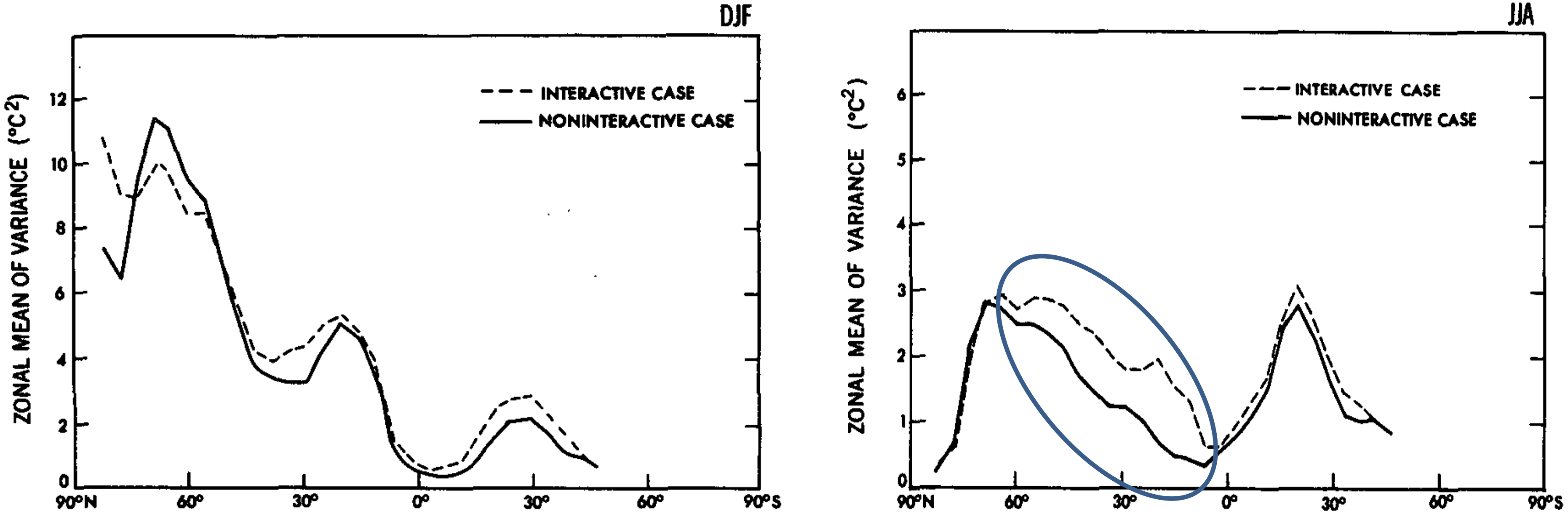
  (i) The partitioning of net surface radiation into sensible, latent, ground heat flux and layer heat/energy content, and

  (ii) The partitioning of precipitation received into evapotranspiration, infiltration, changes in layer water content water content, and runoff.

- In addition, it is also linked to several biogeochemical cycles (e.g. carbon and nitrogen cycles) through the coupling between plants' transpiration and photosynthesis.

- However, these effects are only important in regions where soil moisture is the main controlling factor for evapotranspiration.

Effect of soil moisture on temperature variations



Delworth and Manabe (1988)

- Clearly, the temperature variance for the interactive (varying & interacting) case is much larger than the non-interactive (climatological values) case, indicating the substantial role interactive soil moisture plays in summer surface air temperature variability.

- The magnitude of this increase is latitudinally dependent (increase of variance for the interactive case is largest at low and middle latitudes of the NH summer, and very small at high latitudes). As a fraction of the variance of the non-interactive case, the changes in variance are largest at low latitudes.

- The regional processes are more complex and the spatiotemporal heterogeneity makes it one of the least understood aspects of land-atmosphere interactions.

The regional context: Temperature extremes over India

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

Kothawale et al. (2010); Rohini et al. (2016)

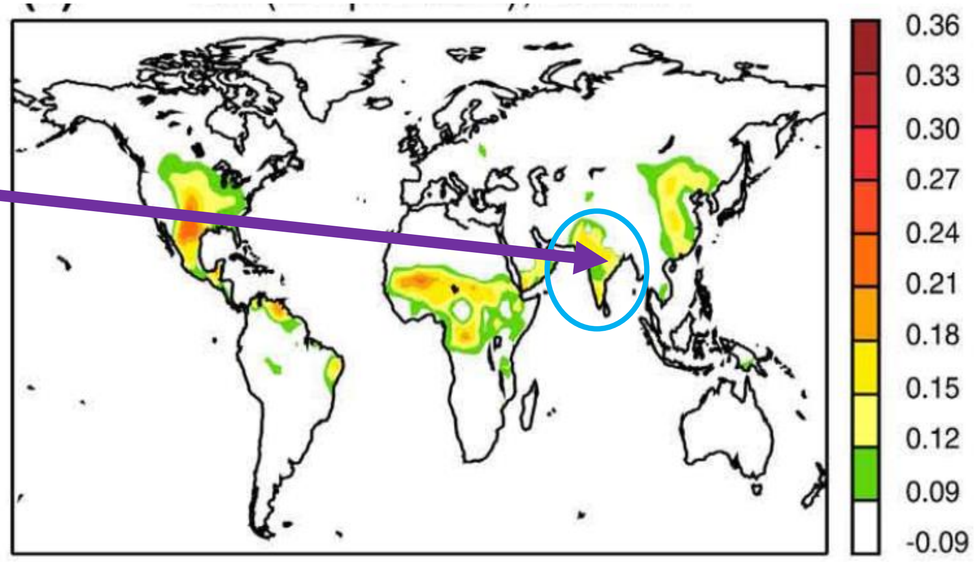
- CMIP5 models project significant increase in Heat Wave frequency (HWF) and Heat wave Duration (HWD) over central and northwest India by 0.5 events per decade and 4–7 days per decade respectively (shown to be caused by the strengthening of mid-tropospheric high, depletion of soil moisture and increased sensible heat fluxes.

Rohini et al. (2019); Krishnan et al. (2020) (MoES climate change Assessment report)

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

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

- Since there exists significant seasonal/sub-seasonal variability in soil-moisture across India (as noted in observational records), we assessed its role in shaping the temperature extremes over the region.



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

Seneviratne et al. (2010)

Examining the impact of SM-T coupling on extreme temperature (ExT)

- Impact of soil moisture-temperature (SM-T) coupling on extreme temperature (ExT) is examined through MRI-AGCM (3.2) high-resolution (~60 km) climate model.
- A suite of model experiments are analyzed (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 & 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.

(The reasoning for 20% decrease/increase is inspired by observed variations in SM)

Experiment	**Forcing used**	**Period**
HIST	Natural (e.g. volcanoes and solar variability) and anthropogenic forcing (e.g. greenhouse gases (GHG), aerosols etc.). Uses observed monthly SSTs and SI concentration from COBE-SST.	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)

Examining the impact of SM-T coupling on extreme temperature (ExT)

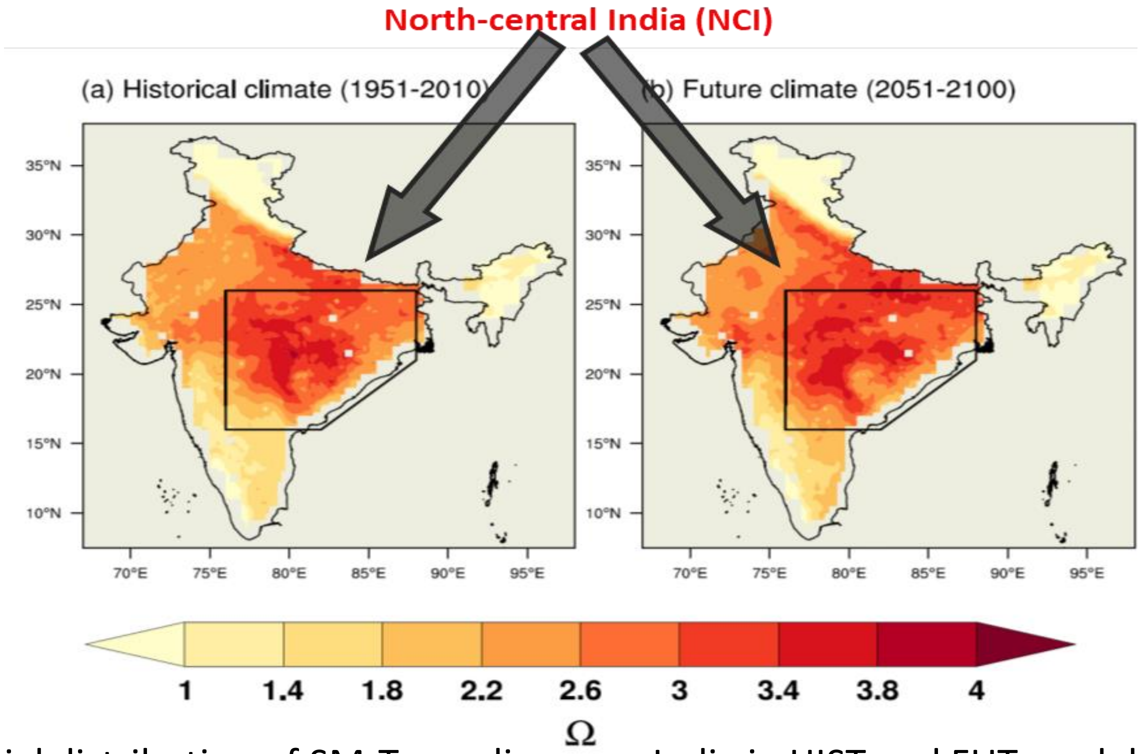
- The present study evaluates **ExT** characteristics on an annual scale.
- For the HIST (as well as the FUT) experiment, extreme temperature (ExT) event is defined if the daily T_{max} value at each grid point is greater than 90^{th} percentile (computed from HIST exp.) of the corresponding day and persists at least for three consecutive days.
- Total number of extreme temperature events per year is defined as extreme temperature frequency (ExTF) index;
- Total number of days in each event is counted as extreme temperature duration (ExTD) index;
- Extreme temperature intensity (ExTI), is the measure of maximum T_{max} for each year at each grid point.

Soil moisture-temperature coupling (Ω)

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.



Spatial distribution of SM-T coupling over India in HIST and FUT model experiments. Coupling hot-spots are located across north-central India (NCI)

Examining the impact of SM-T coupling on extreme temperature (ExT)

- Intermediate SM regions are more sensitive to near-surface temperature variability than wet and dry regimes.

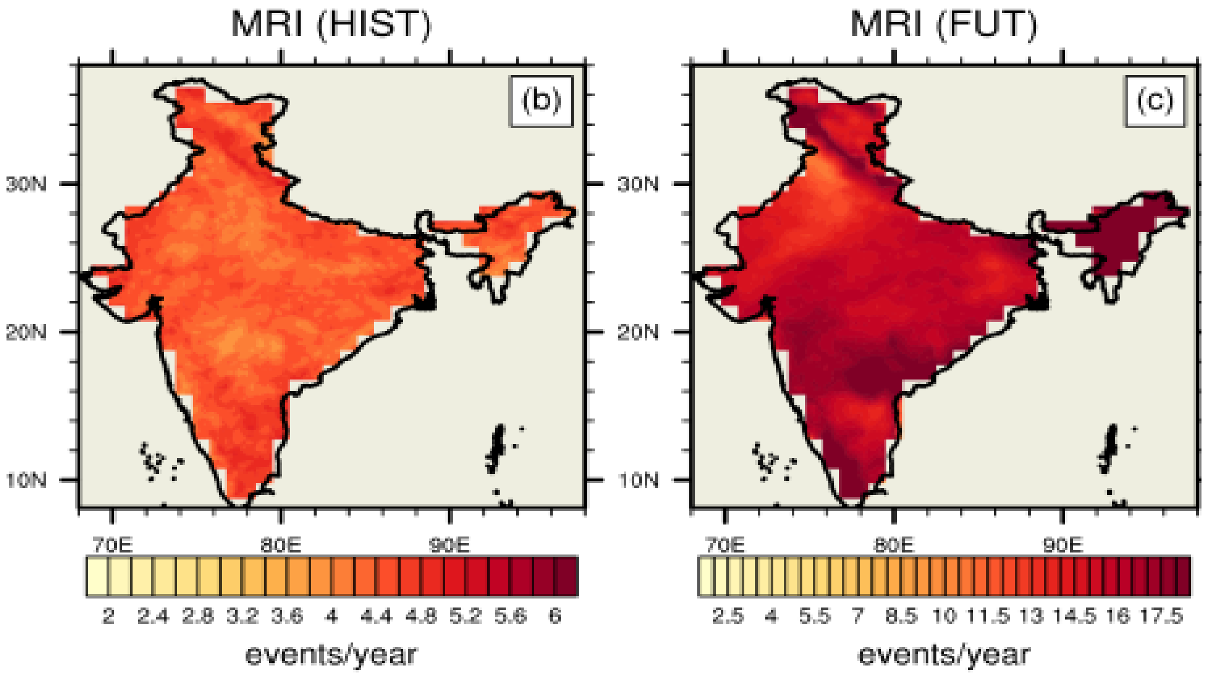
- The regions such as the Western Ghats and north-east India (with wet SM conditions) are mainly energy control evaporation regime whereas regions like north-west India (with very dry SM conditions) mainly have weak evaporation variability.

- For the historical period, it is noted that at least 4 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.

- It indicates significant impact of climate change on temperature extremes over the Indian region.

ExT frequency (ExTF) in HIST and FUT simulations



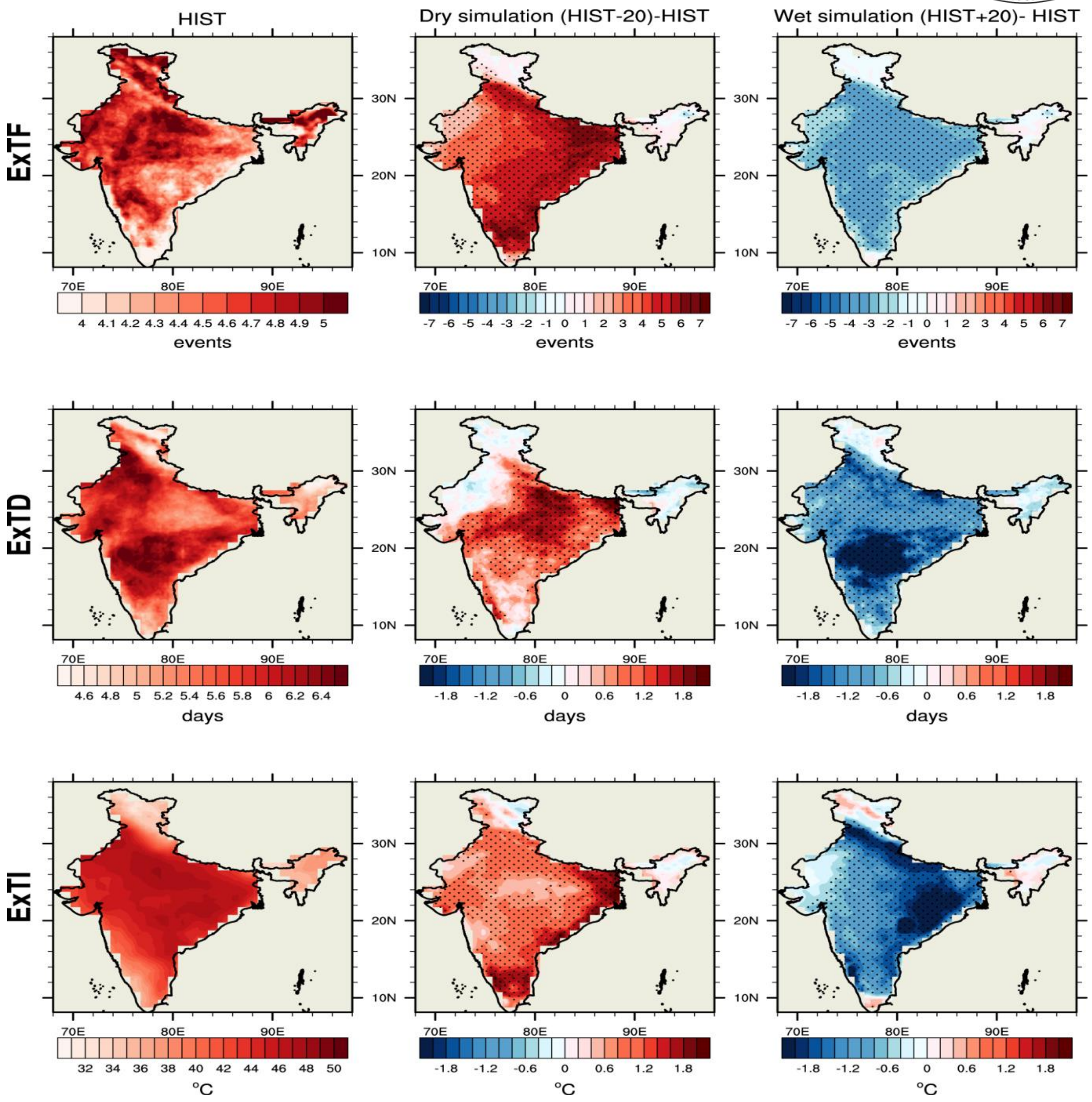
Impact of soil moisture on temperature extremes (HIST)

- In HIST experiments, on an average <u>drier SM conditions (HIST-20) increase</u>:

  ExTF by 4–5 events per year;
  ExTD by 1–2 days per event; and
  long-term mean ExTI at least by 0.6 °C.

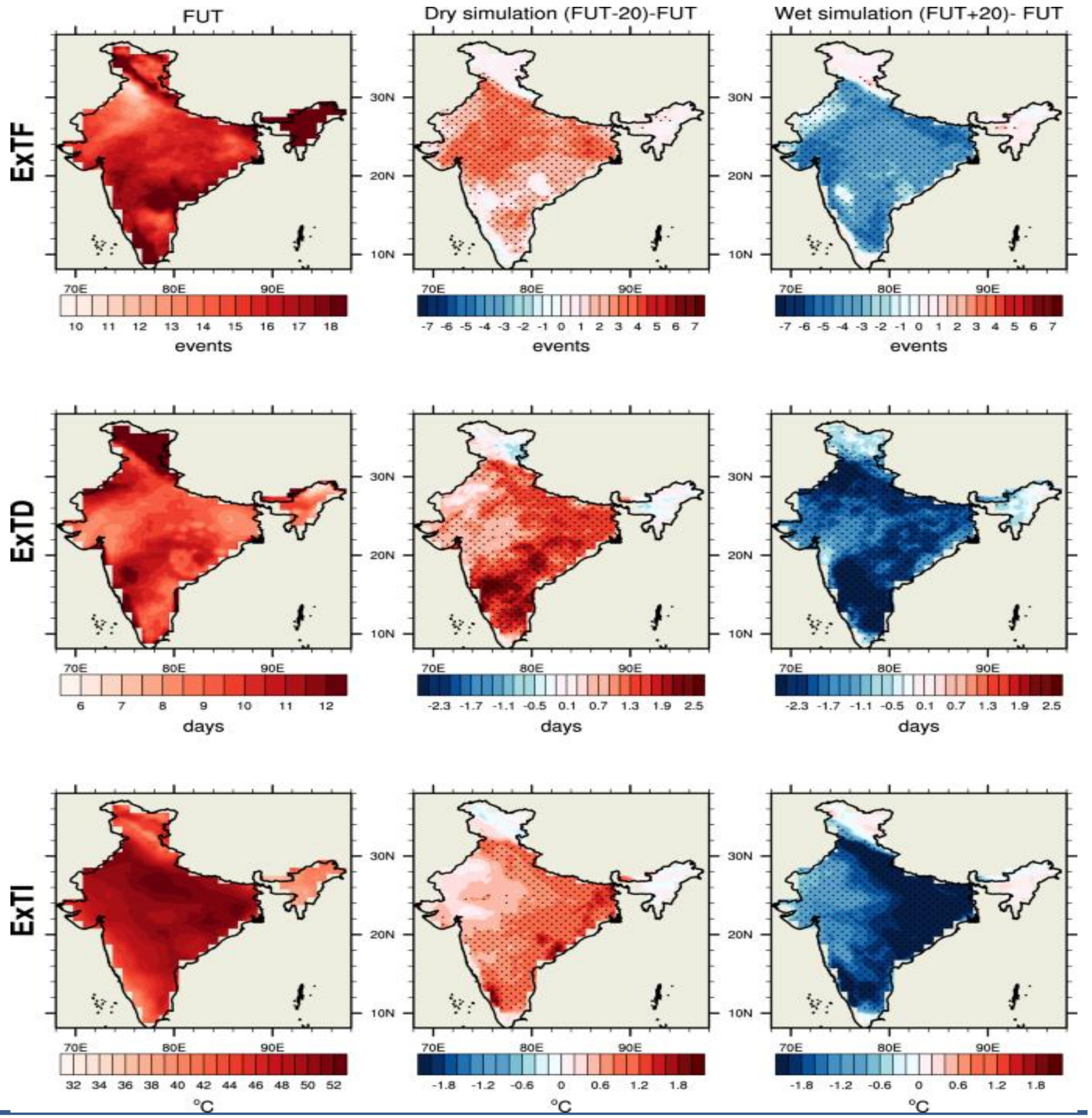
- In contrast, <u>wet SM conditions (HIST + 20) tend to reduce</u>:

  ExTF 1–2 events per year;
  ExTD by 2–3 days per event; and
  ExTI by ~0.5 °C (long-term mean).



Impact of soil moisture on temperature extremes (FUT)

- Future climate sensitivity experiments demonstrate similar results to historical simulations, albeit with a smaller impact of soil moisture over the Indian region.
- The FUT-20 simulation intensifies ExTF by 1–2 events per year, 0–1 days per event, and long-term mean ExTI by ~1 °C than that of the FUT experiment.
- Whereas results from the FUT + 20 experiment indicate reduction of ExTF by 3–4 events per year, ExTD by 3–4 days per event, and long-term mean ExTI by ~2 °C.
- A comparison between the control (HIST and FUT) and the sensitivity experiments (HIST-20, HIST + 20, FUT-20 and FUT + 20) indicate that almost 70% or more area of the Indian region is expected to experience significant change in the ExT characteristics.

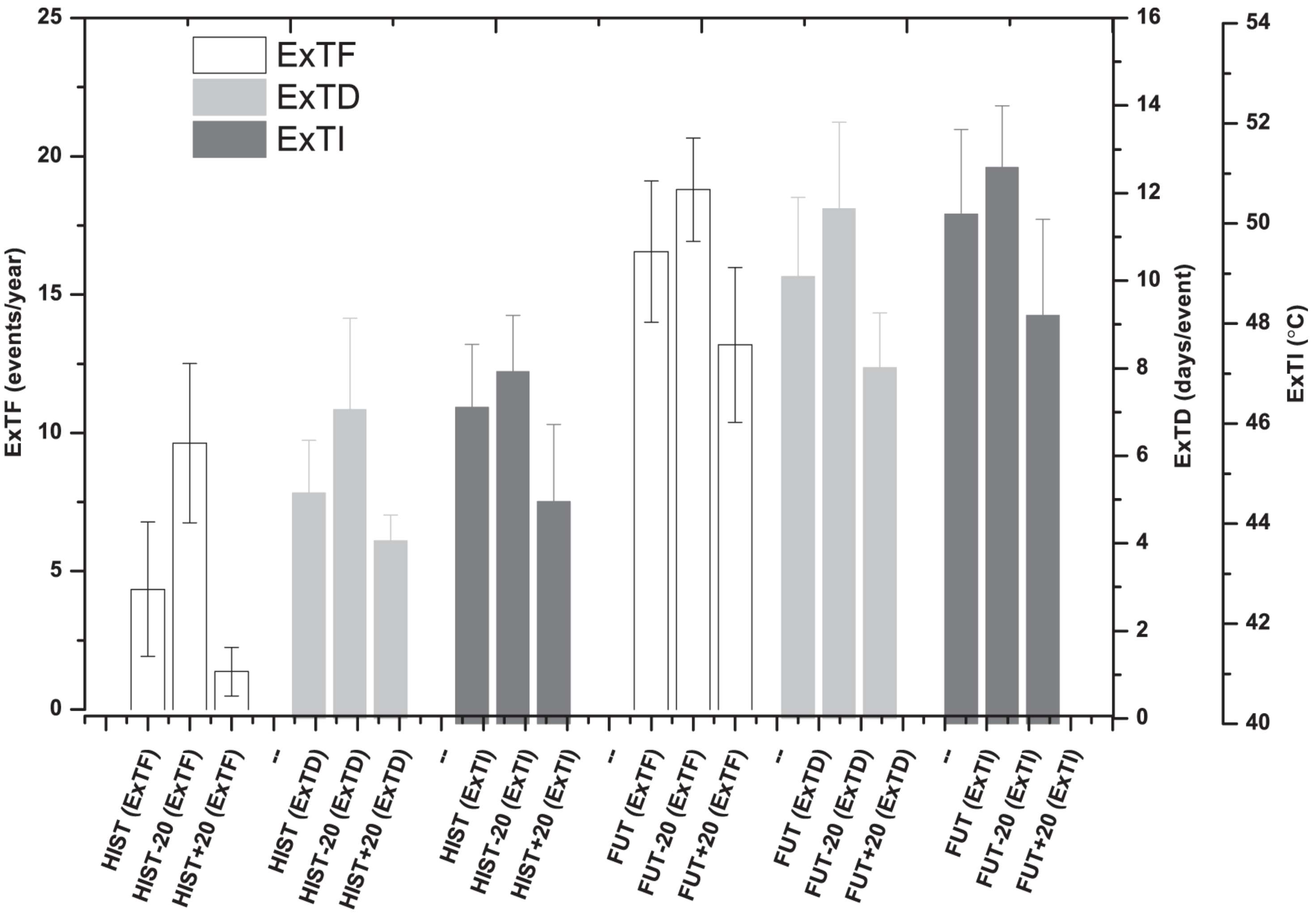


Impact of SM on ExT over NCI

- We noted an increase of ~5 ExTF events per year over the NCI from the HIST-20 experiment, with average increase in ExTD of 1.8 days per event and ExTI ~ 0.71 °C w.r.t the HIST experiment.

- Whereas wet simulation (HIST + 20) reduces ExTF by ~3 events per year, ExTD by ~1 day per event, and long-term mean ExTI ~1.88 °C w.r.t the HIST experiment.

- The FUT-20 experiment shows an increase of ExTF by ~2.2 events per year, ExTD by ~1.55 days per event, and long-term mean intensity ~0.93 °C under dry SM conditions w.r.t the FUT experiment.



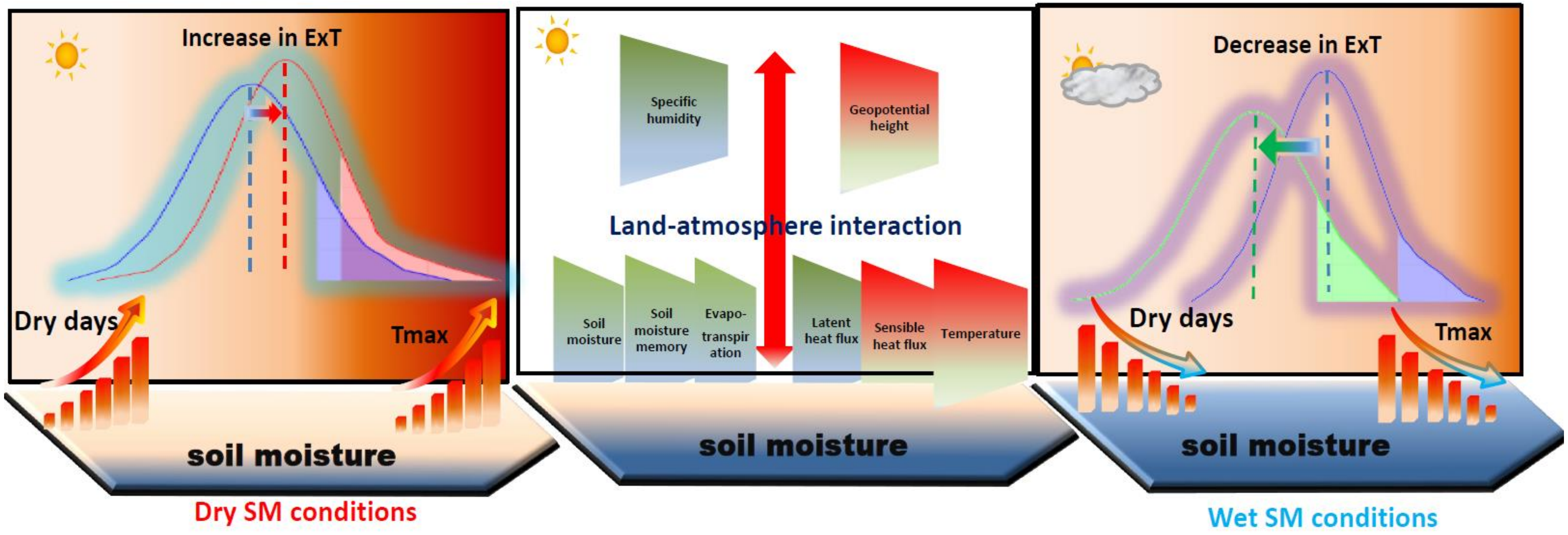
- While, for the FUT + 20 experiment (w.r.t the FUT control) we find a significant decrease in ExT characteristics (decrease of ExTF ~3.3 events per year, ExTD by 2 days per event and long-term mean ExTI ~2.02 °C) over NCI.

Mechanism of soil moisture impacts on temperature extremes

- *We proposed the following mechanism which helps understand the SM-T coupling on temperature extremes through 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.

- Whereas in wet conditions the near-surface air temperature is moderated through the enhanced LHF and less conversion into the SHF. This limits the high temperature occurrences.



*more details available in: Ganeshi et al. (2023). Soil moisture revamps the temperature extremes in a warming climate over India. *npj Clim Atmos Sci* 6, 12. https://doi.org/10.1038/s41612-023-00334-1

Summary and Conclusion

- Findings indicate that more than 70% area of the Indian landmass is projected to have experienced significant changes in characteristics of ExT due to SM variations.
- In particular, larger impact of SM perturbations on ExT is seen over the north-central India (NCI), a hotspot of strong SM-T coupling.
- It is seen 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, changes in evapotranspiration and SM memory.
- Modulation of surface energy partitioning, induced by drier SM (decrease SMM) and decreased ET rate, leads to enhance the SHF which raises the surface air temperature and induces more frequent and intense temperature extremes. Opposite happens in wetter SM conditions.

Thank You!

More information about model and model experiments

- The Meteorological Research Institute's MRI-AGCM3.2 is used in the present diagnostic study for analyzing ExT and land-atmosphere interactions over India. Here, we use the ~60 km resolution version of the MRI-AGCM3.2, having 64 vertical levels and 3 active soil layers. The land component of MRI-AGCM3.2 is the Simple Biosphere model (SiB). The model uses observed monthly sea-surface temperature and sea ice concentration from Centennial Observation-based estimation (COBE-SST2), whereas climatological monthly sea ice thickness is prescribed lower boundary conditions.

- In addition, the external forcing is configured with observed values of global mean concentration of greenhouse gases, MRI Chemistry climate model (MRI-CCM) output for three-dimensional distribution of ozone, and MRI Coupled Atmosphere-Ocean General Circulation Model (MRI-CGCM3) output.

- The HIST experiment use both natural (e.g. volcanoes and solar variability) and anthropogenic forcing (e.g. greenhouse gases (GHG), aerosols etc.), whereas in FUT experiment the global mean temperature becomes 4 K warmer than the pre-industrial climate. The global increase in temperature for the future 4 K simulations corresponds to that around the end of the 21st century under Representative Concentration Pathway 8.5 scenario of CMIP5.

- The simulations are initialized on the 1st day of each month by perturbing SM from the top three layers with corresponding fields from the HIST and FUT simulations. The dry SM simulations are initialized by decreasing the SM by 20%, whereas, in the wet SM experiment, SM is increased by 20%. After introducing the initial SM perturbation, the model is subsequently integrated for one month at a time so as to generate simulations of atmospheric and land surface variables (including SM) on a month-by-month basis. The dry and wet SM sensitivity experiments were initialized with the same initial lateral boundary conditions as that of HIST and FUT simulations except for the above-mentioned SM perturbation.

More information about model and model experiments

- This study is mostly regional in nature which requires high resolution setups. The usage of state-of-the-art coupled climate models may have the advantage of studying atmosphere-ocean coupled processes, but those model struggle in simulating the regional changes in the land-atmosphere interactions and temperature extremes (Haarsma et al., 2016; Yukimoto et al., 2012). Many previous studies It has been noted that, past modelling studies have already used the atmospheric general circulation models to exclusively investigate the complexities of the land-atmosphere coupling characteristics across the globe and found them to be robust in capturing these processes (Koster et al., 2004; Seneviratne et al., 2010).