Climate Change Impact on the Indian Monsoon

Prof. B. N. Goswami,

Former Director, Indian Institute of Tropical Meteorology, Pune, India,
Conceived and Led the India's 'Monsoon Mission' Project. (2008-2014)

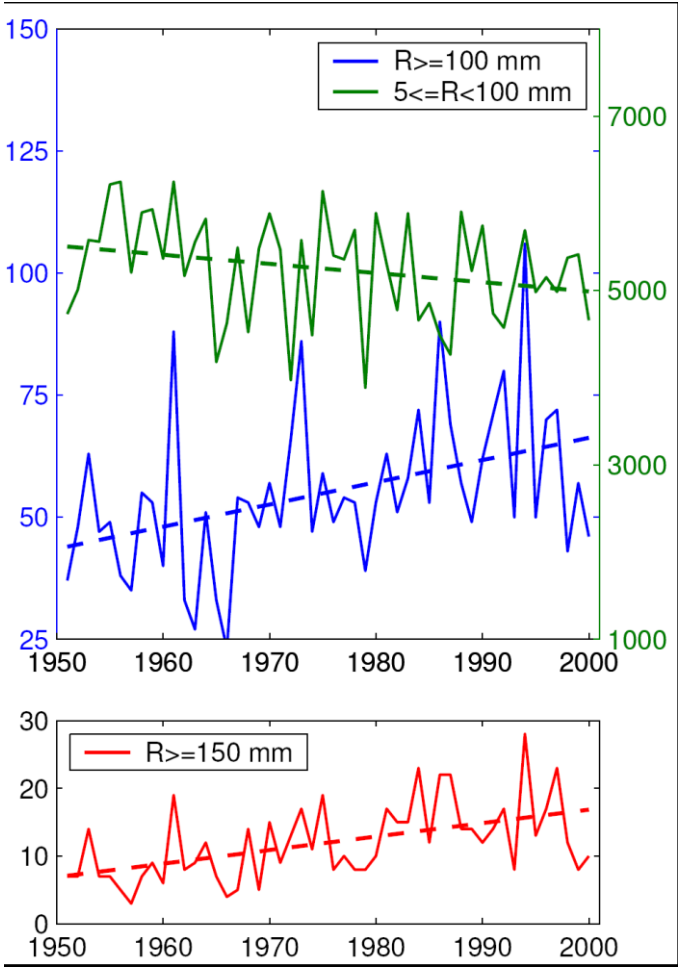
Currently:
SERB Distinguished Fellow & Professor of Practice,
Department of Physics,
Cotton University, Guwahati, India

Climate Change Impact on the Indian Monsoon ?

- Importance of 'Regional (Indian) Monsoon' research
- 'What we know' & 'What we don't Know'
- Uncertainty in Projection of Indian monsoon

Climate Change Impact on Indian summer Monsoon Rainfall:

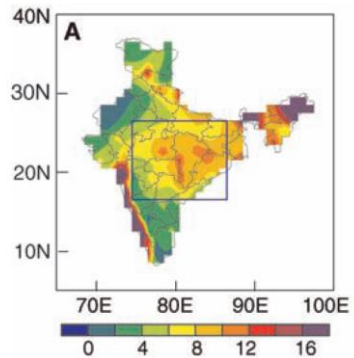
#1: Increases the Frequency of Extreme events over India



Goswami B.N., Venugopal V., Sengupta D., Madhusoodanan M.S., Xavier Prince K., 2006:, **Science**, 314, 5804, 1 December, 1442-1445.

Low & Moderate events

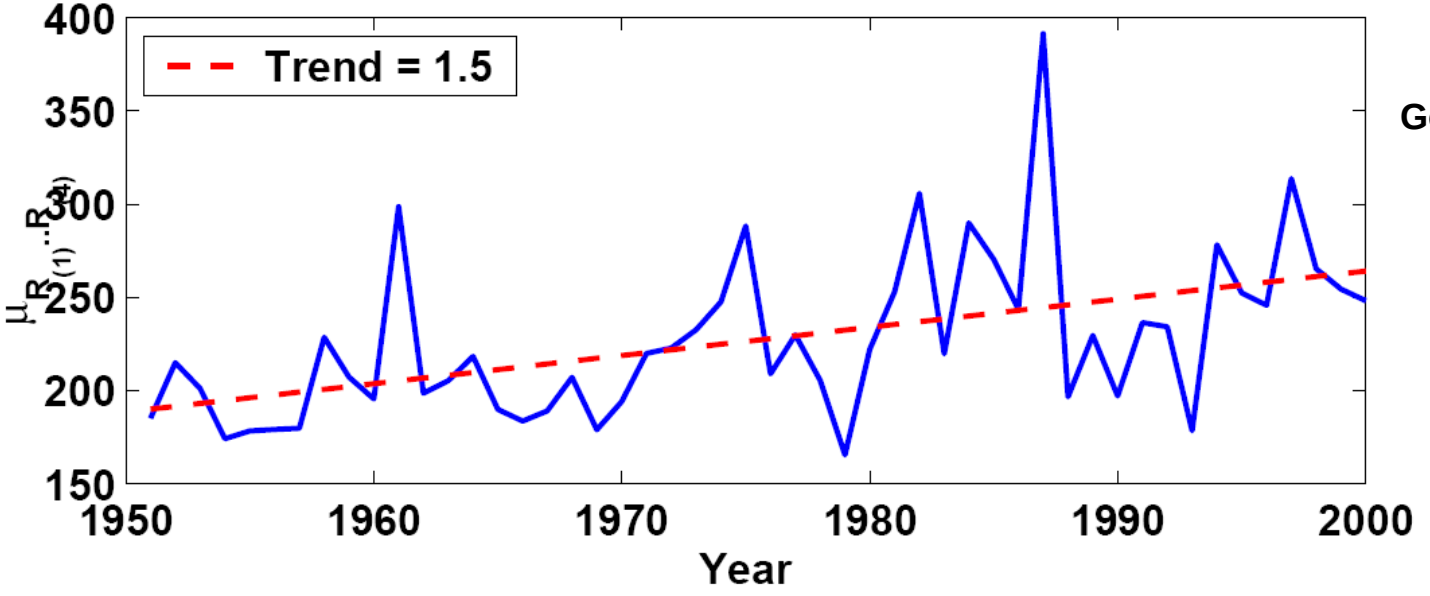
Heavy events (>10cm)



V. Heavy events (>15cm)

Climate Change Impact on Indian summer Monsoon Rainfall:

#1: Increases the intensity of extreme rainfall over India

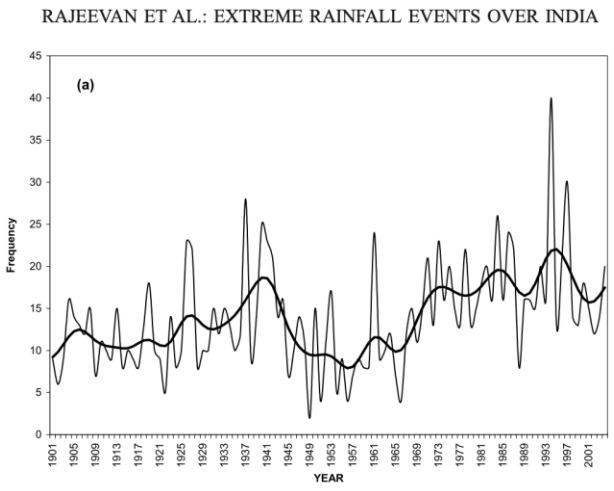


Goswami et al., Science, Dec. 1, 2006 , 314, 1442-1445

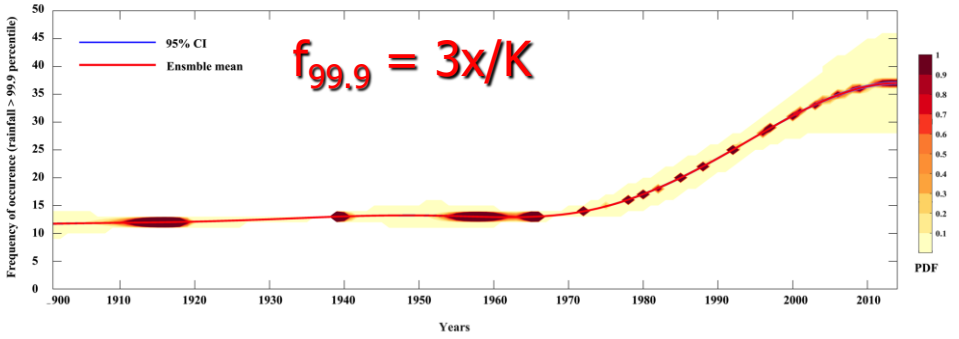
~40% increase ion intensity in 50 years!

Time series of av. Intensity of four largest events in a year

How does the Frequency of Occurrence & Intensity of extreme rain events (99.9 percentile) Scale with Global Temp Change? We quantify.

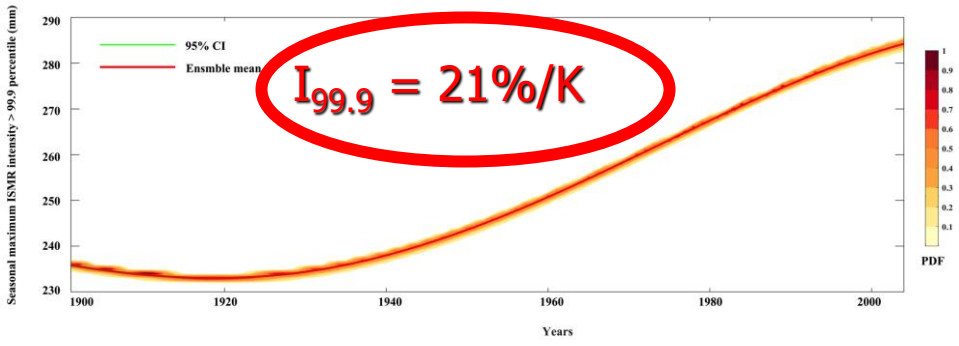


Based on 1° x1° daily rainfall over Indi between 1901-2014 (Rajeevan et al., 2008, GRL)



Frequency

Rajesh et al., 2021, JGR (Atmos)



Intensity

Nonlinear trend of Frequency and Intensity estimated by Empirical Mode Decomposition (EMD)

Climate Change Impact on Indian summer Monsoon Rainfall:

#2: Increases the total quantum of seasonal rainfall over India

Quantifying Climate Change impact on All India JJAS Rainfall (ISMR)

Rajesh et al., 2021: JGR, Atmosphere,

10.1029/2020JD033511

ISMR is Increasing trend @ (2.71 +- 0.6)%/K

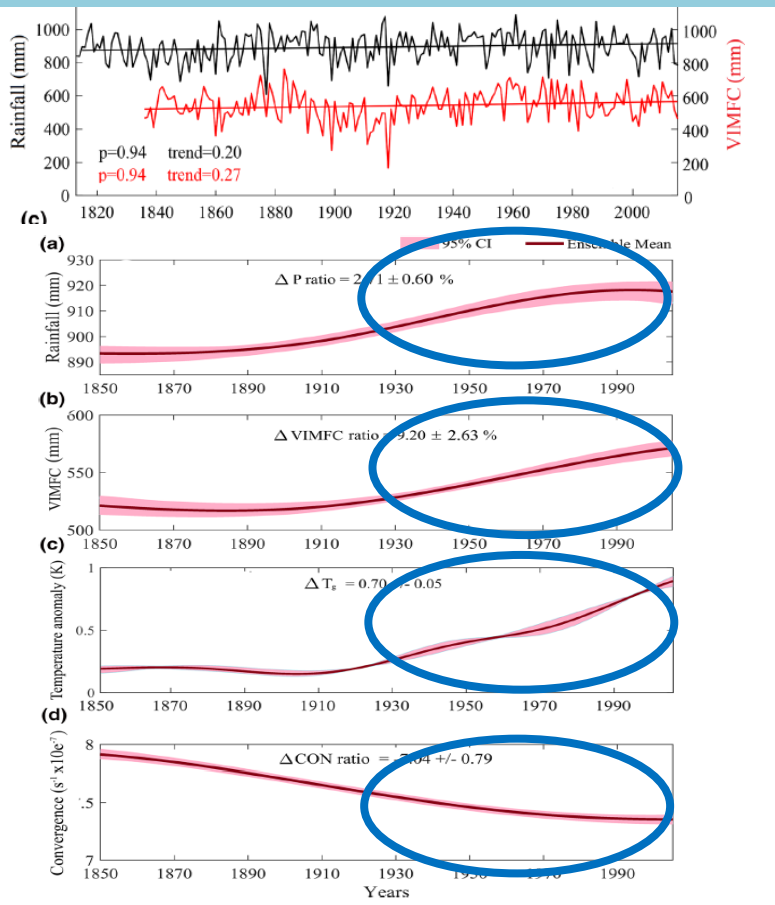
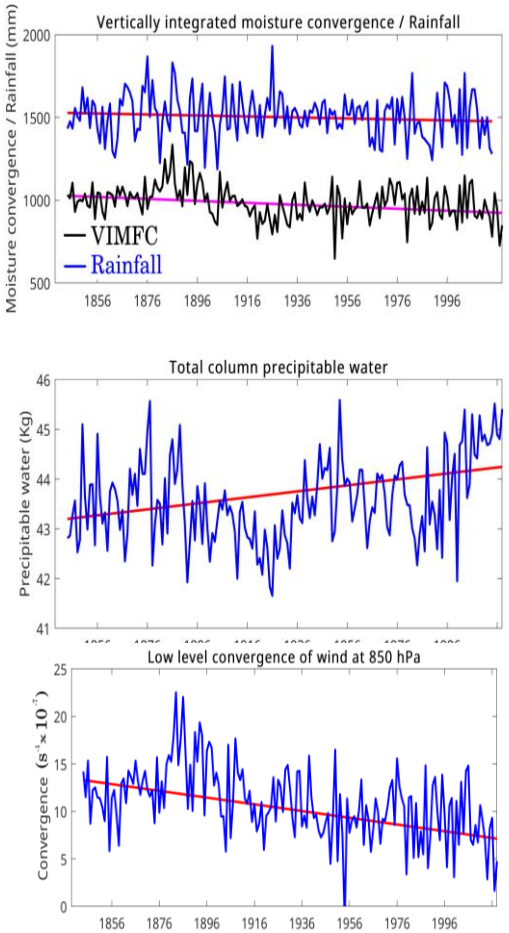


Figure 2. Ninety-five percent CI bounds of the nonlinear secular trends (light pink shading) decomposed from CEMD, using Monte-Carlo (MC) simulations perturbed with 2% of the amplitude of year-to-year variability of original time series for (a) ISMR, (b) VIMFC, and (c) global mean surface temperature (T_g) and (d) area averaged convergence of 850 hPa level winds over the Indian land region. All the trends are calculated for a common period from 1850 to 2005. The ensemble means of the decomposed trends are represented by the thick (dark red) lines. ISMR, Indian Summer Monsoon Rainfall.

While the JJAS rainfall is increasing CI rainfall, over NEI, JJAS it has a decreasing trend.

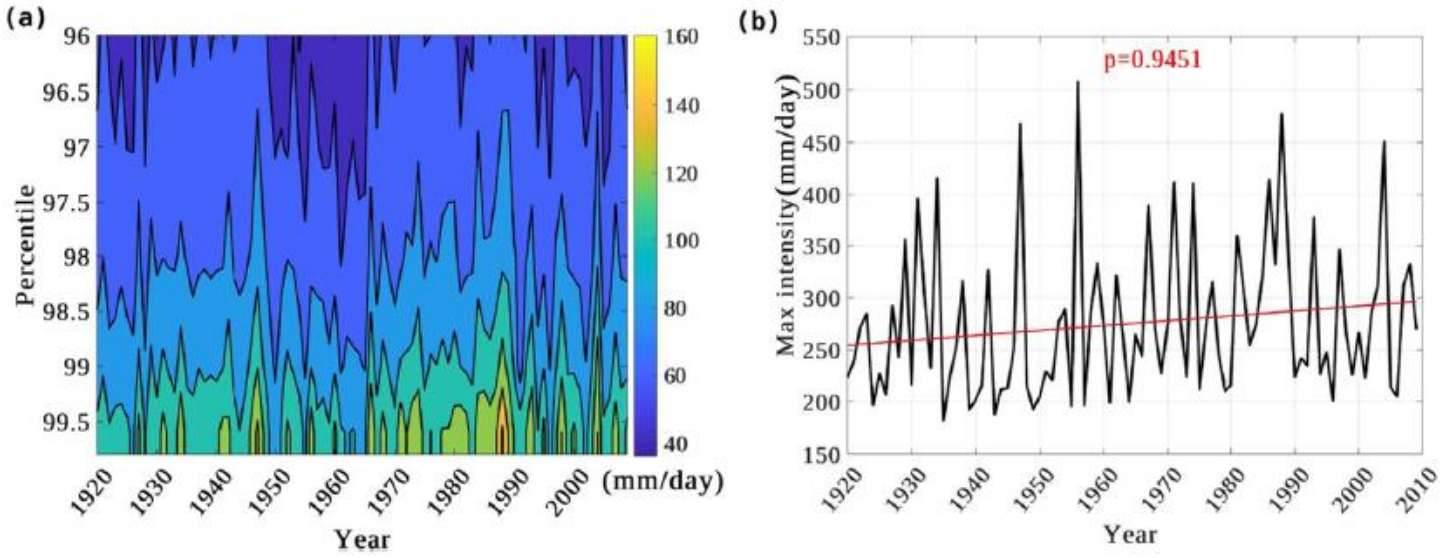
- Circulation is weakening over the NEI at a faster rate than that over the CI.
- Over the NEI, the decreasing trend of mean rainfall is matched with a 'decreasing' tend of VIMFC
- Although the column precipitable water content is increasing (middle panel), the decreasing trend of VIMFC is due to a much stronger 'decreasing' trend of low-level wind convergence (bottom panel).
- Why? Global 'stationary' circulation associated with climate change has a large-scale ascending (descending) motion over CI (NEI)



The JJAS rainfall over NEI is decreasing @ **(-3.2 +- 1.65)%/K**

Zahan et al., 2021, Climatic Change, https://doi.org/10.1007/s10584-021-02994-5

While the JJAS mean rainfall has a decreasing trend over NEI, the Frequency and Intensity of daily Extreme rainfall events have an increasing trend.



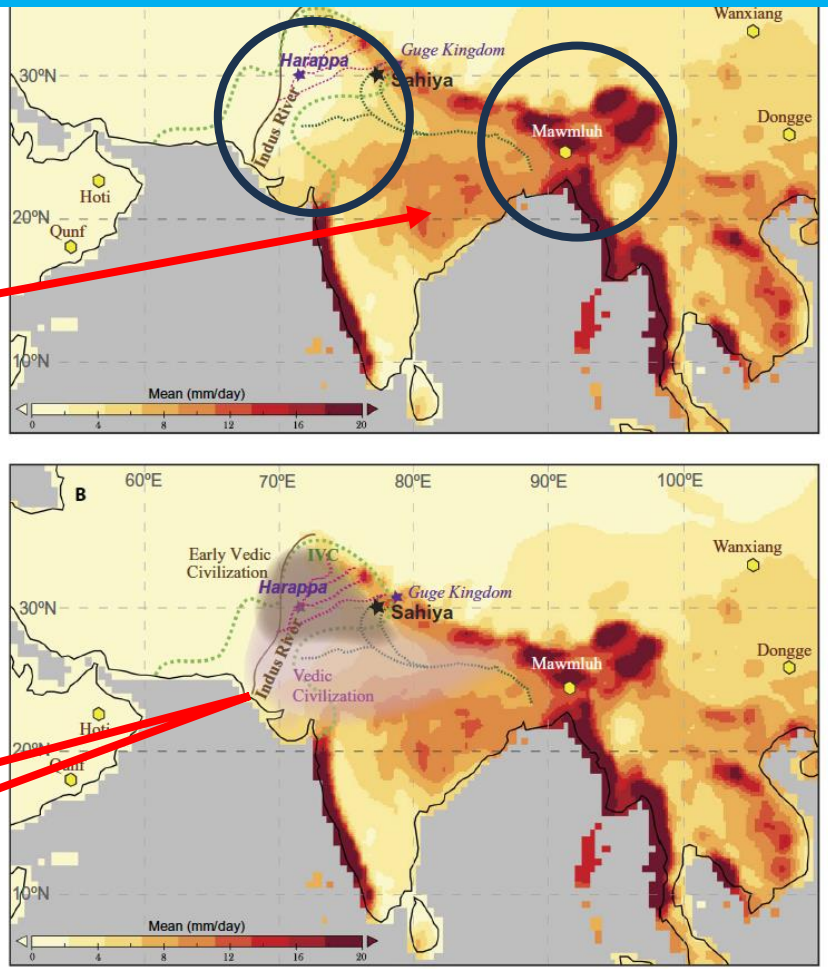
(a) Increase in intensity of the daily extremes. (b) maximum value of rainfall during the season.

- Frequency of occurrence ($F_{99.5}$) is increasing @ (+51 +- 4.99)%/K
- The Intensity ($I_{99.5}$) increasing @ (+12.5 +- 3.32)%/K

*Note that 99.5 percentile events over the NEI are larger than 40 cm/day as opposed to 15 cm/day over the Central India

#3:What is Climate Change doing to the Spatial Distribution of Indian Monsoon Rainfall?

The wet east and semiarid west is an iconic feature of Present- Day Indian Monsoon. But was is always like that?



3000 to 5000 years BP

In the past, During Harappan Civilization and Vedic Civilization, there is evidence that north-west India was very WET.

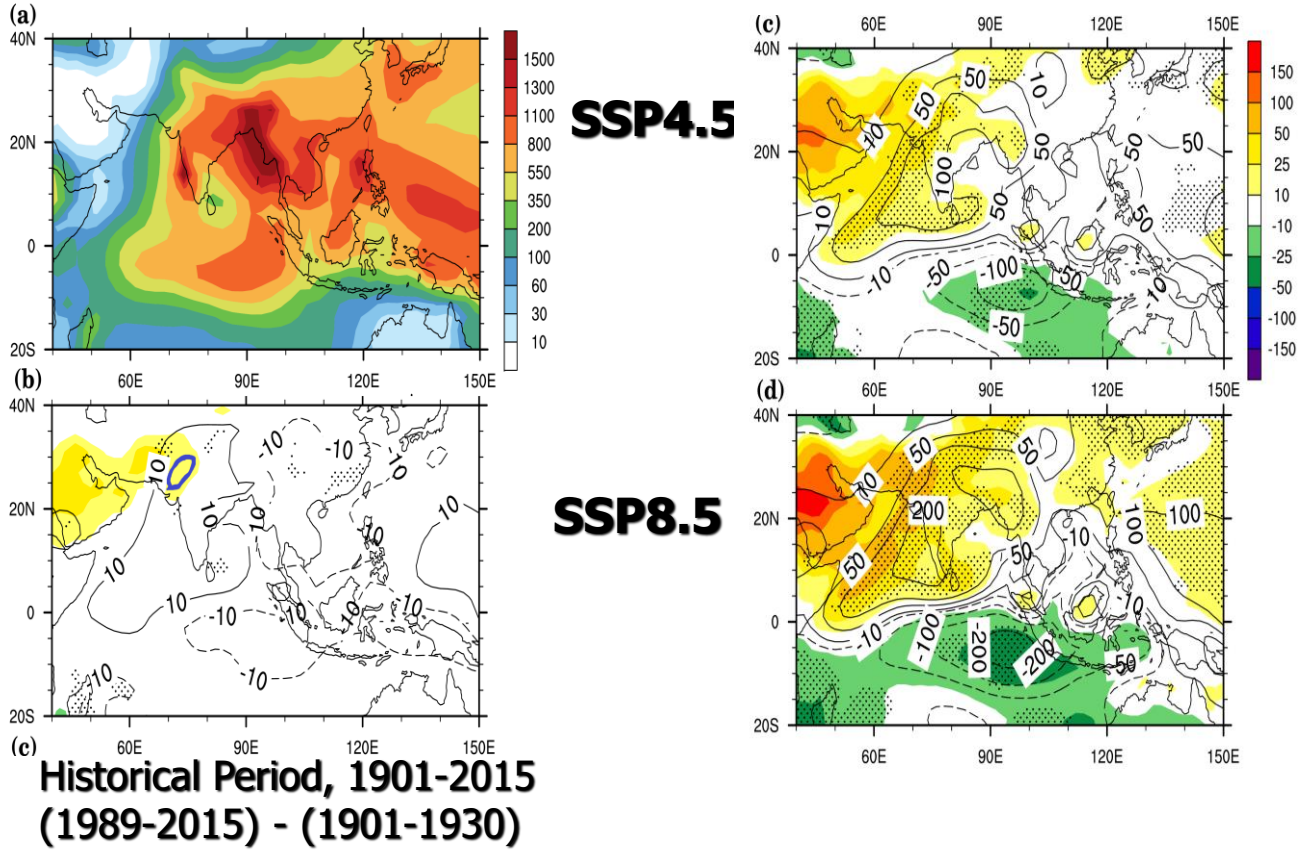
Kathayat et al., 2017: Science Advances

An important Science question on Expected Large-scale Changes of precipitation under Climate Change?

- While it could be counterintuitive, we ask could climate change transform the semiarid northwest India into a humid core monsoon like climate?
- As against the 'wet to get wetter' and 'dry to get drier' paradigm under Climate Change, could 'dry gets wetter' happen under some conditions?

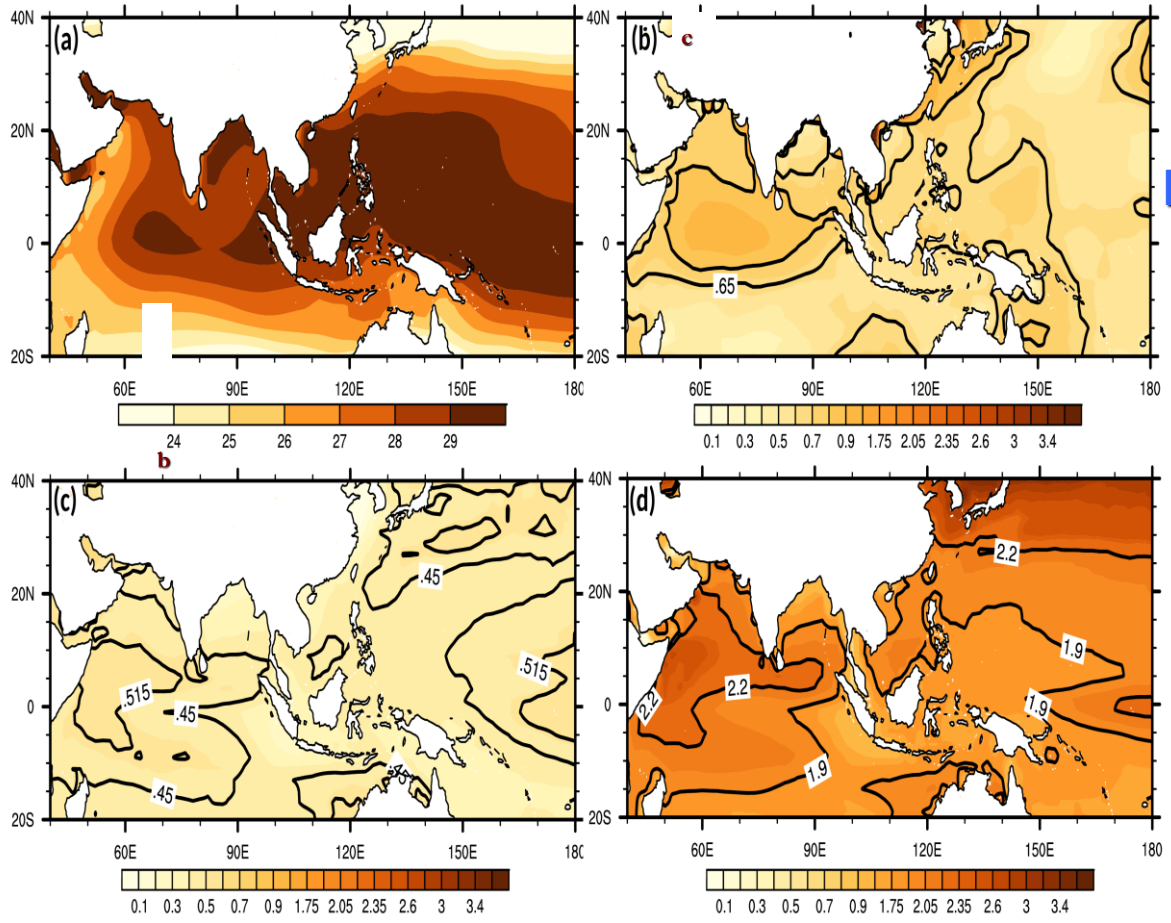
Climate Change Impact on Indian summer Monsoon Rainfall:

#3: Decreases the East-west asymmetry of seasonal rainfall north of 15° parallel over India



Rajesh & Goswami, 2023: Potential demise of India deserts, Earth's Future, e2022EF003459. https://doi. org/10.1029/2022EF003459

The Westward Expansion of Monsoon Rainfall is a result of Westward Expansion of the Indian Ocean Warm Pool



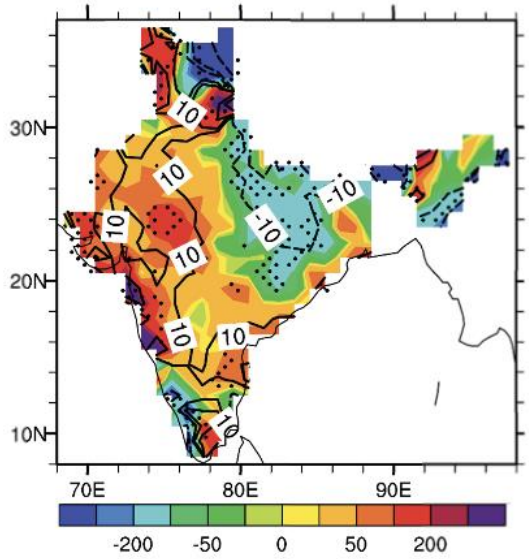
Hist

RCP4.5

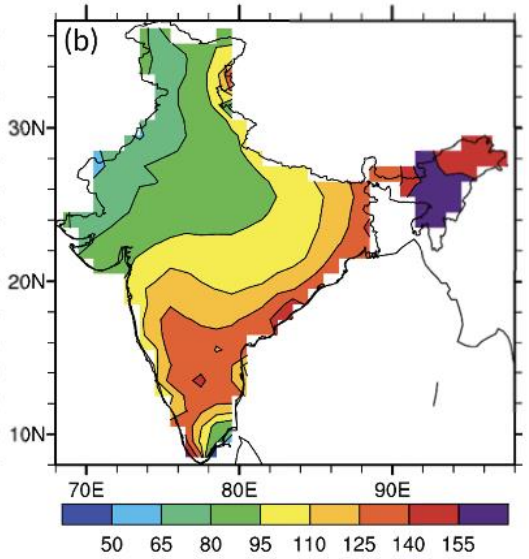
RCP4.5

Fig. 2| Observed and simulated changes in the Indian Ocean Warm Pool (a) Present JJAS SST climatology from HadISST (1979-2015) (shading); (b) Changes in observed JJAS SST climatology between the past 30-years (1901-1930) with current 30-years (1985-2014) and (c) the changes in the ensemble mean SST climatology simulated by 34 CMIP6 historical models between present (1985-2014) and the past (1901-1930).(d) The difference between multi-model ensemble mean projected climatology for SSP2-4.5 for the projected period (2071-2099) with the past (1901-1930). The thick black SST contour in (c&d) is provided to distinguish the regions between strong warming and relatively less warming. The SNR is greater than one for the entire domain.

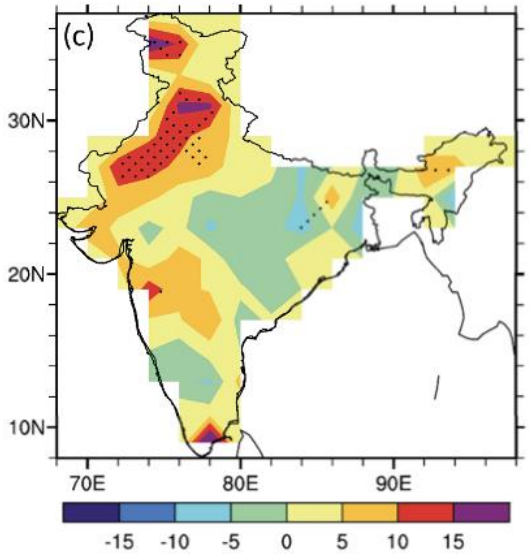
%P change



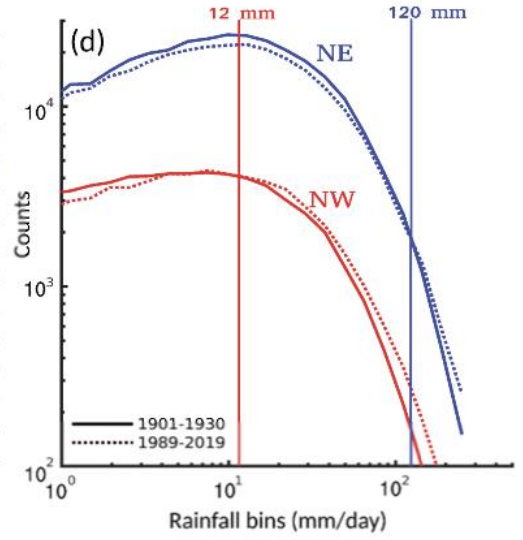
Clim. LRS



LRS Change days



Rainfall Frequency distribution



The increase in rainfall over NWI is happening by Lengthening the rainy season (LRS) by 10-15 days and increasing the frequency of 1 cm/day to 20 cm/ day rain events during the Historical period.

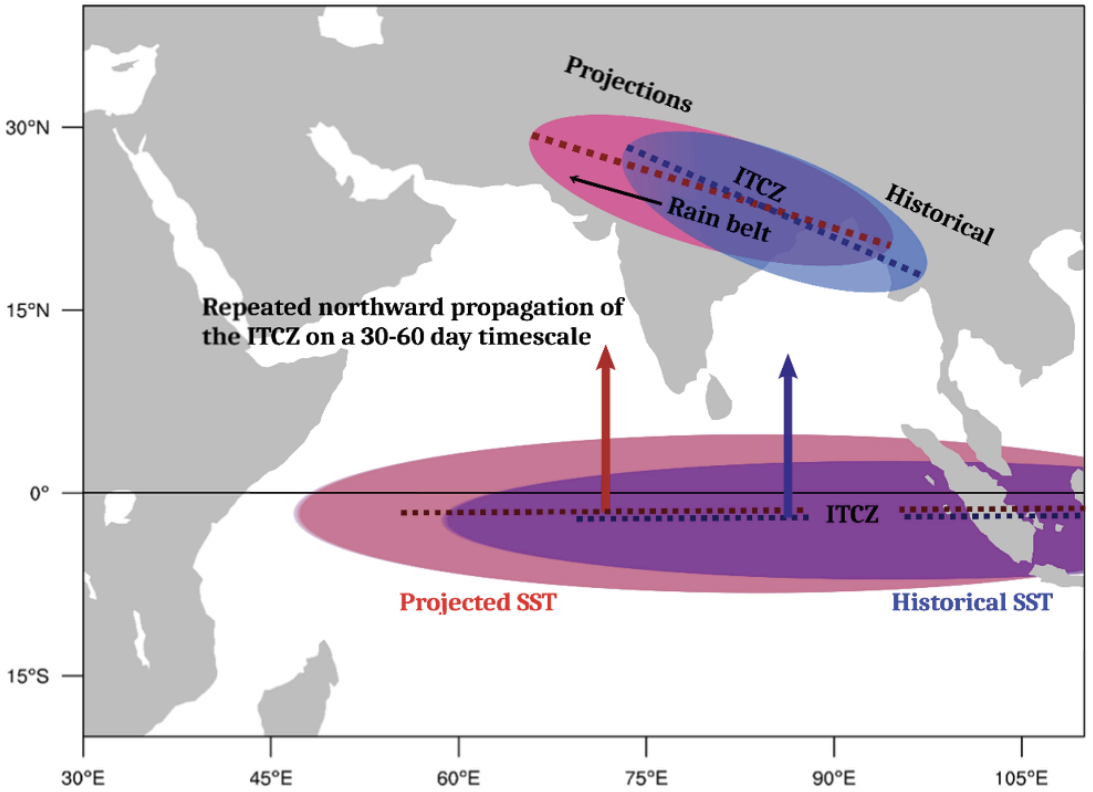
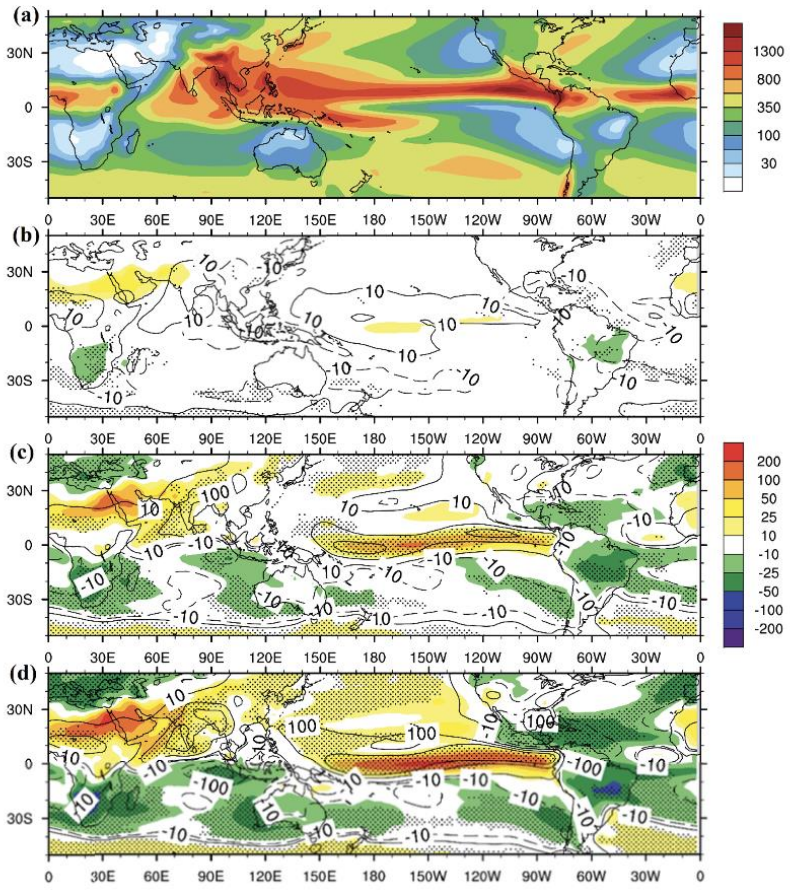


Fig 4. Illustration of the mechanism of the westward expansion of ISMR. The schematic diagram highlights the key differences between observed and predicted changes caused by the westward movement of warm water in the equatorial Indian Ocean and the expansion of the monsoon rain belt towards the west. With the shift of warm water to the west, the region where intraseasonal oscillations (ISOs) originate and are regulated has expanded beyond the previous limits set by the oceanic band of the Intertropical Convergence Zone (ITCZ). Consequently, the monsoon rain belts have also shifted westward because of this expansion.

The westward expansion of Indian monsoon Rainfall is part of a westward expansion of Global ITCZ



Clim.

% Diff, Historical

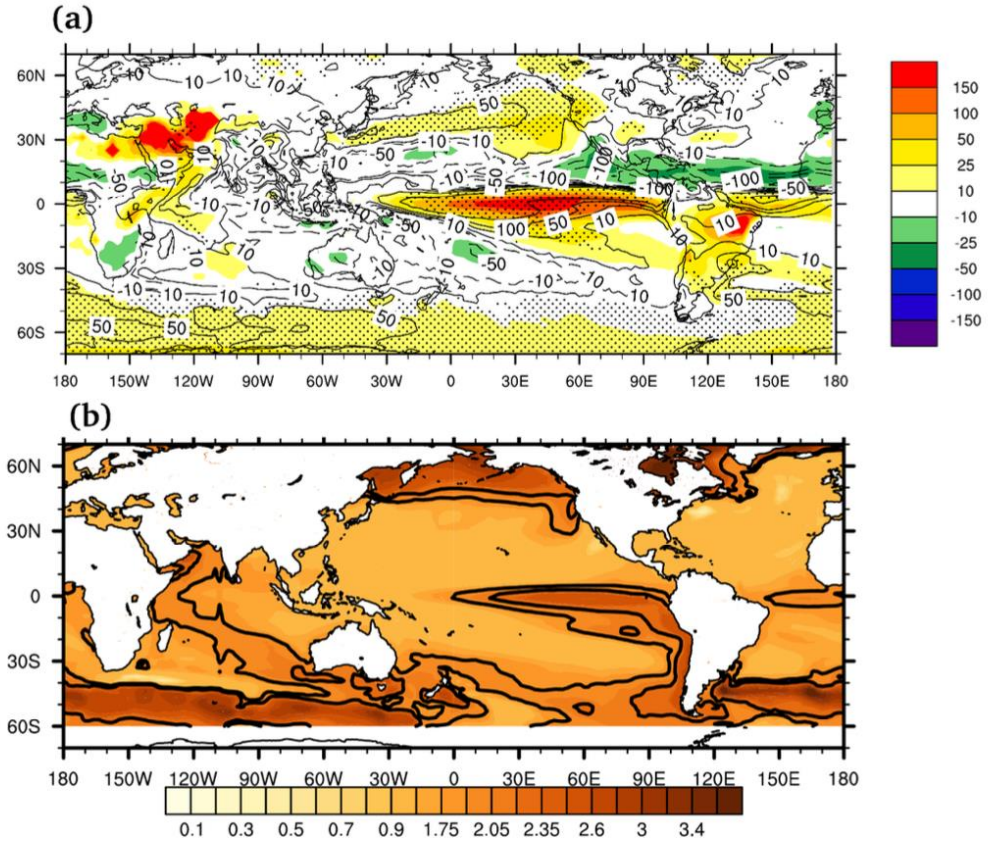
% Diff, RCP4.5

% Diff, RCP8.5

Multi-model Ensemble mean simulation of JJAS rainfall

Fig 5. Changes in simulated boreal summer monsoon rainfall (a) Global distributions of present-day JJAS MME accumulated rainfall climatology (mm) from CMIP6 historical simulations (shading) (1979–2015), similar to Fig 1, but shown for the entire tropical region (b) Contours represent rainfall climatology differences calculated as $PR_{pres} - PR_{past}$ during the simulated historical period; (c) rainfall climatology differences calculated as $PR_{proj} - PR_{past}$ for the SSP2–4.5 ensemble; and (d) for the SSP5–8.5 ensemble, respectively. The color shading in (b, c, and d) represents the percentage change (%) in rainfall amount with reference to the past climatology (PR_{hist}) and the contours represent the changes in seasonal accumulated rainfall amount (mm). The dotted area denotes the regions where the signal-to-noise ratio (SNR) (inter-model standard deviation) of magnitude of the projected trend (MME mean change) is greater than one.

Our conclusions that the westward expansion of Indian monsoon is largely driven by greenhouse gas (GHG) forcing is supported by a series of 4xCO experiments under CMIP6.



- Abrupt 4xCO_2 experiments for about 150 years by AOGCMs.
- Difference between JJAS Clim. Of first 30 years and last 30 years.
- Precipitation changes are % of baseline
- SST changes are in ^{O}C

Implications: Opportunities & Challenges

- India is the only place in the world, where Climate Change will have a potential beneficial influence. This is an **opportunity** the people of the region could not afford to miss.
- However, it is also fraught with **challenges**. The rapid increase in Frequency and Intensity if Extreme rainfall events going to create havoc via hydrological disasters, floods and landslides, more so over the Northwest India.
- The findings are well quantified and has ‘high confidence’. The policy makers need to pay attention and develop appropriate long-term Adaptation and Mitigation policies.

Gap Areas and Way Forward

Unravelling an Additional Source of ISMR Predictability

- After Walker's discovery of association between ENSO and ISMR, the scientific basis of tropical seasonal predictability established during TOGA era and ENSO remained the only Predictable driver for ISMR.

- However, ENSO explains only 35% of ISMR variability. Need for additional Predictable drivers for ISMR explaining additional fraction of remaining ISMR variability. In a series of studies, we establish that NA SST is an additional source of ISMR predictability.

- Our studies establish that Extratropical SSTs can influence the variability and predictability of Tropical climate!

- Goswami et al.,, 2022:), npj Climate and Atmospheric Science, 5:58, https://doi.org/10.1038/s41612-022-00281-3
- Borah, P. J., et al., 2020: Science, doi:10.1126/science.aay6043
- Rajesh and Goswami, 2020: Climate Dynamics, https://doi.org/10.1007/s00382-020-05407-y
- B. N. Goswami, et al., 2006: Geophys. Res. Lett., 33, L02706, doi:10.1029/ 2005GL024803

Gap Areas and Way Forward

- We need to pay closer attention to regional differences within the south Asian Region. An example, Northeast India.
- The event-to-event variability or 'complexity' is limiting the skill of both Weather and Seasonal prediction.
- How to extend the useful skill of Seasonal Prediction of ISMR? Is there a physical basis of long-lead predictability of ISMR?
- Deep learning AI can overcome the 'error growth' problem and achieve useful long-lead prediction of ISMR (manuscript under review)

- **Saha et al., 2023**:Present and future of the South Asian summer monsoon's rainy season over Northeast India , npj Climate and Atmospheric Science 170
- **Sharma et al.,** Variability and predictability of the Northeast India summer monsoon rainfall, Int J Climatol. 2023;1–21.
- **Sharma et al**., 2022: Mechanism for high "potential skill" of Indian summer monsoon rainfall prediction up to two years in advance, *Q J R Meteorol Soc*. 2022;1–13. DOI: 10.1002/qj.4375

Gap Areas and Way Forward

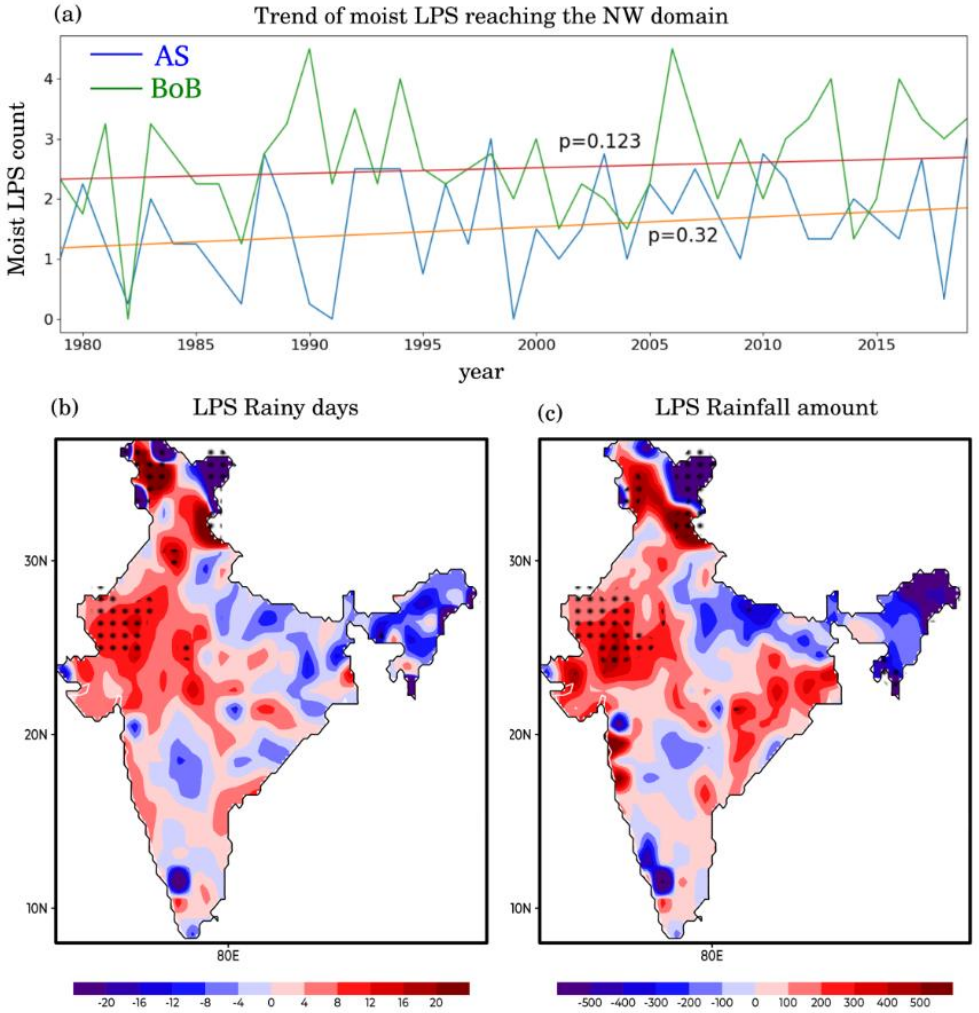
- Reduce uncertainty in projection of Indian monsoon rainfall by reducing biases in ISMR simulations by Climate Models. CMIP6 models have large biases in simulating ISMR.

- That is a slow process. In the meanwhile, to have better confidence in the CMIP6 projections, we find an Emergent Constraint for correcting for biases in Projections of ISMR.

- **Choudhury, B.A., Rajesh, P.V., Zahan, Y. and B. N. Goswami**. Evolution of the Indian summer monsoon rainfall simulations from CMIP3 to CMIP6 models. Clim Dyn (2021). https://doi.org/10.1007/s00382-021-06023-0

- **Rajesh, P. V., & Goswami, B. N.** (2022). A new emergent constraint corrected projections of Indian summer monsoon rainfall. *Geophysical Research Letters*, *49*, e2021GL096671. https://doi.org/10.1029/2021GL096671

Thank You

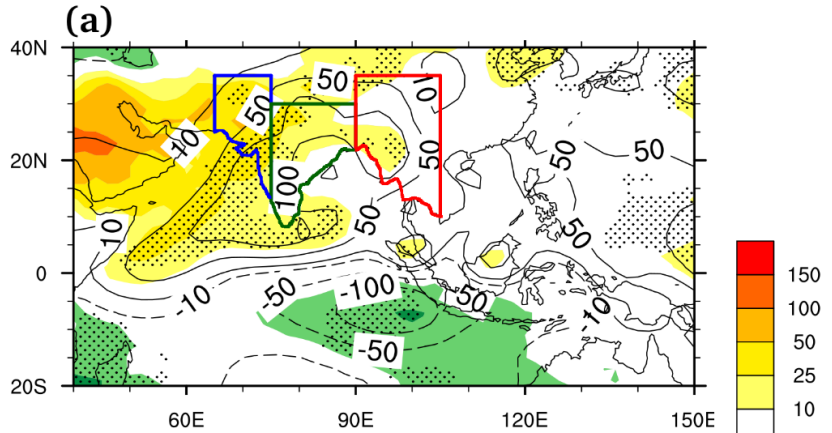


Penetration of more low-pressure systems (LPS) deeper in to NWI due to westward expansion of the ITCZ contributes to increased rainfall over the NWI.

Fig S4. (a) The variations in LPS counts for systems emanating from the Bay of Bengal (BoB) (green) and the Arabian Sea (AS) (blue), which penetrate the deep interior (NW) of the Indian subcontinent (domain 70^{O}E–76^{O}E,20^{O}N–30^{O}N) within the last four decades. The LPS data is obtained from the Global Track dataset of monsoon LPS (Vishnu[4](Vishnu et al., 2020), ERA reanalysis). Using the LPS data, the corresponding rainfall amount and LPS duration are derived using IMD 1 degree data. (b) The trend of total LPS rainy days from 1979 to 2015, and (c) accumulated rainfall amount (mm) from moist low-pressure systems (LPS) originating from both the AS and the BoB during the JJAS season.

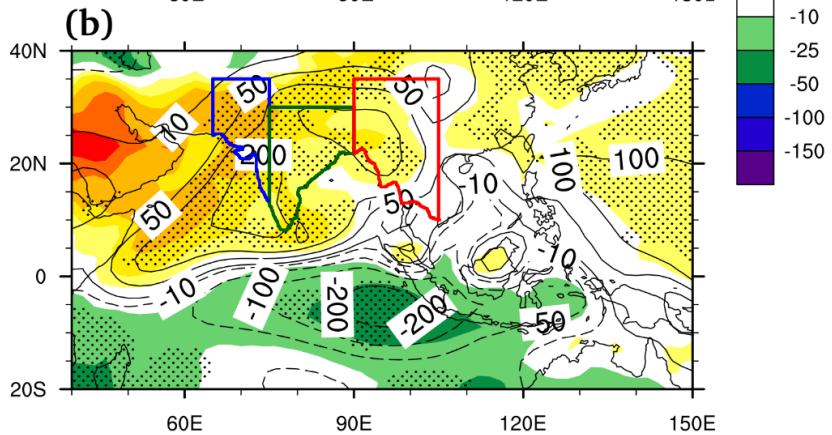
Westward Expansion of Indian Monsoon Rainfall ; Medium Term

SSP4.5



Mean Rainfall over NWI increases by 50-100% by 2050

SSP8.5



Mean Rainfall over NWI increases by 50-200% by 2050

Rajesh & Goswami, 2023: Potential demise of India deserts, Earth's Future