Trends in Intraseasonal Variability of the Indian Summer Monsoon

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Fluctuations in rainfall

Monsoon affects every walk of life over the South Asian Region

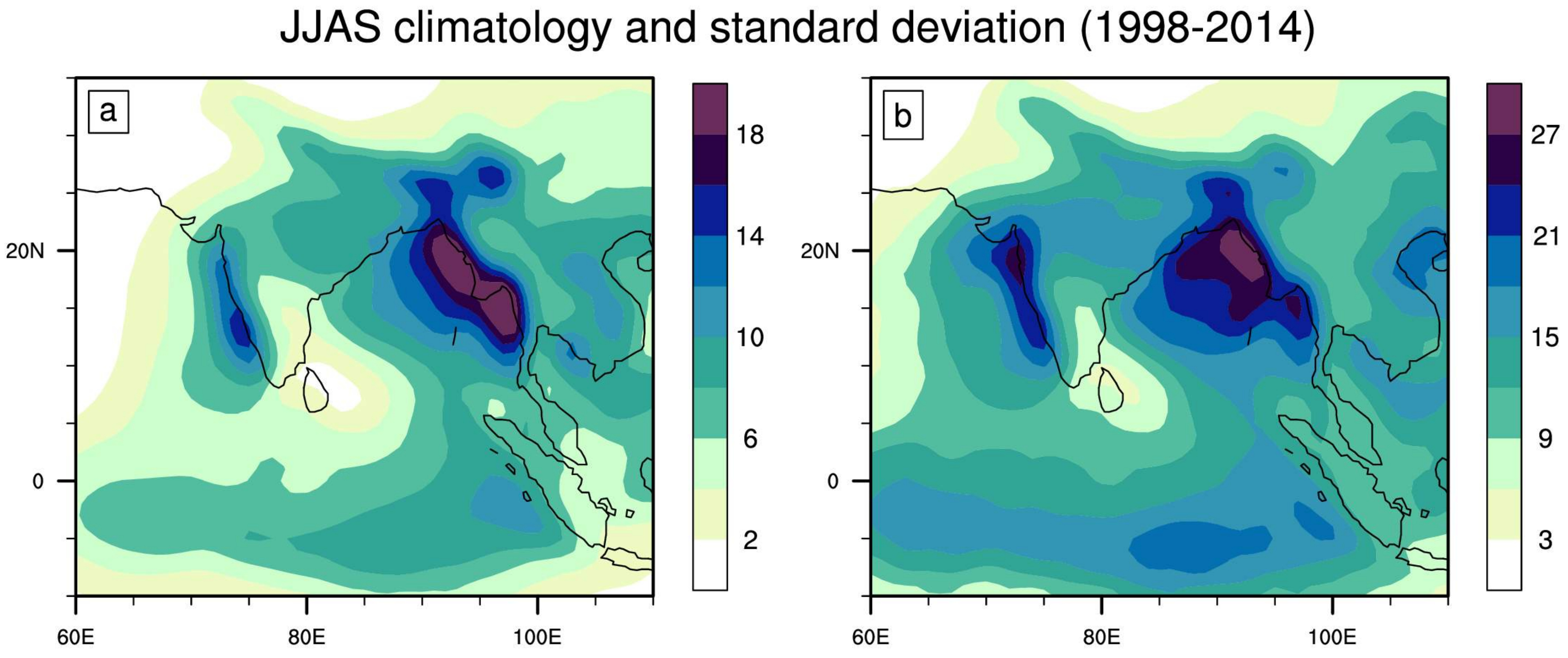
GOALS:

1. **Understand** the intraseasonal behaviour in the Indian summer monsoon rainfall.

2. Identify any **change** in the nature of the intraseasonal variability (ISV) in last few decades.

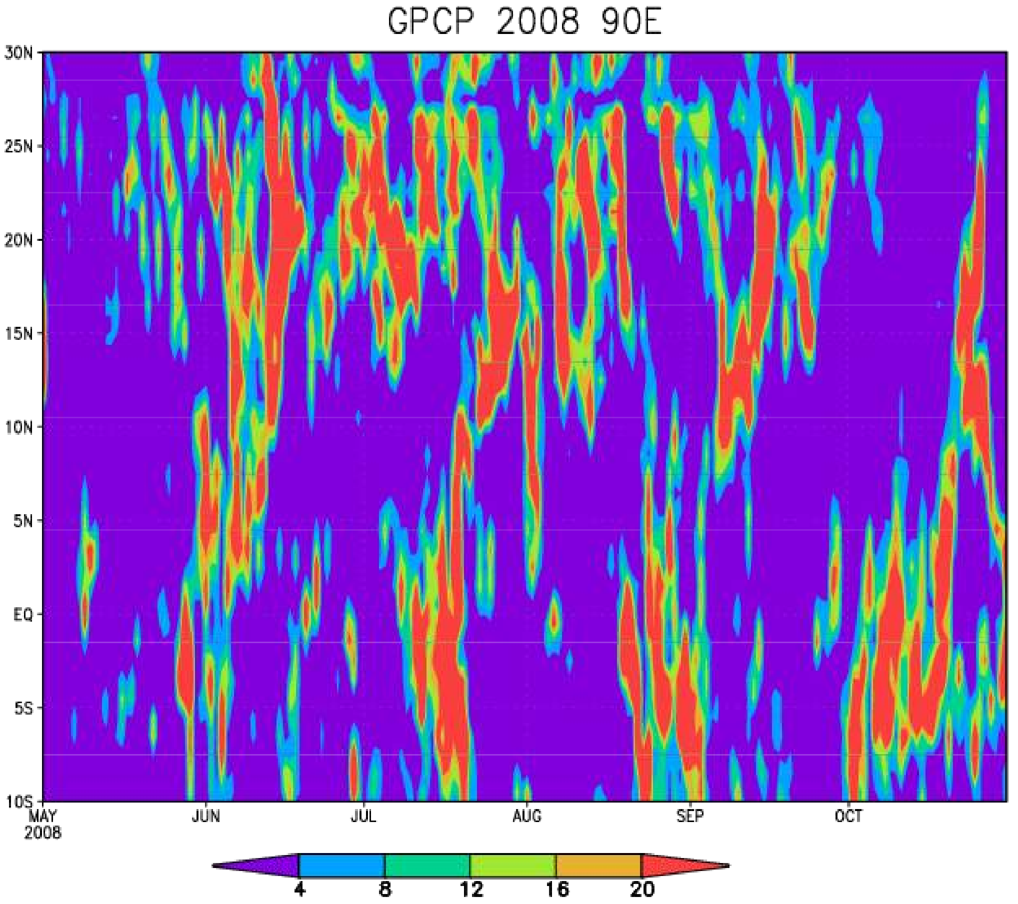
3. **Association** of ISV with extreme rainfall events and strength of Monsoon.

The Mean Monsoon



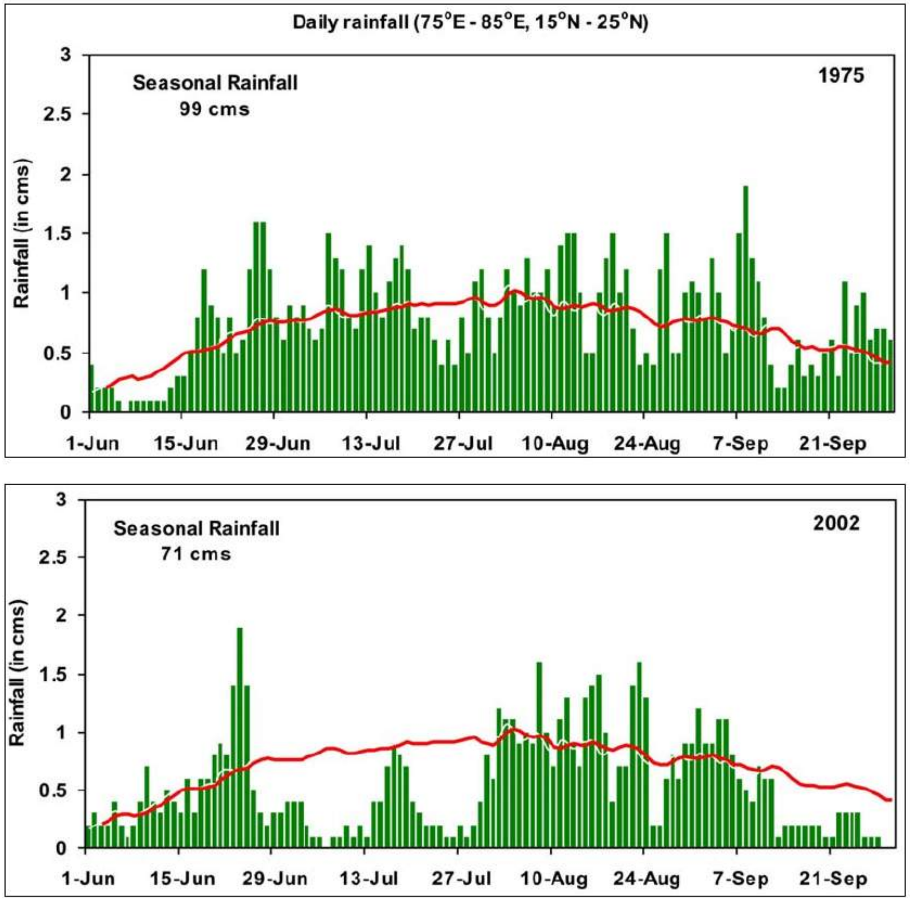
- Main regions of Rainfall are the Western Ghats, Mynamar mountains, monsoon trough in the north and the equatorial Indian Ocean in the south

Intraseasonal Structure of Rainfall

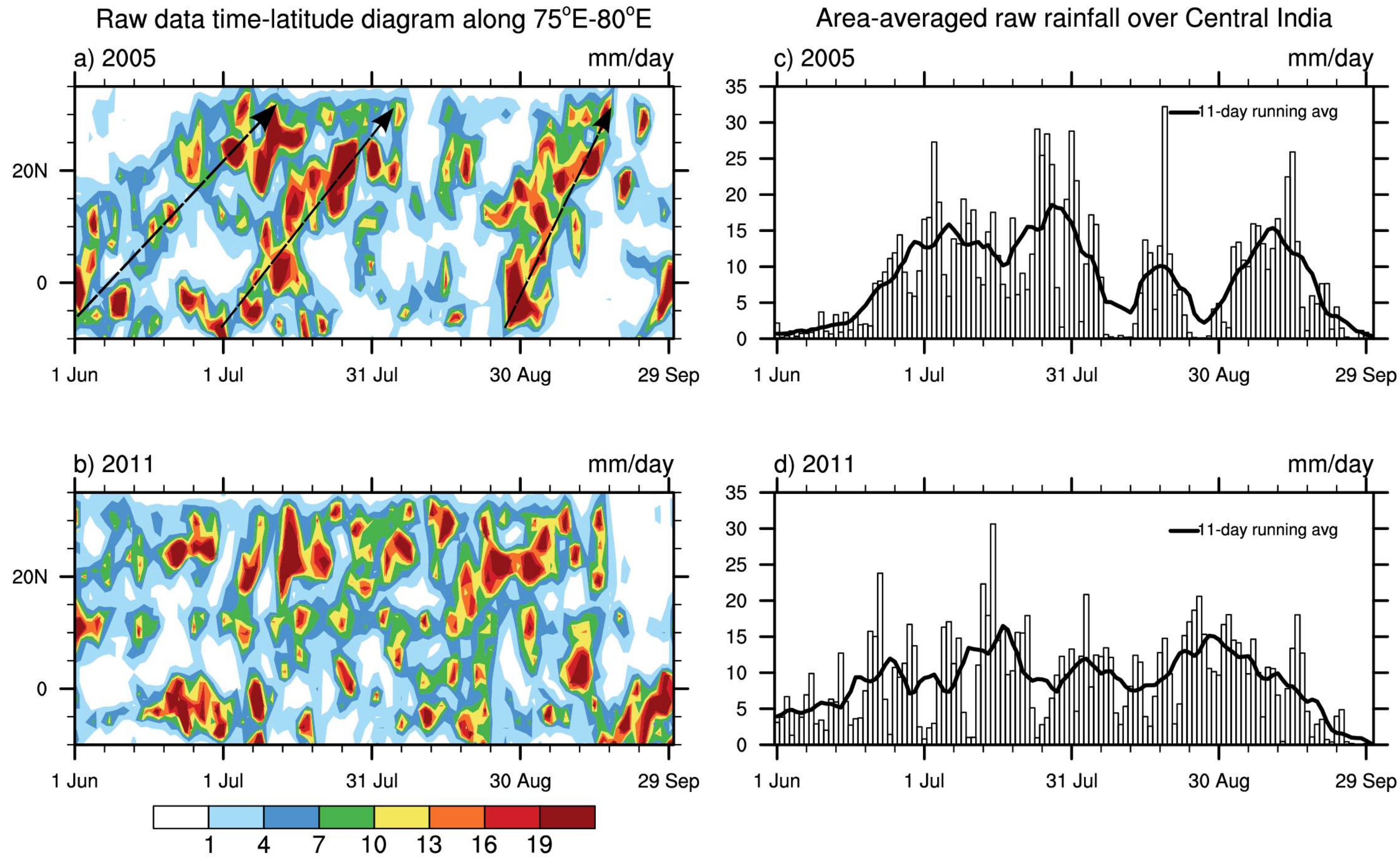


- Northward moving cloudbands. Seen every year. Unique to Indo-Pacific region
- Discovered by Sikka and Gadgil around 1980
- Generate over warm equatorial Indian Ocean and culminate in monsoon trough
- Typical time-interval between poleward progations 20-60 days

Active & Break Cycles of Monsoons



- Longer Periods of higher rain over central India in strong monsoon years (1975)
- Longer Periods of weaker rainfall in weak monsoon years (2002)



- Poleward propagations from equatorial Indian Ocean to Monsoon Trough
- Periodicity of approximately 30-60 days between these events
- Active Break Spells of monsoon have periodicity ranging from 15 -30 days

Two types of ISO:

1. Northward propagating **low-frequency ISO** (typically more than 20 days time-interval):

2. Northward and westward propagating **high-frequency ISO** (typically 10-20 days time-period):

Study of Rainfall ISO

1. Previous studies mainly in terms of either wind or OLR data due to the lack of quality precipitation data over the tropics. ISO in rainfall data in a larger domain?

2. Most studies on 30-90 day mode. Less studies on the high-frequency ISO mode.

3. Different years ==> Different ISO characteristics. A **statistically significant index to measure the strength of the ISO modes** can be useful in understanding the ISV of a particular year.

4. Modulation of the rainfall anomalies over India by the ISO modes.

5. Can information about ISO phases lead towards a better understanding of rainfall over certain regions?

6. Are there long term trends in ISO?

7. Do these trends impact the monsoon strength?

How to extract the ISO modes?:

Monsoon: Highly nonlinear and multiscale structure in both time and space.

Linear filters: hinder the fundamental understanding of a nonlinear, chaotic system.

Empirical Orthogonal Function (EOF): Dimension reduction tool; has many limitations (e.g., EOF modes may not correspond to individual dynamical modes or will be strongly influenced by the nonlocal requirement that modes maximize variance over the entire domain).

==> RPCA, ICA, NLPCA and many other variations of EOF technique evolved to overcome these.

We have used Multi-Channel Singular Spectrum Analysis (MSSA) for this purpose

How to extract the ISO modes?:

- Extract information from short and noisy time series and thus provide insight into the unknown or only partially known dynamics of the underlying system that generated the series (Ghil et al. (2002)).
- Extract the oscillatory patterns (ISO) present in the monsoon rainfall data.

How to extract the ISO modes?:

A glimpse of the MSSA method:

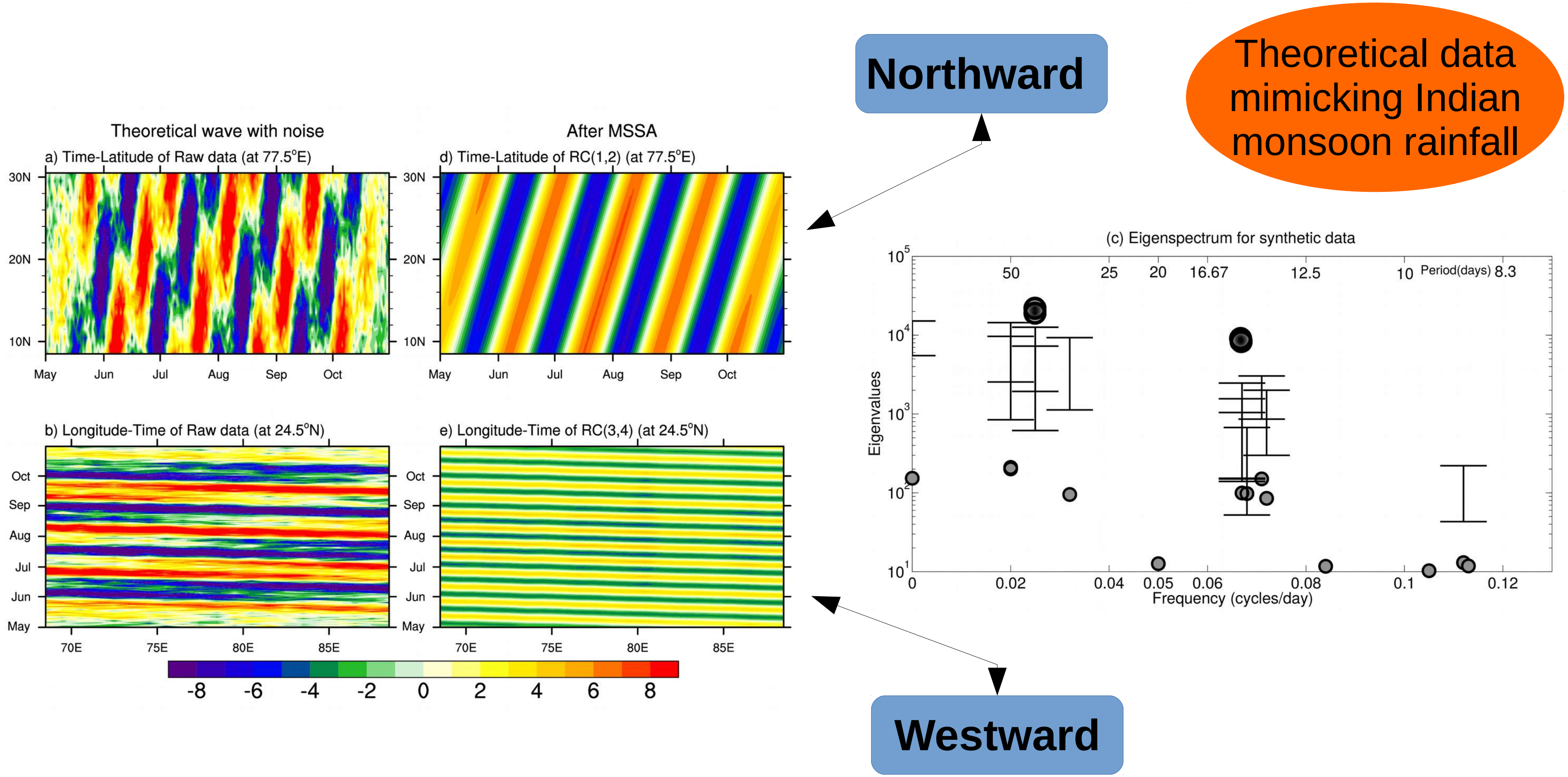
- Spectral method; bandwidth and shape of the filters are provided by the data instead of the user.
- Diagonalizes a lag-covariance matrix of the multi-channel time series with lags ranging from 0 to M-1; M = window length (**60 days**).

  ==> ST-PCs, ST-EOFs and eigenvalues.
- Applied a significant test (Allen and Robertson (1996)).

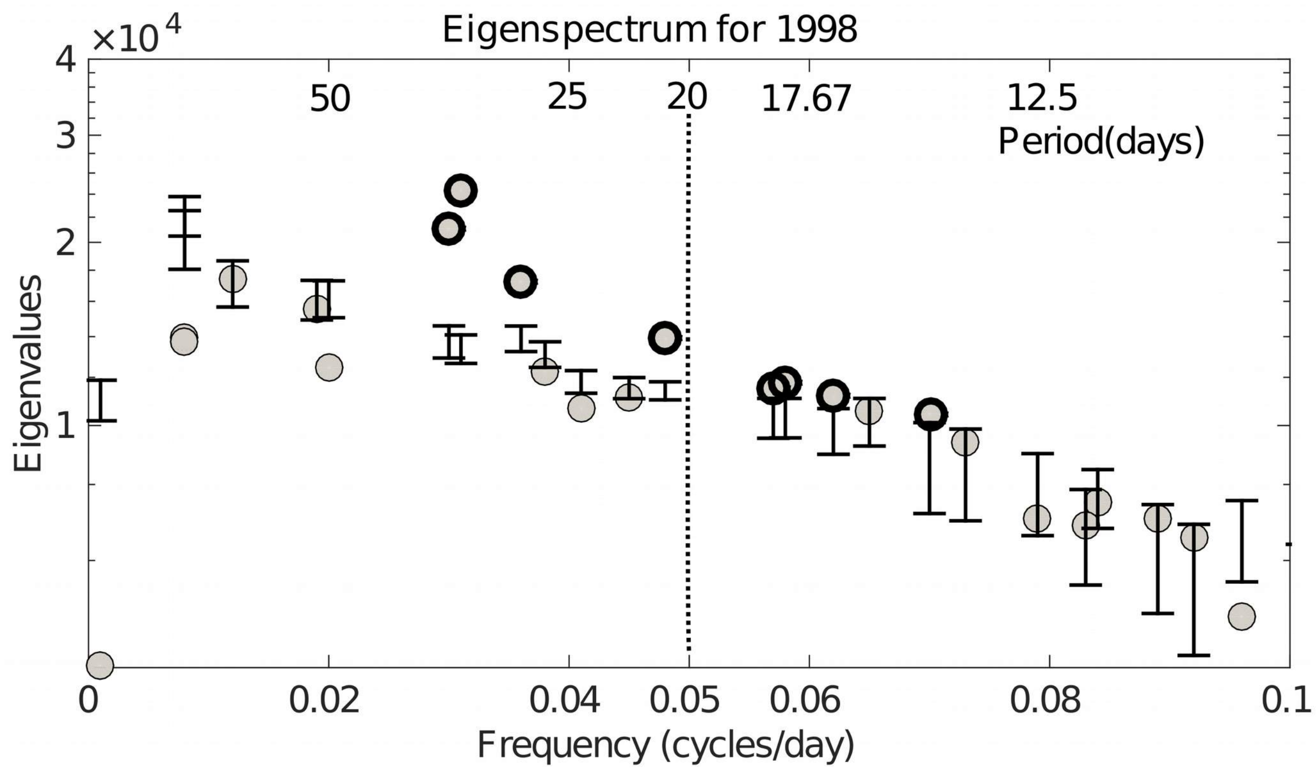
- To get an idea, fit a theoretical wave in space-time, mimicking rainfall over India during May-October: northward (40-day) and westward (15-day) oscillation.

How to extract the ISO modes?:

- Reconstruction of the individual components **(RCs)** of the system's behaviour is obtained by convolving the corresponding ST-PCs with the ST-EOFs.



Application to rainfall data (TRMM):



MSSA applied to May-October data each year (5-day smoothed). Domain: 10S-35N, 60E-110E.

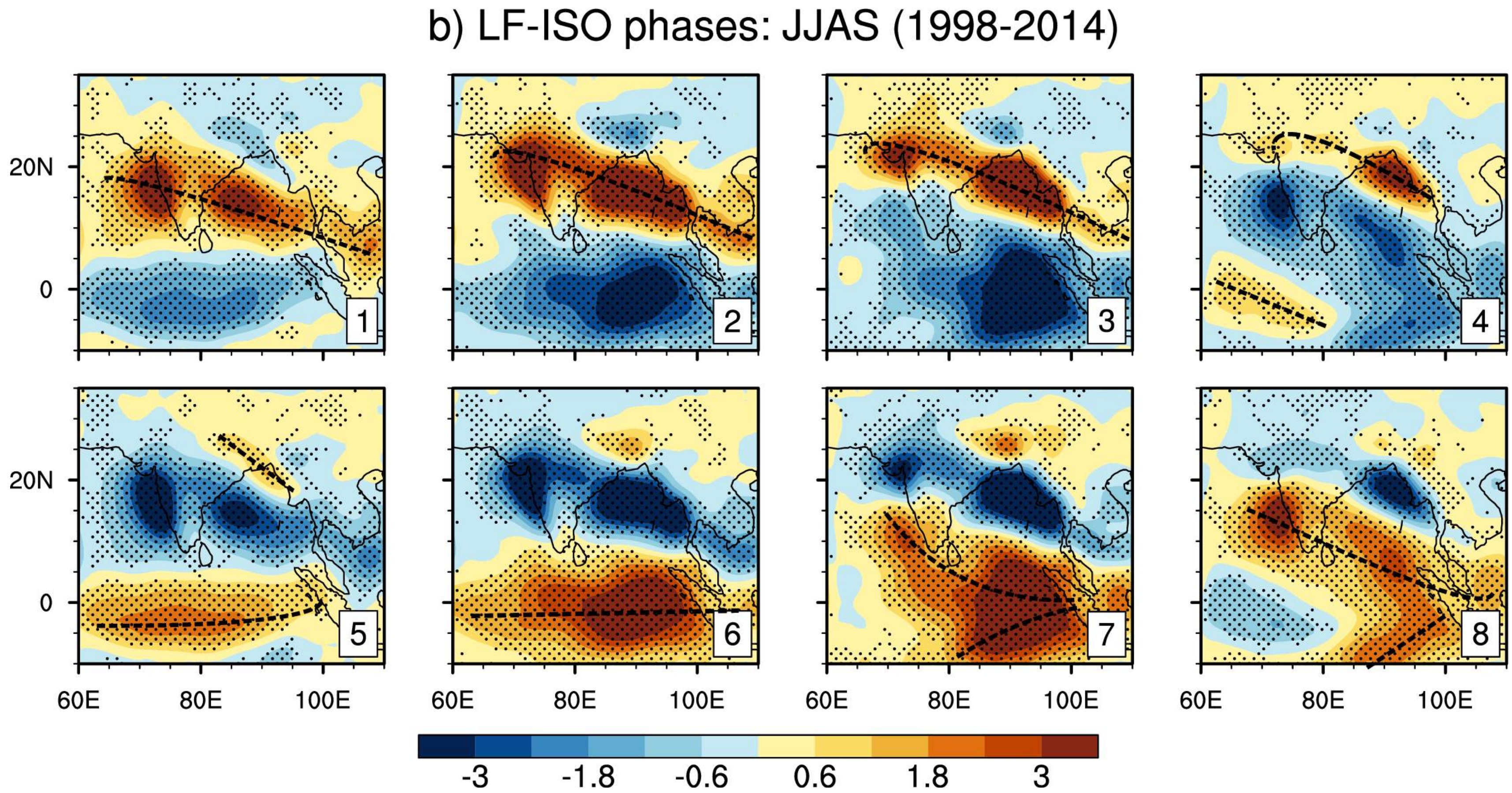
Low-frequency modes: LF-ISO=RC(1)+RC(2)+RC(4)+RC(7)
High-frequency modes: HF-ISO

Phase composites:

- Take an individual RC (space x time).
- Apply a conventional PCA to it.
- Use the first PC = b(t).
- Use first time derivative, b'(t).
- Normalize both of them => c(t) and c'(t).
- Calculate the argument of the complex number c'(t)+ic(t) => θ(t), phase angle.
- θ(t) lies within (-pi, pi).
- Divide the phase plane in eight equal parts.
- Average the RC in each part.

Phase composite achieved!!

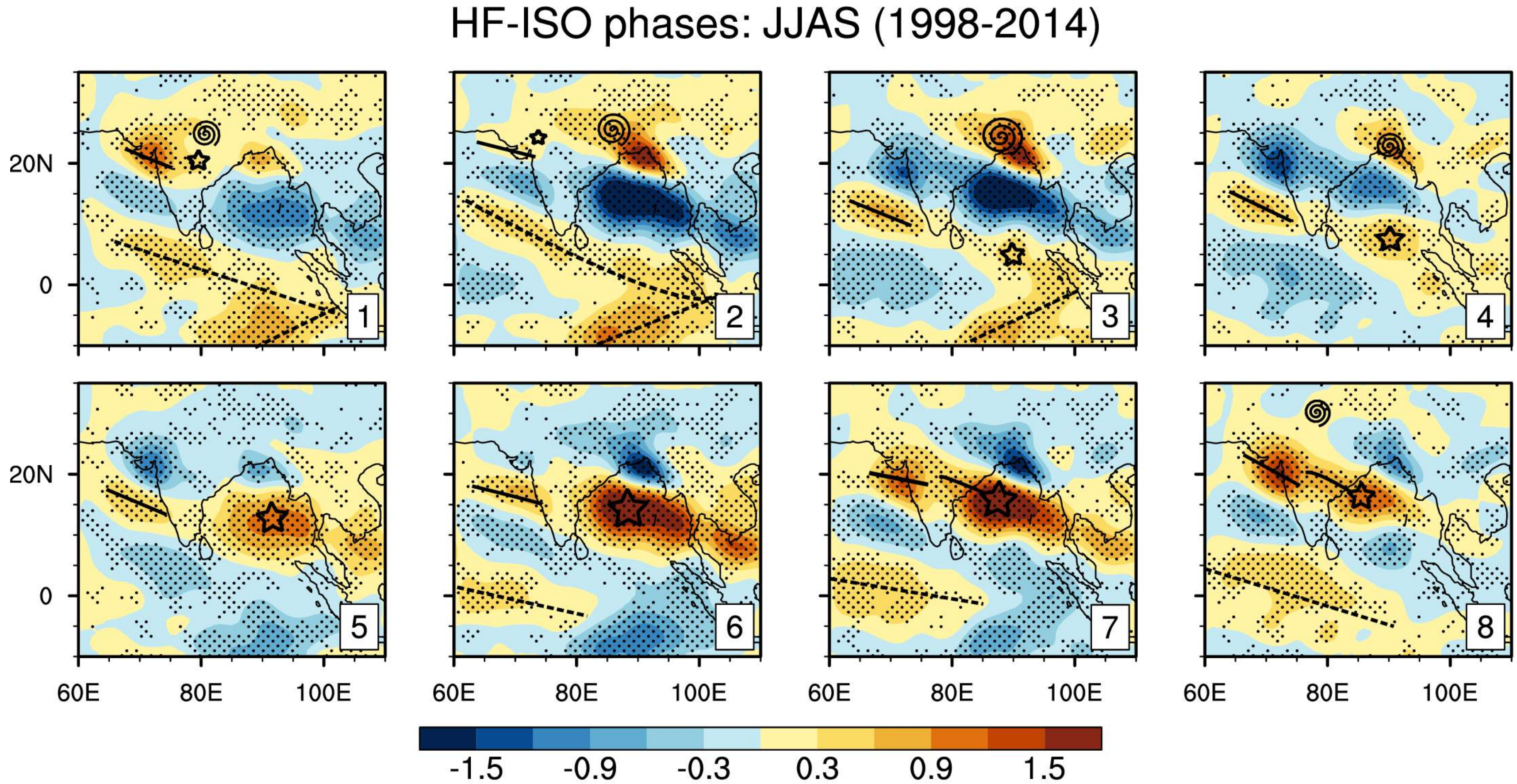
Space-time evolution of ISO modes:



Average of phase composites of all the significant modes (each scale) each year. Take average of all the years.

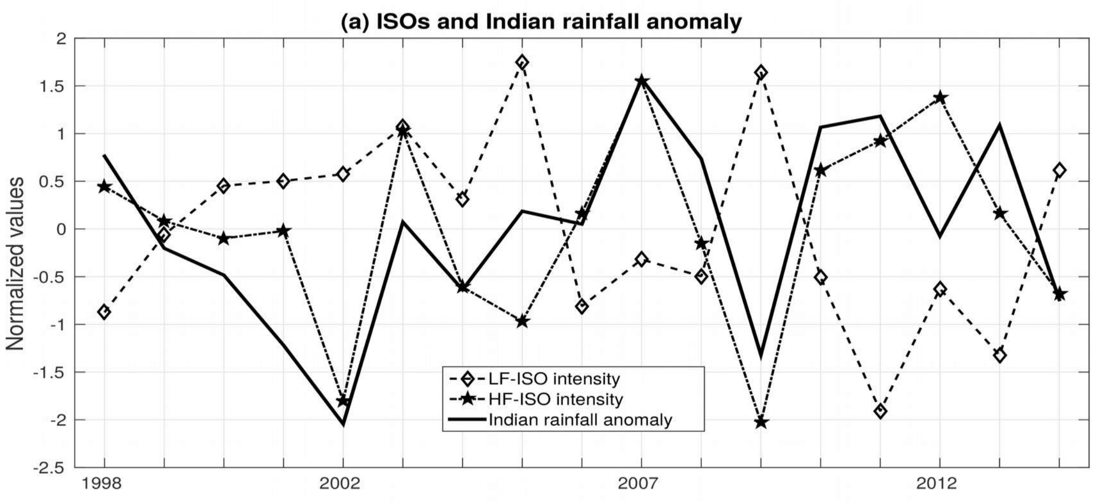
LF-ISO: Northward propagation from equatorial region. Associated with an eastward propagation near the equator. (Units: mm/day)

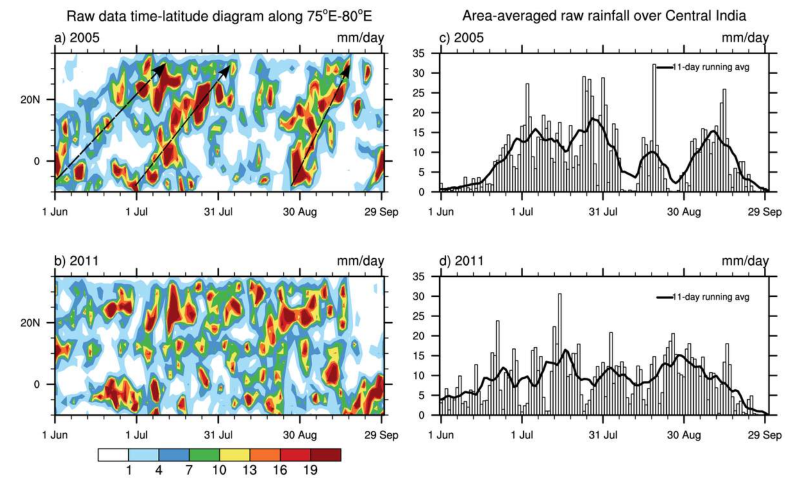
Space-time evolution of ISO modes:

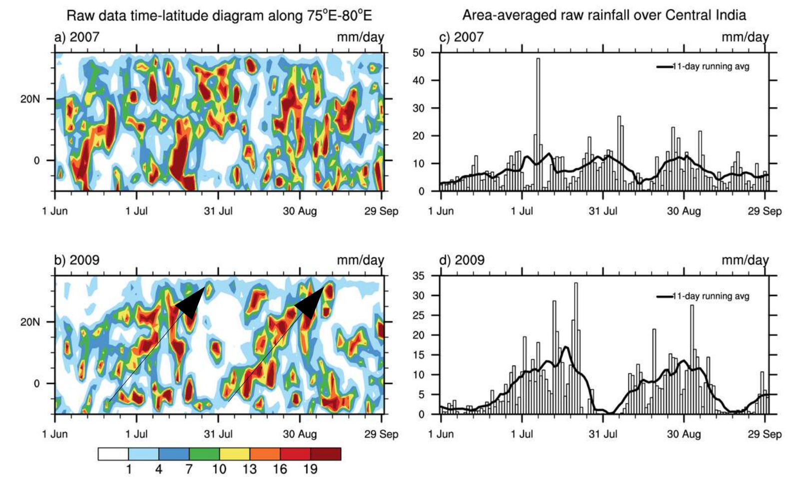


HF-ISO: Northward and westward propagation in lower latitudes. Associated with an southeastward propagation from higher latitudes. (Units: mm/day)

Defining ISO intensity:







ISO intensity: Add up the variance explained by the significant eigenmodes in LF- and HF-ISO band every year.

LF-ISO explains **15-43%** of total variability.
HF-ISO explains **7-18%** of total variability. (5-day smoothed)

R(LF-ISO intensity, Indian rainfall anom.)=-0.64
R(HF-ISO intensity, Indian rainfall anom.)=0.73

ISO intensity and rainfall:

Correlations:

Region	LF-ISO	HF-ISO
Central India (18°–26°N and 75°–82°E)	-0.58*	0.56*
Bay of Bengal (10°–20°N and 85°–95°E)	-0.21	0.12
Arabian Sea (10°–20°N and 60°–70°E)	-0.25	0.36
Central Equatorial Indian Ocean (5°S–5°N and 75°–85°E)	0.03	0.02

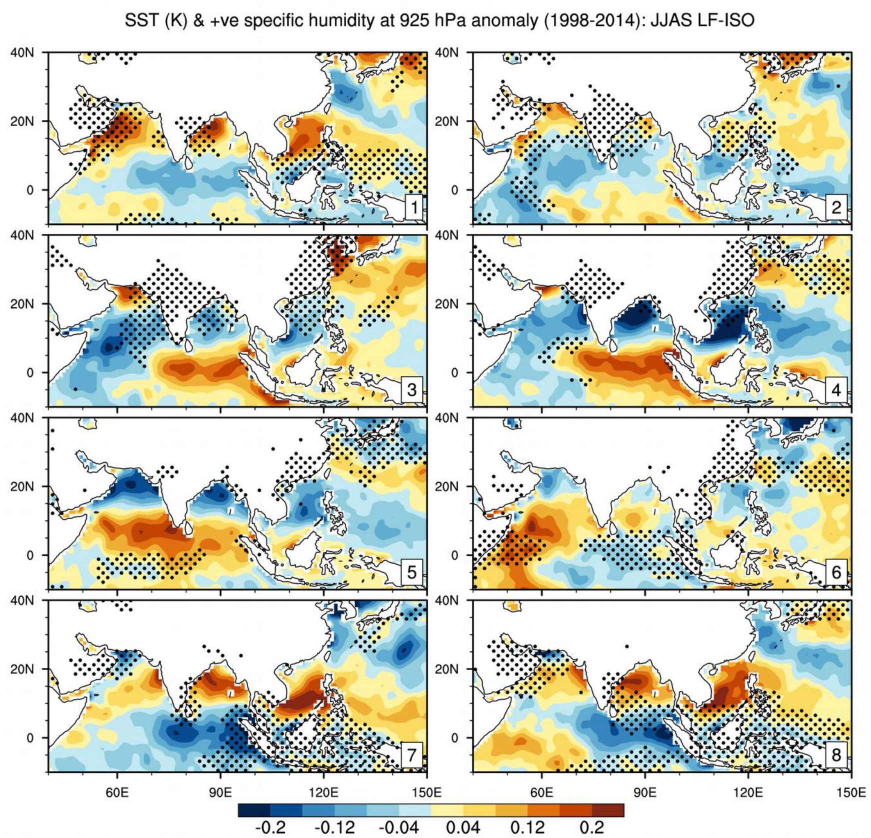
ISO intensities are not correlated with the rainfall over oceanic regions!!

Strongly correlated with CI rainfall, as well as, All-India land rainfall.

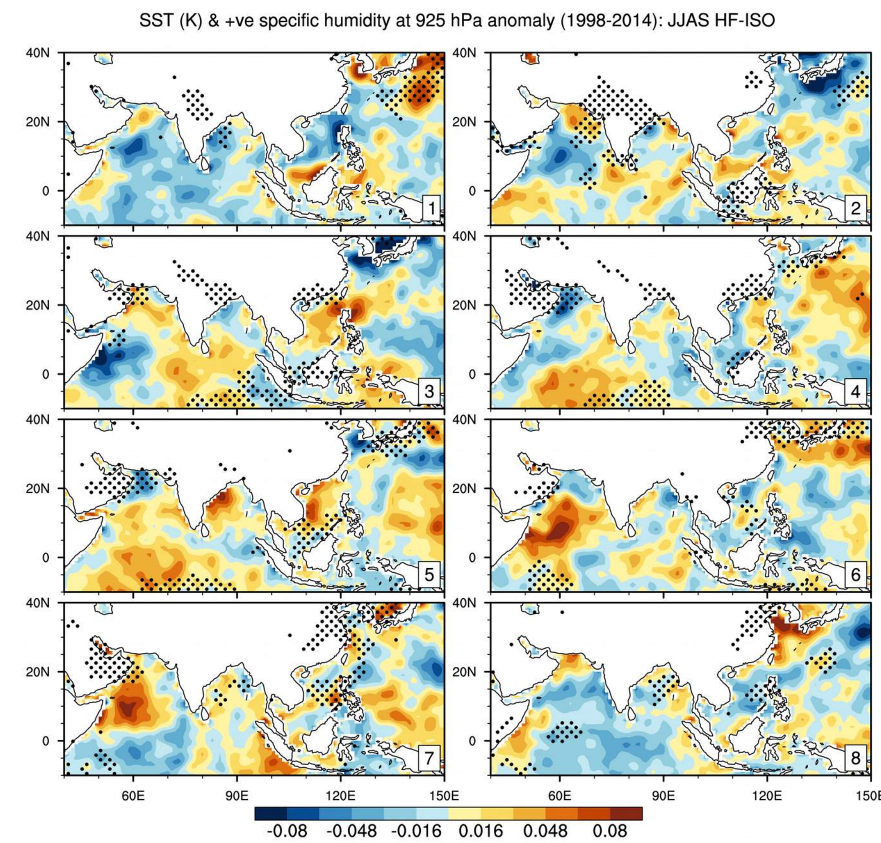
ISO nature does not remain same in droughts and floods!

Rainfall ISO and SST:

LF-ISO



HF-ISO



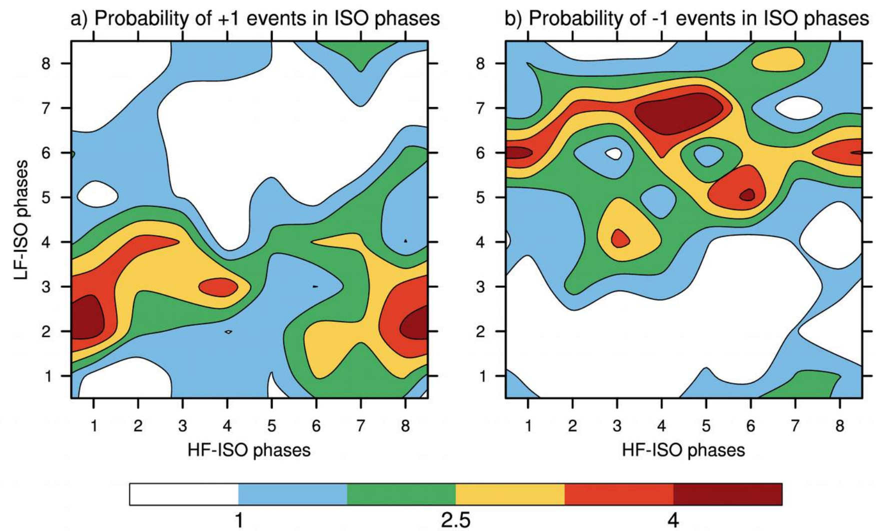
Color: SST anomaly
Dots: +ve specific humidity anomaly

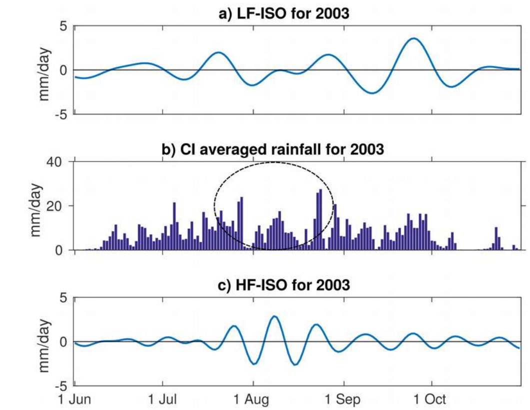
ERA-Interim Reanalysis
SST: NOAA OISST v2

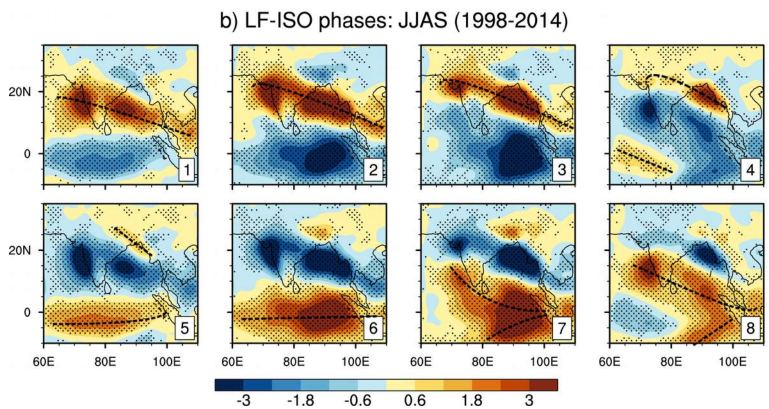
HF-ISO does not have a strong association with SST (boundary forcings)!

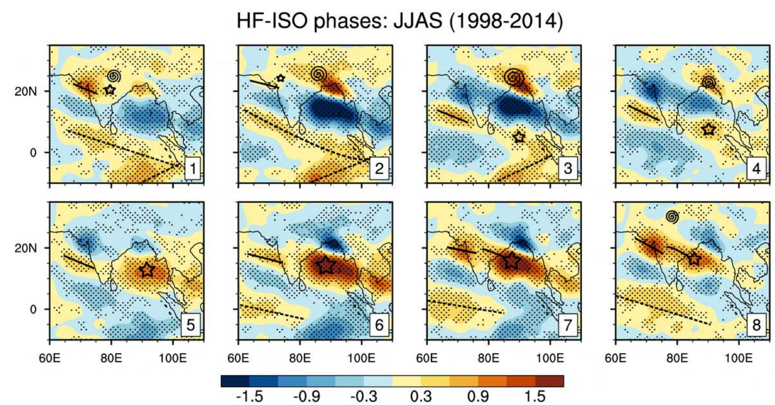
ISO and Indian rainfall:

+1/-1 events: based on normalized CI rainfall anomaly









LF-ISO primarily modulates the rainfall events over CI. HF-ISO also plays a significant role in modulating the probability of occurrence of rainfall over CI.

Summary of ISO Structure:

1. Understanding of the basic intraseasonal model in Indian summer monsoon rainfall.

2. Quantified the intensity of ISV. How this quantity varies with total rainfall over India?

3. Modulation of CI rainfall by the ISO modes.

Next: **Is there any change in the nature of ISV in last few decades?**

If yes, then what is the pattern of the change?

TRMM data is not sufficient to observe the change (limited to only 1998 onwards).

2. Changing Climate and ISO variability

ISO modes in IMD rainfall data:

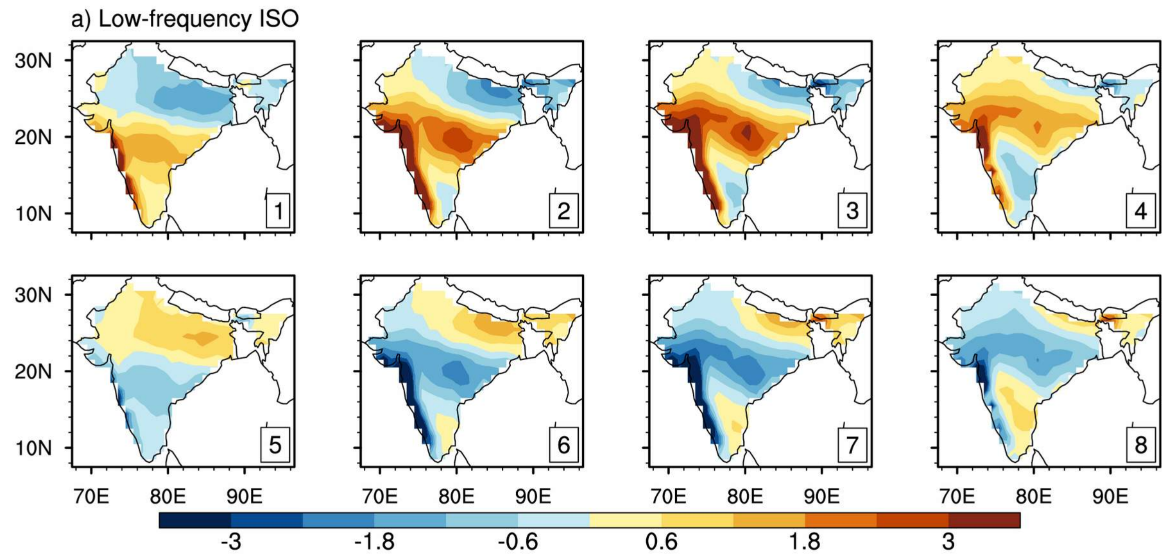
TRMM is too short to understand long-term changes

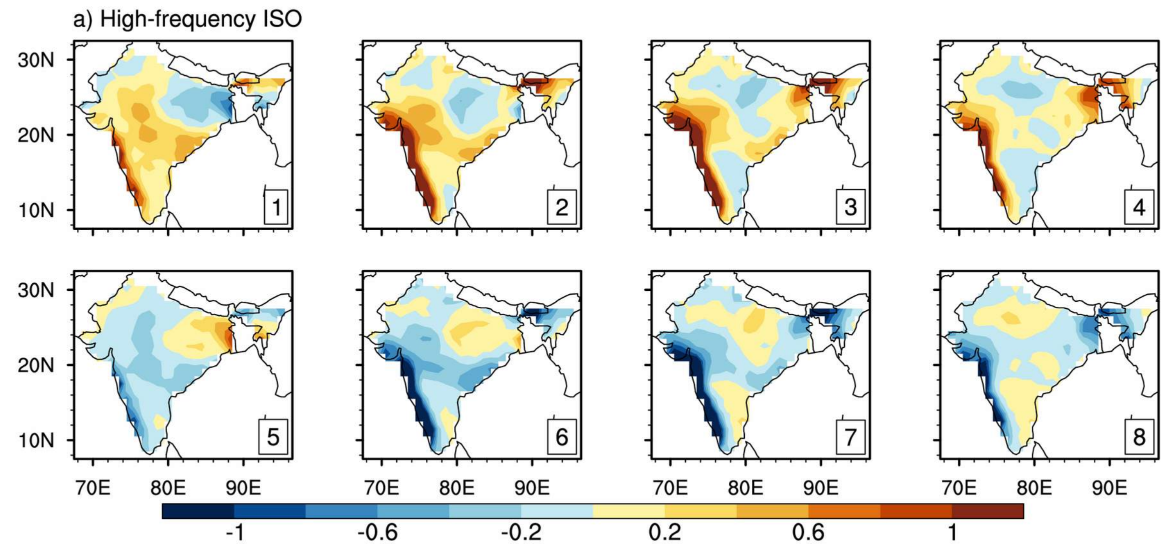
Used **IMD** gridded rainfall data (1951-2013)! (Rajeevan (2006))

Applied MSSA in similar way.

Extracted ISO modes similarly.

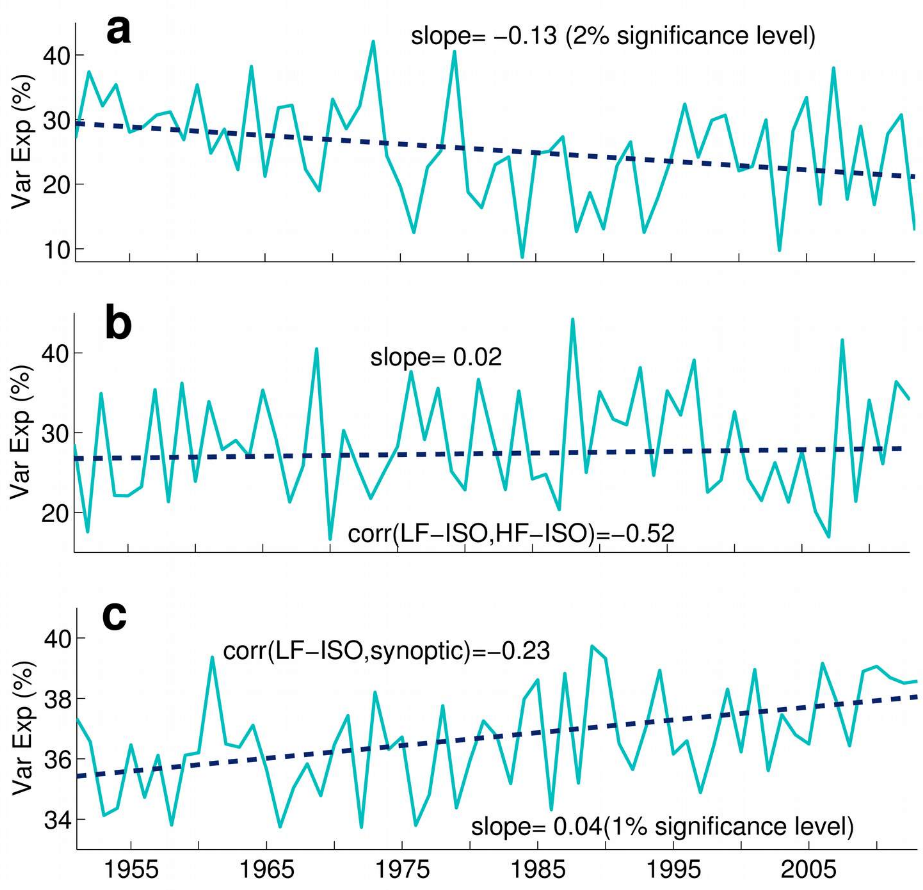
Created phase composites in a similar technique.





Units: mm/day

Weakening of LF-ISO:



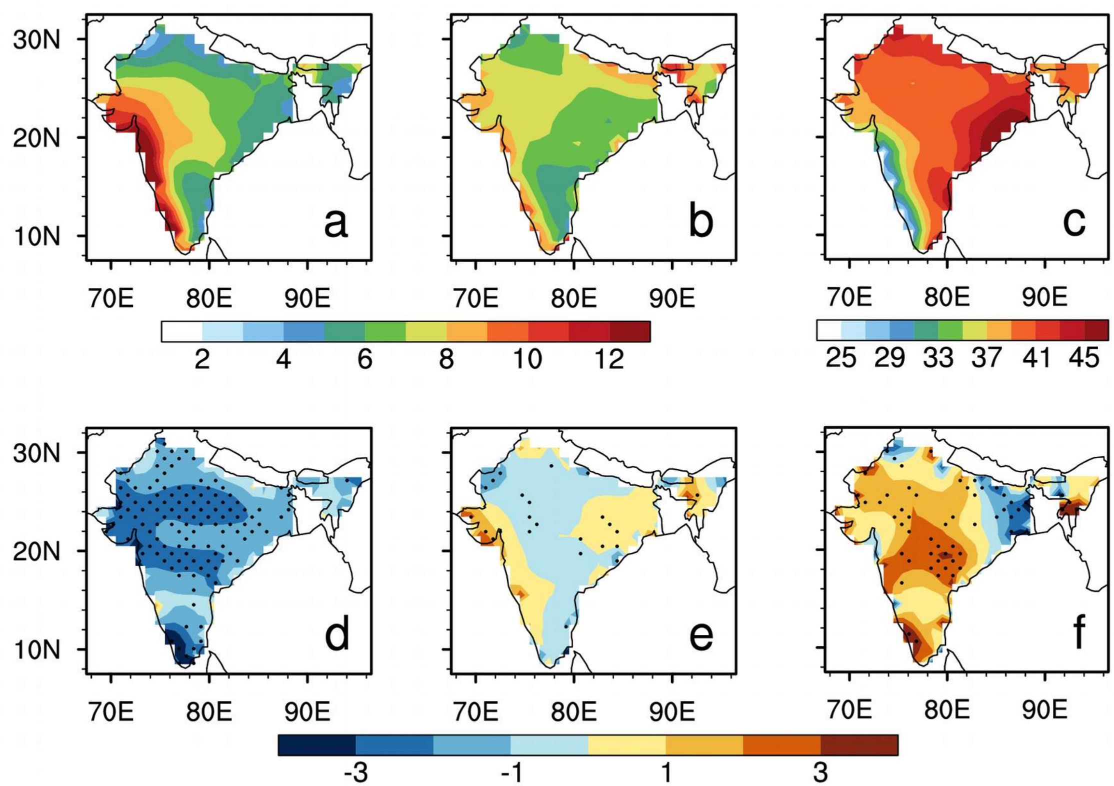
- LF-ISO shows a decreasing intensity from 1951-present (the period when Climate Change is significant)
- HF-ISO shows no significant trend
- Synoptic scale shows a decreasing trend!

Weakening of LF-ISO:

Values are given as **percentage** of total variance at a location.

Why 1980?
1. Splits timeseries into two equal parts.
2. Regime shift.

	LF-ISO	HF-ISO	Synoptic	



Pre (1951-1980)

Post(1980-2010)-Pre

Significant reduction in LF-ISO variance over the CI region and western India.

Increase in synoptic variability over CI.

Summary of ISO Trends:

1. Calculated the ISO intensities for a longer period.

2. A decreasing trend in LF-ISO intensity over the last six decades.

3. HF-ISO intensity remained the same.

4. Increase in synoptic variability.

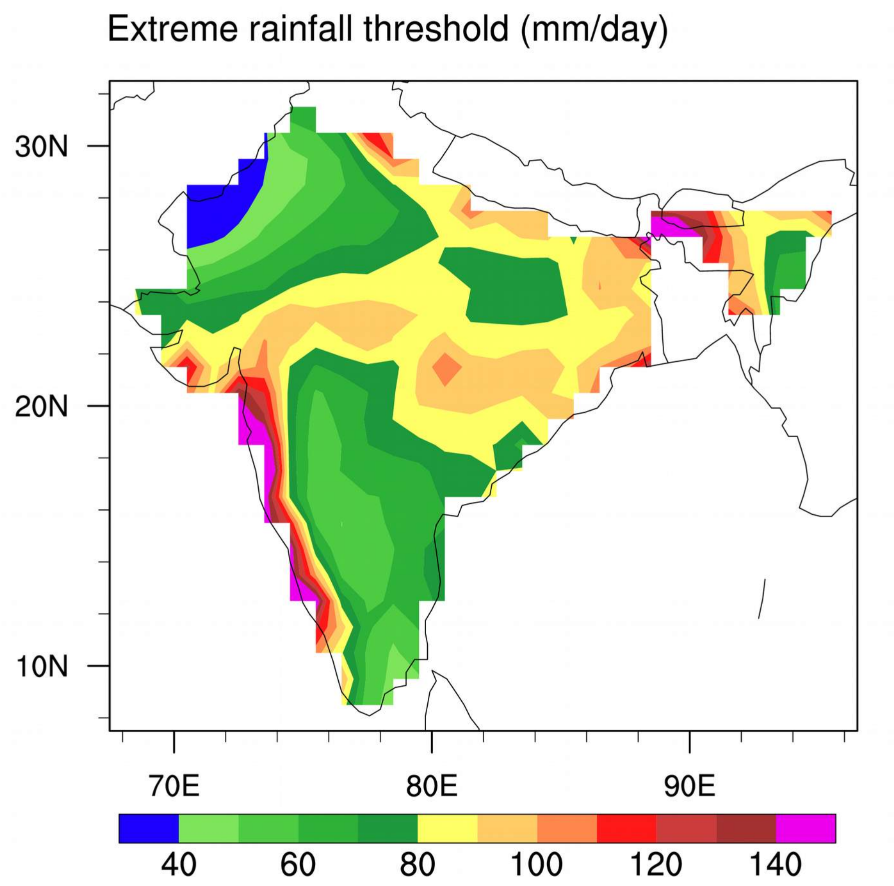
==> Increase in short scale rainfall events?

==> Increase in extreme rainfall events?

If yes, then how they are associated with LF-ISO?

3. Association of ISV with extreme rainfall events.

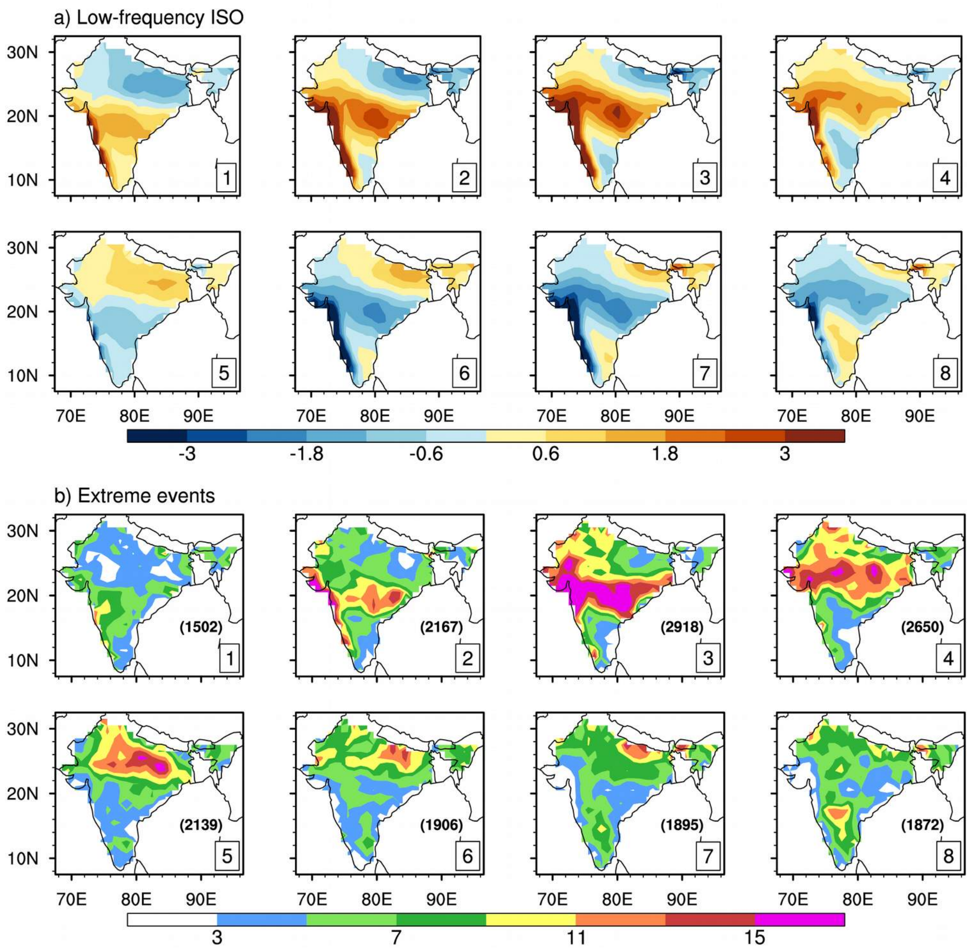
Defining extreme rainfall events:

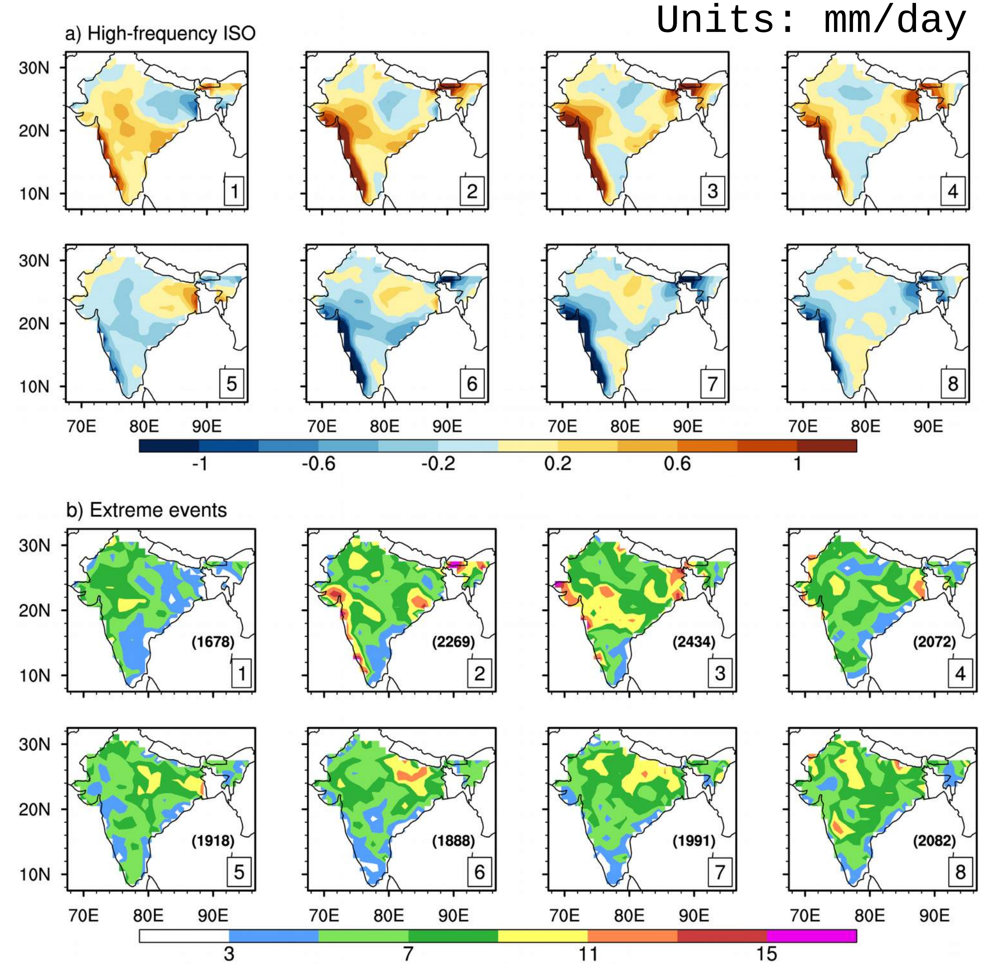


99.5th percentile value at each point as the threshold for extreme event. Different regions will have different threshold.

Association:

Units: mm/day

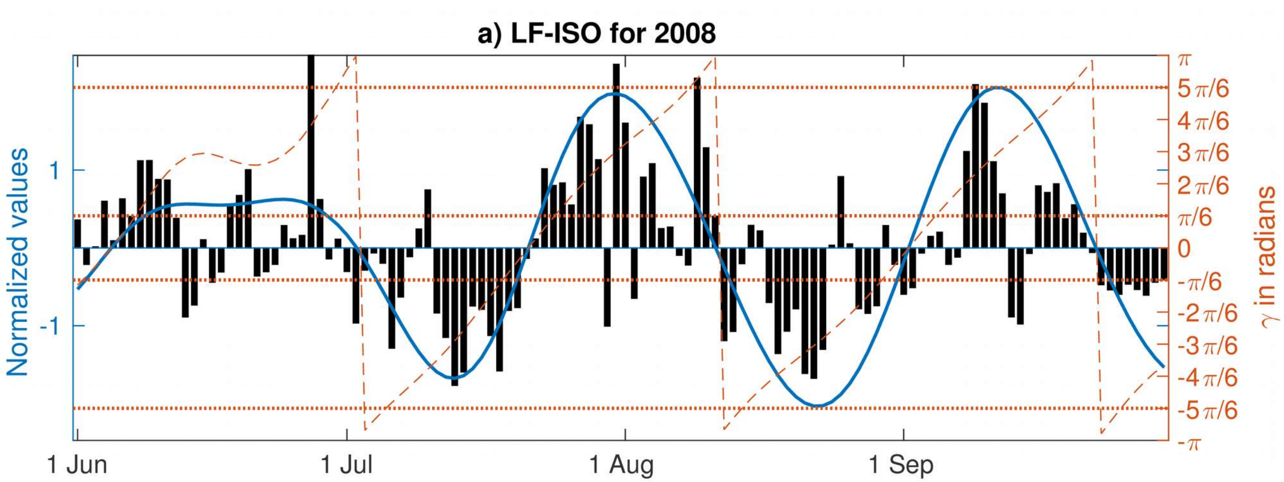


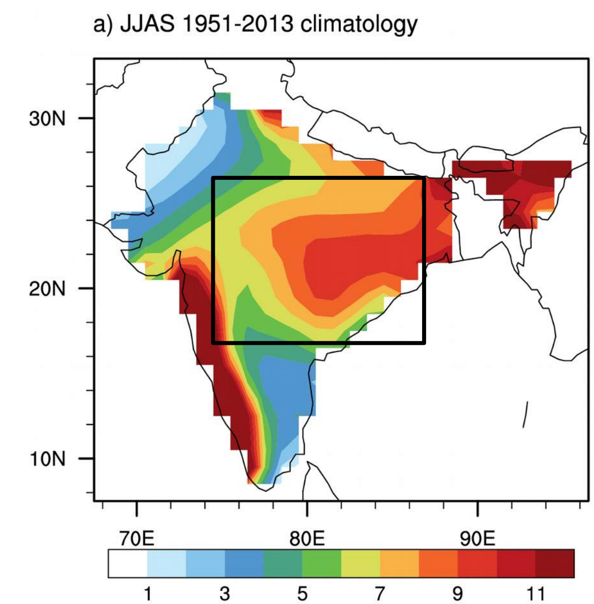


Strong association of extremes with LF-ISO phases.

Weaker in HF-ISO case!

Defining active and break phases (LF-ISO):





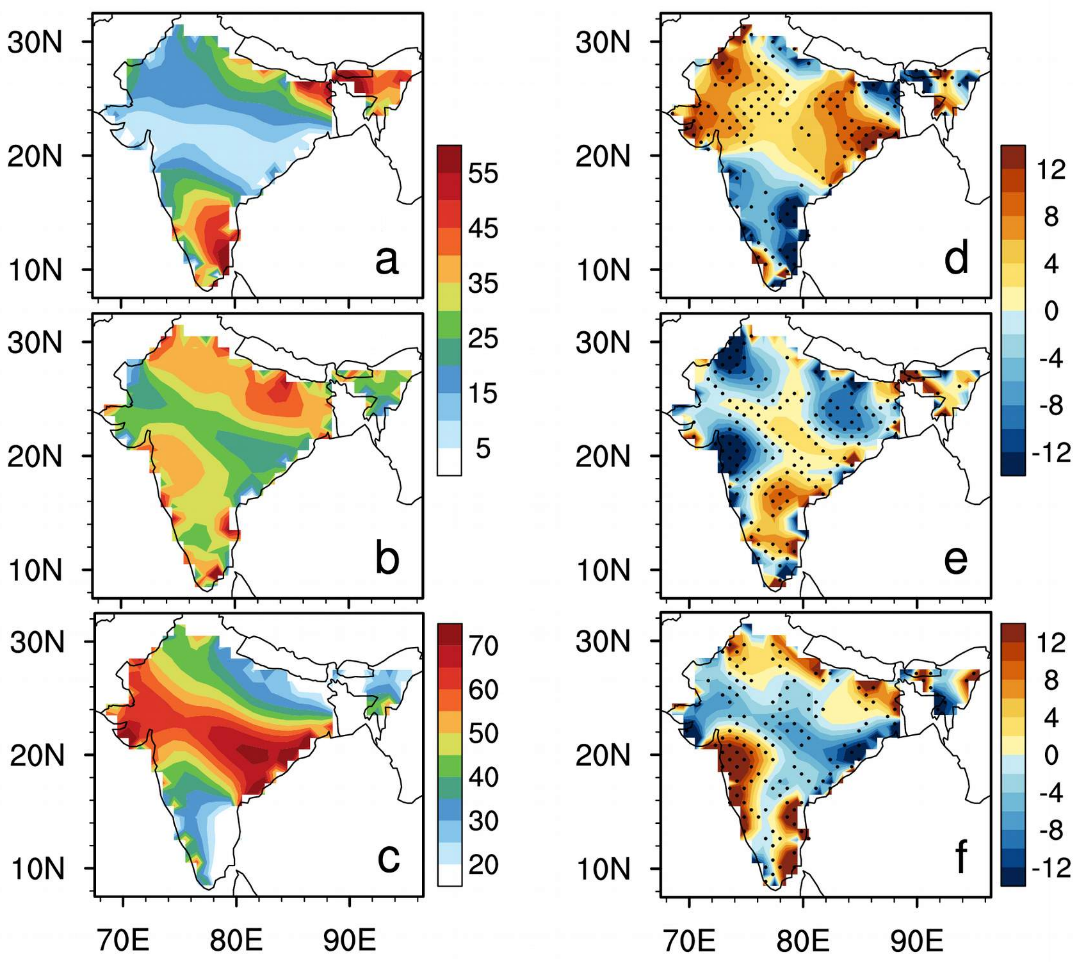
$$\gamma(t) = Arg(Y'(t) + iY(t))$$

Y(t) = Normalized LF-ISO timeseries avgd over CI, Y'(t) denotes the derivative of it.

$$ISO\ Phase = \begin{cases} Break, & \text{for } \gamma \in (-5\pi/6, -\pi/6) \\ Transition(Break - Active), & \text{for } \gamma \in (-\pi/6, \pi/6) \\ Active, & \text{for } \gamma \in (\pi/6, 5\pi/6) \\ Transition(Active - Break), & \text{for } \gamma \in (5\pi/6, \pi)\ or\ (-\pi, -5\pi/6) \end{cases}$$

Change in association:

Pre(1951-1980) **Post(1980-1951)-Pre**



Break

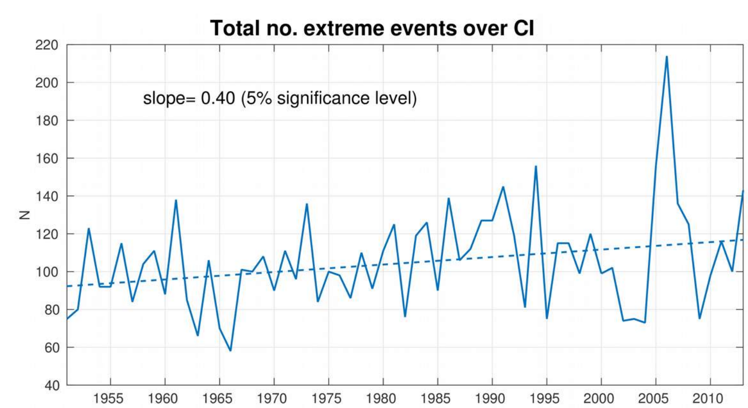
Trans

Active

Almost **8% of the extremes** events are now occurring in breaks/transitions instead of active, in the backdrop of an increasing extreme events!

Major changes are over CI region.

(Karmakar et al. (2015))



Values are given as **percentage** of the total extreme events at a location.

Our Understanding from Observations

1. Significant increase in the number of extreme events over all-India, especially CI.

2. Defined active-break phases of LF-ISO over CI.

3. Decrease in the percentage of extreme events in active phase, increase in break phase.

==> Association between actives and extremes is weakening.

In previous section we found a decreasing trend in LF-ISO intensity.

Are those two facts associated?

In other words, **are more extremes in breaks disrupting the rhythmic nature in monsoon rainfall?**

4. Extreme Events and the Changing Mean Monsoon

Model details:

Community Earth System Model (CESM) version 1.2

- Community Atmosphere Model version 5 **(CAM5)** physics.
- **Climatological SST** and sea-ice (present day).
- Interactive Community Land Model version 4.0 (CLM4).
- All initial conditions are set to present day levels.
- Horizontal resolution: Finite volume **0.9 x 1.25**.
- Vertical resolution: **30 levels**, hybrid sigma-pressure system.
- Deep convection: **Zhang-McFarlane** (1995).
- Shallow convection: Park and Bretherton (2009).

Is a state-of-the-art climate model.

Experiments:

1. **Control run**:

Run as default.

Run for 11 years continuously (1st year excluded from any analysis).

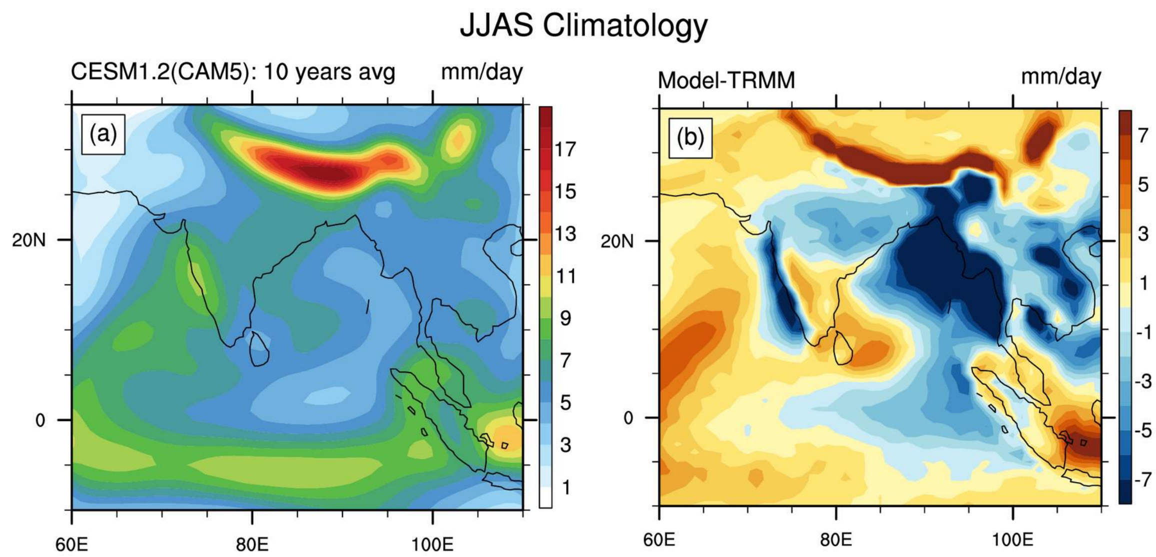
2. **Heating run**:

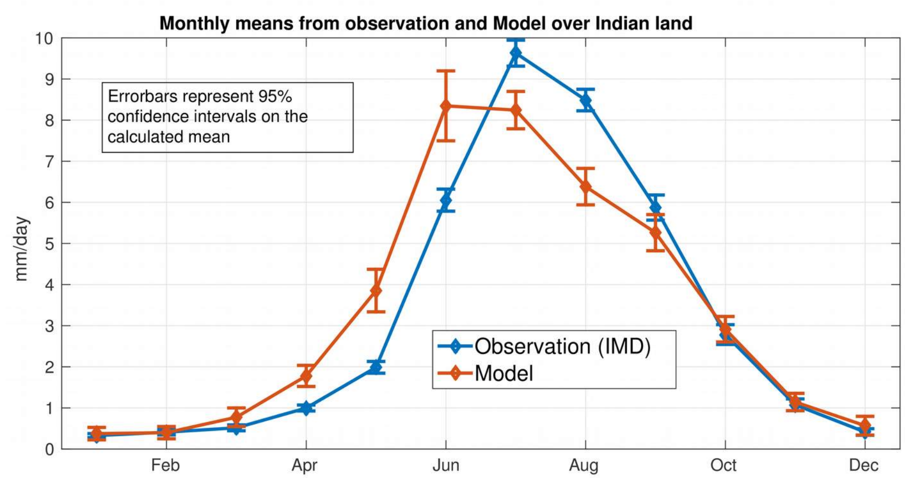
Mimic the <u>extreme rainfall events over CI</u> region.

Appropriate heating in the atmospheric column will make conducive environment for convection in JJAS.

Runs are started every June 1st (using restarts from control run) and continues for 5 months.

How good is the control run?:

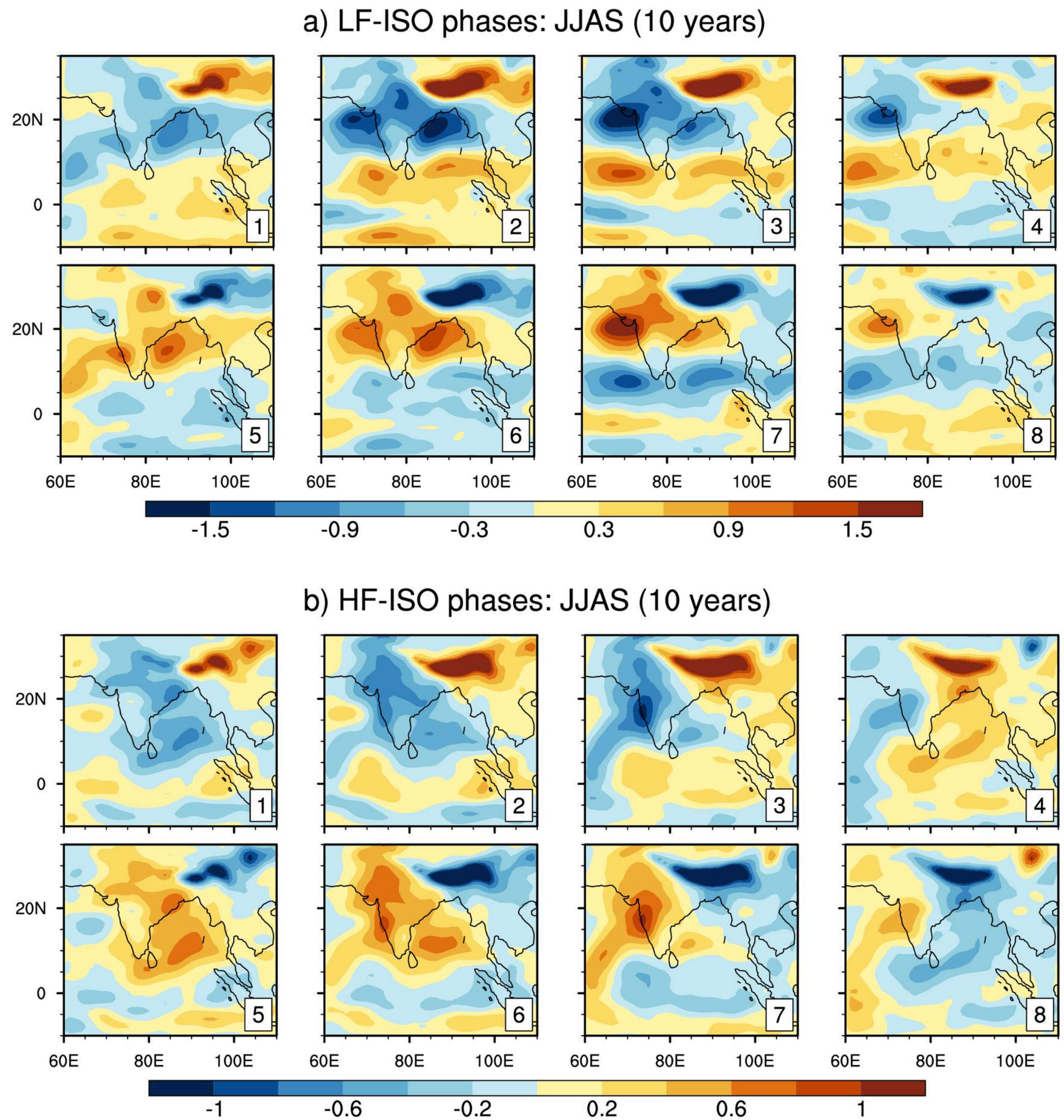




Dry bias over CI, BoB and Burmese coast.

Captures the annual cycle.

Model ISO:



Units: mm/day

MSSA applied to extract ISO modes in a similar approach.

LF-ISO: northward propagation. Northwest-southeast tilt is missing!

HF-ISO: westward propagation.

Designing the heating run:

Rudimentary information needed to generate extremes over CI:

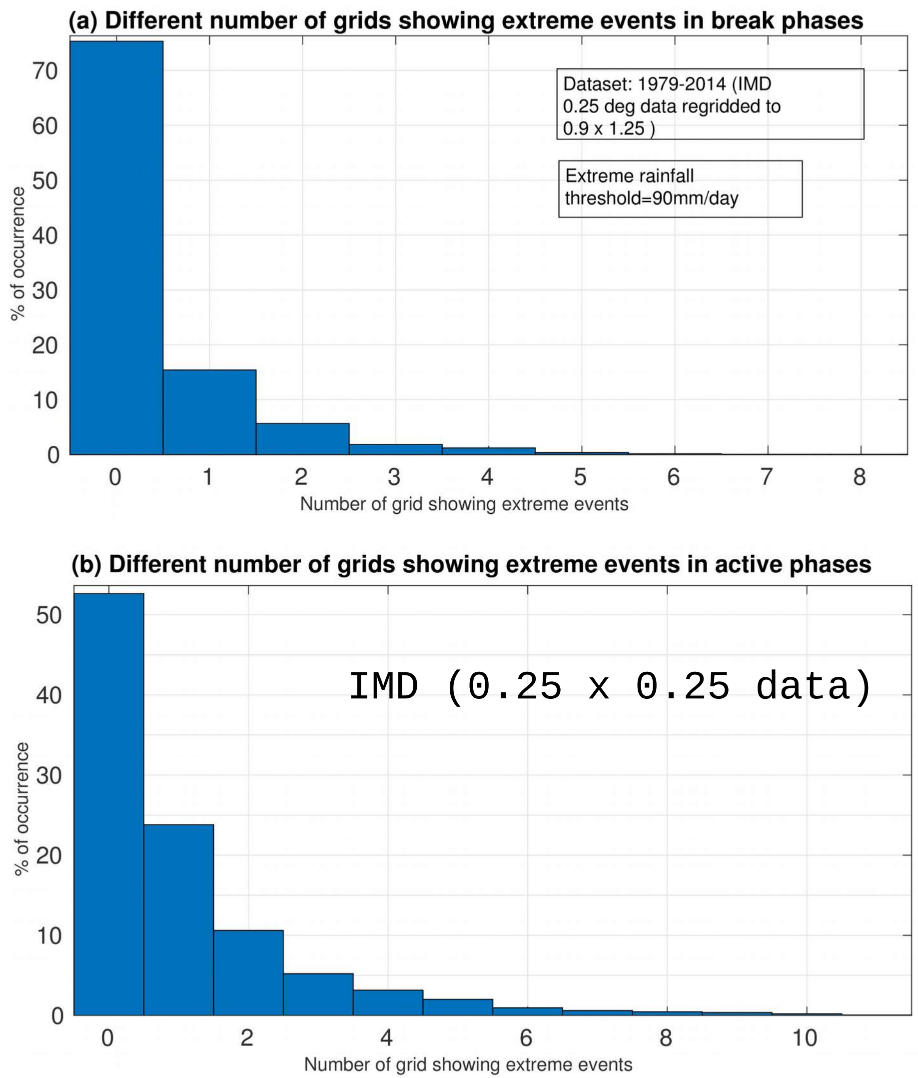
1. How many points do we need to heat?
2. How many days should we heat?
3. Should we heat the entire day?
4. What should be the heating profile?

We will be focusing on CI.

Target: Heat the break days in control run.

Extremes in observation:

Define active/break episodes over CI using previous equation. Only JJAS days.



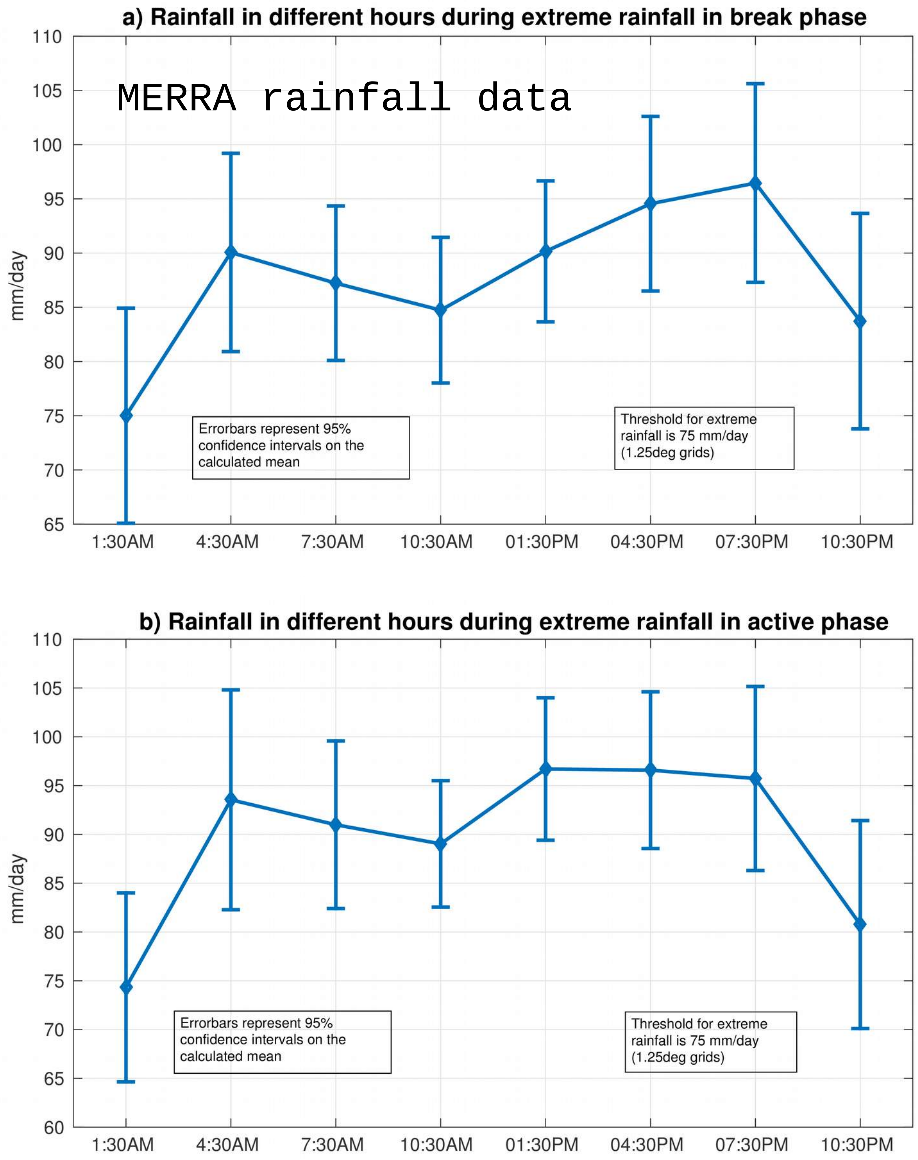
Only 25% of the break days have atleast one extreme grid.

For actives: 45%.

Reasonable to add heat only on **10-12 days during breaks** per season, over **1-2 grids**.

These days (break) and grids will be **randomly chosen**.

Extremes in observation/reanalysis:



Does not rain uniformly over the entire day.

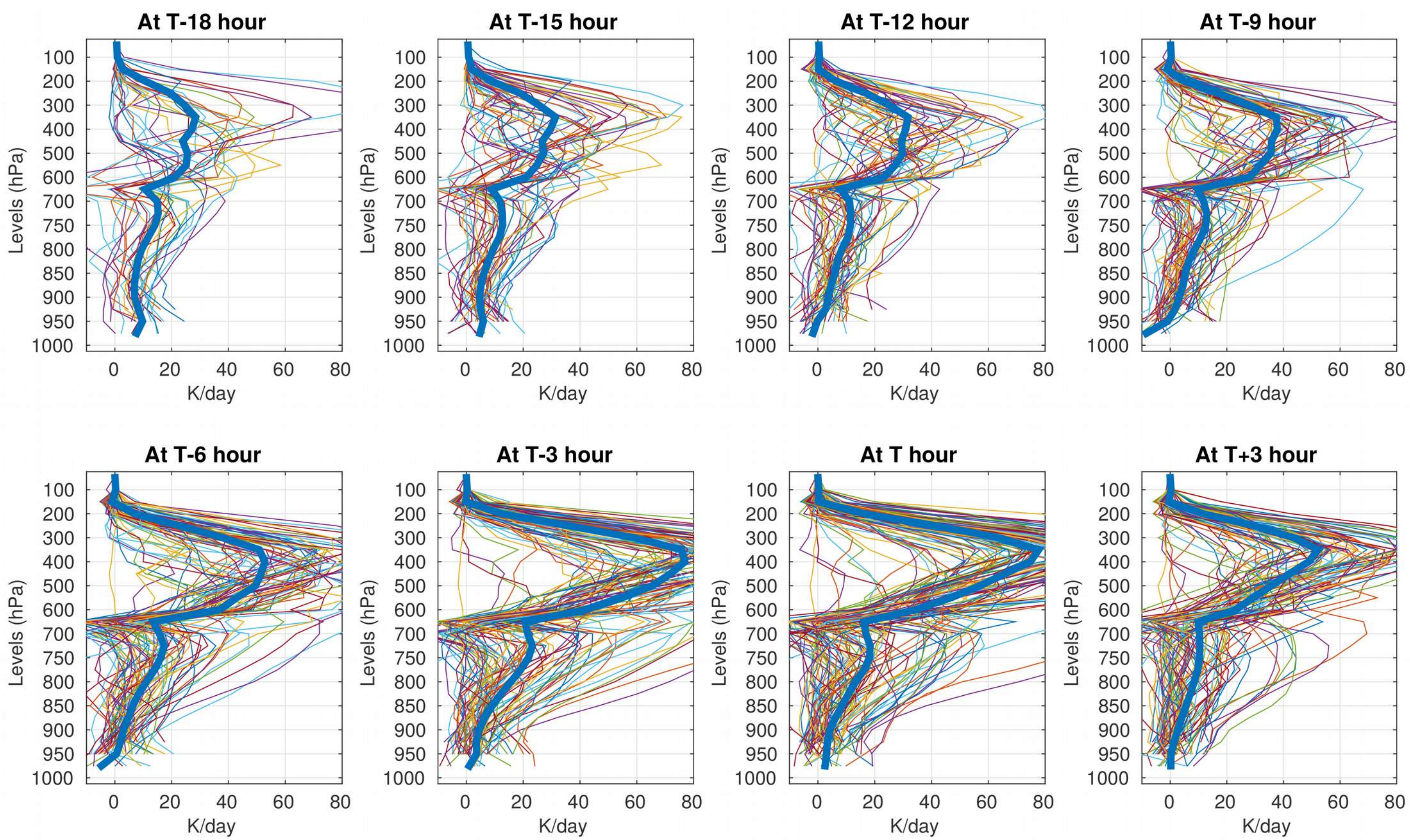
Breaks: Peak at 7:30PM (UTC)

Actives: Peak at 1:30-7:30PM (UTC)

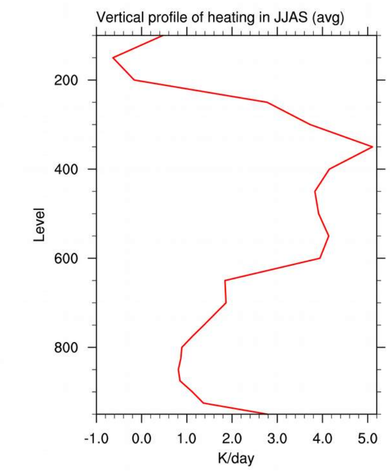
==> **No need to prescribe heating for the entire day to make rain.**

Extremes in observation/reanalysis:

a) Break phases



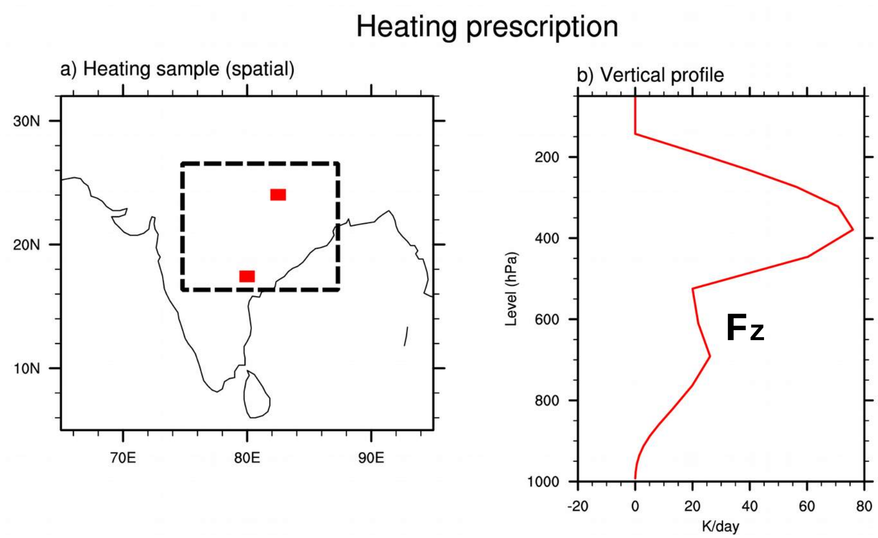
MERRA temperature tendency (from physics) data

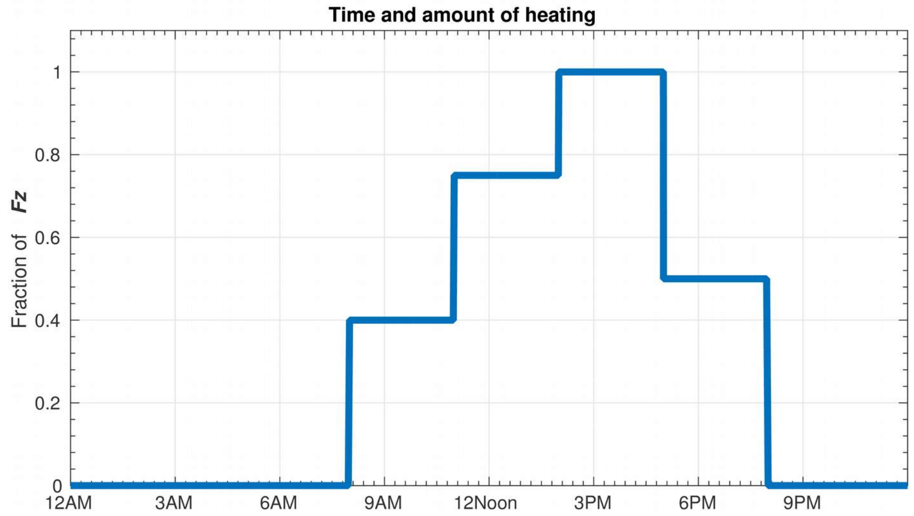


Heating is not uniform over the entire day.
Maximum on or just before the maximum rain.

==> **Heating must have a diurnal variation.**

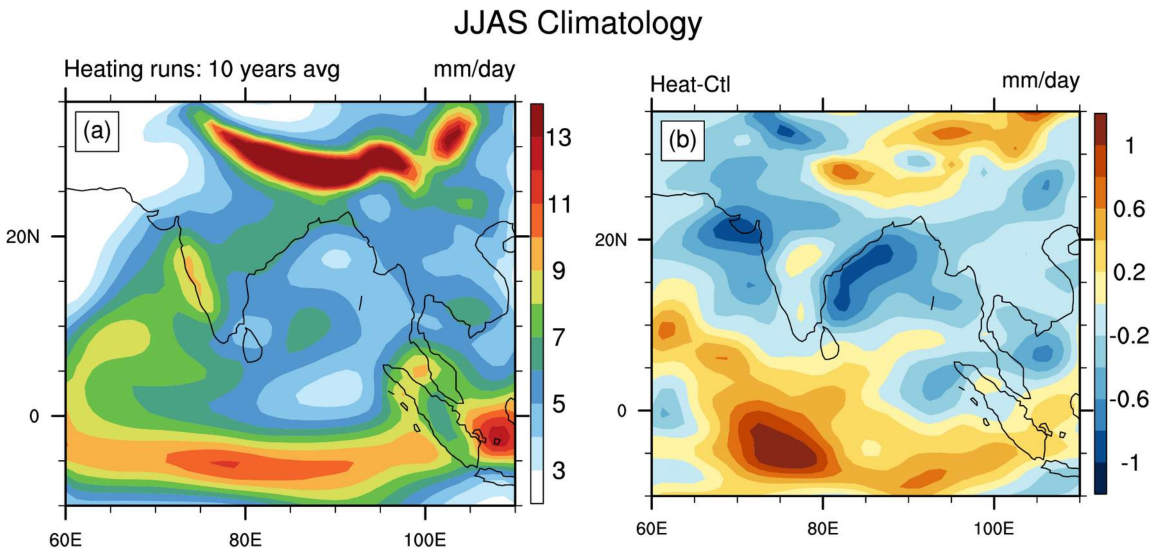
Heating prescription:

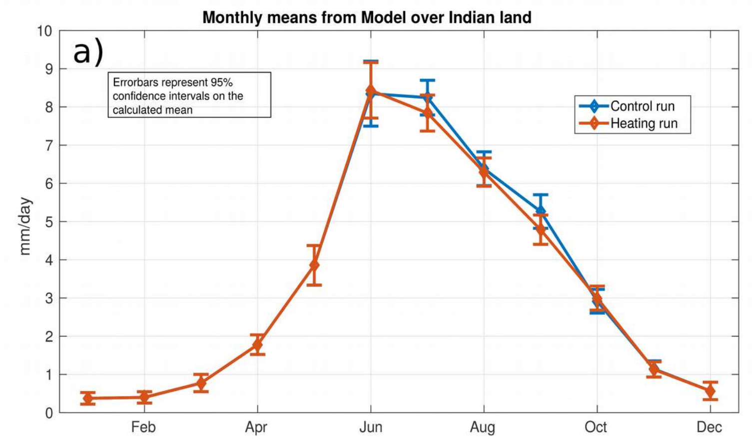


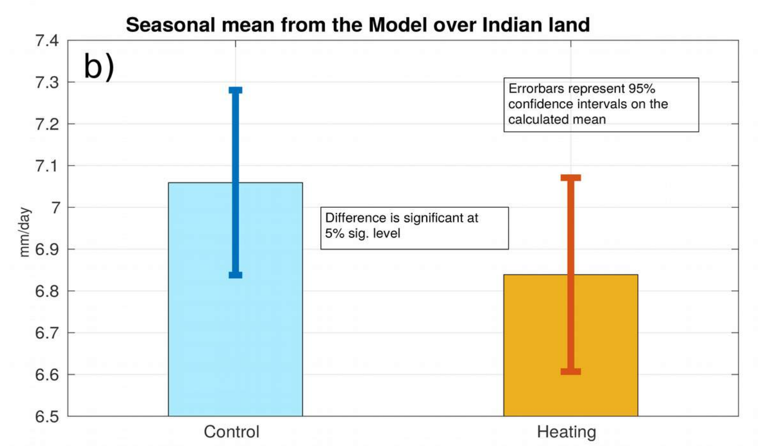


Parameter	Prescription	Quantity
Days of heating	Randomly chosen break days (control run)	Roughly 10-12 days in a season
Number of grids to heat	Randomly chosen land points over CI	1 or 2
Time of heating within a day	12 hours	8AM-8PM, Max at 2-5PM
Amount of heating	As in the figure	F_z

Results from the heating run:







Reduction of mean rainfall over Indian region.

Increase over the equatorial Indian Ocean.

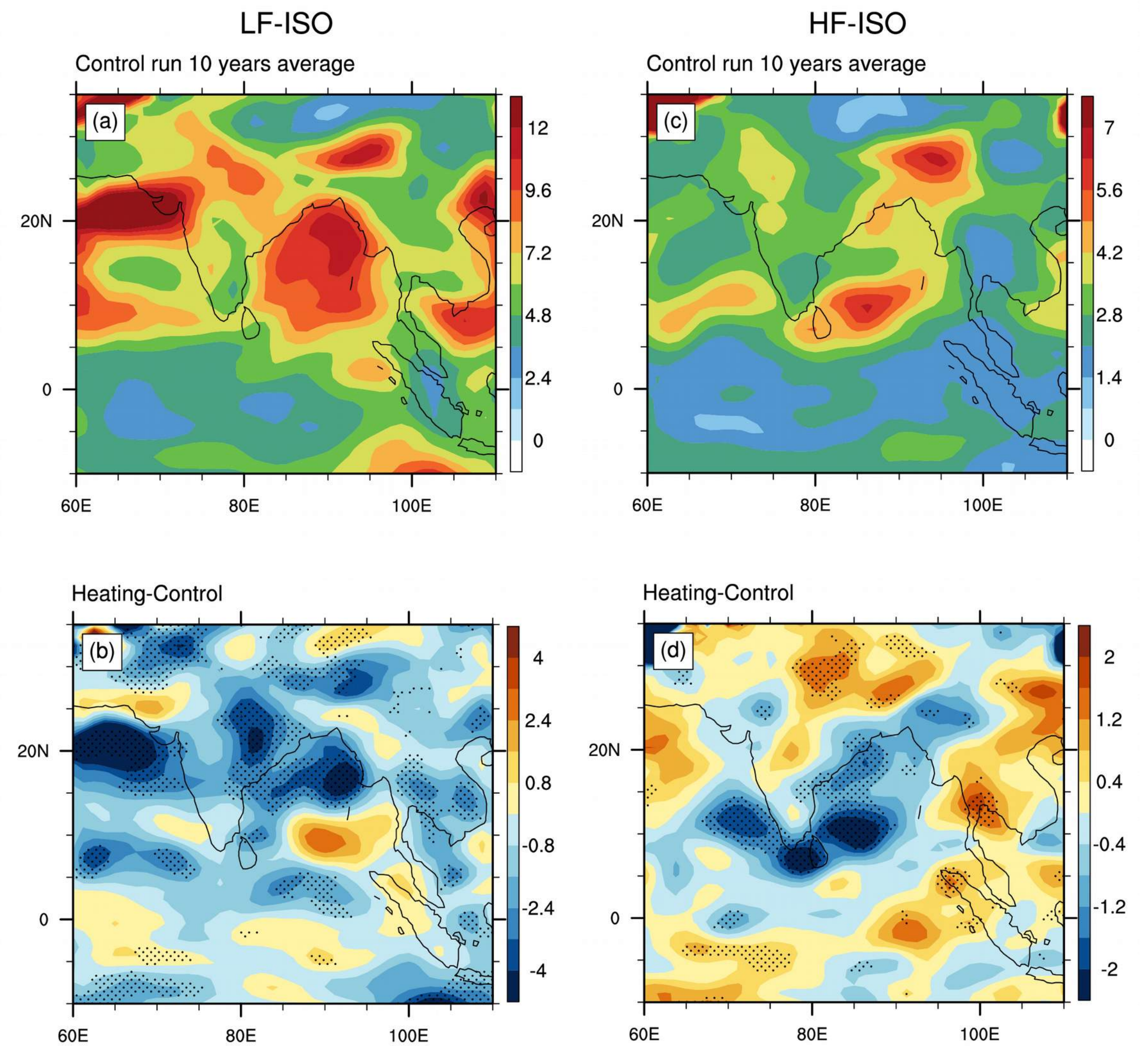
Results from the heating run:

Calculate the ISO modes using similar technique.

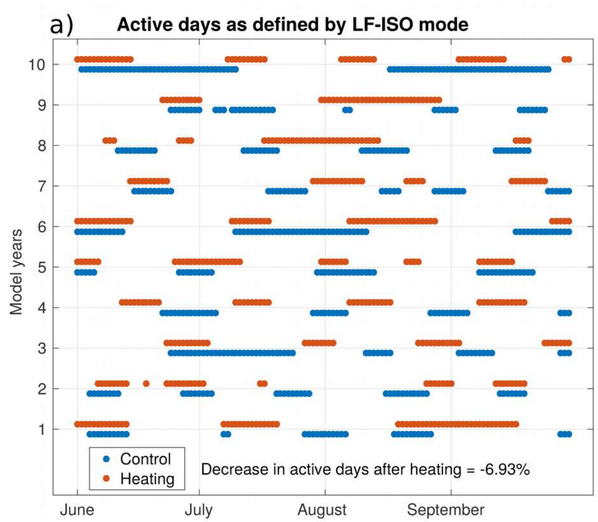
Calculate the **percentage** of variance explained by LF- and HF-ISO modes to the total rainfall.

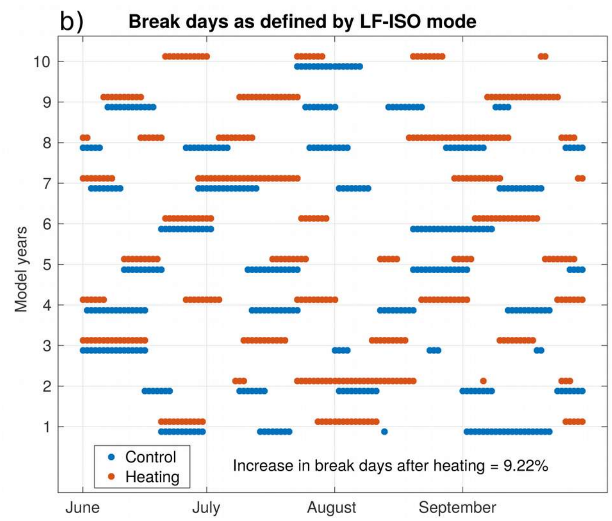
Significant reduction of LF-ISO variability over CI, BoB, AS region.

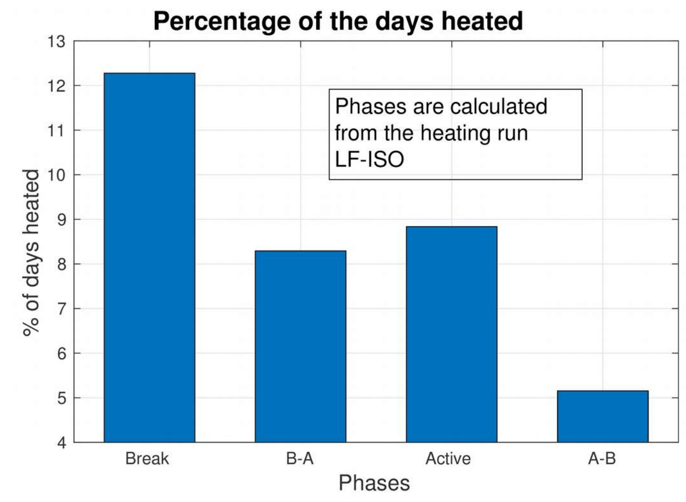
HF-ISO remained almost the same.

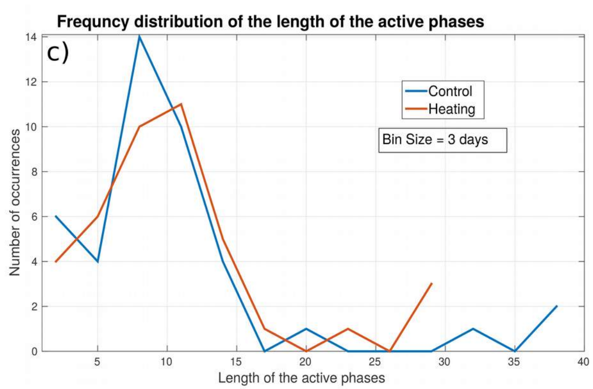


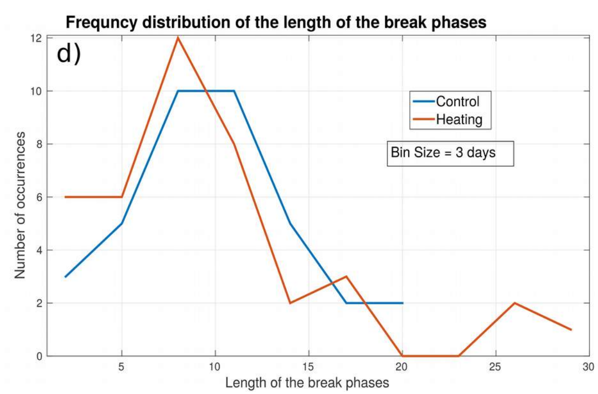
What makes LF-ISO intensity reduced?:









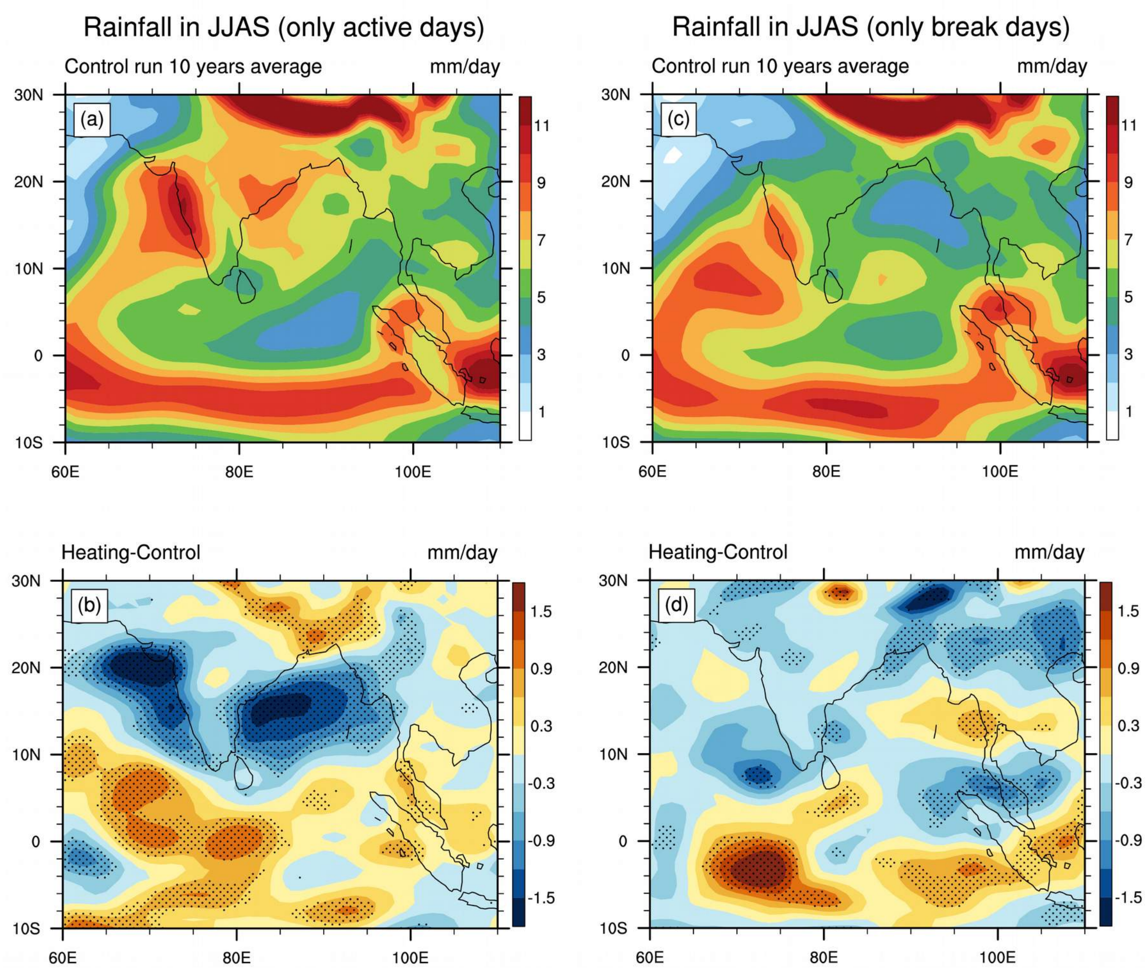


Heating prescribed on the breaks of control may not be in break in the heating run. But that is fine!

Total number of break days and tendency of longer breaks have increased.

Total number of active days and tendency of longer actives have decreased.

What makes LF-ISO intensity reduced?:



Rainfall in active days is decreased in the heating run.

Breaks rain remained almost the same.

Less active day rain ==> less variability in LF-ISO scale!

What makes active days rain reduced?:

Stability of the atmosphere:

Define Vertical Moist Stability (VMS) of atmosphere:

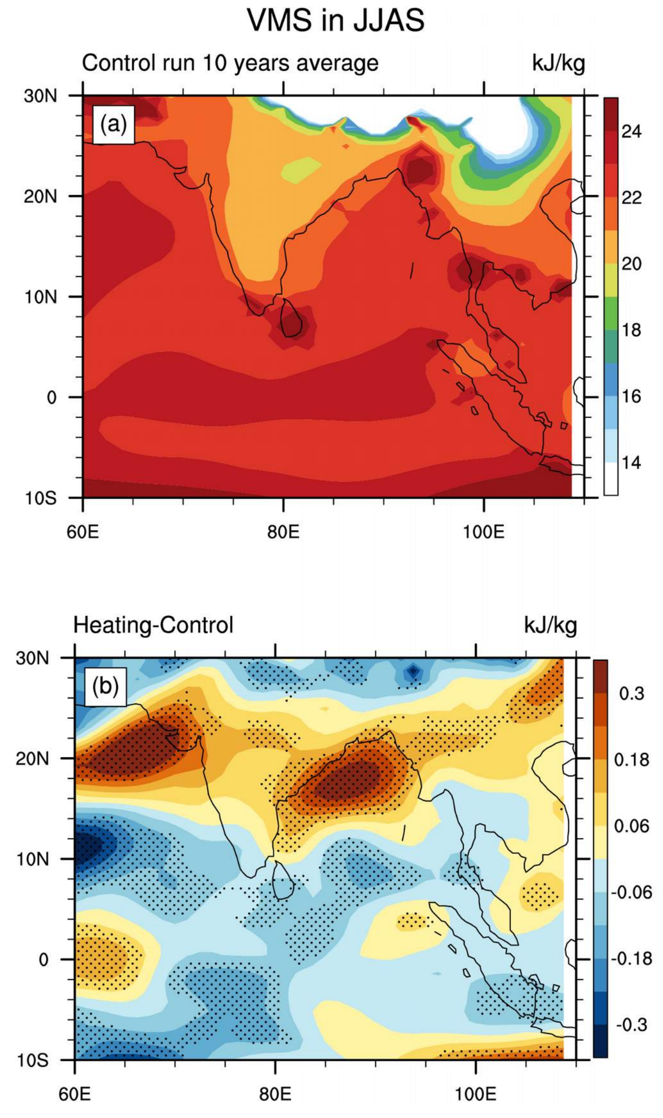
$$VMS = MSE_{top} - MSE_{bot}$$

$$MSE_{top} = \frac{1}{(P_{mid} - P_{top})} \int_{P_{top}}^{P_{mid}} M dp$$

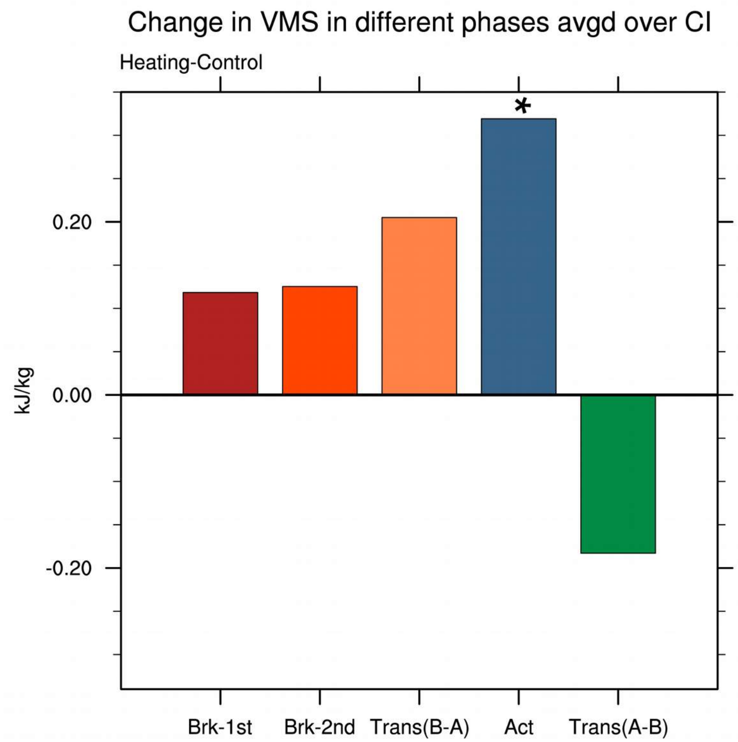
$$MSE_{bot} = \frac{1}{(P_{sfc} - P_{mid})} \int_{P_{mid}}^{P_{sfc}} M dp$$

$$M = C_p T + gZ + L_c q$$

More VMS (Higher Stability) => Less rain!



What makes active days rain reduced?:

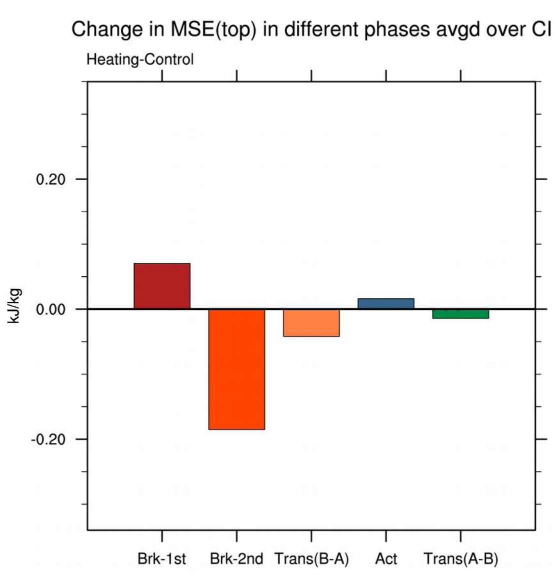


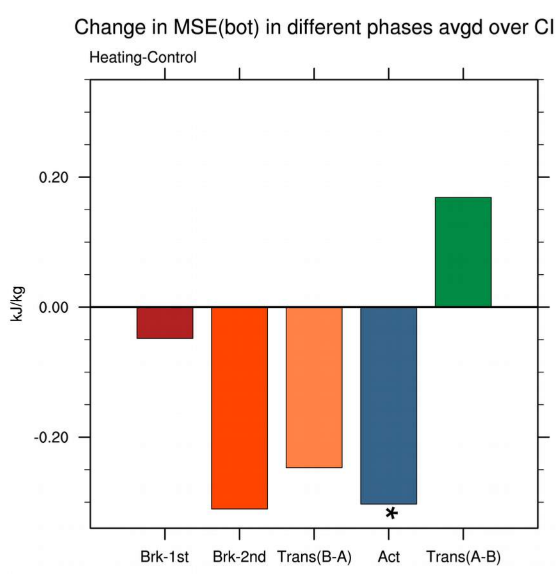
Break the break phase in two equal parts for better understanding.

Significant increase in VMS in active phase in heating run

=> Less unstable atmosphere

=> **Less rain!**





But VMS is a necessary condition, **not sufficient**, for generation of deep convection.

What makes active days rain reduced?:

Possible mechanism that triggers convection over the Indian region:

1. Generation of an anomalous high over central Asia.

2. Strong easterly shear over Indian region.

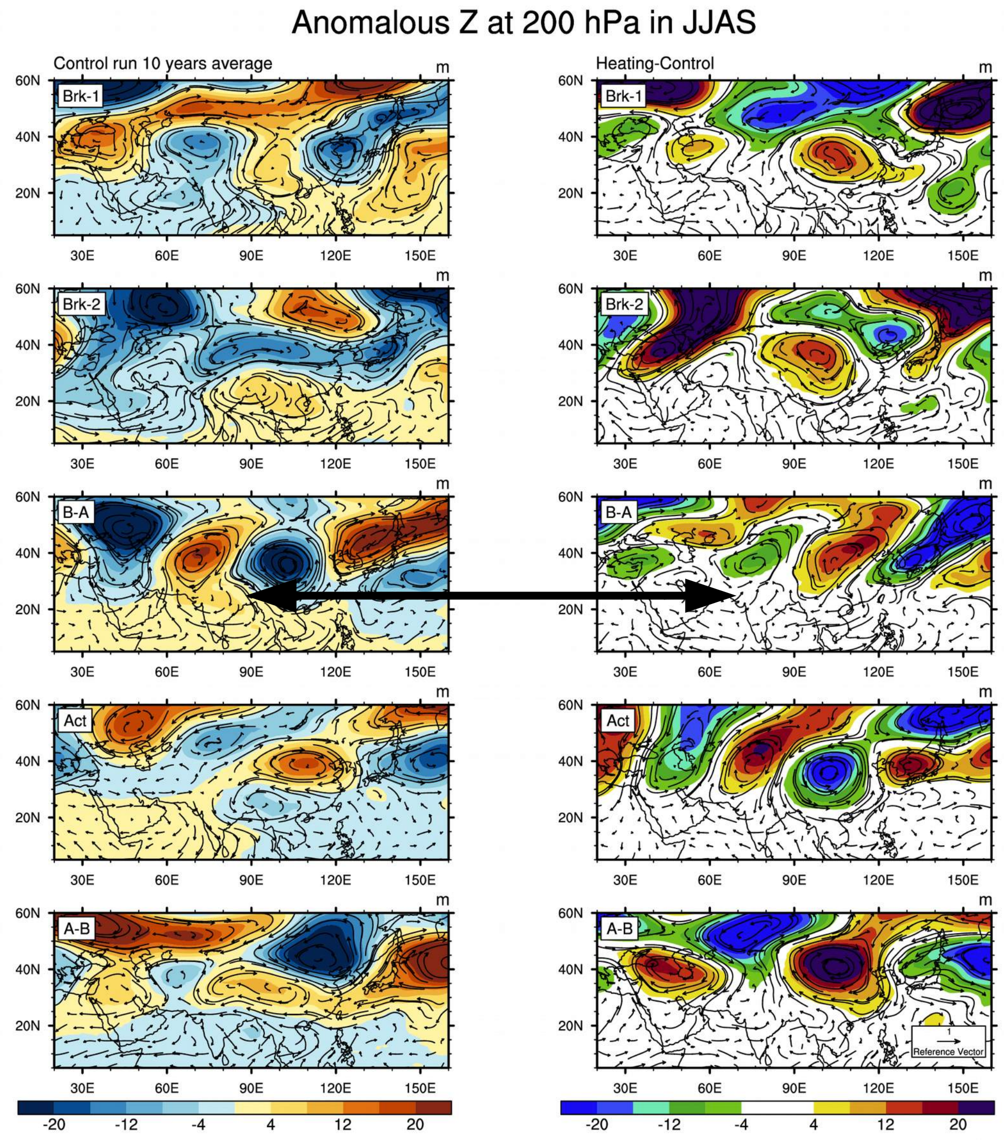
3. Destabilizes the equatorial Rossby waves (Moorthi and Arakawa (1985), Wang (1990)).

4. Enhanced Rossby wave instability in the presence of boundary layer and strong easterly shear (Xie and Wang (1996)).

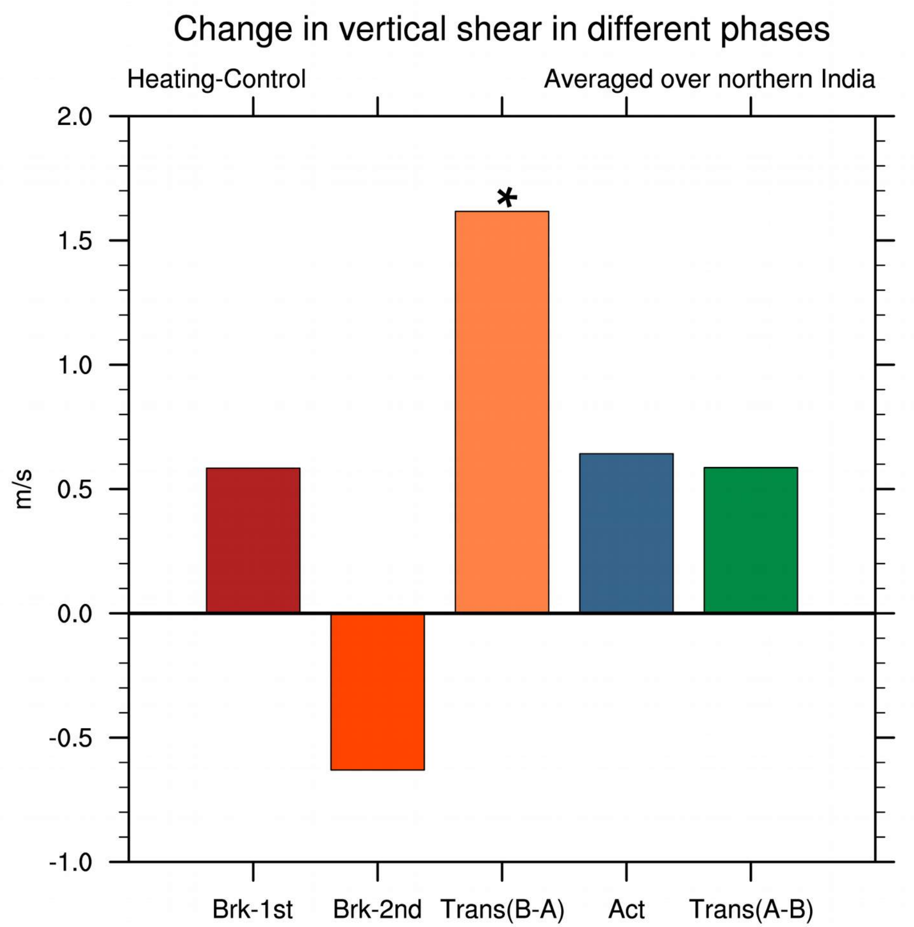
5. Increased precipitation over India! (Ding and Wang (2007)

Steps 1-5 => 4-5 days!

Need to look at B-A transition phase!!



What makes active days rain reduced?:

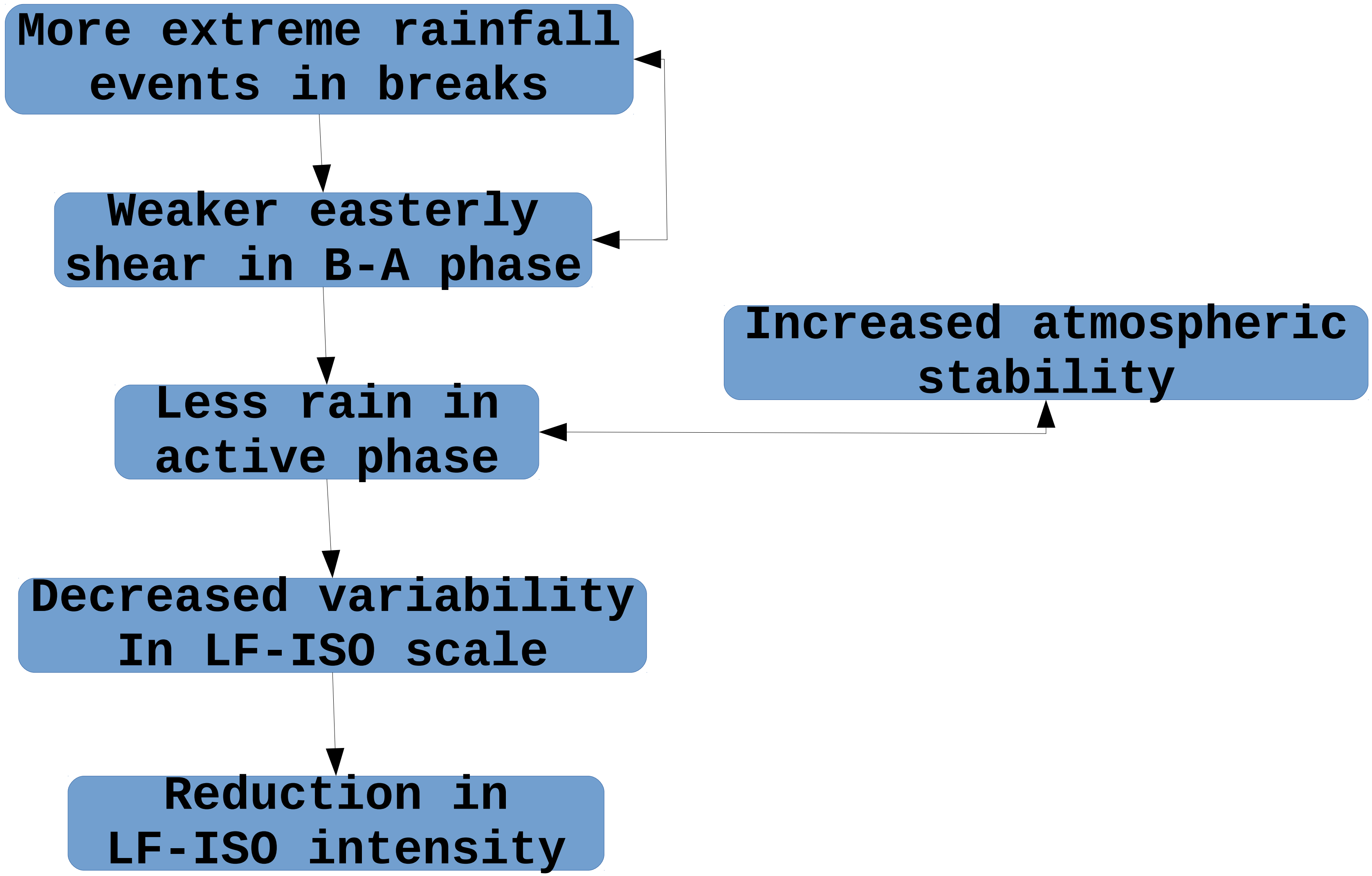


Vertical shear is -ve over Indian region during JJAS!

Significant reduction of easterly shear over the northern Indian region in heating runs B-A transition phases.

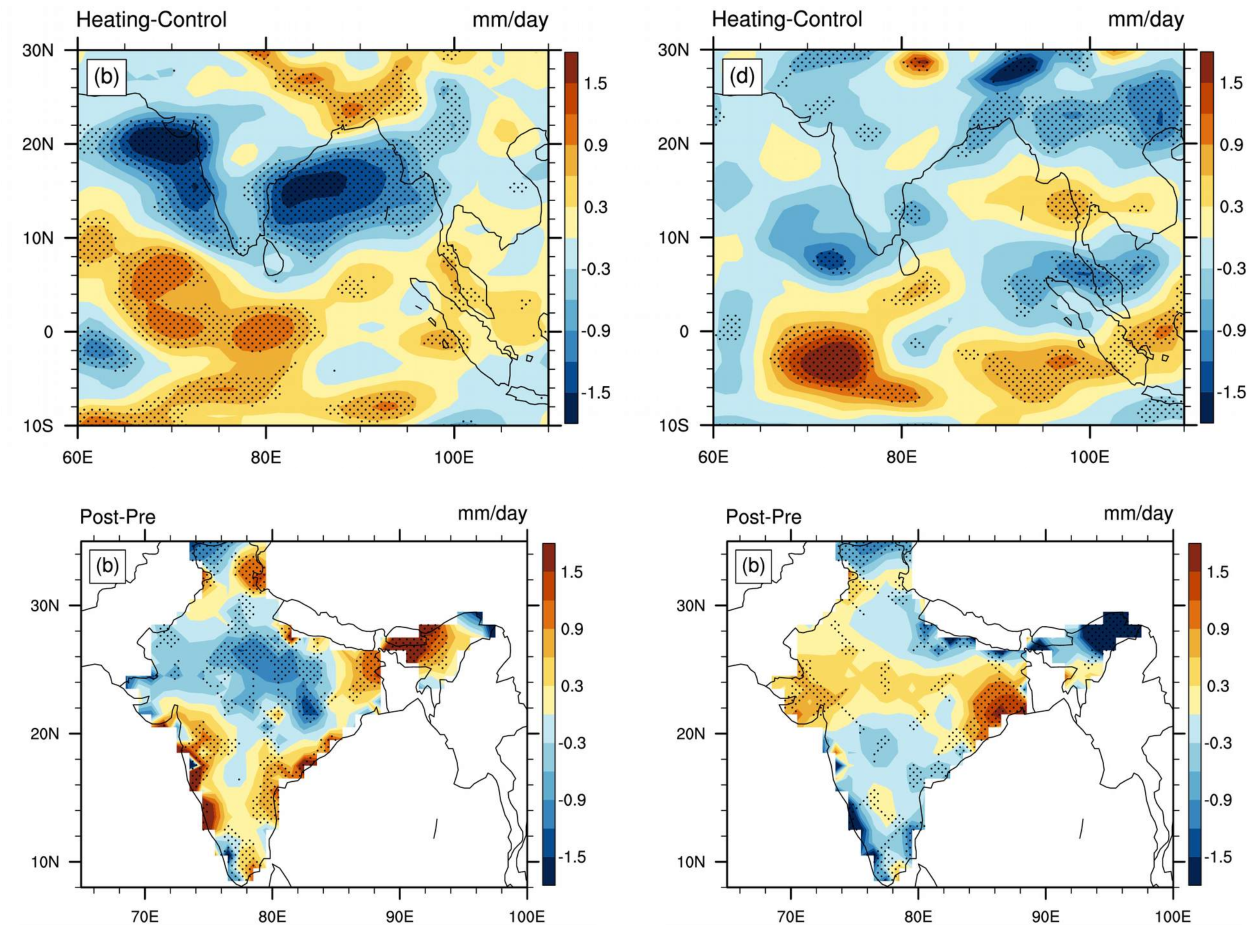
What makes active days rain reduced?:

In summary:



Do Observations Show this?

Rainfall in active days (change) **Rainfall in break days (change)**



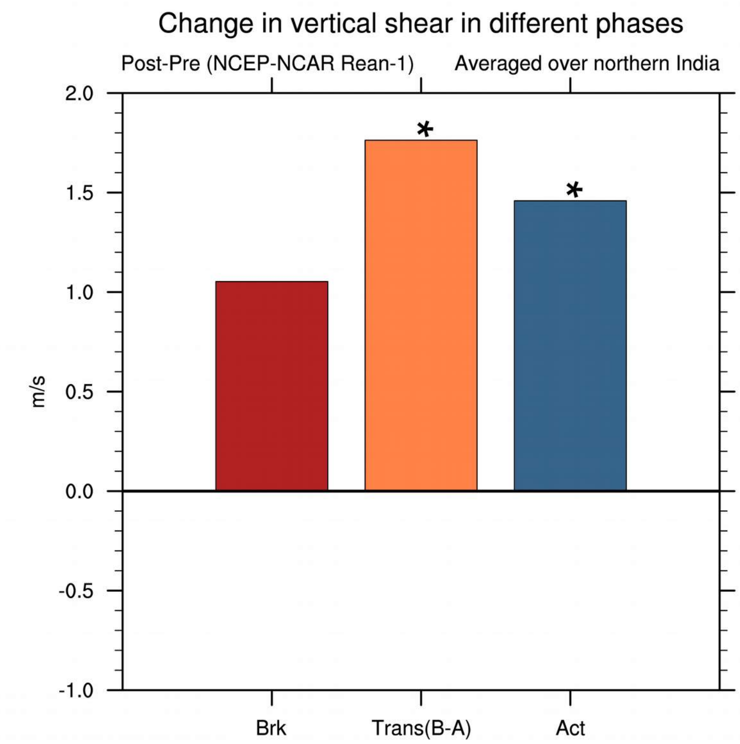
Model

Observation (IMD)

We find similar changes in observation also!

Change in Vertical Shear

From observation (NCEP-NCAR ReAn-1):



LF-ISO phases are from IMD data.

We find similar changes in observation also!

Conclusions:

1. **Evolution** of ISO in Indian monsoon rainfall: LF-ISO and HF-ISO.
2. How LF- and HF-ISO modes **modulate** rainfall over CI region.
3. A statistically significant **quantity** to measure the intensities in ISO modes.
4. A **decreasing trend** in LF-ISO intensity over the last few decades.
5. A **decrease** in relative number of extremes in active phase of LF-ISO.
6. Modeling study to understand the **association** between extremes and LF-ISO mode.
7. A possible **mechanism** to understand the reduction of LF-ISO intensity.

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Thank you very much!!