The Indian Summer Monsoon : An Overview of Mean and Variability

Lecture-6

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The Context:

Why do we want to study mean and variability of Indian monsoon?

- The Indian monsoon is the Largest rain bearing climate system in the world. Civilizations have evolved around it (Kathayat et al. (2017). Currently, economy and livelihood of 1.5 billion people depend on it.

- Therefore, predicting the Indian monsoon rainfall with fidelity one season in advance or at longer lead is a great science question of enormous socio-economic impact.

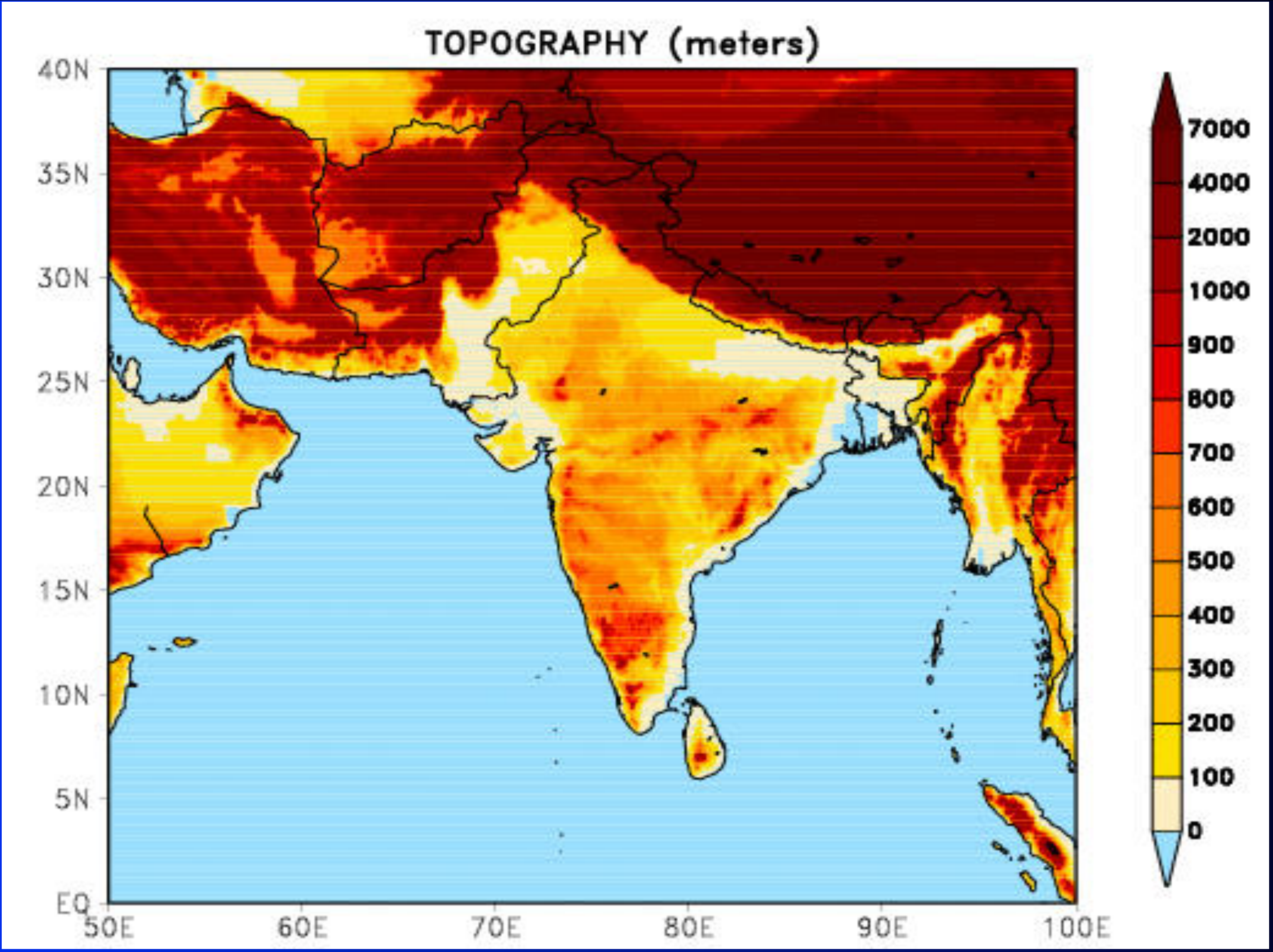
- The ‘potential skill’ or limit on predictability, however, depends on the structure of the ‘mean’ and the amplitude and nature of the ‘signal’ of variability.

→ Need to quantify the ‘mean’ structure and ‘signal’ of variability

Outline

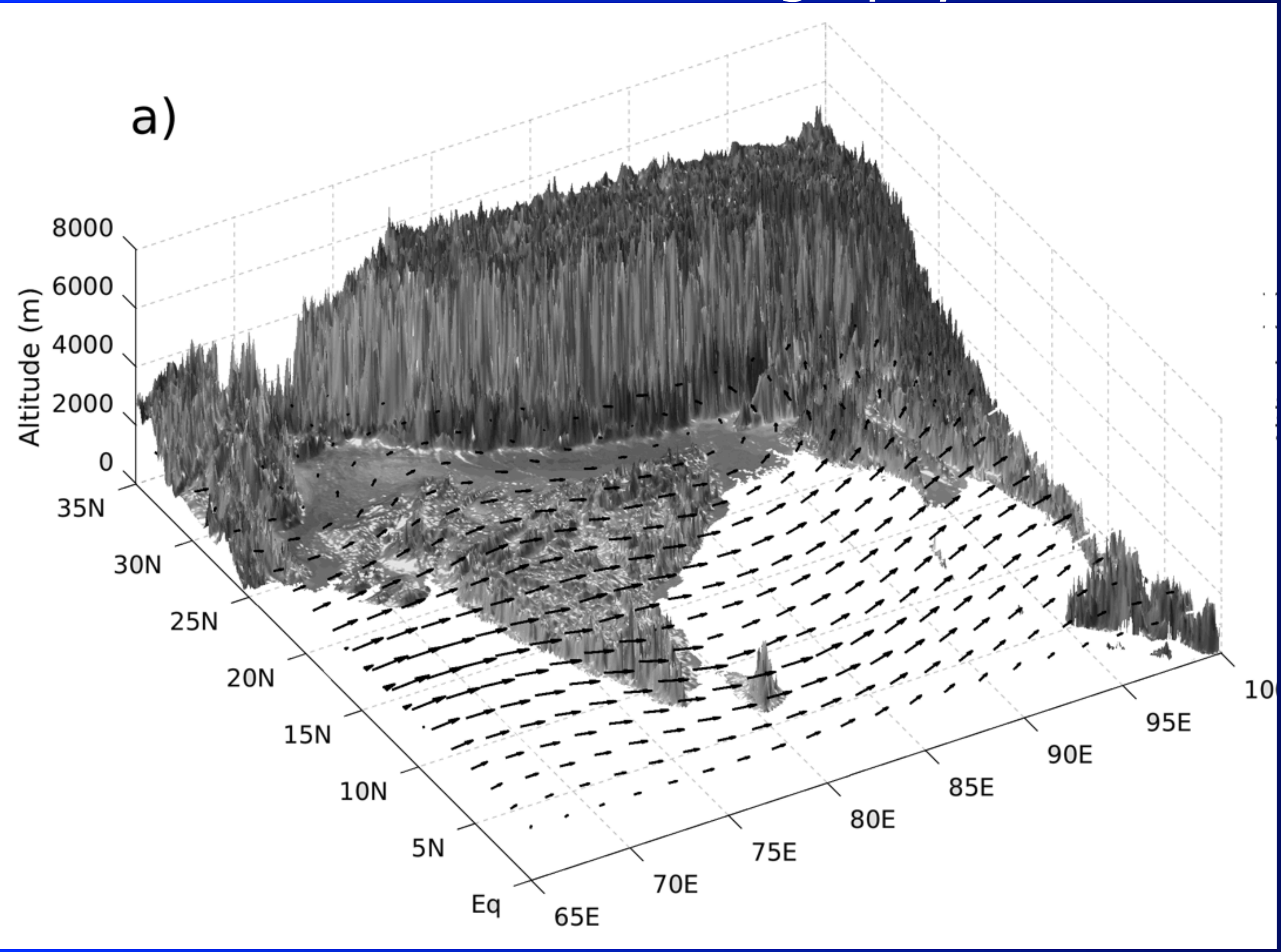
- Indian summer monsoon: A phase of the Monsoon Annual Cycle
- Some basic characteristics
- Interannual Variability & link with the ENSO
- Interdecadal variability & link with the AMO
- Model biases in simulating mean and variability : Prediction/Predictability

The geographical environment is critical for existence of present day monsoon:



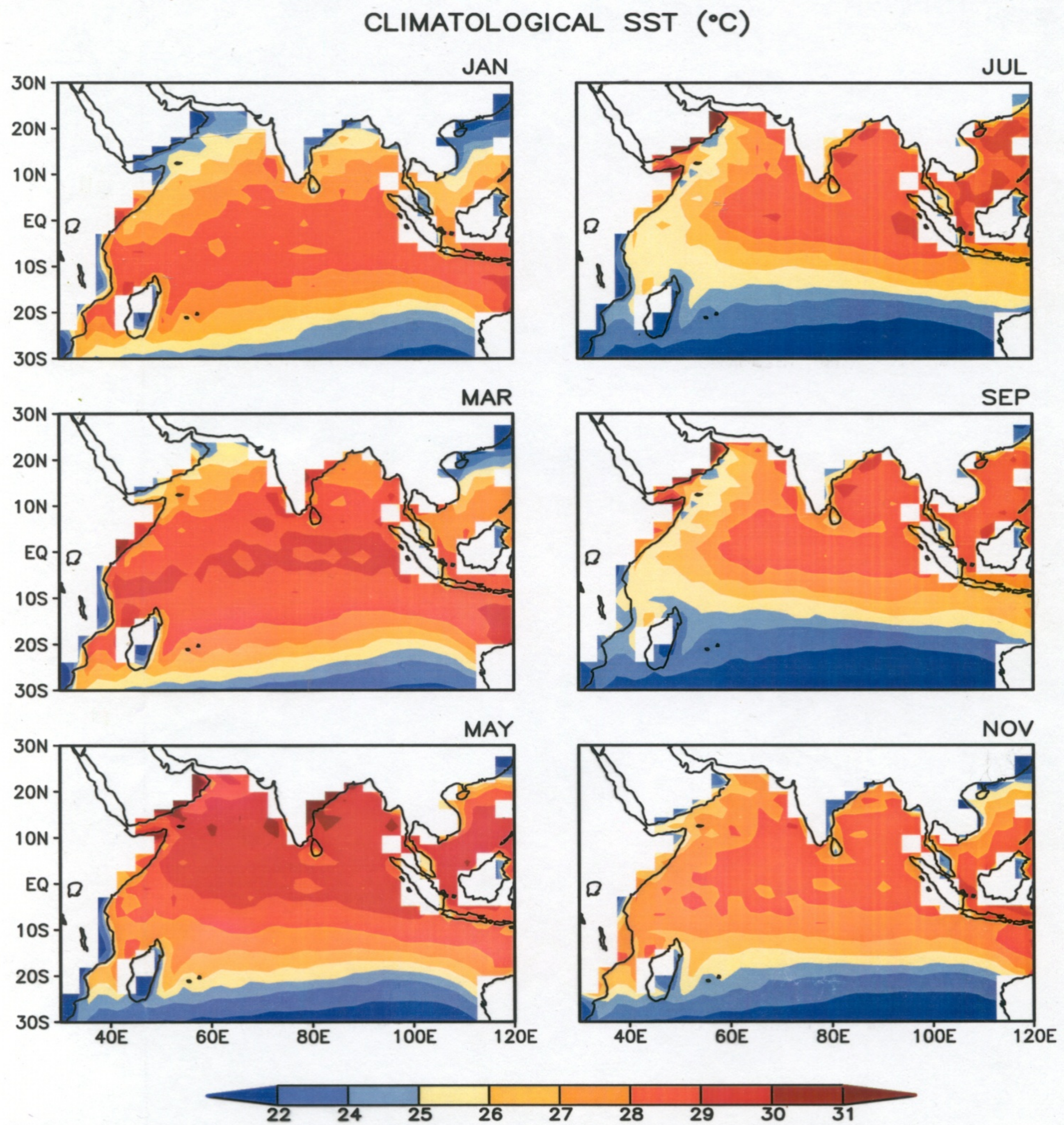
Tall mountains to the north, continent in between three sides surrounded by warm Oceans

A 3-D view of the orography around Indian continent



JJAS Wind at 850 hPa (~1500m) and topography over the region a) All India and. The wind data is obtained from ECMWF's ERA5 reanalysis and the Topography data is from USGG's Shuttle Radar Topography Mission (SRTM) at a resolution of 1 Arc-Second

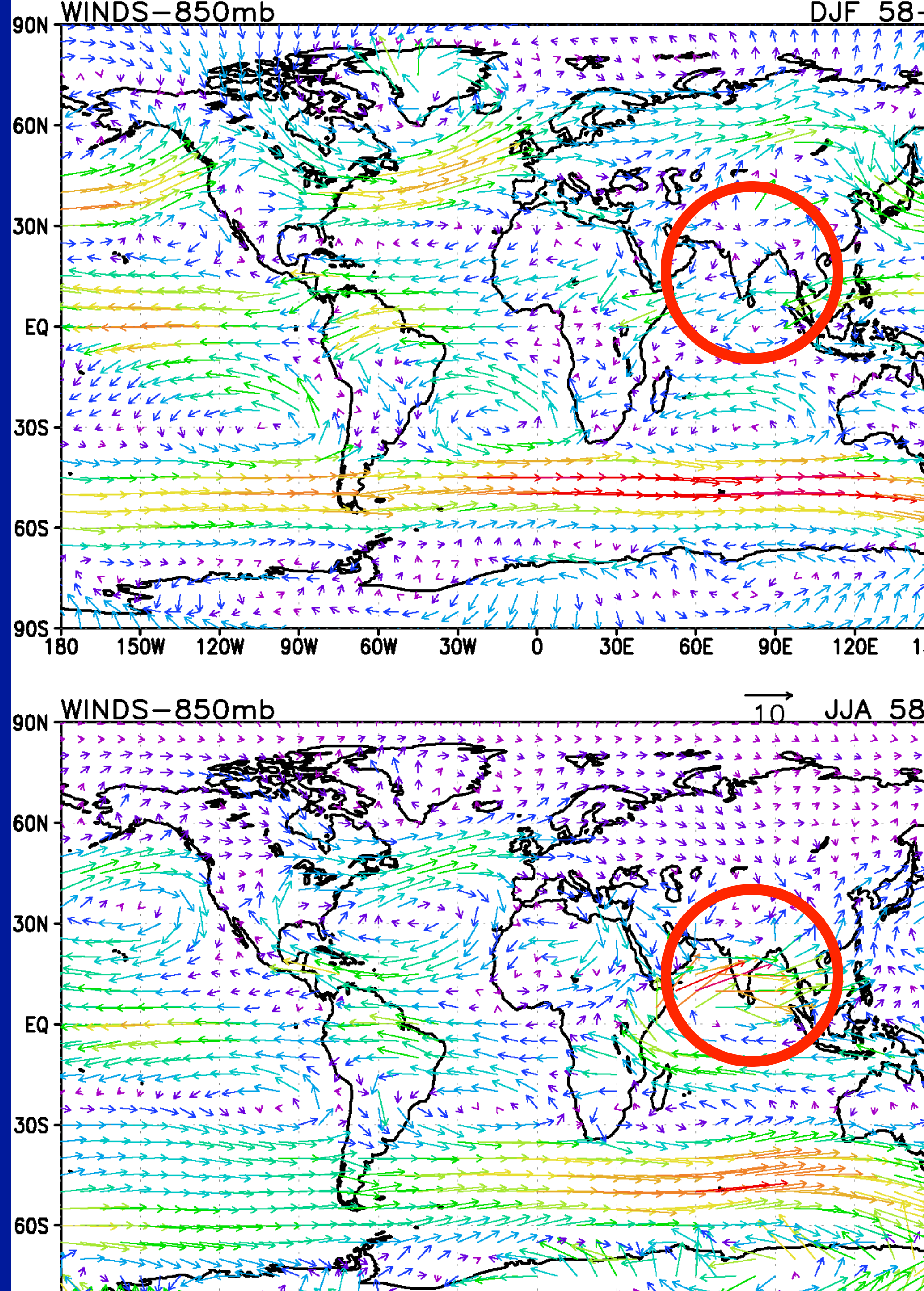
The Oceans to the south is amongst the WARMest in the world almost throughout the year!



The 'Monsoon' has its origin in the Arabian word 'Mausim' (season of winds) referring to seasonal reversal of low level winds over the Arabian Sea

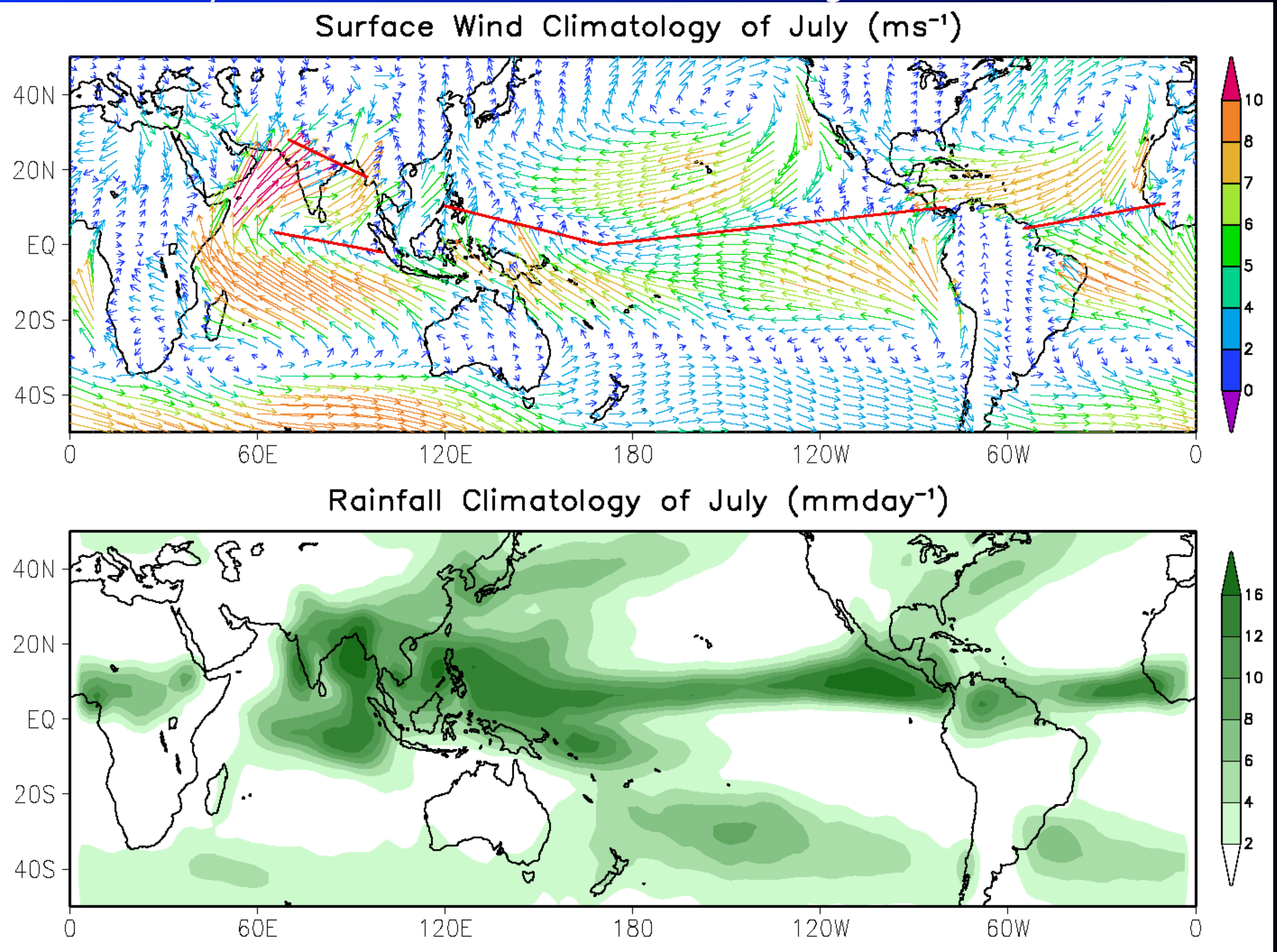
- There is reference to using monsoon winds by mariners as early as by Greek navigator Hippalus (AD 45-47)
- Traders would use flow of wind and current favorable for both the onward and return journey.

Tripati and Rout, 2006: Curr. Sci. 90, 864-871

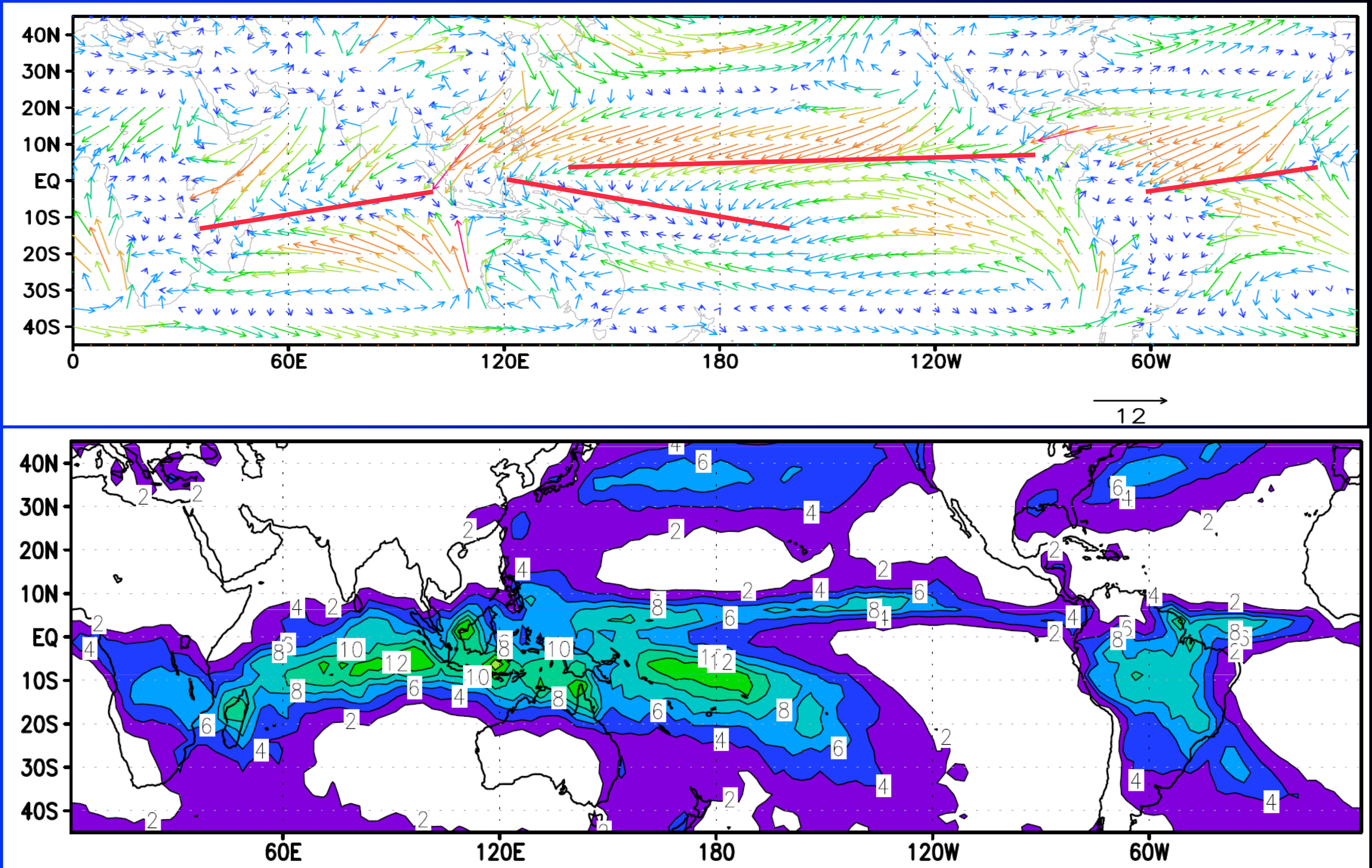


Strongly connected with Global ITCZ

Mean July rainfall and surface wind convergence: Summer ITCZ



Mean January rainfall and surface wind convergence: Winter ITCZ



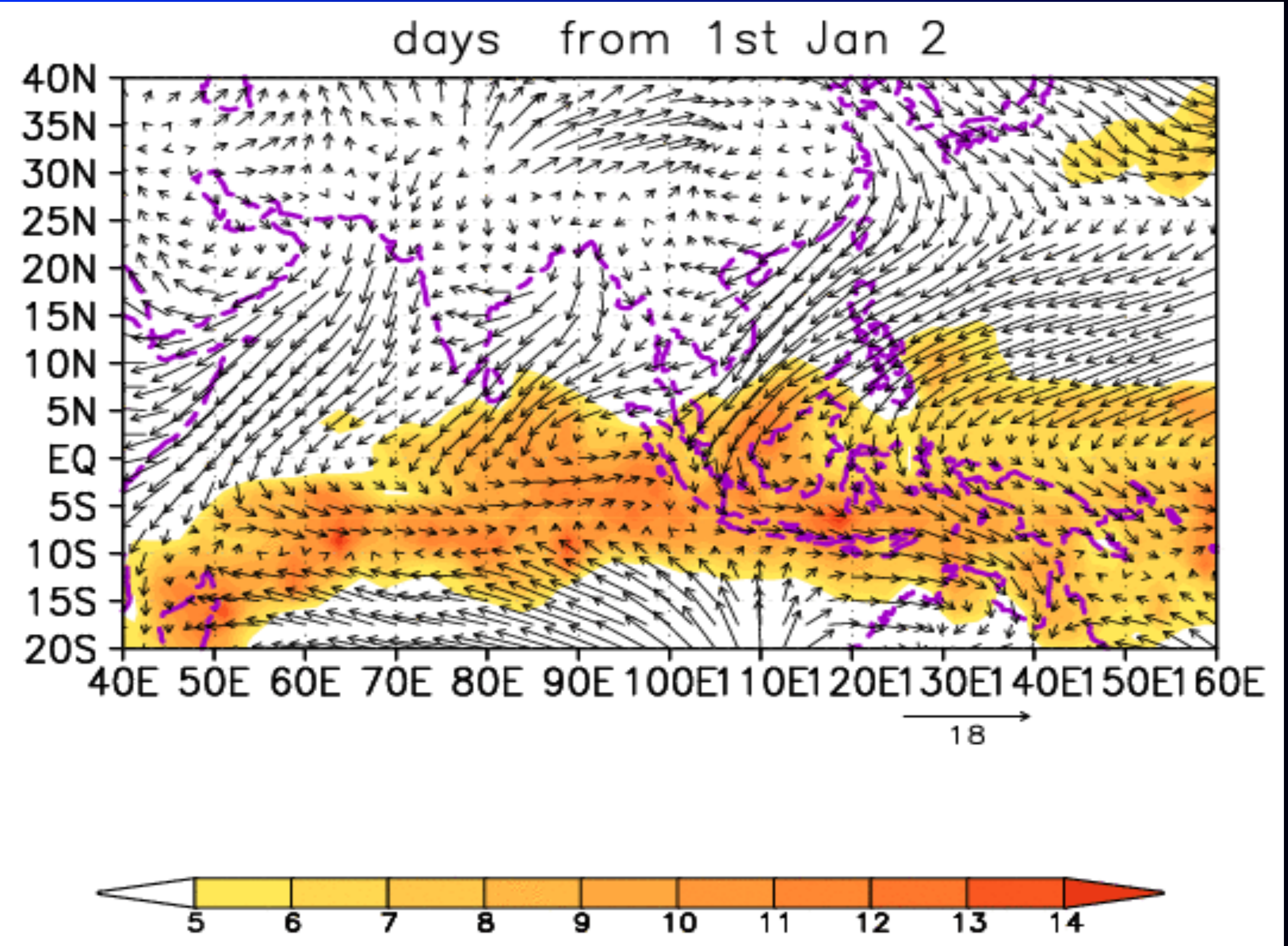
The Indian monsoon cannot be conceived without taking the associated rainfall into account

Therefore,

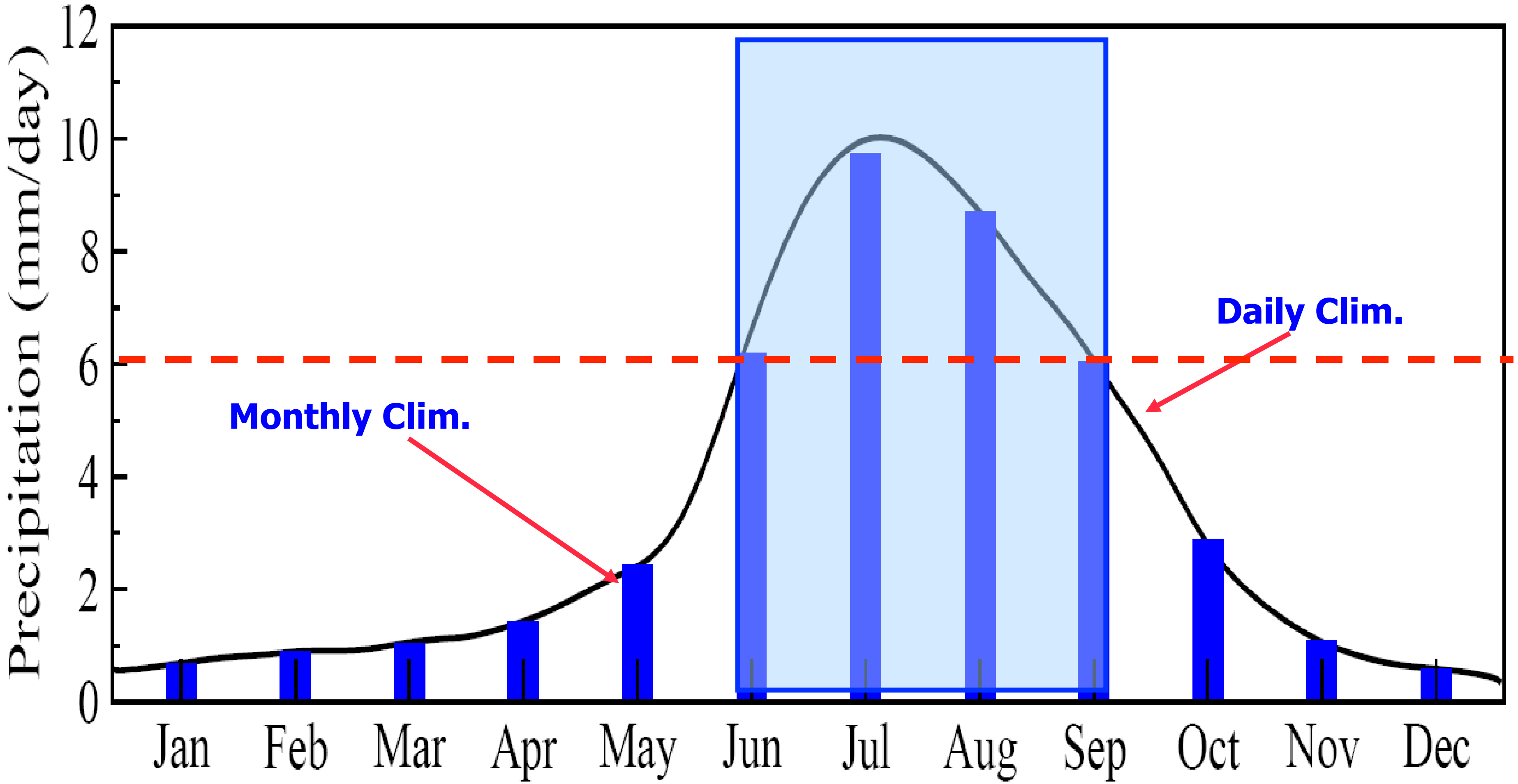
What is the Indian Summer Monsoon?

A Convectively coupled system arising as a manifestation of seasonal northward migration of the Rain Band or Tropical Convergence Zone (TCZ)

Animation of Daily climatological rainfall (shaded) and vector winds at 850 hPa over the full year



The Seasonality being integral part of Indian monsoon, the Indian summer monsoon rainfall (ISMR) is just the summer phase of the 'Annual Cycle of rainfall over India'.



Annual cycle of Rainfall over India

Long term mean JJA precipitation and DJF precipitation

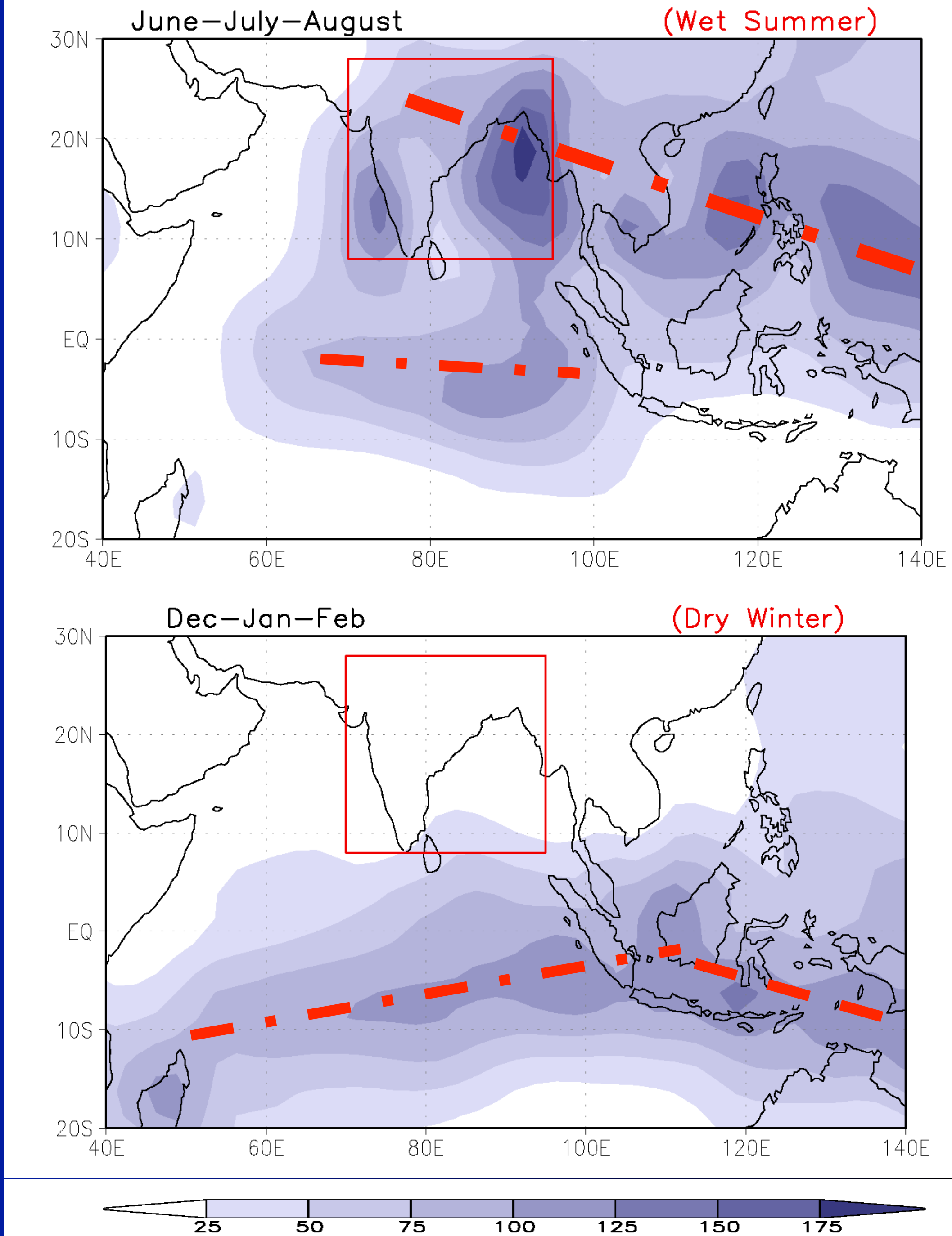
Monsoon ?

Wet- summer

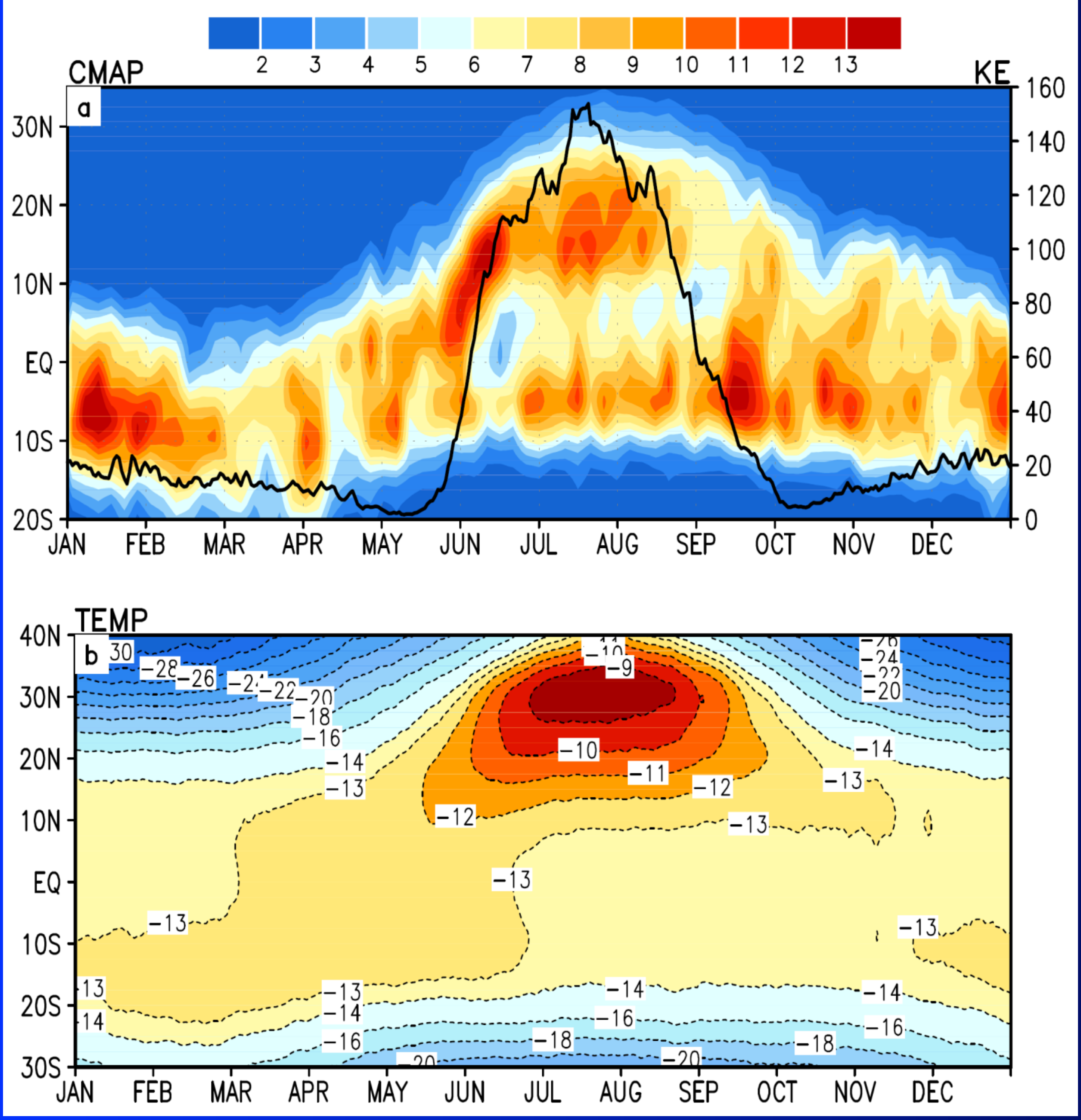
Dry - winter

Some points to note for ISMR:

1. A land ITCZ that is part of large scale southeast-northwest tilted ITCZ
2. A Oceanic ITCZ
3. BoB and NEI P maximum
4. West WH P maximum
5. P minimum southeast peninsula



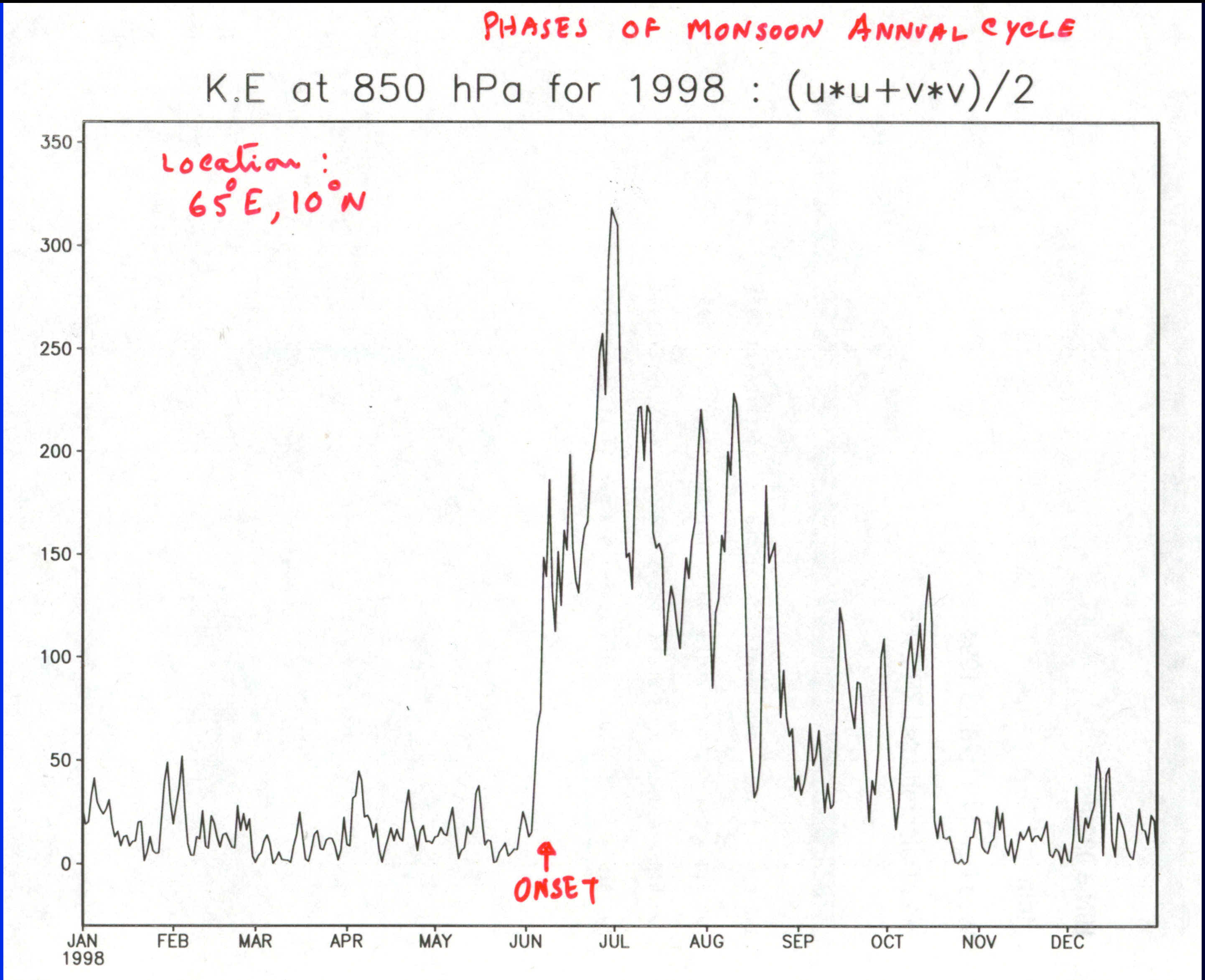
Let us look at the Annual Cycle of the ITCZ and Monsoon with daily rainfall and tropospheric temperature : Onset



Annual evolution precipitation <70E-90E> and K.E of the low level jet (LLJ) <50E-65E, 5N-15N> (black)

Annual evolution tropospheric temp. <700hPa-200 hPa> averaged over <30E-110E>

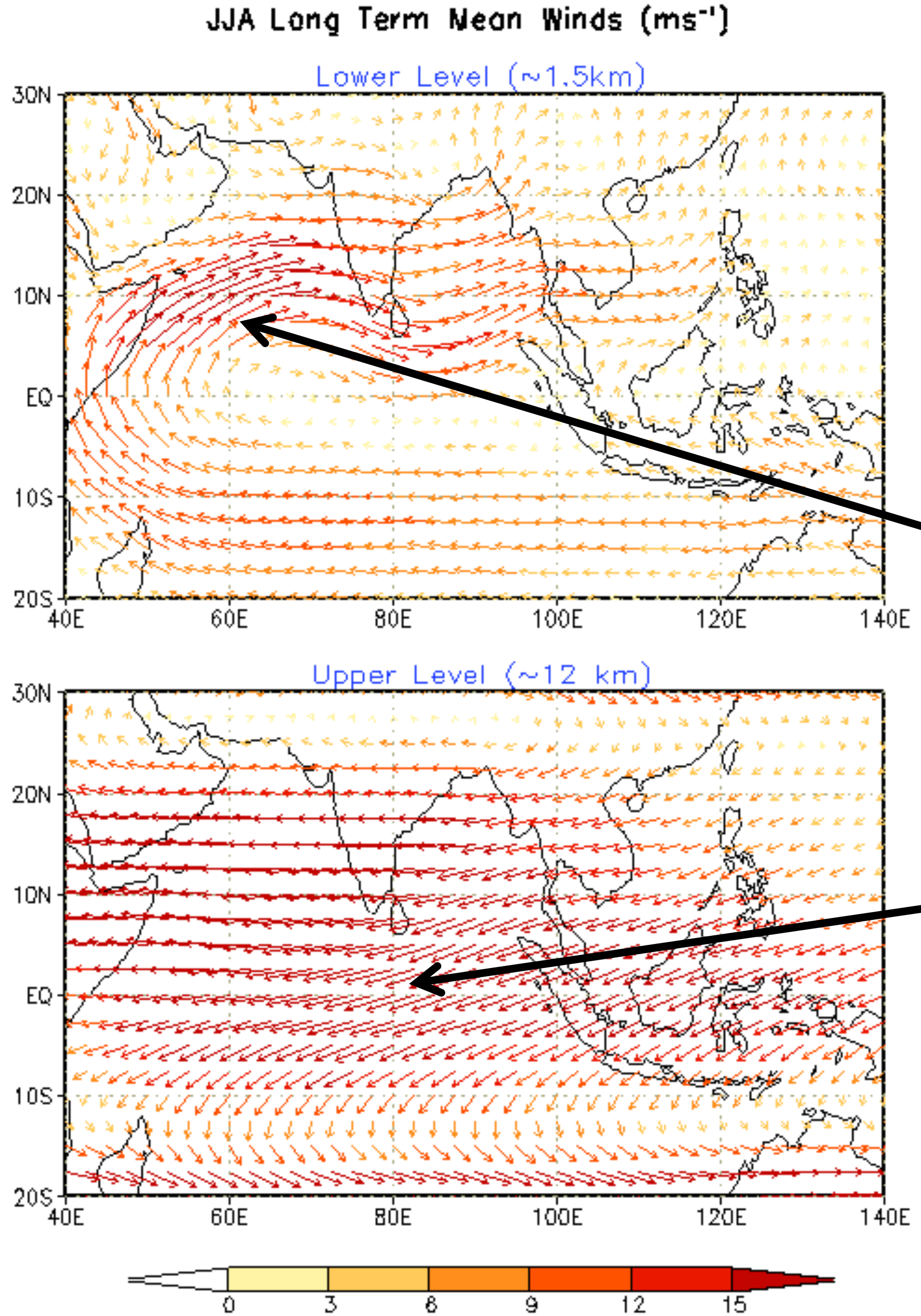
A notable feature of Indian summer monsoon: Sudden Onset!
Often termed as a ‘singularity’ in the annual cycle



Onset of the monsoon

3-D structure of monsoon circulation:

Characteristic features of summer monsoon circulation



Low level, cross-equatorial flow, south-westerlies, westerly jet in Arabian sea

Upper level easterlies, Monsoon Easterly Jet

Convective Coupling:

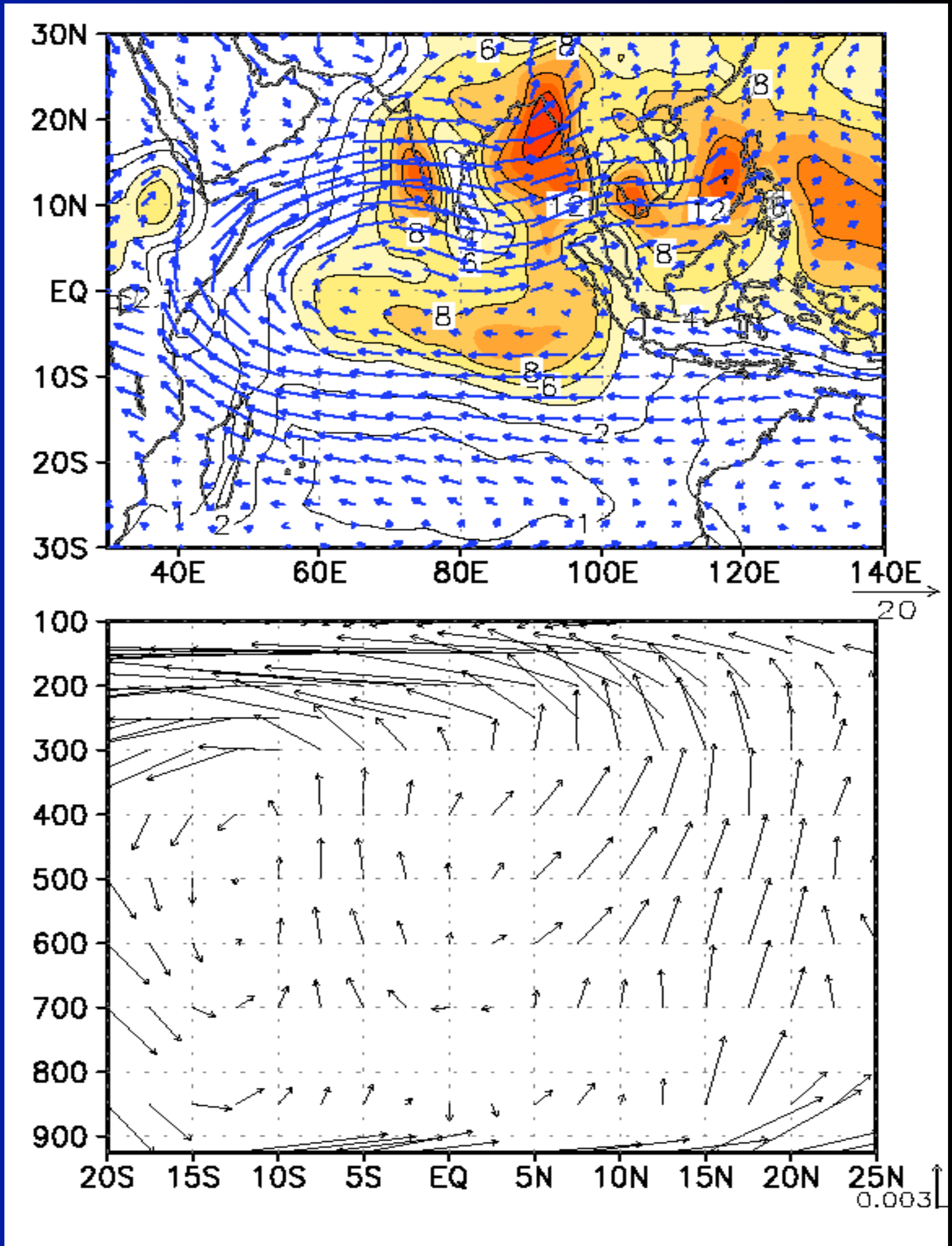
Climatological mean JJAS P and 850 hPa winds

Vertically Deep Circulation:

Mean monsoon Hadley circulation <70E-90E>

$(\overline{[v]},\overline{[w]})$

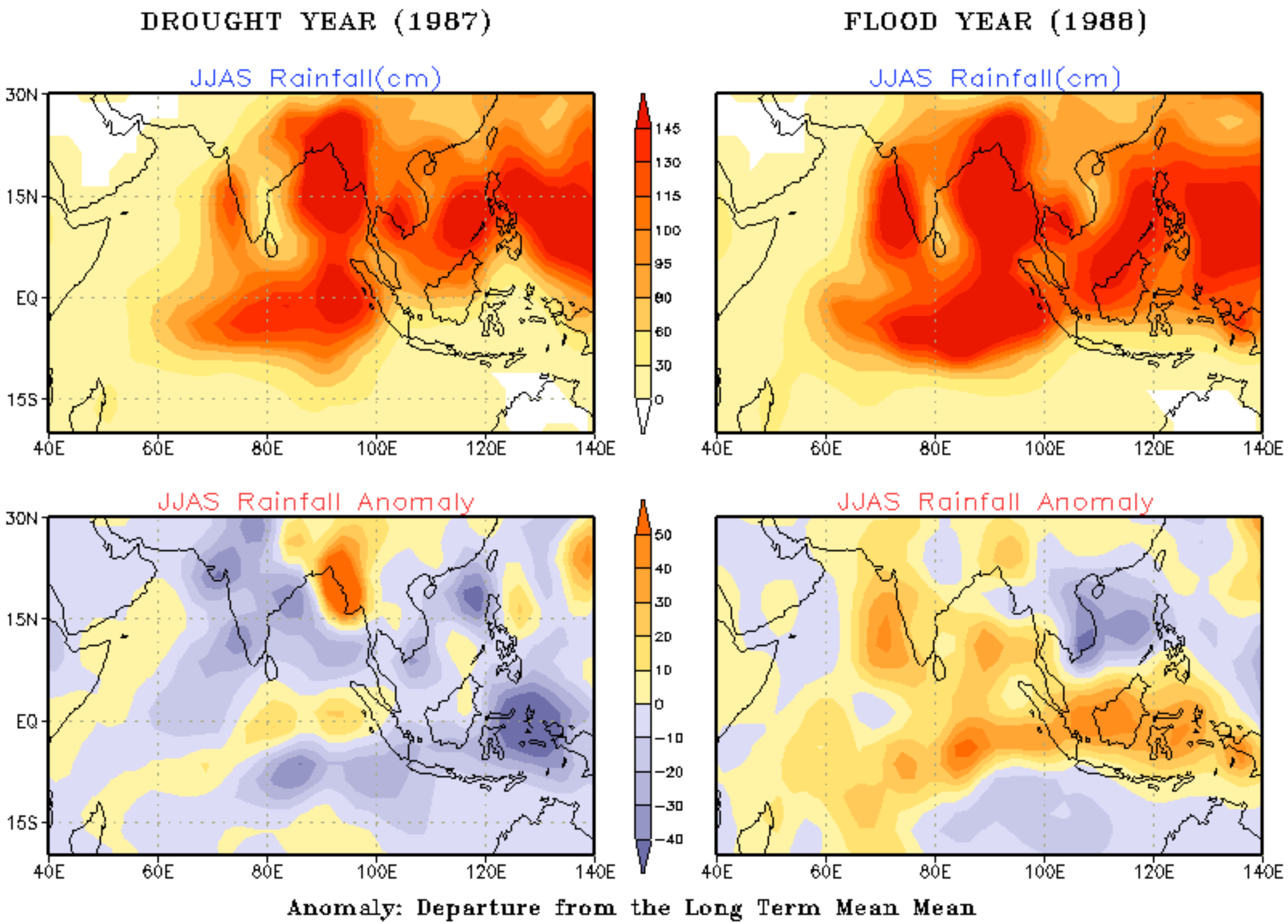
w is multiplied by a factor for visualization of the meridional circulation.

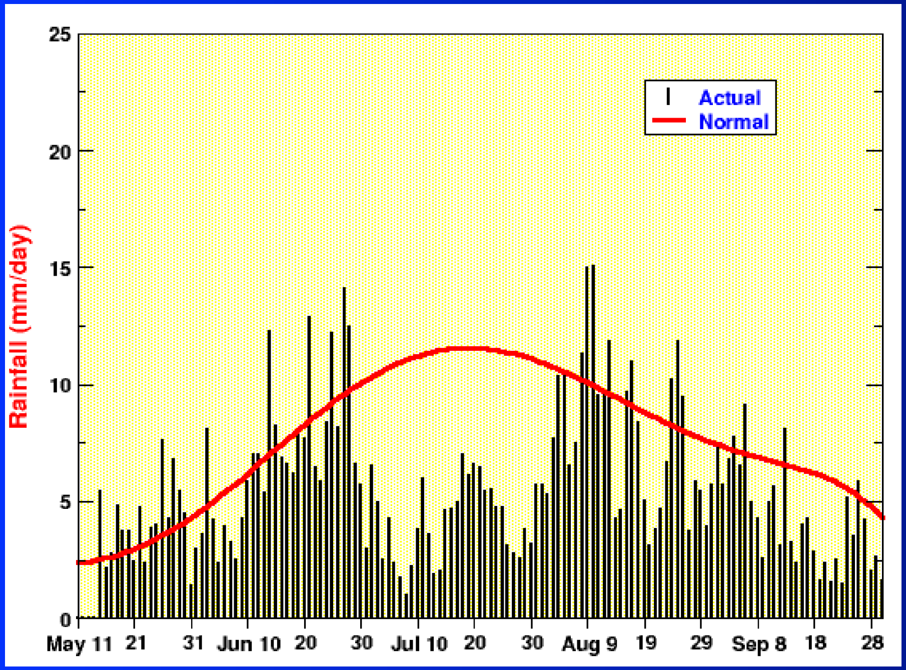


Major characteristic of Seasonal Mean Indian monsoon

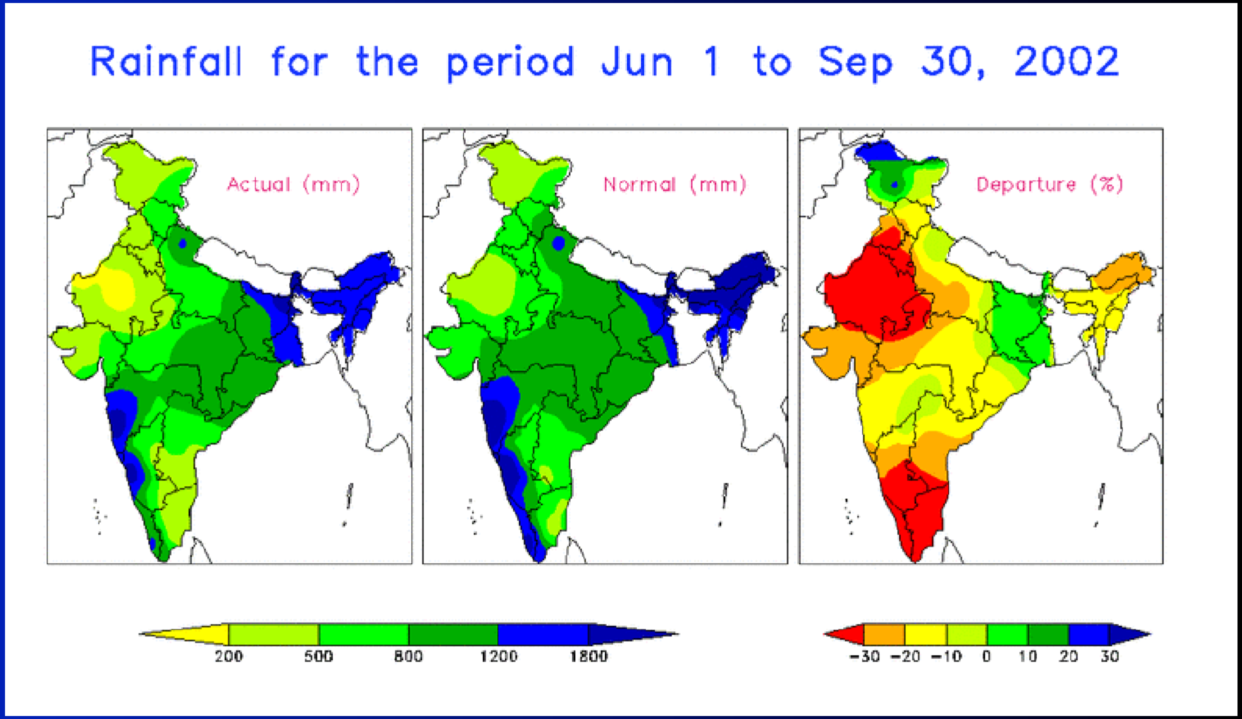
- Wet summer and dry winter
- Manifestation of annual march of the ITCZ from south of Equator to about 25N during northern summer
- Deep baroclinic vertical structure
- Abrupt onset

Year-to-Year (Interannual) Variability of ISMR

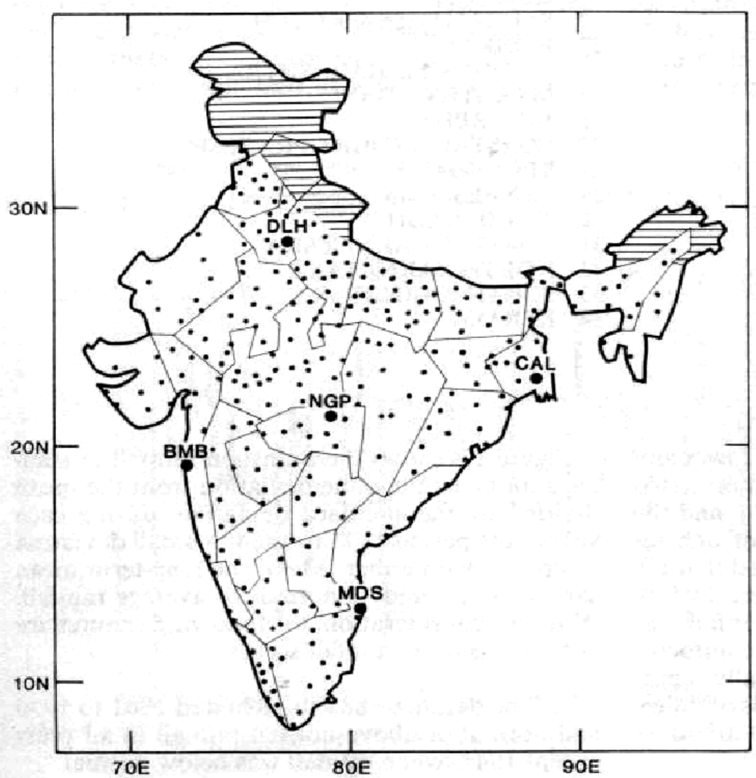




Daily all India rainfall of 2002



- India is fortunate to have long records of rainfall observations from a reasonably good network of rain gauze stations initiated by British in late nineteenth century and early twentieth century.
- Based on 306 such fixed station network Parthasarathy et al. (1994) has constructed monthly & seasonal rainfall over all met sub-divisions and All India rainfall from 1871 onwards now updated by IITM for more than 150 years.
- Based on this data Interannual variability of ISMR has been extensively studied



Shukla 1987: in Monsoons, Fein and Stephens (eds)
John Wiley

306 stations of Parthasarathy et al. (1994)

Fig. 2.6. Network of rain gauge stations over the area considered. The area considered is contiguous India excluding the hatched hilly area.

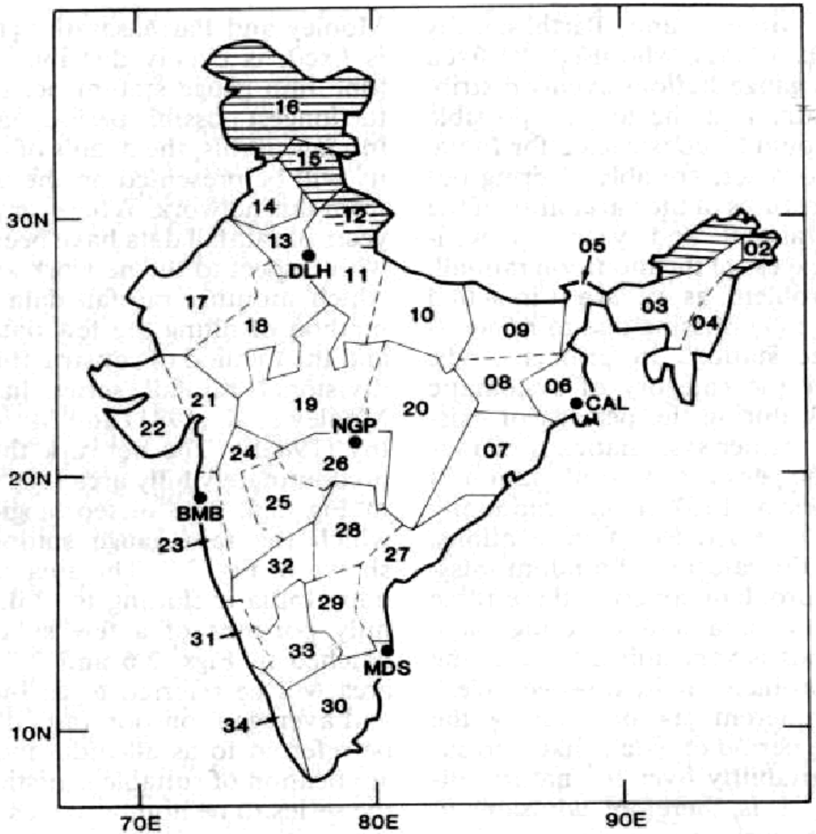


Fig. 2.7. Meteorological subdivisions of contiguous India. (subdivision 1 is Bay Islands and subdivision 35 is Arabian Sea Islands).

2 ARUNACHAL PRADESH
3 NORTH ASSAM
4 SOUTH ASSAM
5 SUB-HIMALAYAN WEST BENGAL
6 GANGETIC WEST BENGAL
7 ORISSA
8 BIHAR PLATEAU
9 BIHAR PLAINS
10 EAST UTTAR PRADESH
11 WEST UTTAR PRADESH PLAINS
12 WEST UTTAR PRADESH HILLS
13 HARYANA
14 PUNJAB
15 HIMACHAL PRADESH
16 JAMMU AND KASHMIR
17 WEST RAJASTHAN
18 EAST RAJASTHAN
19 WEST MADHYA PRADESH
20 EAST MADHYA PRADESH
21 GUJARAT
22 SAURASHTRA & KUTCH
23 KONKAN
24 MADHYA MAHARASHTRA
25 MARATHWADA
26 VIDARBHA
27 COASTAL ANDHRA PRADESH
28 TELANGANA
29 RAYALSEEMA
30 TAMIL NADU
31 COASTAL KARNATAKA
32 NORTH KARNATAKA
33 SOUTH KARNATAKA
34 KERALA

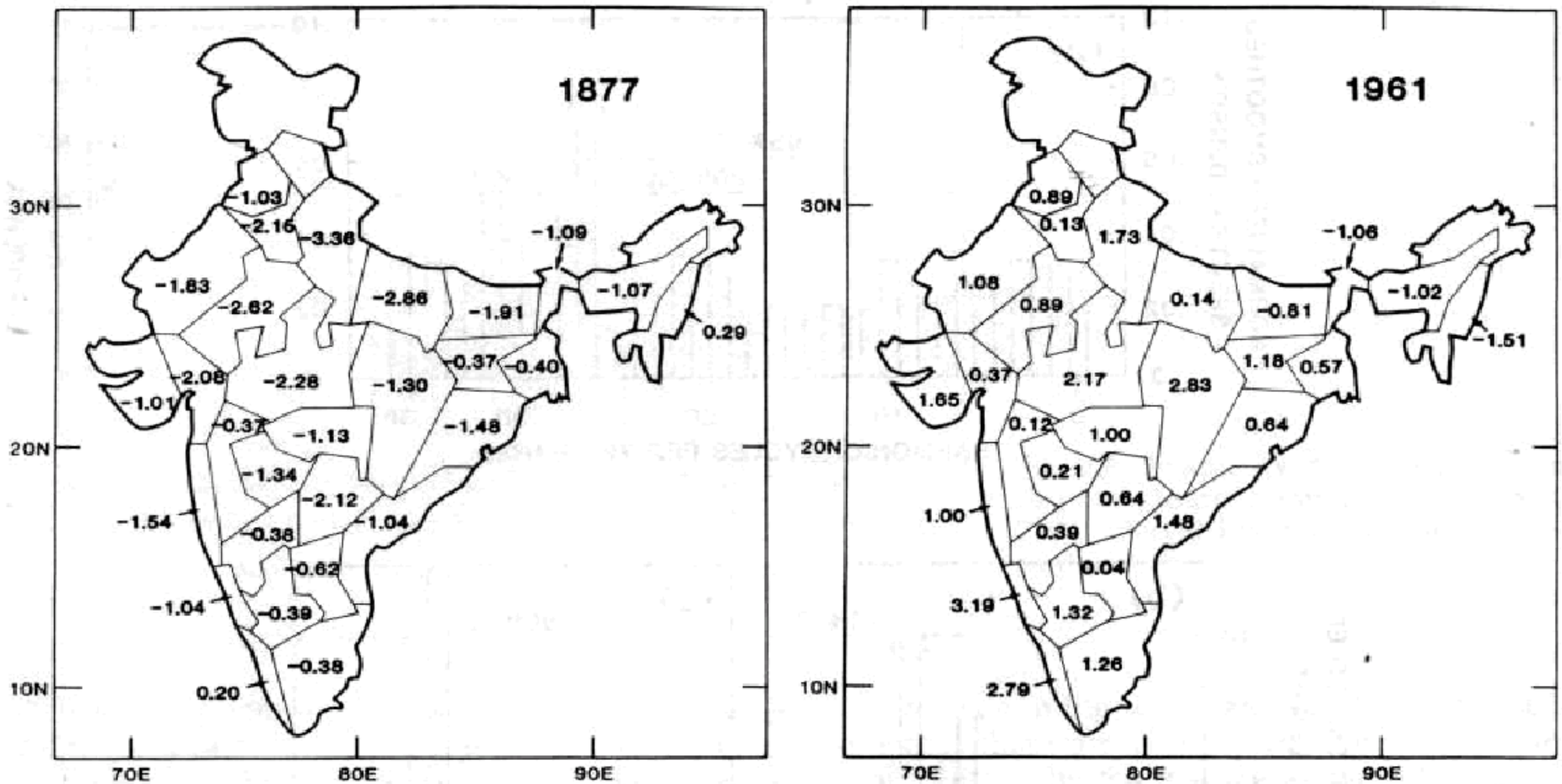


Fig. 2.11. Distribution of subdivisional monsoon rainfall in standard units in 1877 and 1961, the years of lowest and highest all-India monsoon rainfall, respectively.

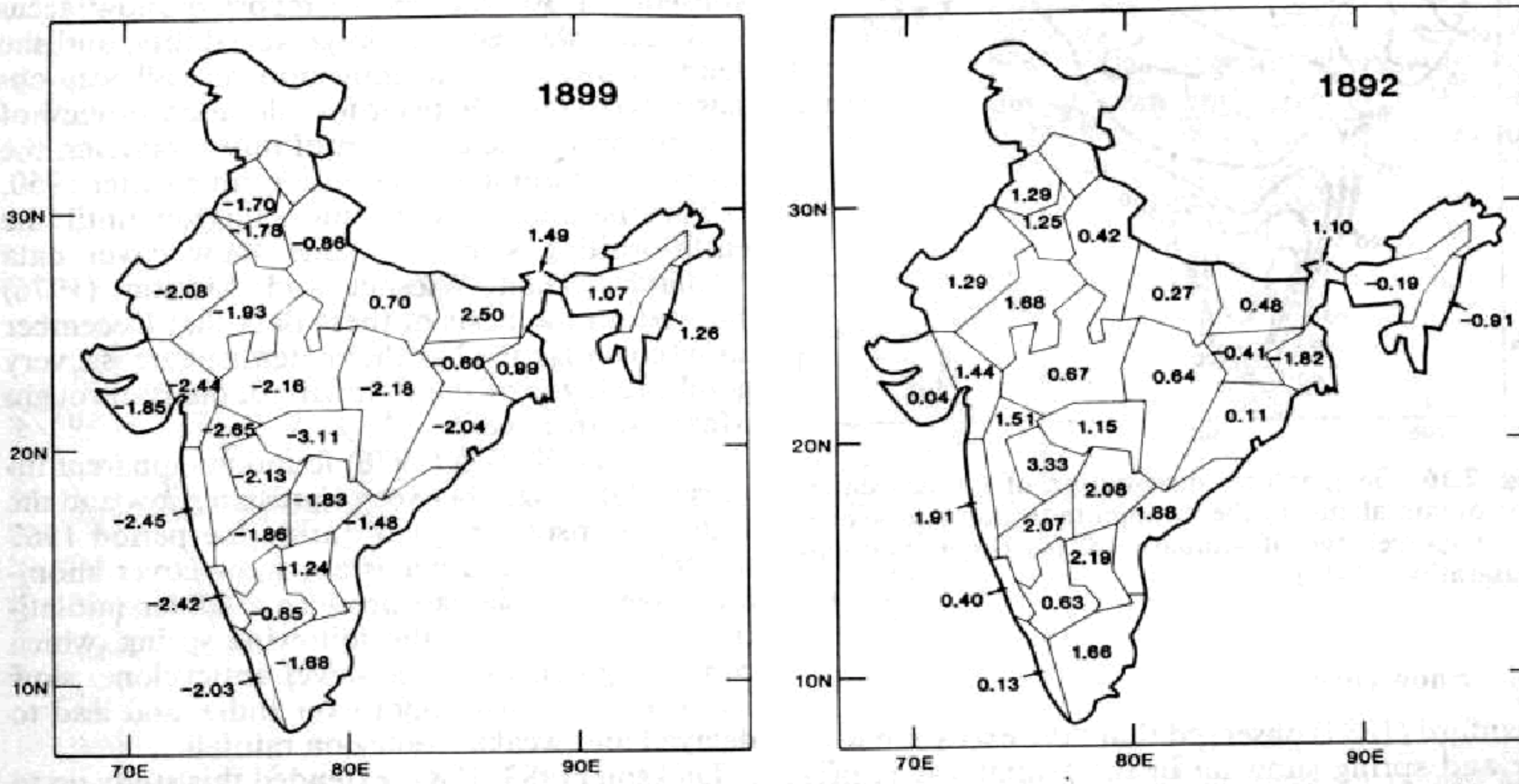


Fig. 2.14. Distribution of subdivisional monsoon rainfall in standard units in 1899 and 1892, the years of maximum incidence of drought and flood, respectively, over India.

INTERANNUAL VAIATIONS

Statistical Properties of All India Summer (June-September) Monsoon Rainfall

- **Mean** :852 mm
- **Standard Dev.** :83 mm
- **Coefficient of Variability** : 9.7%
- **Lowest Rainfall (1877)** : 607 mm
- **Highest Rainfall (1961)** :1017 mm
- **Lowest rainfall (% mean)** : -29%
- **Highest rainfall (% mean)** : +19%

Note: The mean (852mm) of IITM data may change if the # of stations used to create the mean changes. However, the coefficient of variability does change much. You may see the mean given by IMD is slightly different for that reason.

Coefficient of Variability of ISMR with respect to Mean

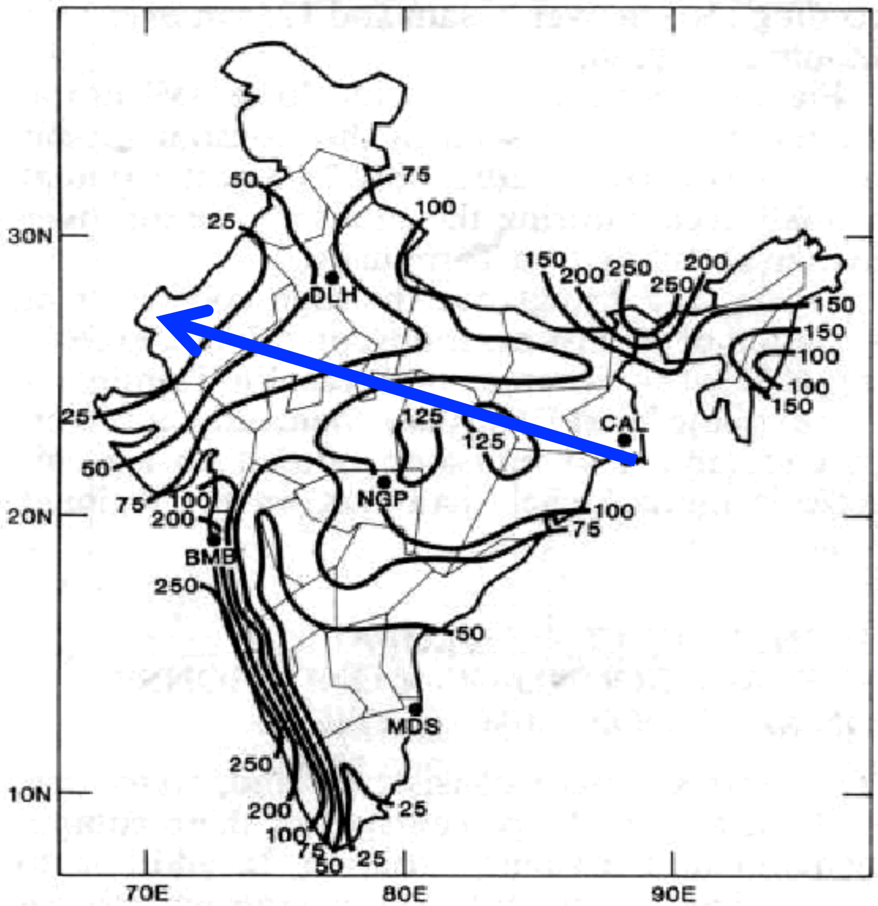


Fig. 2.15. Geographical distribution of the mean monsoon rainfall (cm) over India, 1871–1978. (After Parthasarathy 1984b.)

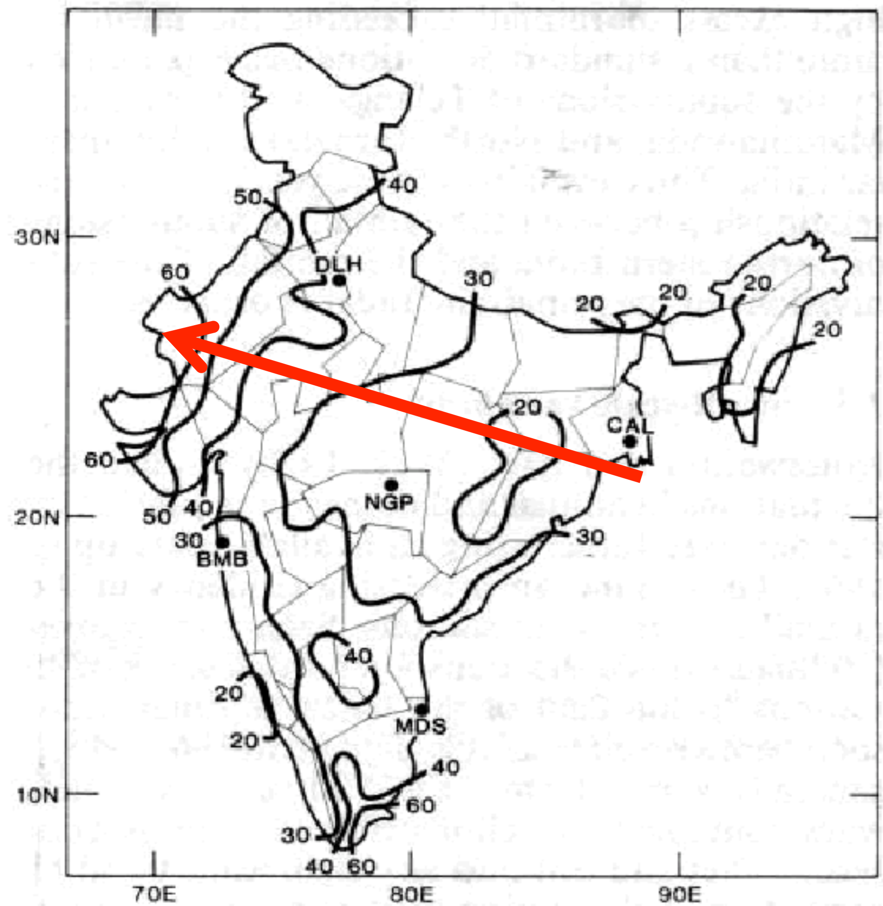


Fig. 2.17. Geographical distribution of the coefficient of variation (%) of the monsoon rainfall over India, 1871–1978. (After Parthasarathy 1984b.)

Mean decreasing

Variability increasing

Strength and weakness of the Parthasarathy et al. (1994) rainfall data

- Rainfall has large ‘small-scale’ spatial variability arising from mesoscale convective systems.
- If the daily rainfall is collected from a variable network of rain gauges, the seasonal mean is affected by ‘sampling’ introducing a ‘spurious’ variaibility of the seasonal mean!
- The strength of Parthasarathy et al data is that it is based on a fixed station network. As a result, this data is a ‘gold standard’ in studying interannual variability (IAV).
- As spatial structure of IAV has large spatial scale 306 stations is adequate to capture it.
- However, for studying small scale processes such as ‘daily extreme rainfall’, it is inadequate.

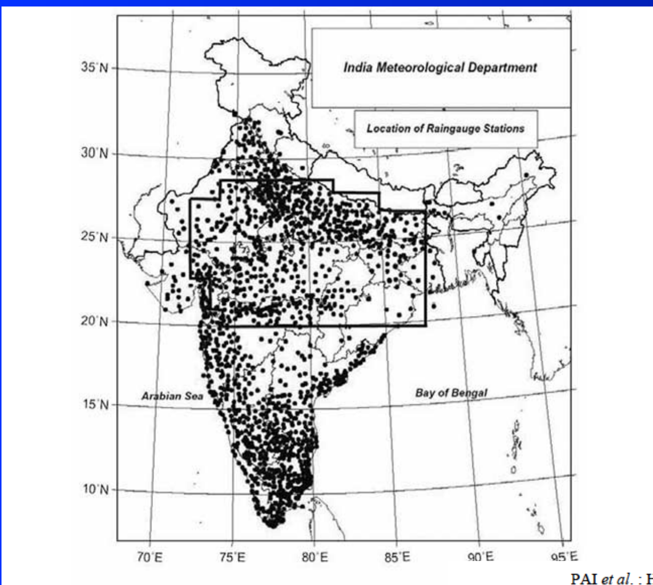
Other Observations Data Sources available for Seasonal mean Rainfall

	Sontakke et al 2008 IITM	Parthasarathy et al 1994 IITM	APHRODITE (over Asian land mass)
Period	**1813-2005**	**1871-2018**	**1951-2015**
Station/Grid	Fixed 316 station for 1901-2005, progressively decreasing for earlier period	Fixed 306 stations	About 2500 variable stations over the Indian region. No. of stations in the NEI is small
Strength	Good for climatology, IAV, Inter-decadal variability	Good for climatology, IAV	Good for climatology, IAV
Weakness	Only monthly means. Not suitable for extreme events	Only monthly means. Not suitable for extreme events	Daily. Not suitable for extreme events in the NEI region. Small no. stations

In recent years, IMD has prepared two valuable gridded daily rainfall data sets.

	Rajeevan et al. GRL, 2008 IMD	Pai et al. 2014, Mausam IMD
Period	1901-2004	**1901-2010**
Station/Grid	**Fixed network of 1380 stations Gridded 1^{O}x1^{O}**	**Variable station network, changing from about 1500 in 1901 to ~7000 stations in 2010 Reporting stations vary from day to day Gridded 0.25^{O}x0.25^{O}**
Strength **Weakness**	**Daily. Good for climatology, IAV, Inter-decadal variability** **Best data set for extreme events too over most of county but not over NEI**	**Daily. Good for climatology, IAV Better spatial distribution of daily rainfall for Mesoscale and synoptic scale events** **Not suitable for extreme events**

Spatial distribution of stations and their temporal evolution for Rajeevan et al.(2008) and Pai et al. (2012) data sets



Rajeevan et al., 2008, GRL, fixed 1308 stations

Pai et al., 2014, Mausam

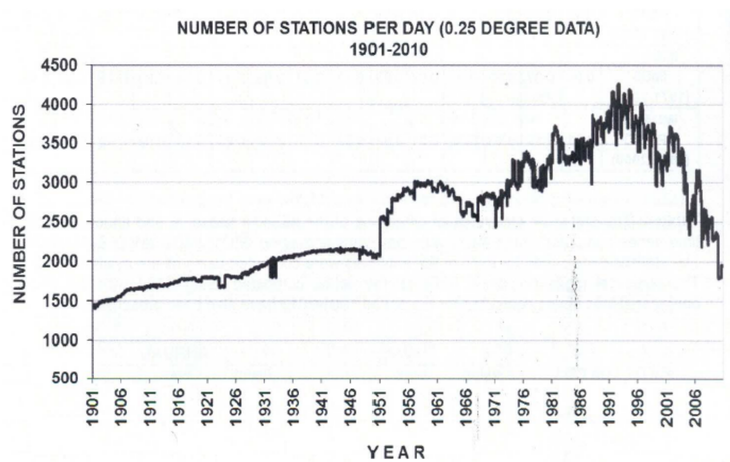


Fig. 2. Daily variation of number of stations used for the development of IMD4

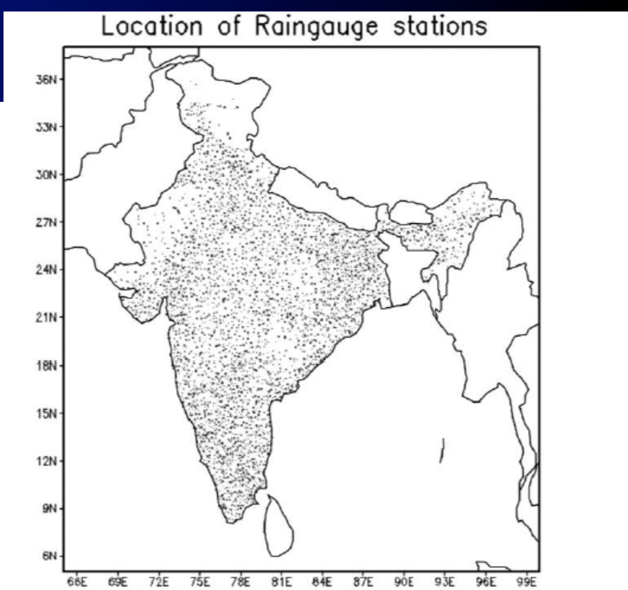
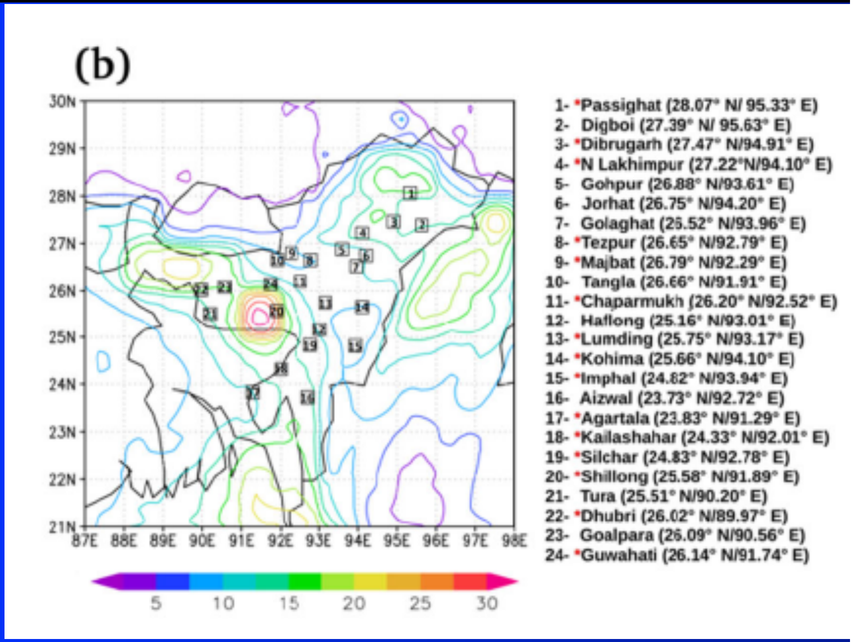


Fig. 1. Network of 6955 rain gauge stationsused for development of IMD4

Problems of the rainfall data sets over the north-east India (NEI)

- NEI is a large region with ~3X all India rainfall and hence represents a Big component of Indian monsoon heat source!
- Parthasarathy et al data has 12 stations on which the monthy means are calculated. Adequate for IAV studies
- The gridded data sets have good number of stations in recent decades. But has less than 10 stations during early years 1901-1950.
- Highly inadequate for extreme rainfall studies
- A good estimate of daily extreme event variability is important for its impact on biodiversity of the region.

Problems of the rainfall data sets over the north-east India (NEI)



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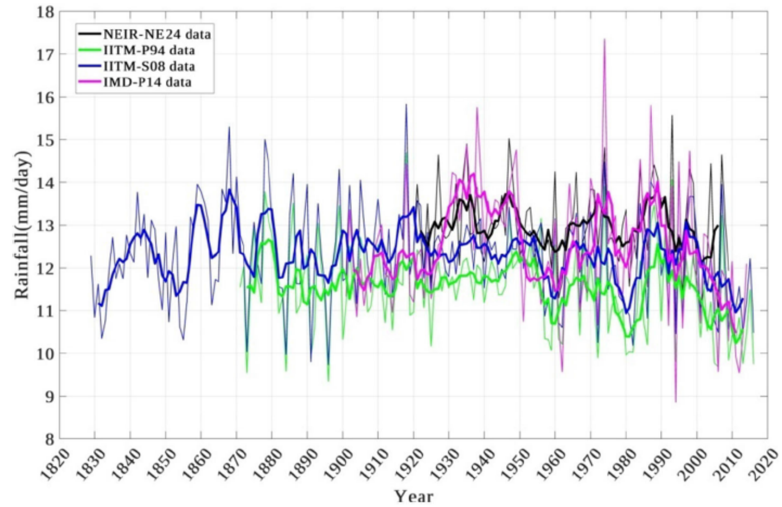


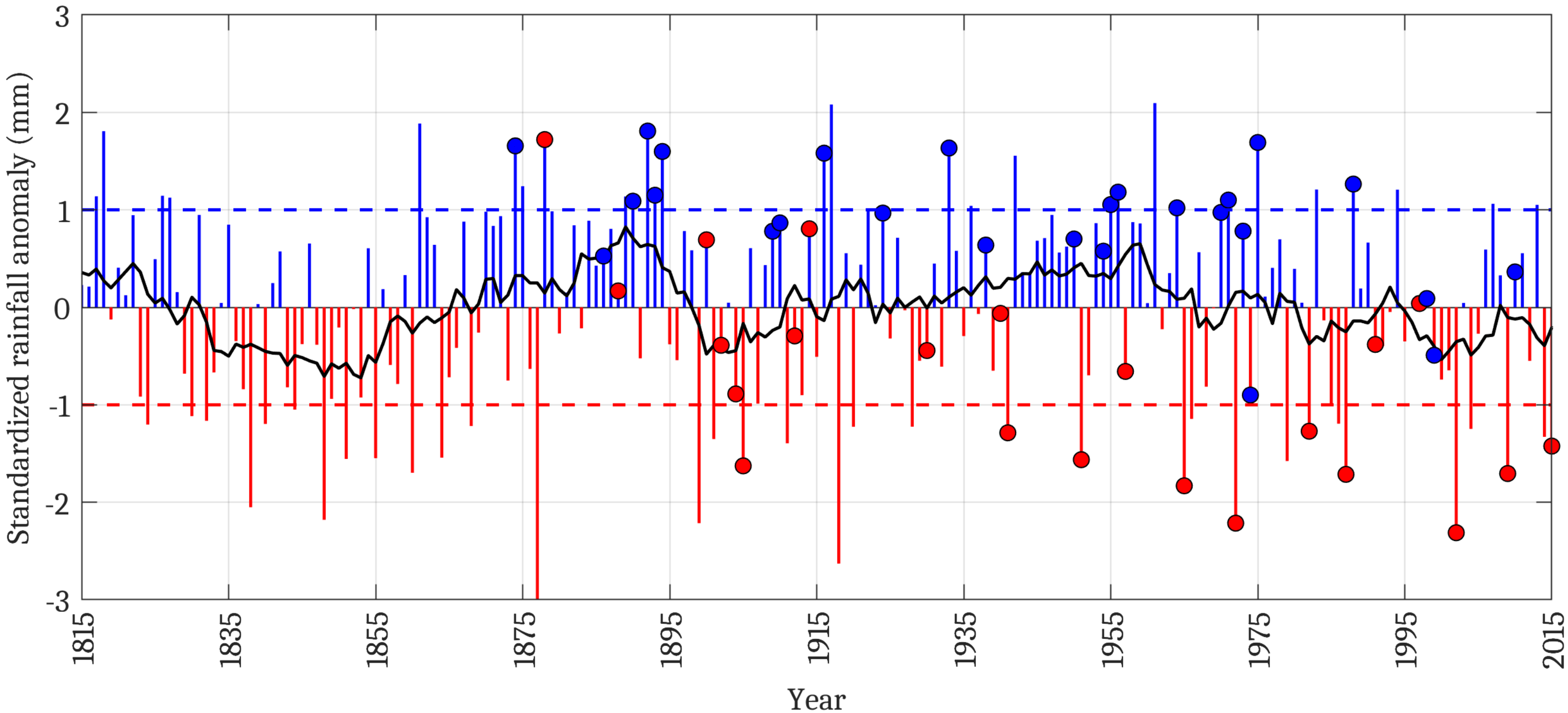
Fig. 2 Seasonal mean rainfall (JJAS) over the NEI from four different data sets from a NE24 station data set (black) during 1920–2009 (Mahanta et al. 2019), **b** IITM dataset (Parthasarathy et al. 1994) during 1871–2016 (green), **c** IITM (Sontakke et al. 2008) during 1829–2006 (blue), **d** IMD gridded data set of 0.25 × 0.25 deg. resolution (Pai et al. 2014) during 1901–2014 (magenta)

NE24➔ A newly constructed daily rainfall data set based on 24 fixed stations (as shown above) for 90 years, 1920-2009. Data gaps in IMD stations have been filled by data mining from nearby Tea Garden! (Courtesy: Dr. Rahul Mahanta, Cotton Univ.)

➔Zahan, Mahanta, Rajesh & Goswami, 2021: Impact of climate change on North-East India (NEI) summer monsoon rainfall, Climatic Change, https://doi.org/10.1007/s10584-021-02994-5

Interannual variability of the Indian summer monsoon

Some notable characteristics ISMR interannual variability..



(A 200+ year long ISMR time series constructed by adding Sontakke et al data to Parthasarathy et al data)

- A strong ENSO-ISMR negative relationship
- But plenty of non-El Nino droughts &non-La Nina Floods
- A clear multi-decadal variability

- Normalized seasonal mean ISMR anomaly (normalized by its own s.d)
- Red dots→ El Nino years
- Blue dots→La Nina years

Spatial pattern of dominant modes of inter-annual variability of Indian monsoon rainfall

Choudhury et al., 2021: Climate Dynamics, https://doi.org/10.1007/s00382-021-06023-0

GPCP is a satellite based monthly rainfall data set over global tropics between 1979 and 2014

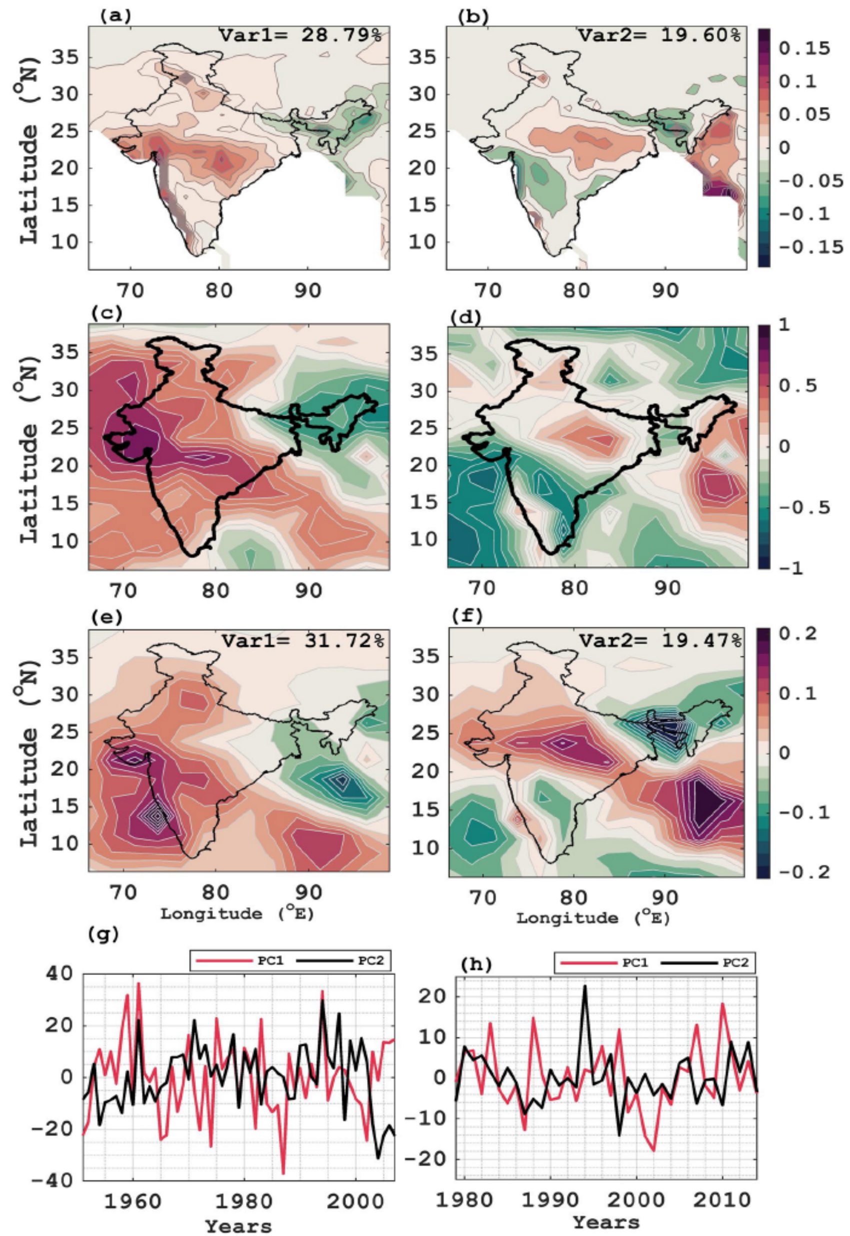


Fig. 9 Two dominant patterns of JJAS rainfall over land India and neighboring areas. **a** EOF1 and **b** EOF2 pattern from Aprhodite data for ISMR for the period 1951–2007. **b** Regressed pattern of PC1 from land based rainfall on GPCP rainfall including ocean regions. **c** Same as **b** but for PC2 of land-based rainfall regressed on GPCP data. Dominant patterns **e** EOF1 and **f** EOF2 of inter-annual variability of land + ocean rainfall from GPCP data for the period 1979–2014. **g**, **h** Show the PC1 and PC2 from Aphrodite data and GPCP data respectively

Association with the ENSO

Southern Oscillation as defined by MSLP Darwin and Indian monsoon rainfall :

Composite of Darwin pressure anomaly for low-rainfall years (drought) and high-rainfall years (floods)

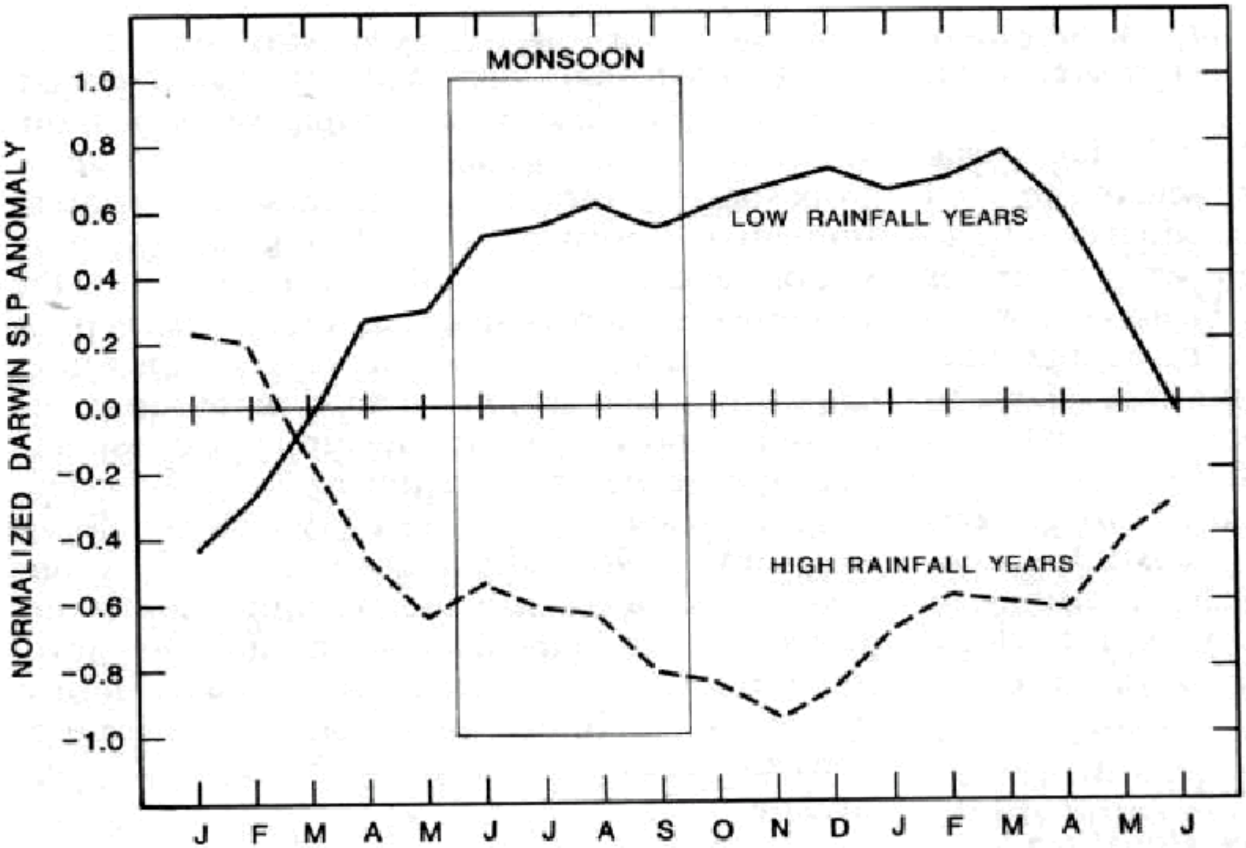
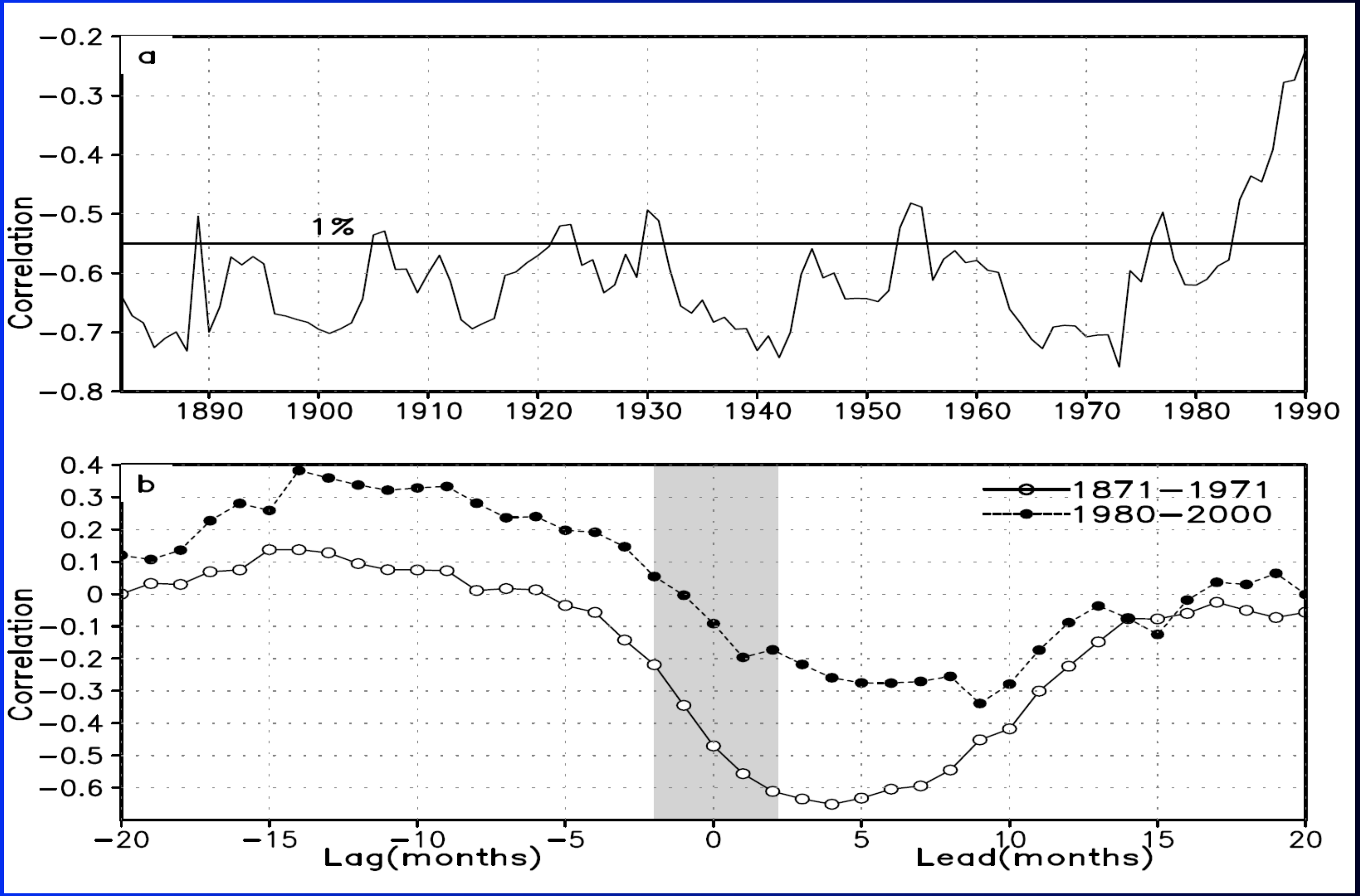


Fig. 2.19. Composite of the normalized Darwin pressure anomaly (three-month running mean) for heavy monsoon rainfall years and deficient monsoon rainfall years. (After Shukla and Paolino 1983.)

Changing ENSO-Monsoon Relationship



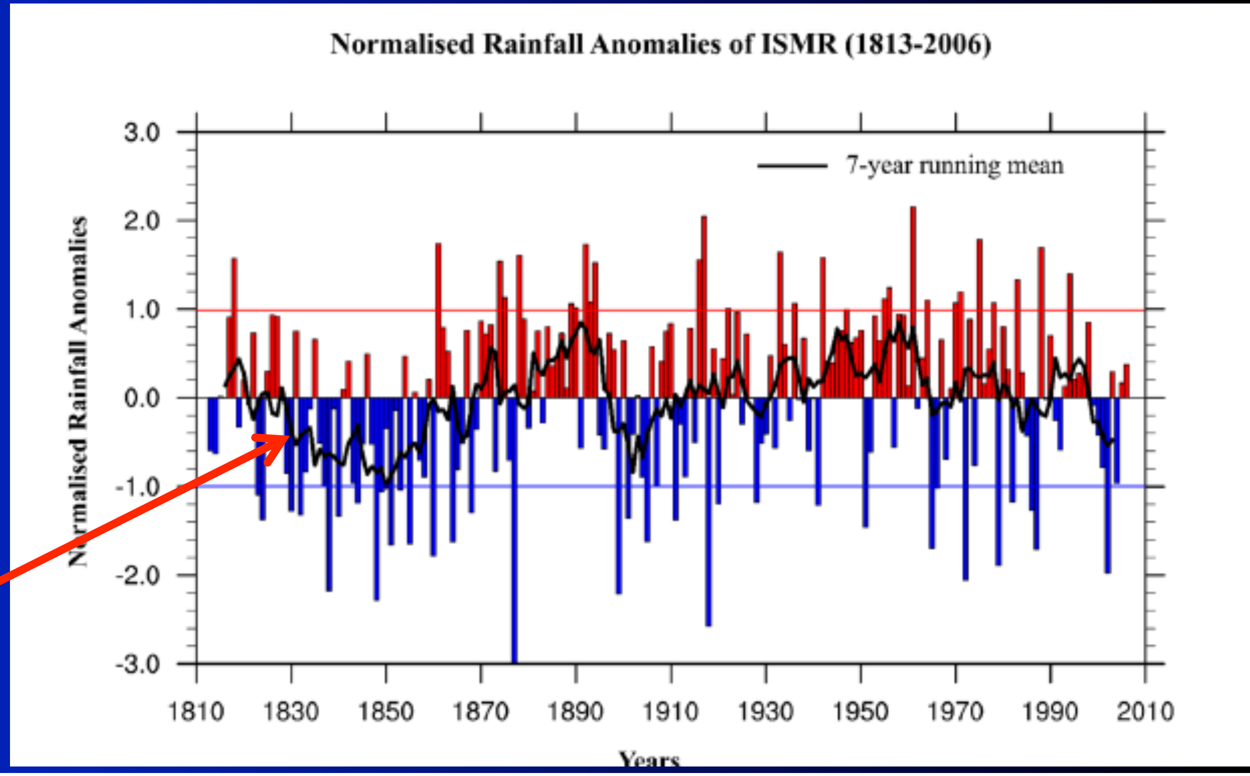
(a) 21-year sliding window correlation between AIR and Nino3 SST, (b) lead-lag correlation between AIR and Nino3 SST during the period 1871- 1971 and 1980-2000.

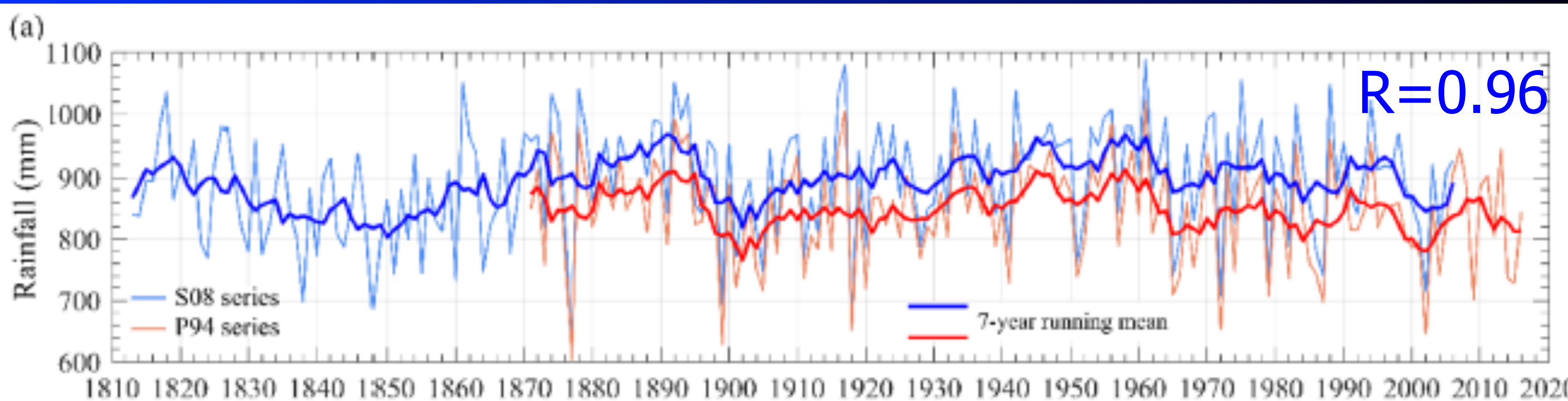
Temporal Modes of ISMR Variability

Sontakke et al. 2008. (1813-2005)

Parthasarathy et al., 1994 (1871-2015)

Multi-decadal variability of ISMR





Rajesh and Goswami, 2020: Climate Dynamics

The EEMD method decomposes a time series into a small set of oscillatory modes and a residual trend explaining the total variance of the time series. The oscillatory modes are also called Intrinsic Mode Functions (IMFs)

- Quasi-biennial has largest variance ~65%
- Quasi-biennial and multi-decadal T~65 yrs are only two statistically significant

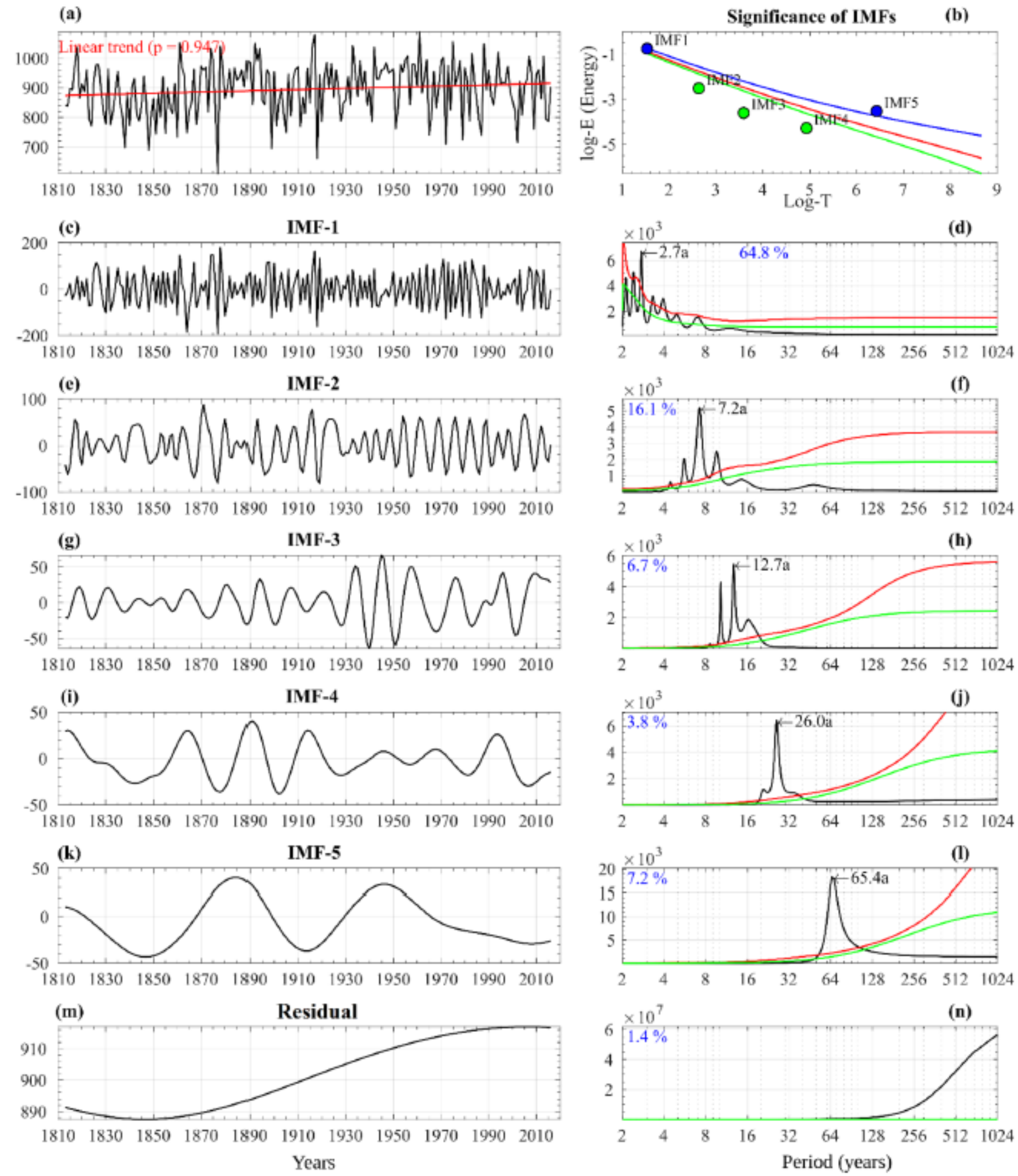
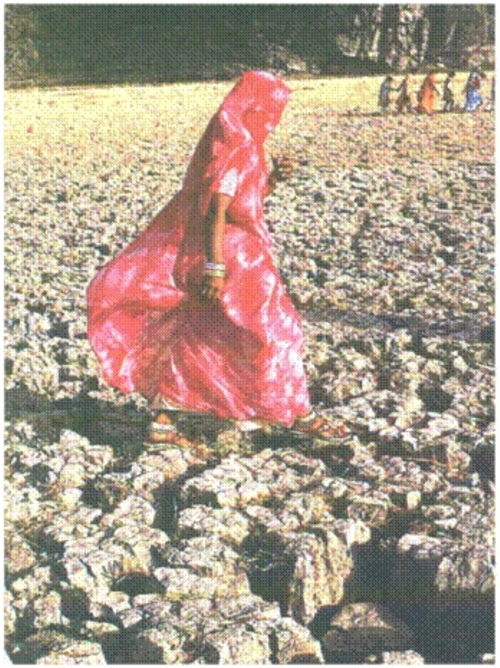


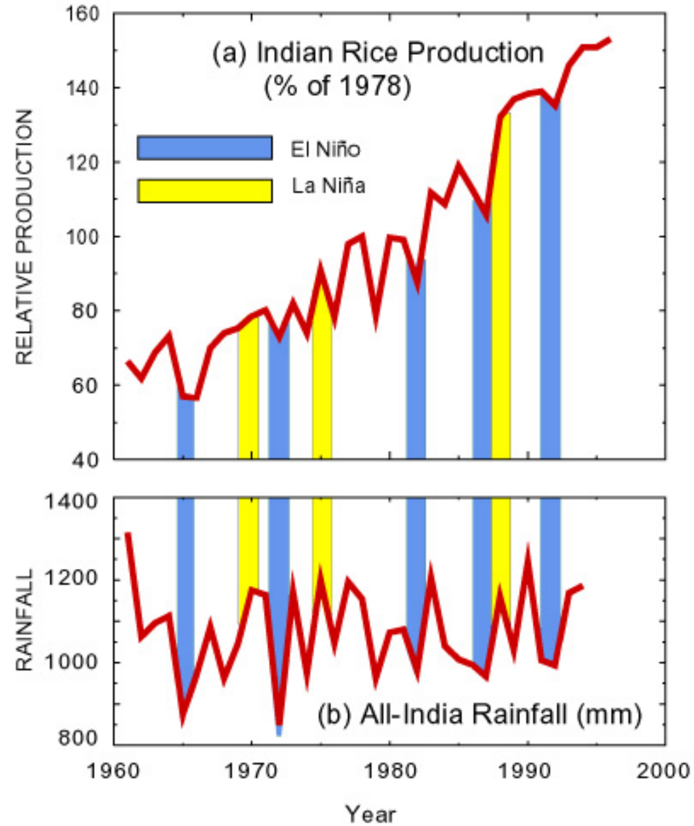
Fig. 3 **a** ISMR time series with linear trend (redline) for a period from 1813–2016 and **b** the statistical significance of the IMFs, where blue, red and green line shows 99%, 95% and 90% CI. **c**, **e**, **g**, **i**, **k**, **m** Six IMF components of ISMR and **d**, **f**, **h**, **j**, **l**, **n** their respective power spectrums. Red lines in the power spectrums show the red-noise at 99% CI using Monte-Carlo algorithm and green lines are the mean spectrum of red-noise modeling. Dominant periodicity (value pointed with arrow) and percentage of variance explained by each mode (blue font) is given in the right panels. Units are in mm



Extremes of Indian summer monsoon such as a large scale Drought and Flood, determine the economy of our country.

The Asian - Australian Monsoon System

Relationship of Indian Rice Production and Indian Rainfall



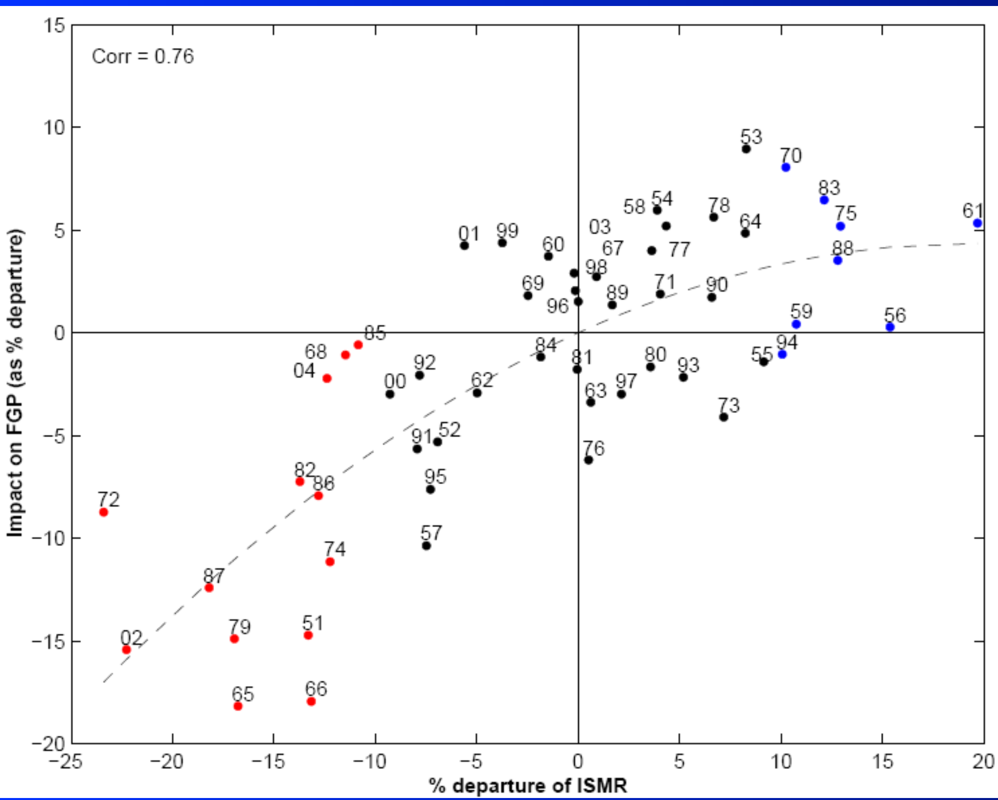
Crop production vs. Indian monsoon rainfall. Notwithstanding the overall growth in rice production in India due to better farming practices and technological development, year-to-year fluctuations in production are determined largely by the success or failure of the summer monsoon which is in turn affected by the particular phase of the El Niño/Southern Oscillation phenomenon (from Webster et al. (1998, J. Geophys. Res., 103, 14451-14510), adapted from Gadgil, 1995, Current Science, 69, 649-659).

LB/G2/99-1

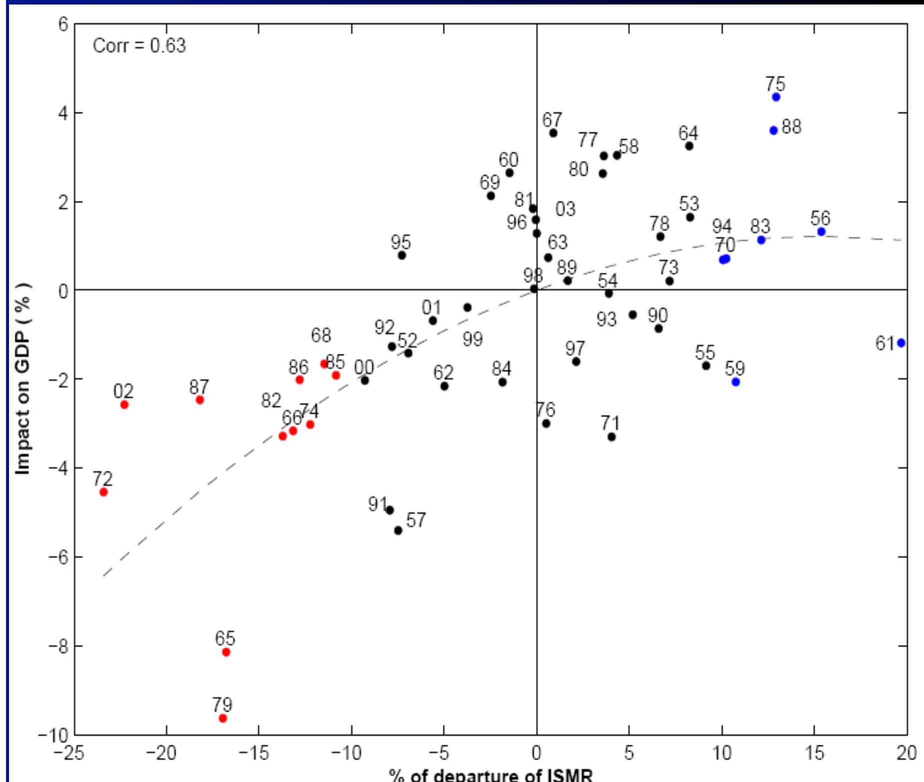
Webster et al., 1998: JGR

Monsoon Rainfall & Indian Food grain production and GDP

Gadgil and Gadgil, Economic and Political Weekly, XLI, pp.4887–4895,2006.



Variation of the impact on food grain production ; drought and excess rainfall years are red and blue respectively.



Variation of the impact on GDP with the monsoon rainfall anomaly; drought and excess rainfall years are red and blue respectively.

Apart from the ENSO, what are factors are known to influence inter-annual variability of ISMR?

European snow cover

Bamzai and Shukla 1999, Kripalani and Kulkarni, 1999, Fasullo, 2004, Saha et al., 2013

PDO

Krishnan and Sugi, 2003, Krishnamurthy and Krishnamurthy, 2014

Atlantic Nino

Yadav R. et al, 2018, npj:CAS; Kucharski et a., 2008 GRL

Southern Annular Mode

Parbhu et al., 2016, 2017, Dou et al., 2017

Eurasian snow cover and ISMR relationship…

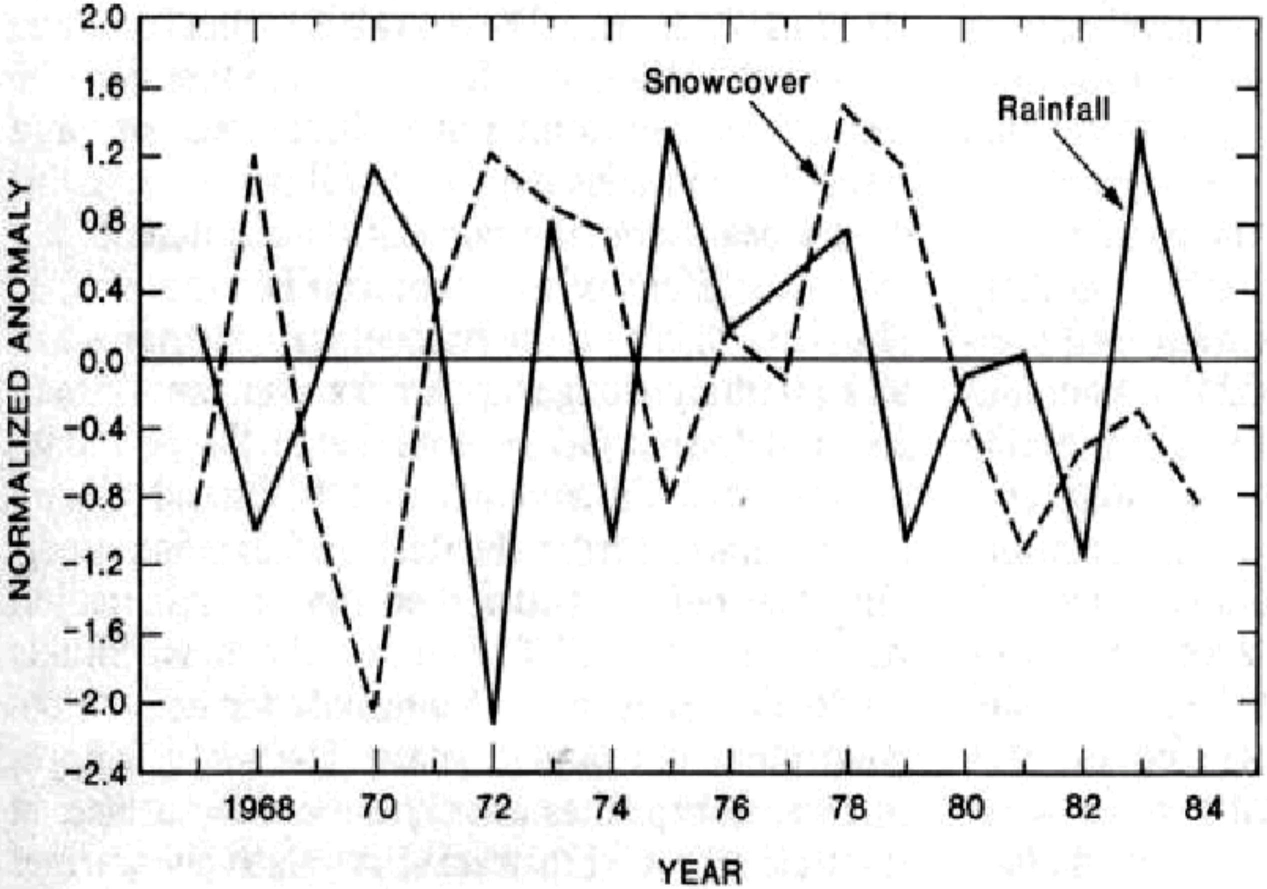


Fig. 2.18. Normalized anomaly of Indian monsoon rainfall and of Eurasian December-to-March snow cover, 1967–84.

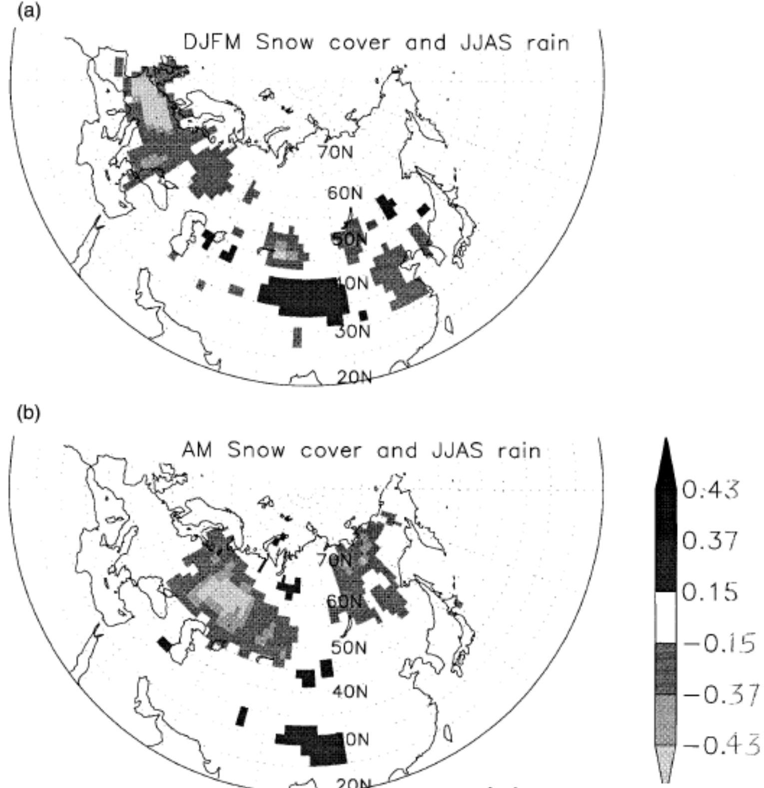
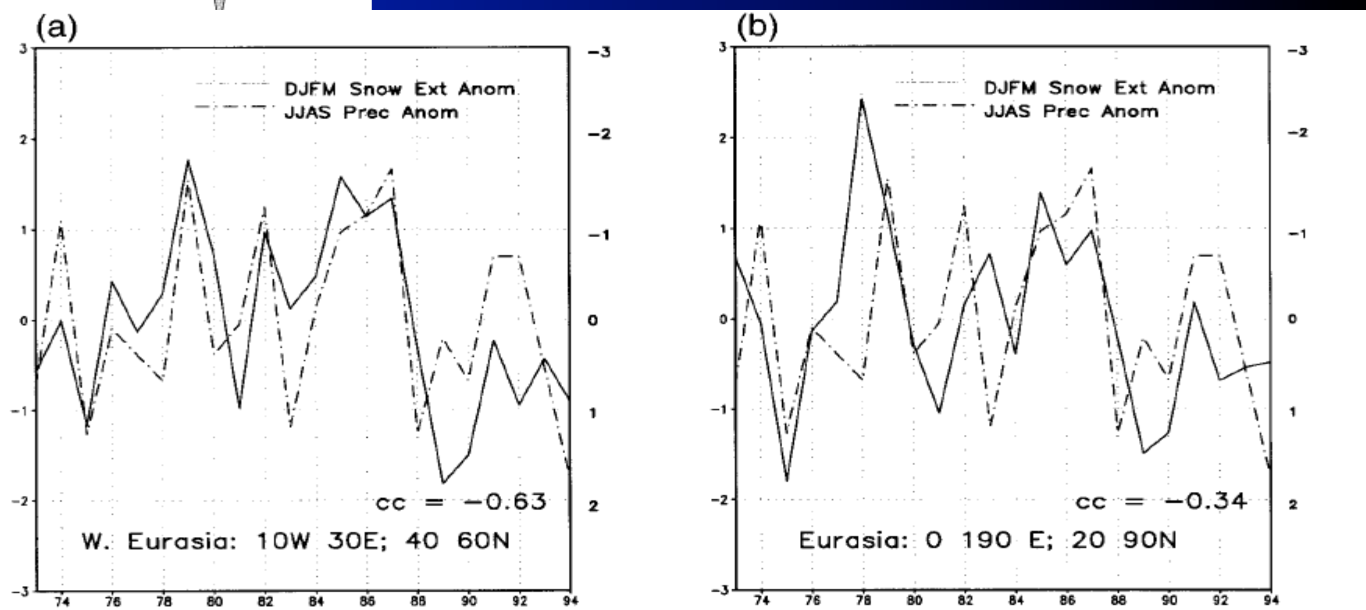


FIG. 4. Correlation coefficient between (a) DJFM snow cover and JJAS monsoon rainfall. Results are based on data for the period 1973–94. Co 95% confidence levels, respectively.



Bamzai & Shukla, 1999

The Eurasian snow-ISMR relationship seem to have changed significantly in recent years!

Zhang et al., Science Advances. 2019; 5 : eaau8932

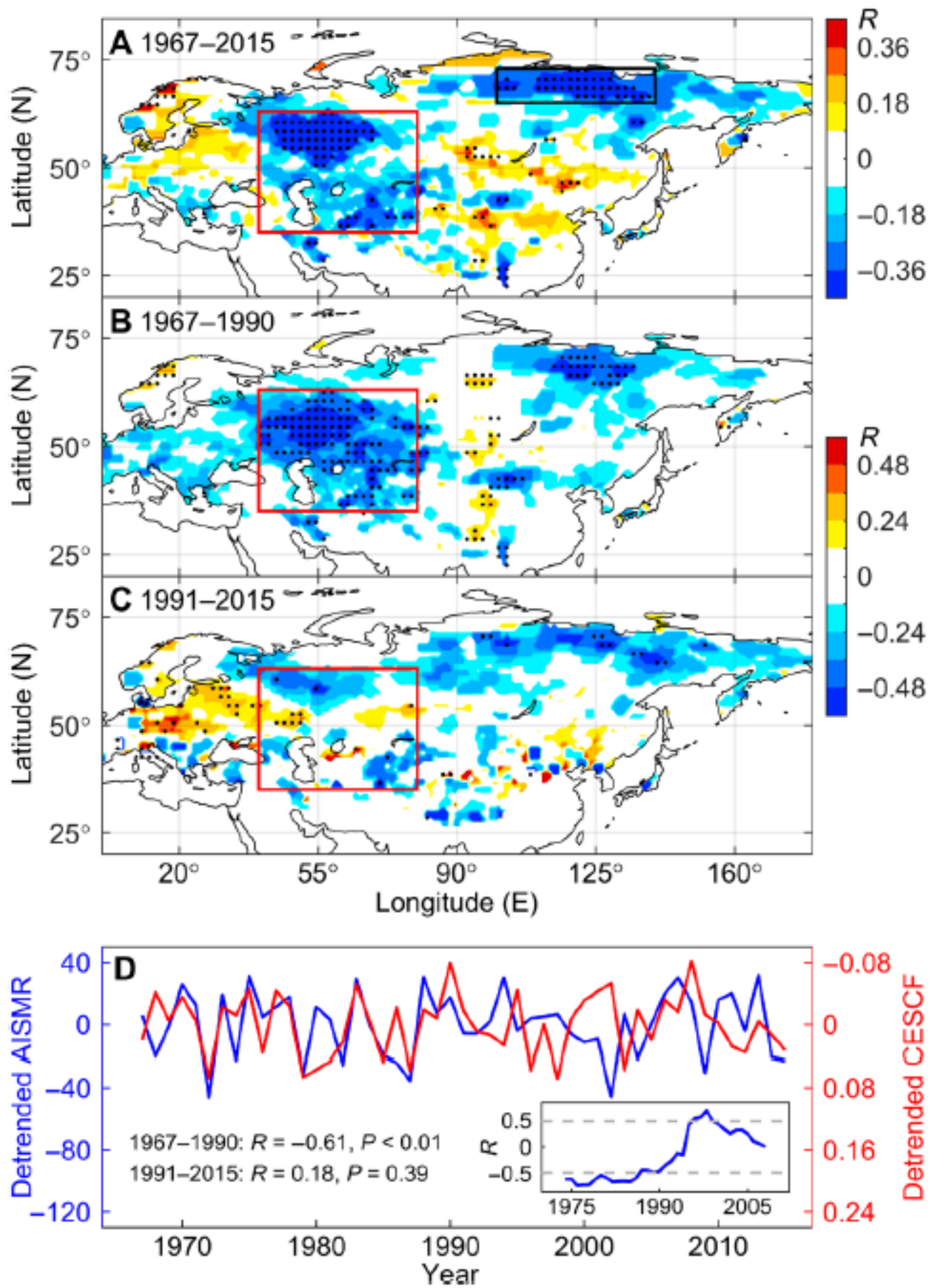


Fig. 1. Shift in the snow-monsoon relationship. (**A**) Spatial distribution of correlation coefficients (R) of spring SCF over Eurasia with AISMR for the period 1967–2015. (**B** and **C**) Same as (A) but for the periods 1967–1990 and 1991–2015, respectively. (**D**) Time series of detrended AISMR and CESCF. AISMR is all-Indian summer monsoon rainfall (June to September) from the Indian Institute of Tropical Meteorology (IITM), and CESCF denotes the area-weighted average spring (March to May) SCF over central Eurasia. Note that the order of the right-side axis is reversed to enable easier comparison of the time series. The line chart embedded in (D) denotes a 15-year sliding correlation between AISMR and CESCF. Significant R values are identified as gray dashed lines ($P < 0.05$). The black dots in (A) to (C) indicate that the R is statistically significant ($P < 0.05$). The red boxes represent the region of central Eurasia (40° to 80°E, 35° to 65°N), and the black box denotes the northeast Eurasia (100° to 140°E, 65° to 73°N).

Pacific Decadal Oscillation (PDO) –ISMR Relationship

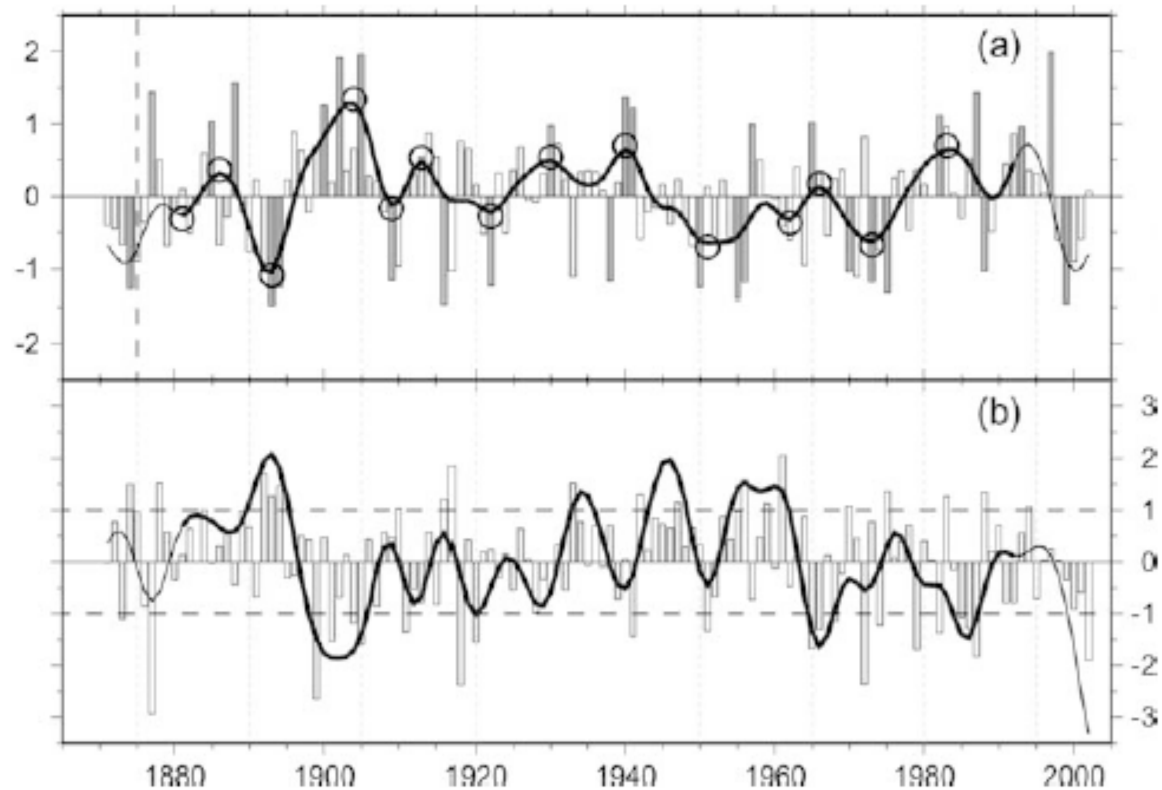
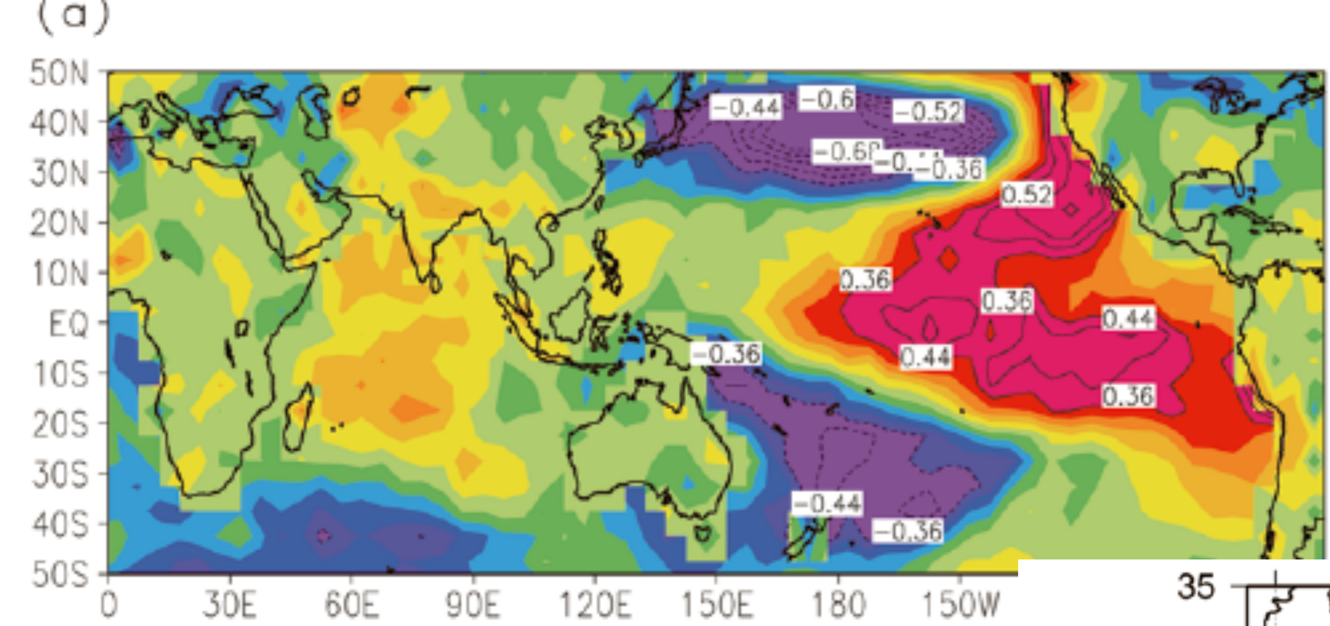


Fig. 2 **a** Time series of the first principal component of the detrended and low-pass filtered SST in the Pacific Ocean domain (120°E–90°W; 45°S–45°N) is shown by the *thick line*. Power spectrum calculations of the filtered PC1 time series show that the integrated power from the high-frequency range (≤ 8-years) is smaller than 1% of the integrated power from the low-frequency range (≥8-years). This point confirms that the low-pass filter practically eliminates most of the leakage of higher frequencies. Since there is ambiguity in defining the decadal timeseries at the ends, due to end-effects of the low-pass filter, the first and last 10-points of the filtered PC1 time-series (shown by *thin line*) are ignored in our data analysis. The *circles* represent seven warm and seven cold reference points selected to construct the warm minus cold (WMC) composites of the PDO. The *bar-graph* shows the time series of first PC of the unfiltered SST in the Pacific Ocean for the period (1871–2002). The *shaded bars* correspond to 15 major El Niño and 15 major La Niña events selected for constructing the WMC com-posites of ENSO. **b** The *bar-graph* shows the time series of the All India Summer Monsoon Rainfall (AISMR) anomalies for the period (1871–2002). The *thick line* is the low-pass filtered time series of AISMR anomalies. The time series have been normalized by their respective standard deviations

Krishnan and Sugi, 2003

Warm minus cold (WMC) PDO composite



Krishnan and Sugi, 2003

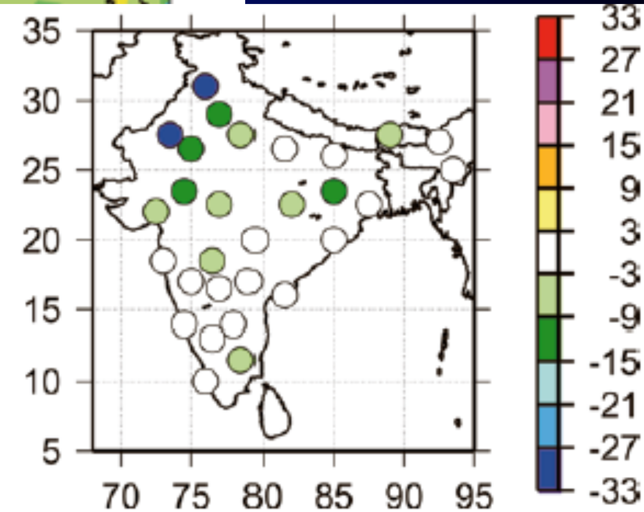
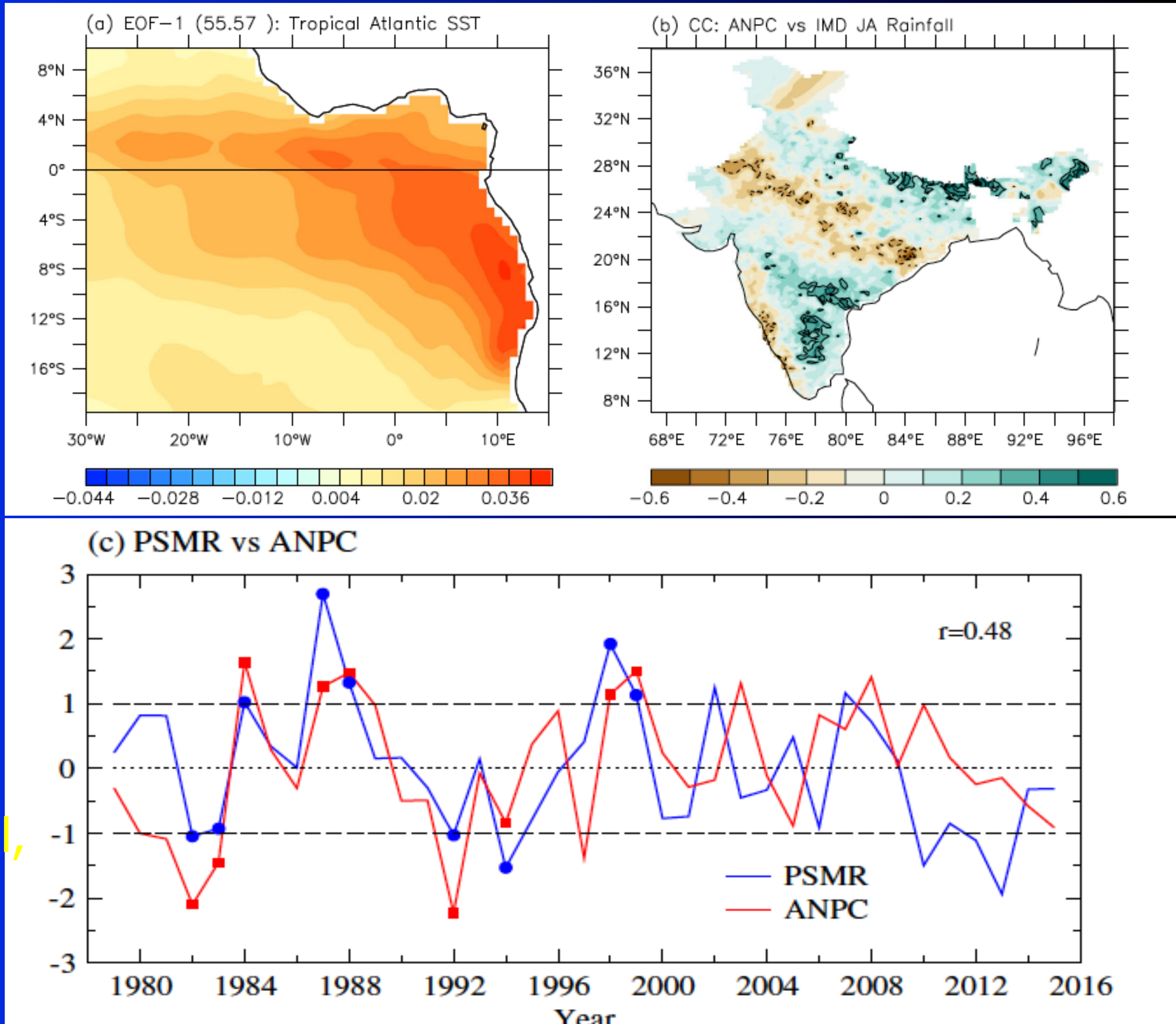


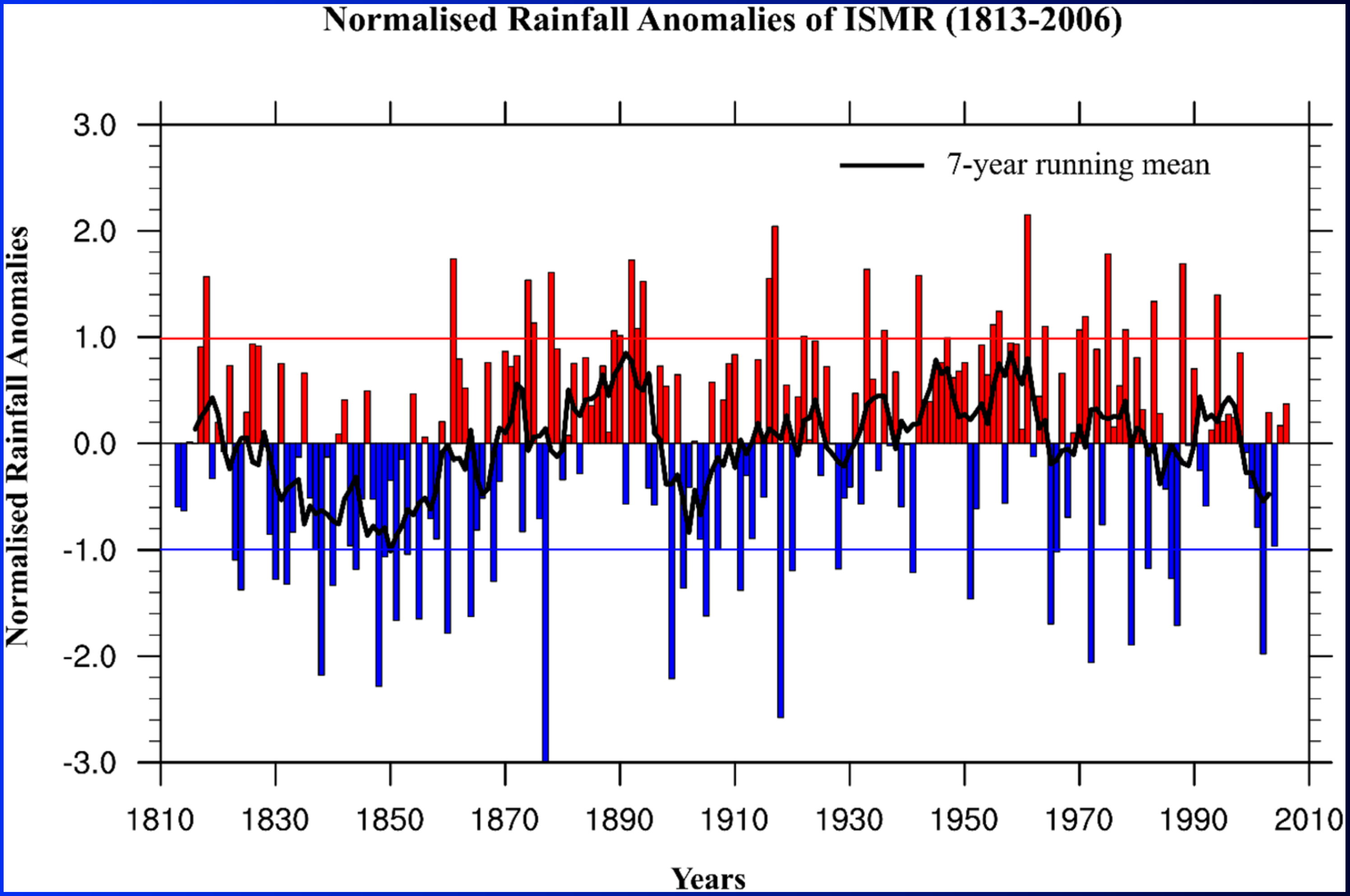
Fig. 4 The WMC decadal composite of low-pass filtered (June–September) monsoon rainfall over 29 sub-divisions of India, expressed as percentage departure from normal, are shown by *circles* located within each sub-division. The rainfall departure from the climatological normal is in the range of 3–9% (on the negative side) over the plains of west Uttar Pradesh (UP); east Madhya Pradesh (MP); west MP; Saurashtra and Kutch. The negative anomalies over Haryana, East Rajasthan and Gujarat are departures in the range of 9–15%. The largest negative departures of the WMC composites are seen over west Rajasthan and Punjab, where the normals are rather small

Atlantic Nino



Yadav et al, 2018

The Multi-decadal Mode of ISMR:



Interdecadal variations of Indian summer monsoon

Why need to study multi-decadal variability of ISMR?

- It has significant amplitude, explains ~7% ISMR variance
- Can modulate interannual variability and predictability of seasonal mean

Table 1 Frequency of occurrence of floods (normalized ISMR index > +1) and droughts (normalized ISMR index < −1) during approximate different epochs of multi-decadal variability

Period	Epoch of multi-decadal mode	Floods	Droughts
1820–1870	Negative	2	**14**
1870–1900	Positive	**9**	1
1900–1930	Negative	3	**7**
1930–1965	Positive	**8**	3
1965–2006	Negative	7	**8**

Rajesh and Goswami, 2020, Climate Dynamics

While ENSO is a major driver of the monsoon, what causes many droughts not associated with El Ninos?

Borah et al, 2020: Science, 370, 1335–133

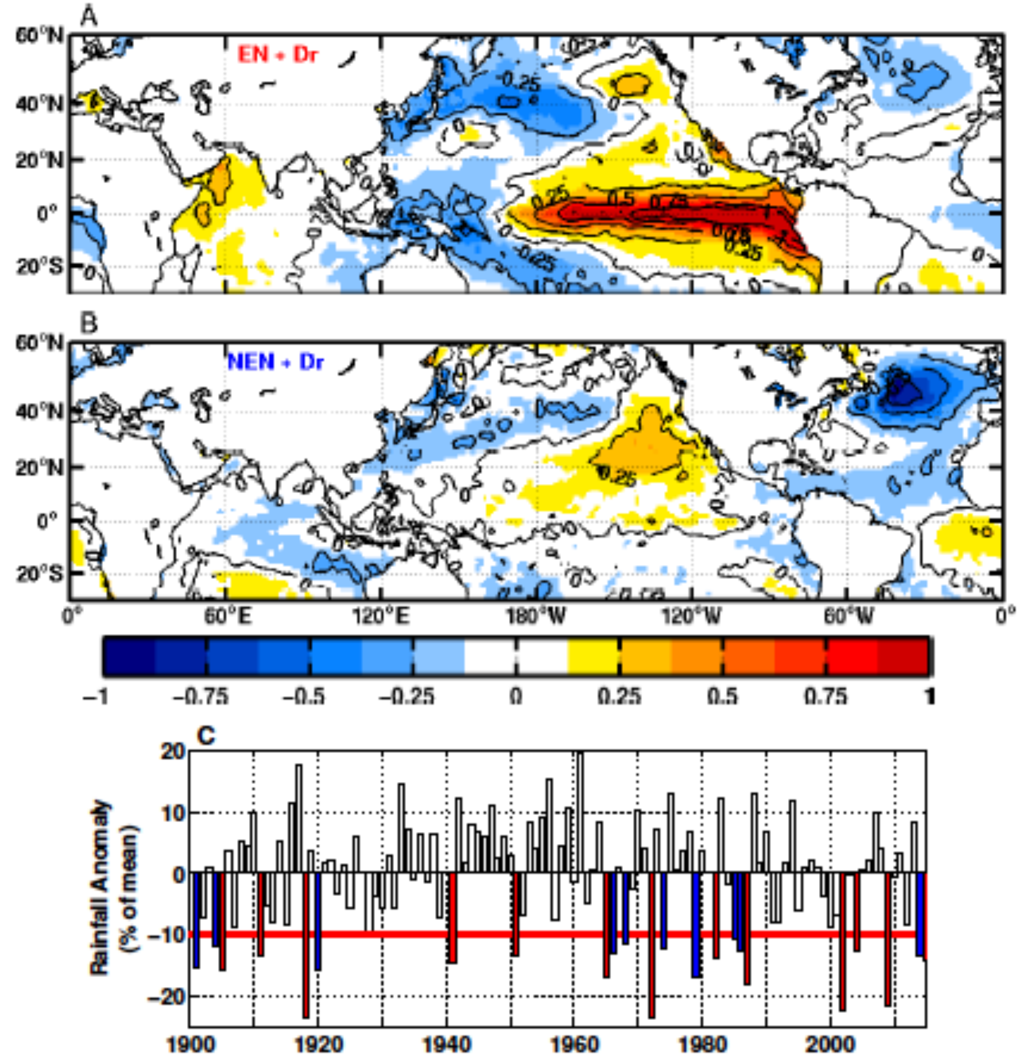


Fig. 1: Spatial distribution of anomalies of detrended JJAS sea surface temperature (SST) for the two types of Indian monsoon droughts: (A) EN + Dr; (B) NEN + Dr. The detrending is based on removal of a linear trend for 1901-2015 at each grid-location, and the maps shown are the average of fluctuations around the trend, for the years listed in Table S1. Based on the 1°, monthly SST product from the Hadley Centre (*39*). Colorbar is in °C. (C) Interannual variation of anomalies of seasonal (JJAS) monsoon rainfall based on the IITM homogeneous Indian monthly rainfall dataset (*38*) for the period 1901-2015. The horizontal red line at -10% denotes the threshold for defining a drought, as per the India Meteorological Department (IMD). The departures marked in red (blue) indicate droughts that occurred during an El Niño (no El Niño) year.

The SST anomalies in the North Pacific are associated with a stationary Rossby wave train that modulate the upper level circulation over Indian region ➔ long breaks➔ weak monsoon

➔ North Atlantic SST can influence interannual variability of ISMR

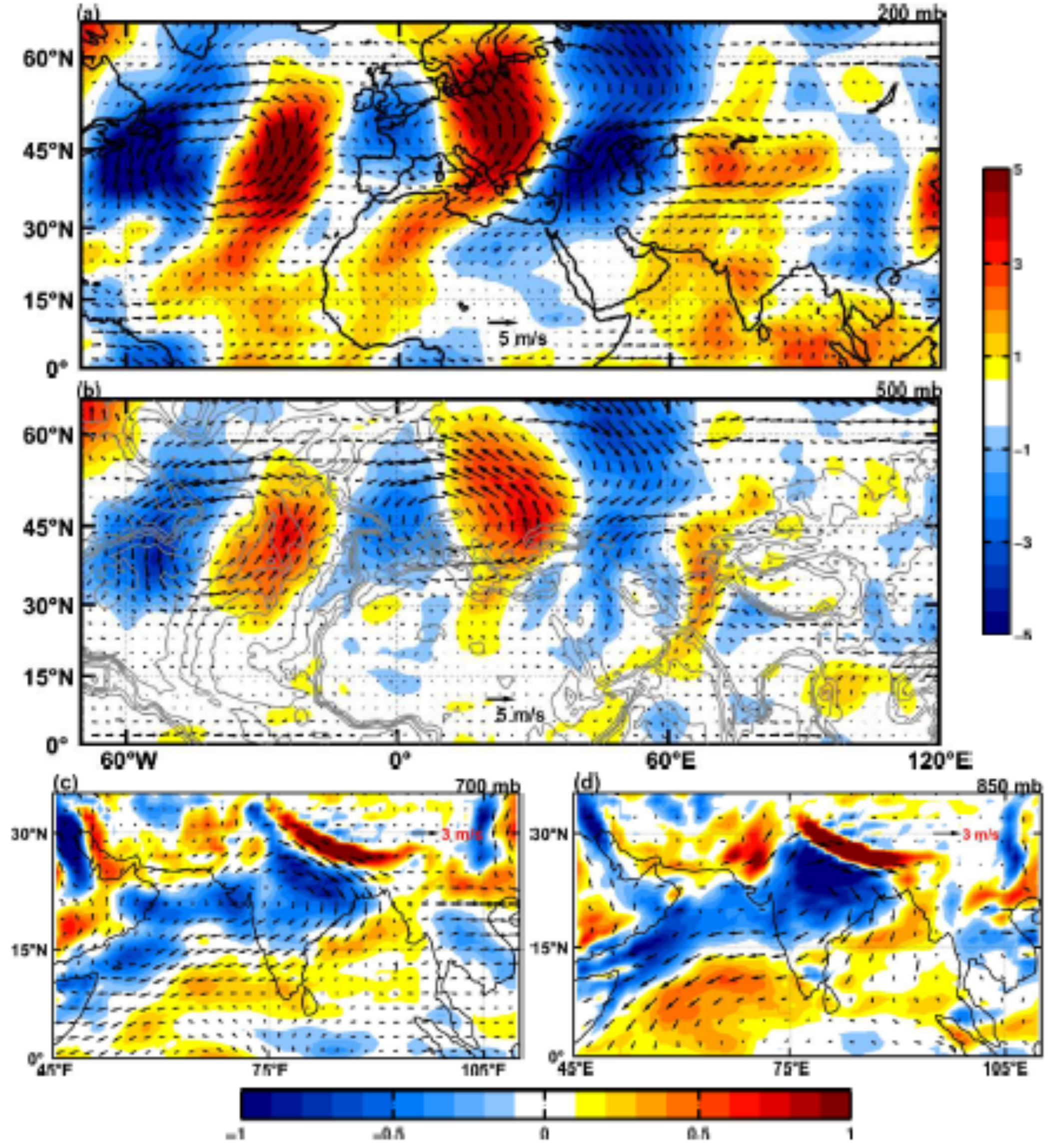


Fig. 4: Composites of anomalies of (top two panels) wind (vectors) and meridional velocity (shading) at (A) 200 mb and (B) 500 mb during the first half of the break (days 81-90; see blue curve in Fig. 2b) in the Indian monsoon rainfall; and (bottom two panels) wind (vectors) and vorticity ($\times 10^5$; shading) at (C) 700 mb and (D) 850 mb, based on the respective break periods late in the season for each of the NEN+Dr years. The gray lines in the 500 mb panel represent topography. Based on ERA 20th Century Reanalysis data (*41*). See Methods section for the construction of composites.

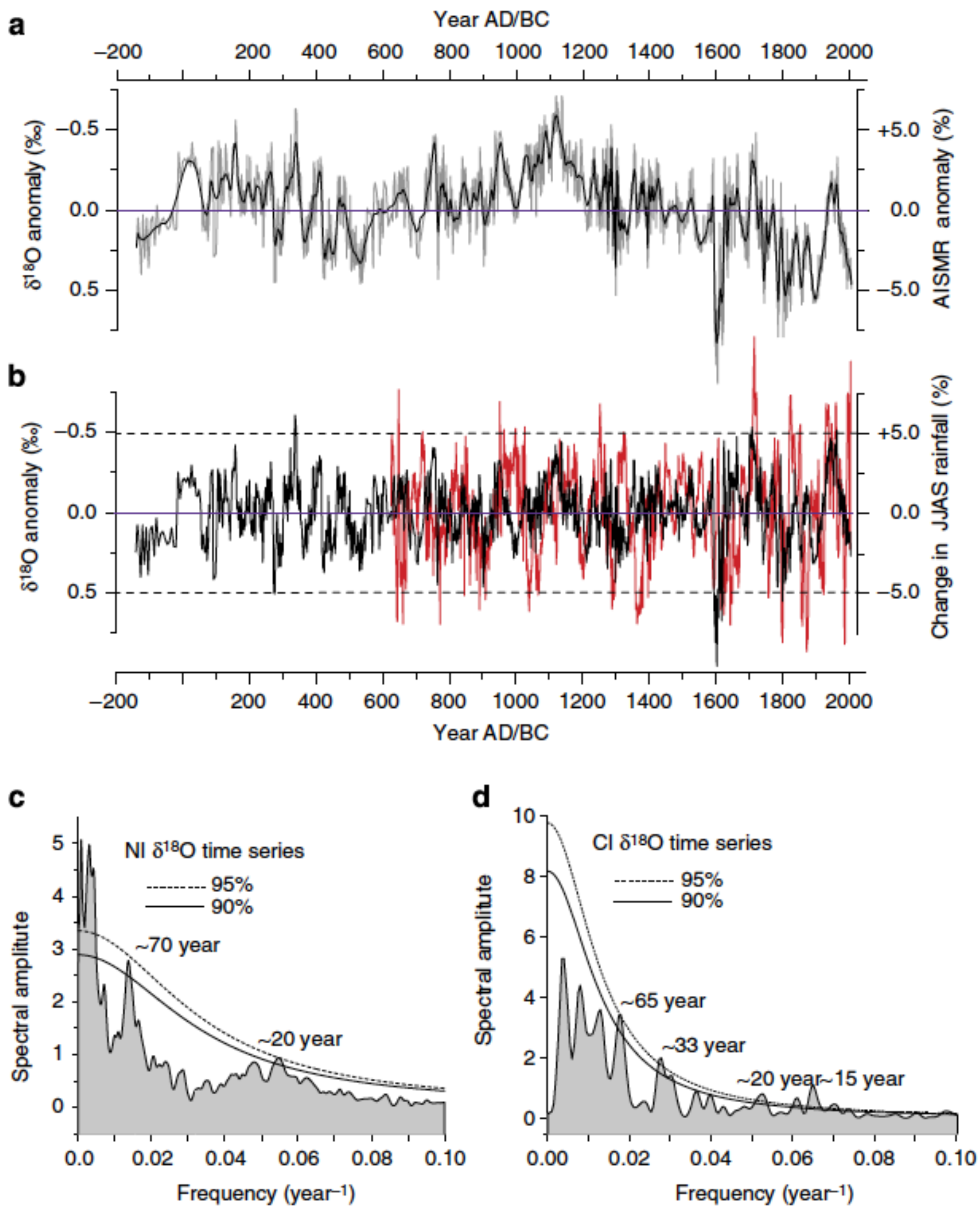


Figure 3 | Time series analysis of the NI and CI $\delta^{18}O$ records. (**a**) The NI speleothem record shown as $\delta^{18}O$ anomalies (relative to the mean of the time series). The $\delta^{18}O$ anomalies are shown both as raw data (grey) and smoothed (11-year running mean) (black) along with the regressed AISMR anomalies (%). (**b**) The comparison between the SSA[44] detrended NI (black) and CI[14-16] (red) speleothem records shown as $\delta^{18}O$ anomalies (raw data). The long-term non-stationary trends in both time series are removed by subtracting the first reconstructed component indicated by SSA of the raw data. The two dashed horizontal lines delineate a 10% change in monsoon rainfall amounts, highlighting the magnitude of multi-decadal variability inferred from our NI $\delta^{18}O$ record. (**c**) Power spectrum of the composite NI and (**d**) CI SSA-detrended $\delta^{18}O$ time series obtained using REDFIT[31] software. A varying number of Welch overlaps were used to optimize bias/variance properties. Spectral band significant above the 90% level are labelled with their period.

NI➔Sahiya Cave ((30360N, 77520E, B1,190m above sea level (m.a.s.l.))

CI➔ Jhumar Cave (18° 52′ N, 81° 52′ E; 600 masl)

Sinha et al., 2011, Nat. Comm

Questions: on Mean

- What maintains the 3-D structure of the Indian summer monsoon and provide a framework to understand its variability?

➔ I hope to provide answer to the question in Lecture-7

Questions: on variability

- What is responsible for the quasi-biennial oscillation of ISMR?

- What drives the Multi-decadal mode of ISMR and what is the teleconnection mechanism?

➔ I hope to provide some answers in Lecture 13

Questions: on Teleconnections

- Physical Mechanisms through which ENSO and AMO influence the monsoon.

➔ I hope to answer this question in Lecture-9

Coupled climate model biases: Implications for Prediction and Predictability

- As on time scales longer than a season, the ocean-atmosphere interactions shape the 'mean', a Coupled Ocean-atmosphere model is required for seasonal prediction.
- However, even though coupled climate models have improved significantly over the years, they still have notable biases in simulating the Indian monsoon as well as some other climate modes.
- The biases limit the models' skill and ability to realize 'potential predictability'

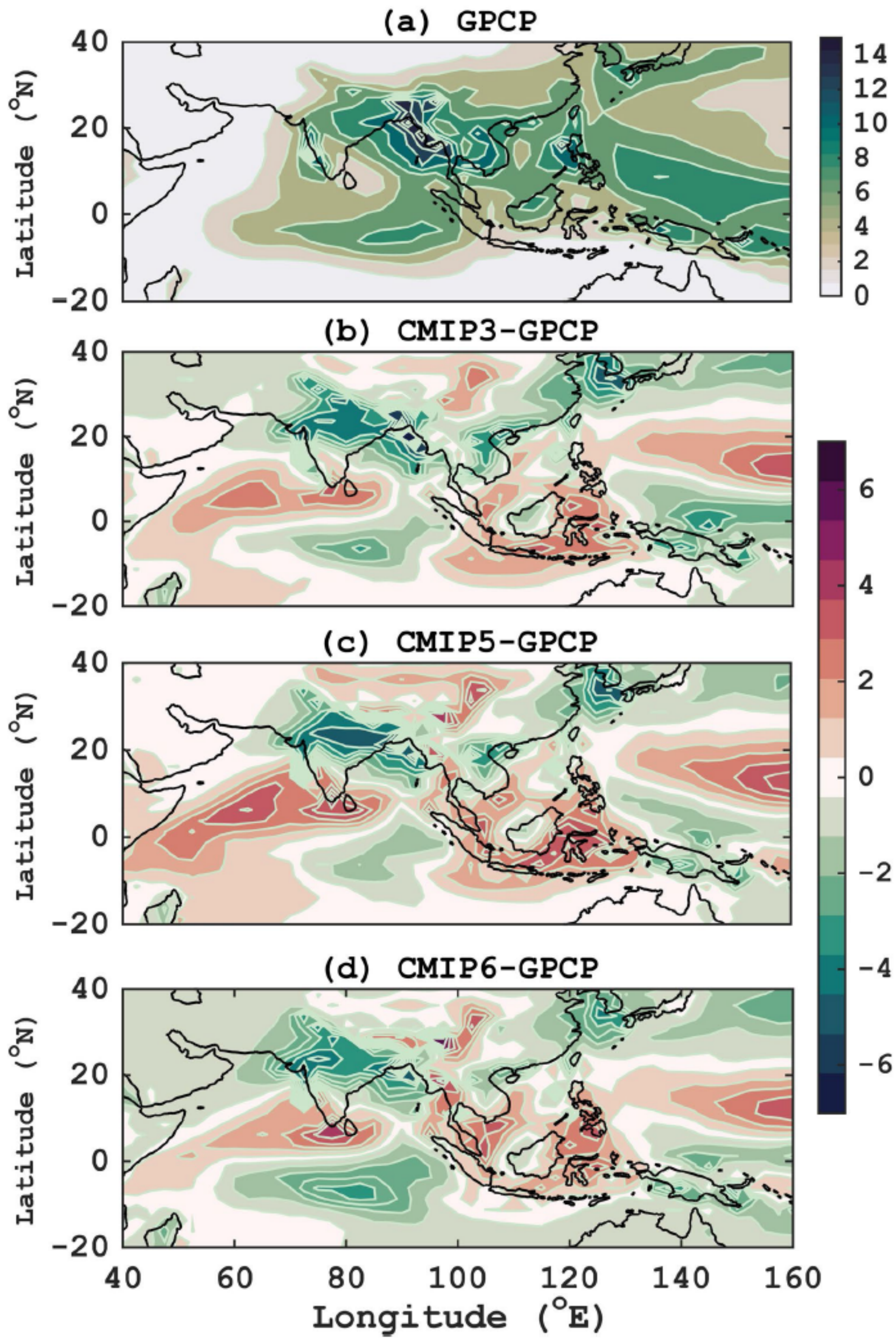
Choudhury, Rajesh, Zahan and Goswamin 2021:Evolution of the Indian summer monsoon rainfall simulations from CMIP3 to CMIP6 models, Climate Dyanamics, https://doi.org/10.1007/s00382-021-06023-0

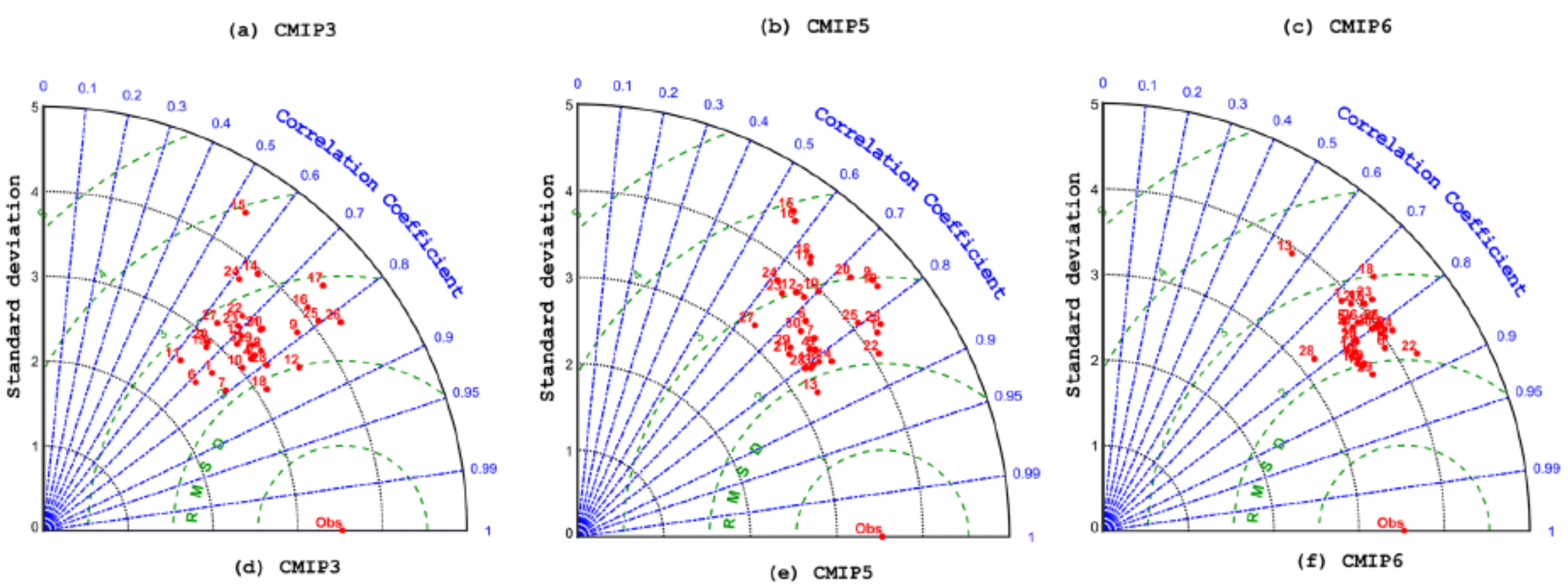
CMIP3→27 models

CMIP5→30 models

CMIP6→30 models

Fig. 1 **a** Climatological mean JJAS rainfall from GPCP (1979–2015) (mm/day) **b** bias of multi-model ensemble mean (MMM) of climatological JJAS rainfall simulated by 23 CMIP3 models with respect to GPCP climatology (mm/day) **c** same as **b** but for MMM of 30 CMIP5 models **d** same as **b** but for MMM of 30 CMIP6 models. As the common period of simulated and observed rainfall is only for 20 years and CMIP3 simulations are available only up to 1999, climatology of simulated rainfall is calculated based on 36 years (1964–1999)




(a) CMIP3
(b) CMIP5
(c) CMIP6
Correlation Coefficient
Standard deviation
RMSD
Obs
(d) CMIP3
(e) CMIP5
(f) CMIP6

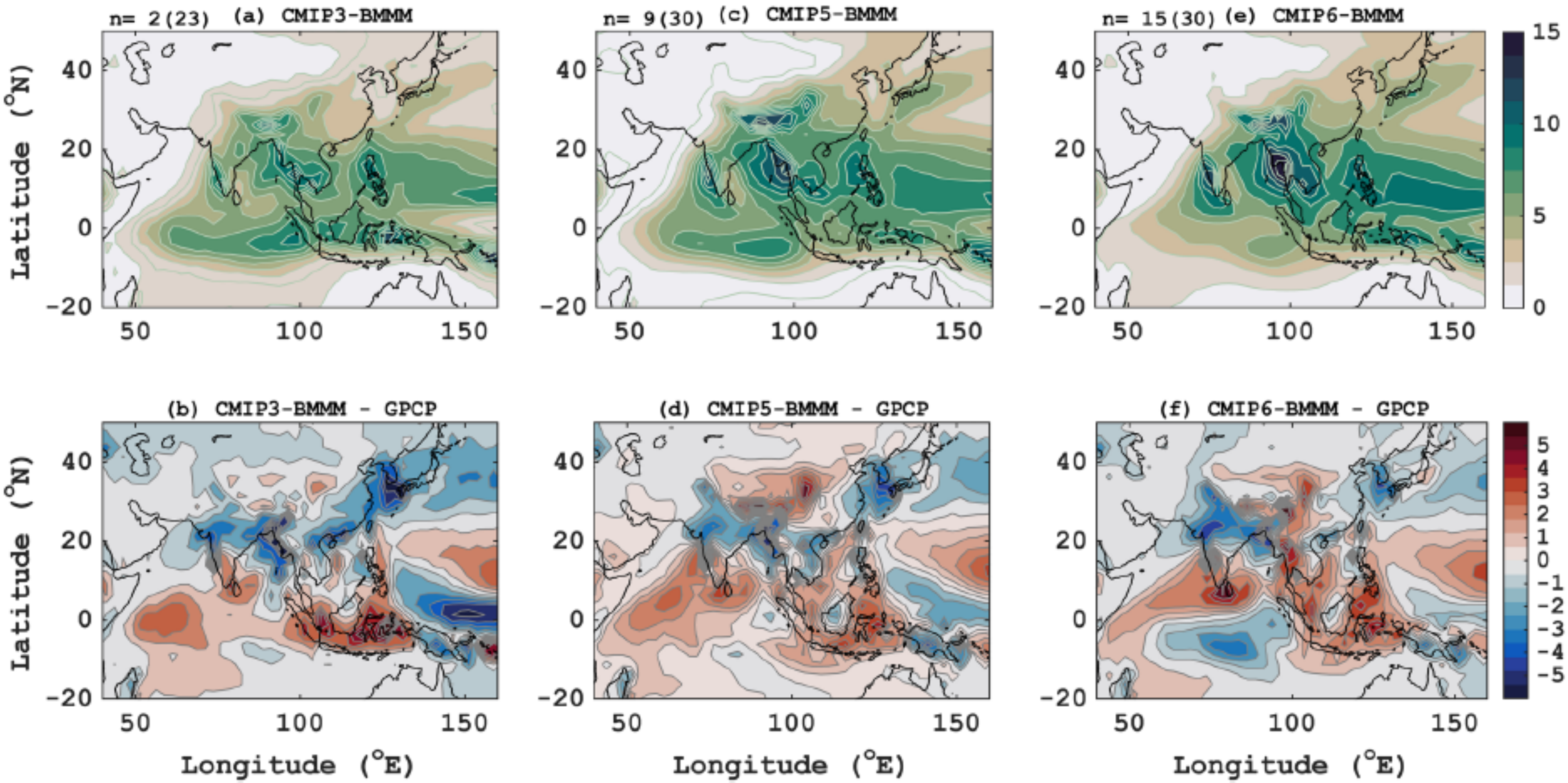


Fig. 3 Spatial plot of MMM consisting of 'best' models having pattern correlation of simulated climatological mean JJAS rainfall with observation greater than 0.8 (BMMM) for **a** CMIP3 **c** CMIP5 **e** CMIP6. Here 'n' denotes the number of models in each class with the total number of models in parenthesis. The JJAS mean bias, **b** CMIP3-BMMM *minus* GPCP **d** same as **b** but CMIP5-BMMM *minus* GPCP and **f** CMIP6-BMMM *minus* GPCP

Observed Location of ITCZ ~23ᴼN

Simulated Location of ITCZ ~13ᴼN

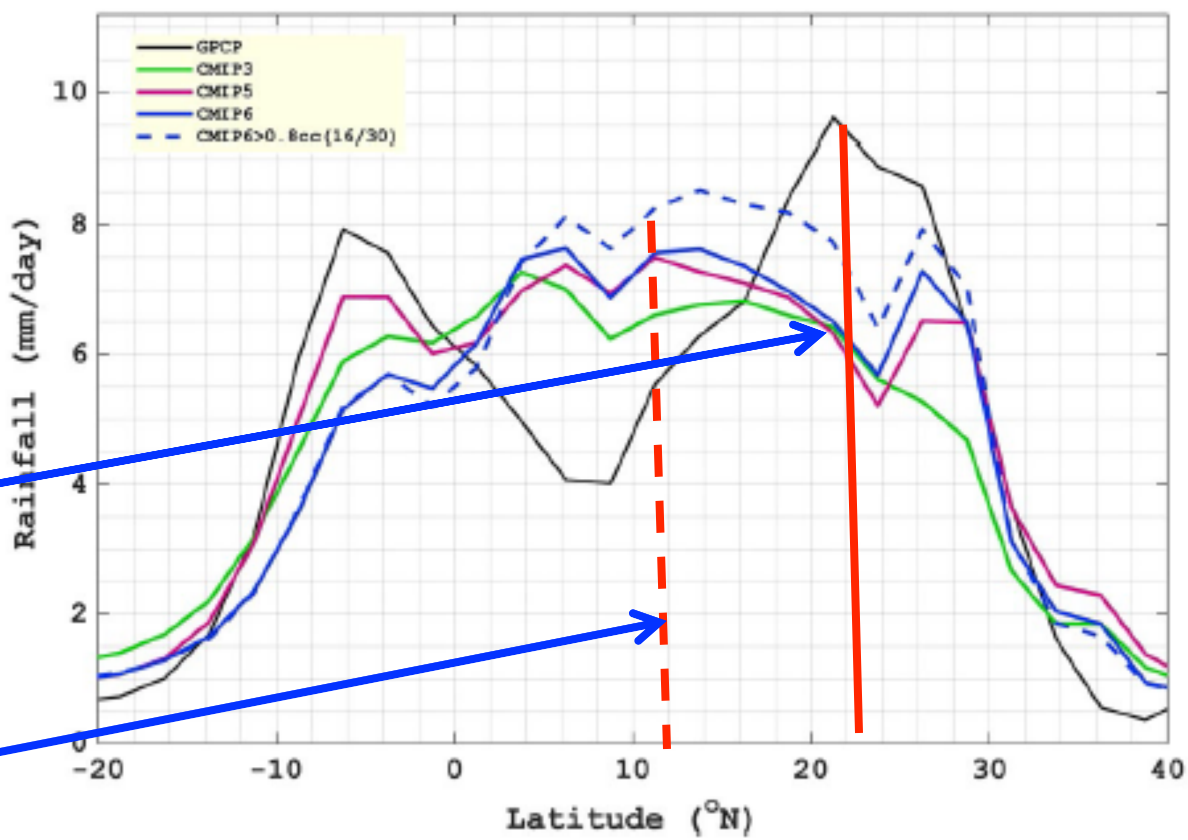
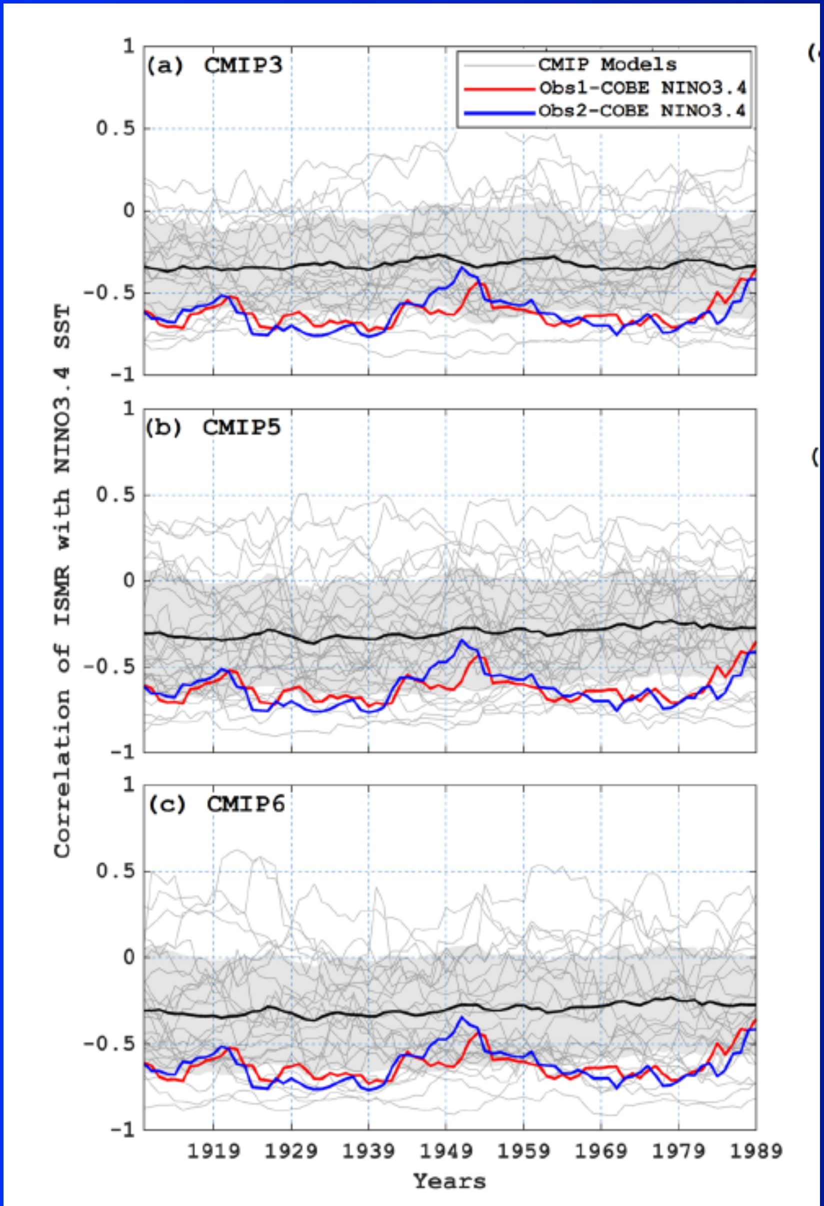
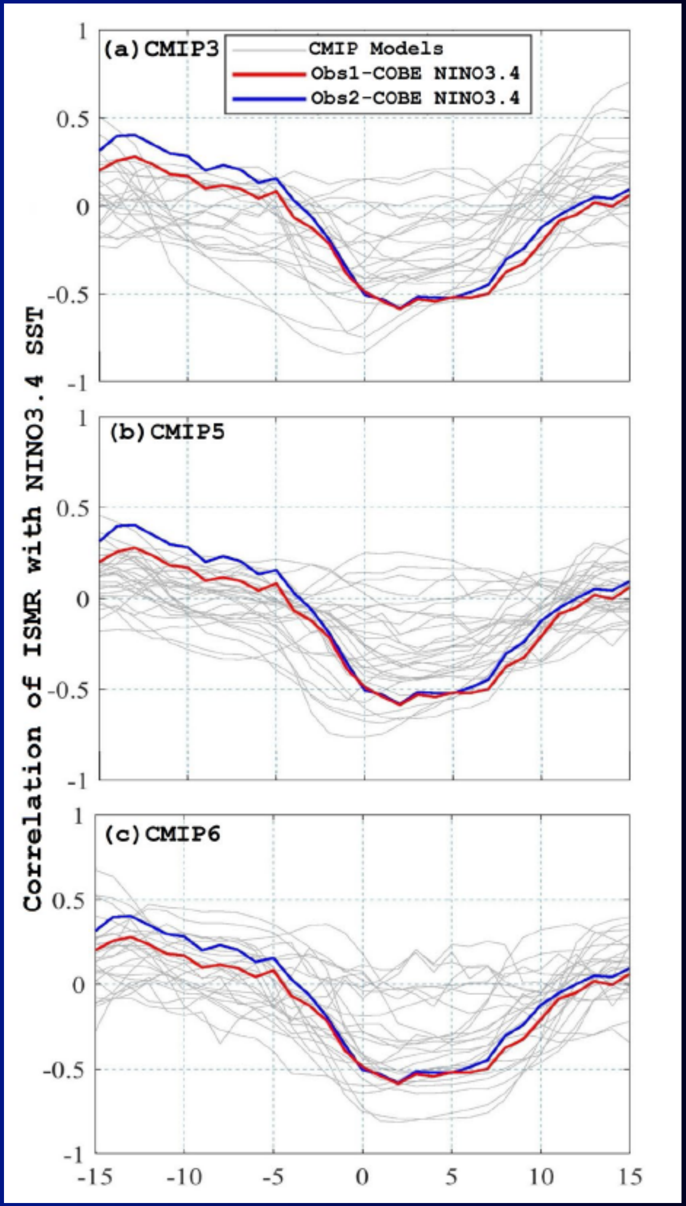


Fig. 4 Zonal mean of climatological rainfall between 75 and 90° E as a function of latitude from observations (black), MMM climatology of CMIP3 (green), CMIP5 (magenta) and CMIP6 (blue) models together with BMMM of 15 'good' CMIP6 models (dashed blue) line. The 'good' models used are BCC-CSM2-MR, BCC-ESM1, CESM2-FV2, CESM2-WACCM, CESM2, E3SM-1-0, E3SM-1-1-ECA, E3SM-1-1, GFDL-CM4, GFDL-ESM4, INM-CM5-0, MIROC6, MPI-ESM1-2-HR, NESM3, NorESM2-MM, and SAM0-UNICO

Biases in simulating ENSO-ISMR Relationship

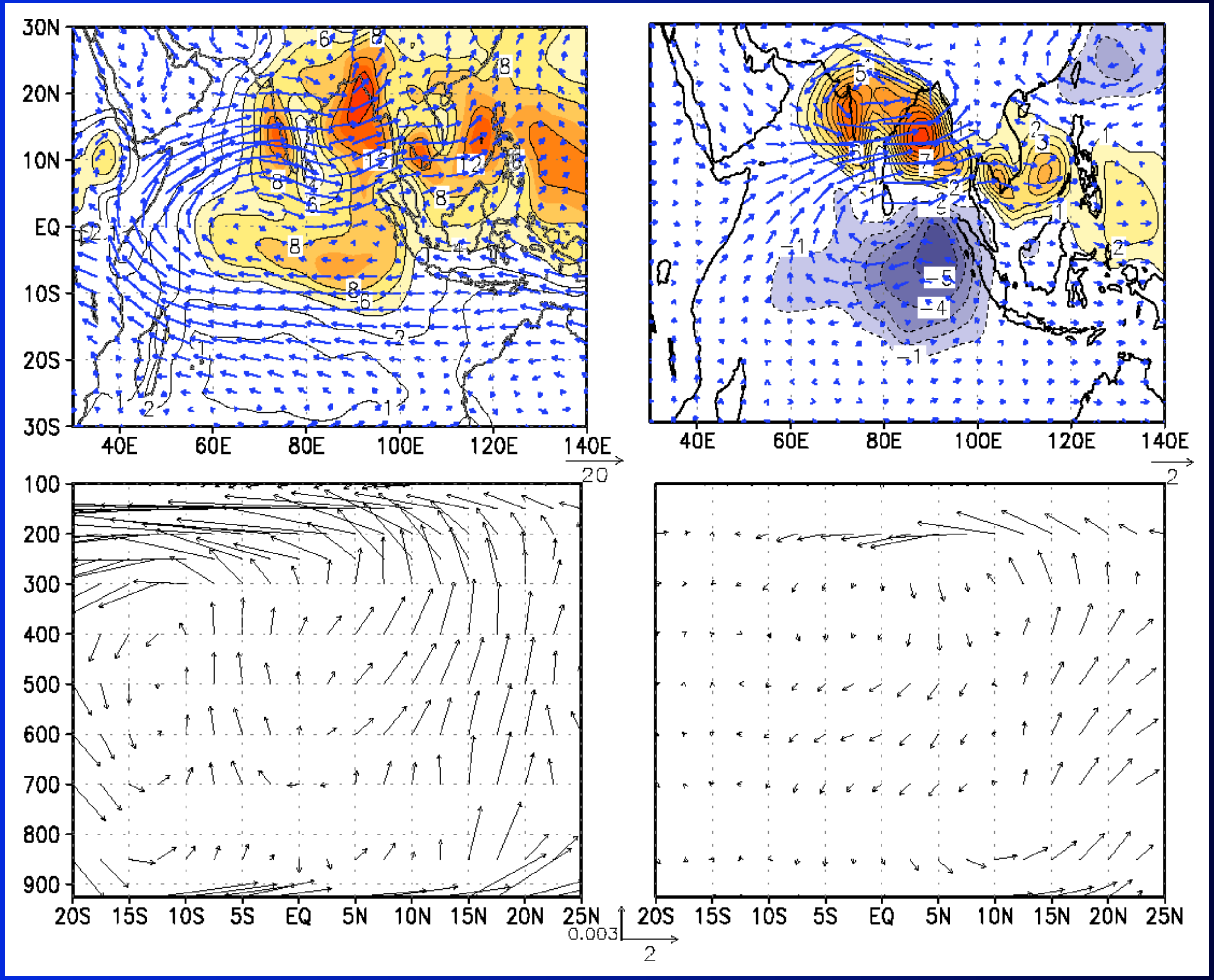




Thank you

Climatological mean JJAS
P and 850 hPa winds

P and 850 hPa wind anoms
during 'Active' phase



Mean monsoon Hadley circul.

70E-90E

Anom. Hadley circul. In an 'active' phase,

70E-90E