# Understanding the Indian monsoon response to anthropogenic GHG and aerosol forcing: Lessons learned


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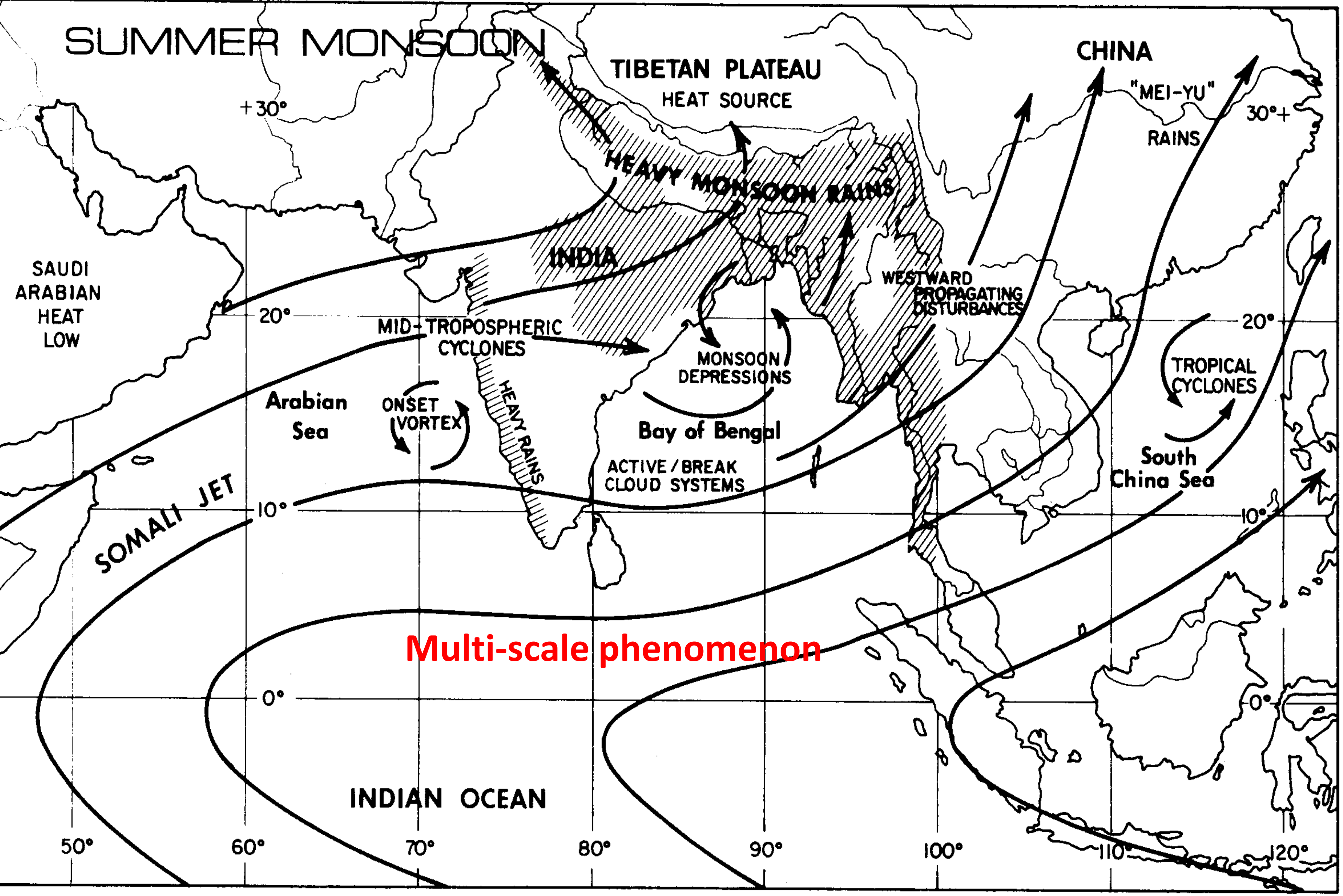
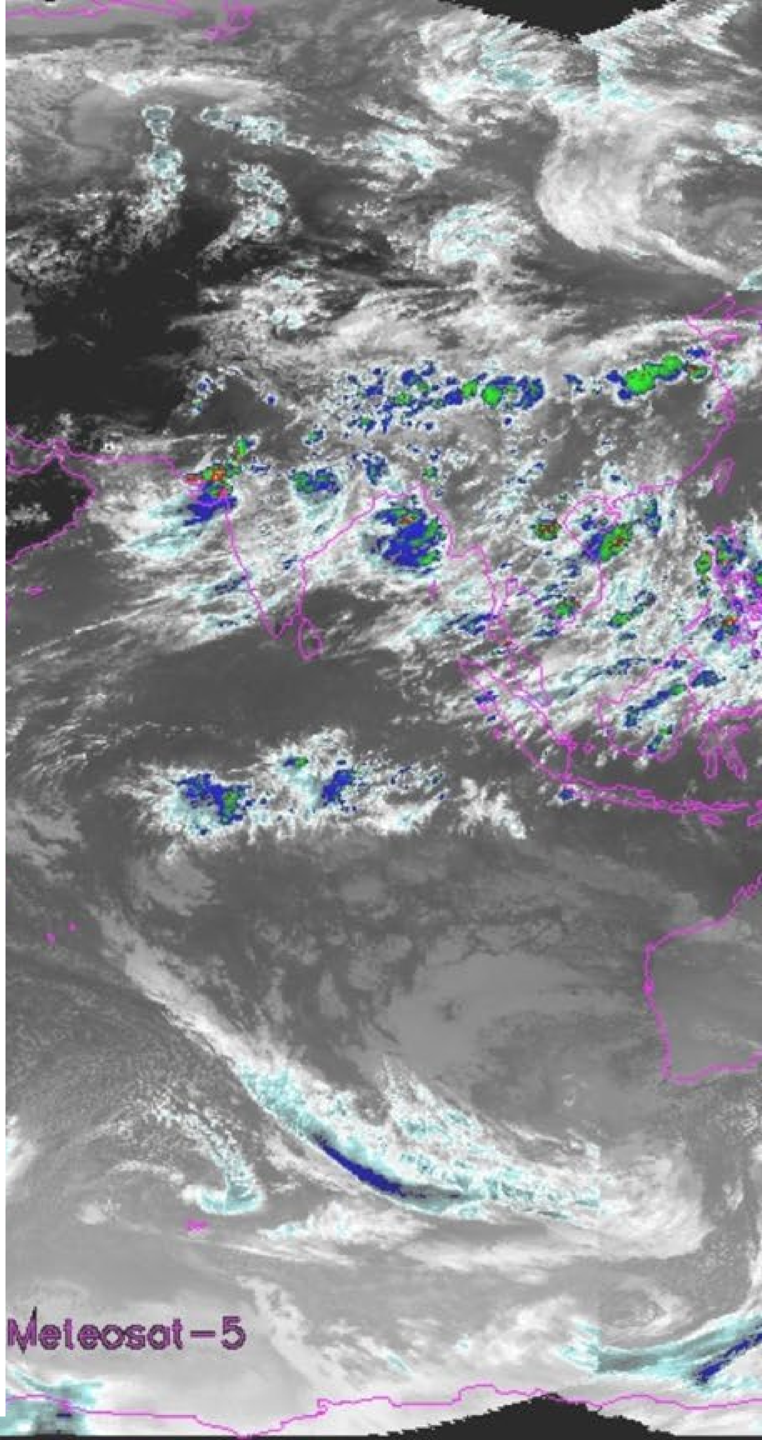
**IP4 and 10th Annual Workshop on Climate Change**

IITM, Pune

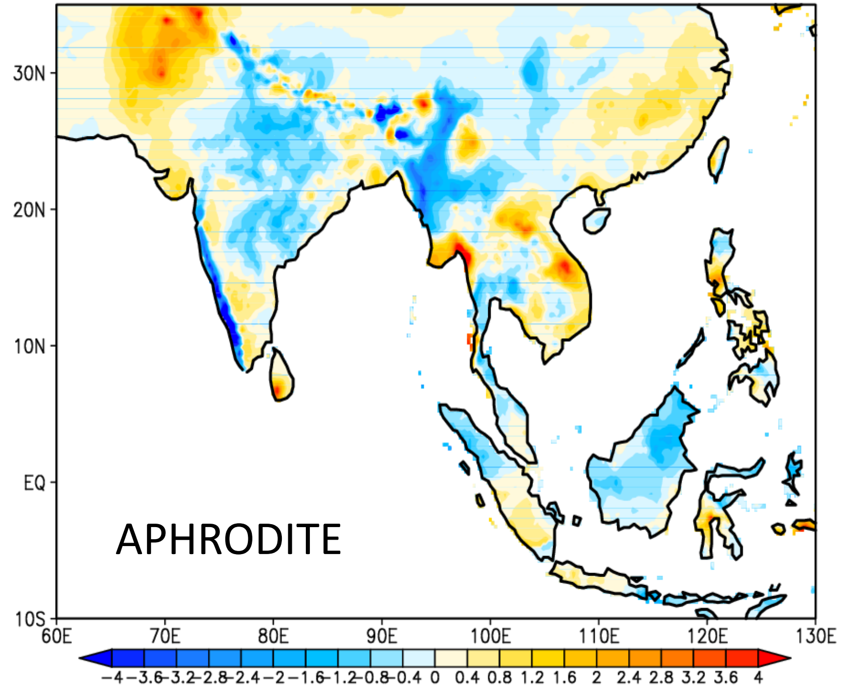
25-28 November 2019

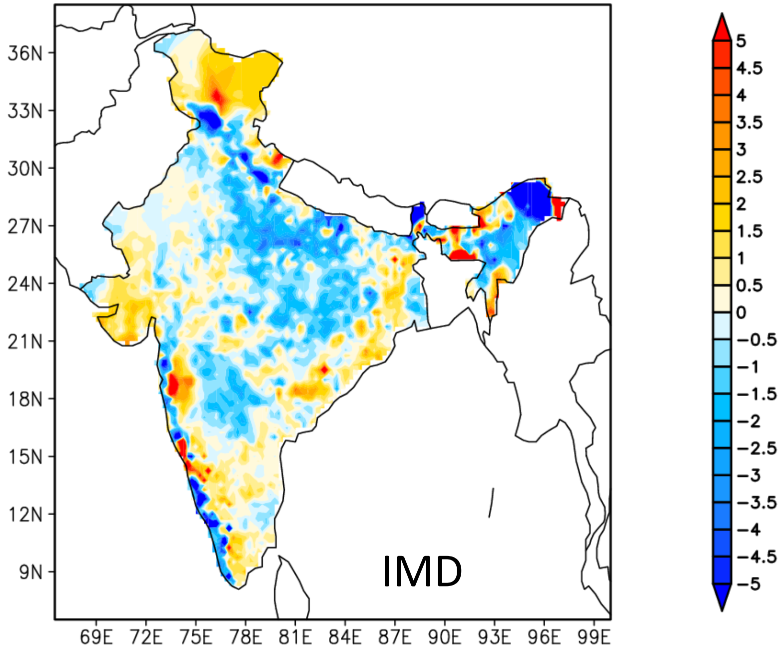


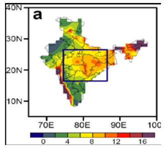

**Primary synoptic and smaller-scale circulation features that affect cloudiness and precipitation in summer monsoon region**. Locations of June to September rainfall exceeding 100 cm over the land west of 100°E associated with the southwest monsoon are indicated (from Rao, 1981). (Adapted from Johnson, R. H., and R. A. Houze, Jr., 1987)

# Trend in JJAS precipitation during 1951-2014



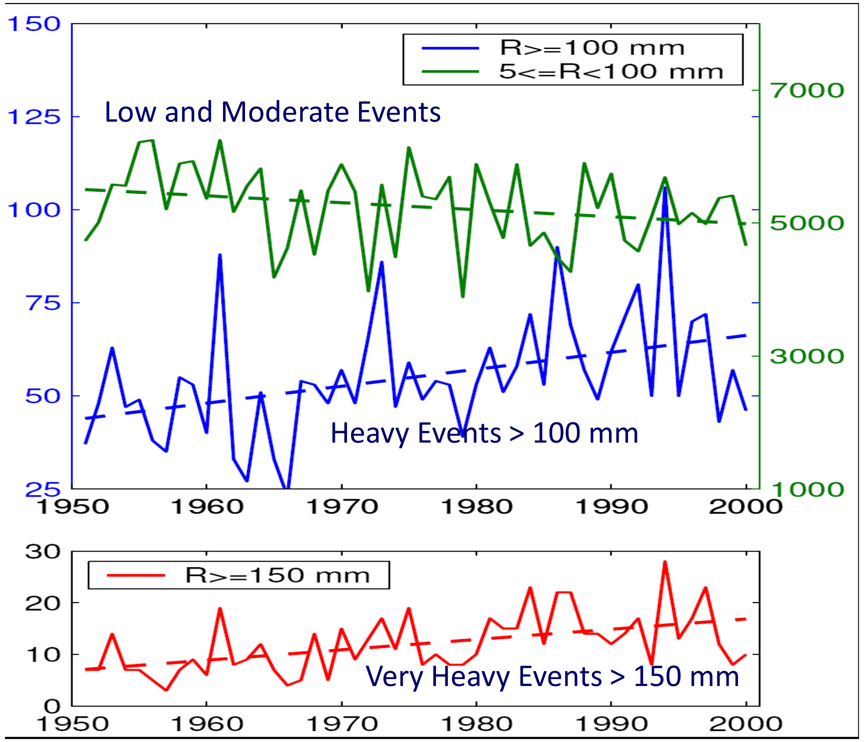




# Changes in daily precipitation extremes



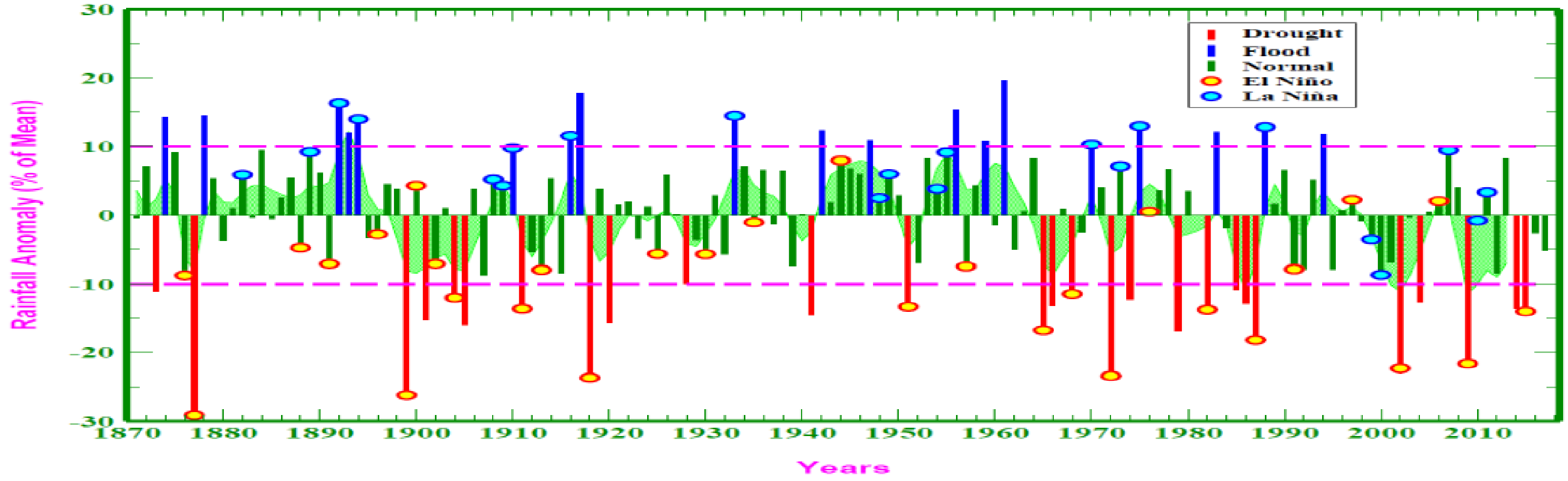
Goswami et al. 2006

Timeseries of count over Central India

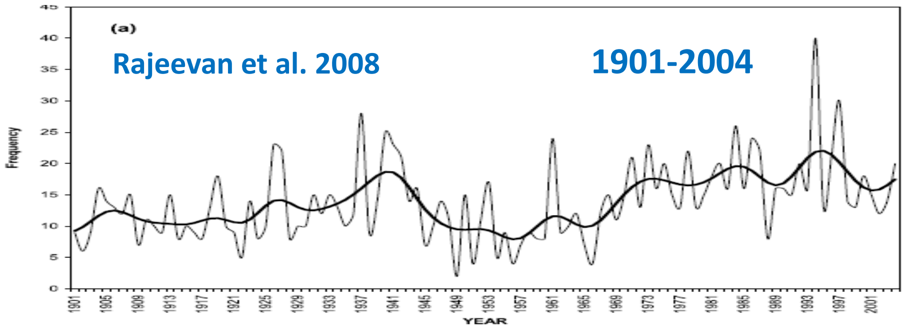



## All-India Summer Monsoon Rainfall, 1871-2017

*(Based on IITM Homogeneous Indian Monthly Rainfall Data Set)*




Time-series of count of very heavy rainfall occurrences (R > 150 mm) over Central India

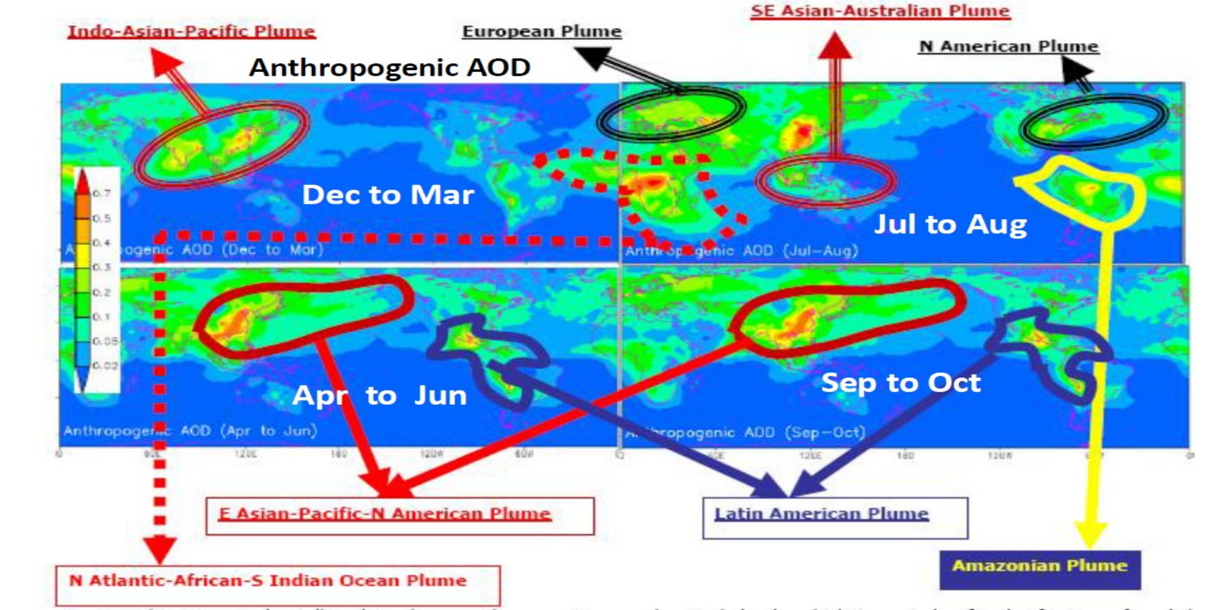


# Aerosol forcing: Fundamental driver for the physical climate system

Atmospheric brown clouds: Hemispherical and regional variations in long-range transport, absorption, and radiative forcing

Ramanathan et al. JGR-2007

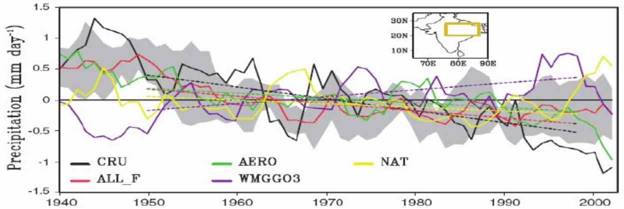
ABCs (eg. sulfate, organics, black carbon, ash, dust, sea-salt, etc) alter absorption and reflection of solar radiation and influence climate




**Emerging consensus of the role of anthropogenic aerosols on the decreasing trend of the South Asian monsoon precipitation**

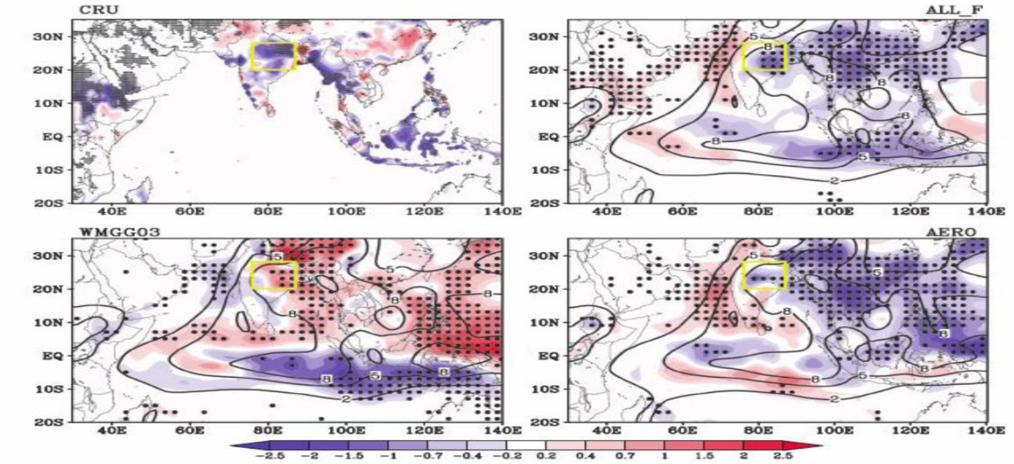
**Physical mechanisms for the aerosol-monsoon connection include:**

- Reduction of solar insolation (' solar dimming ' ) at surface through scattering & absorption by aerosols, decrease of meridional SST gradient between equator & 25°N, resulting in decreased moisture convergence and suppressed convective activity over the Bay of Bengal (Ramanathan et al. 2005, Meehl et al. 2008).
- Scattering-type aerosols over the Asian continent can induce large-scale cooling over the Northern Hemisphere causing inter-hemispheric energy imbalance and weaken the boreal summer monsoon circulation (Bollasina et al. 2011, Undorf et al. 2018)
- Decrease of meridional gradient of tropospheric temperature & vertical wind-shear (Ganguly et al. 2012)
- Increase of atmospheric static stability due to solar absorption by the aerosol layer (0-3 km) in the lower levels (Ramanathan et al. 2005)
- Role of enhanced CCN counts in disrupting organized convection of the monsoon depression . Impacts of air pollution over Asia **(Krishnamurti et al. 2012)**
- Surface cooling over the Indian subcontinent (Sanap et al. 2015)
- Decrease of water vapor availability (Salzmann et al. 2014)



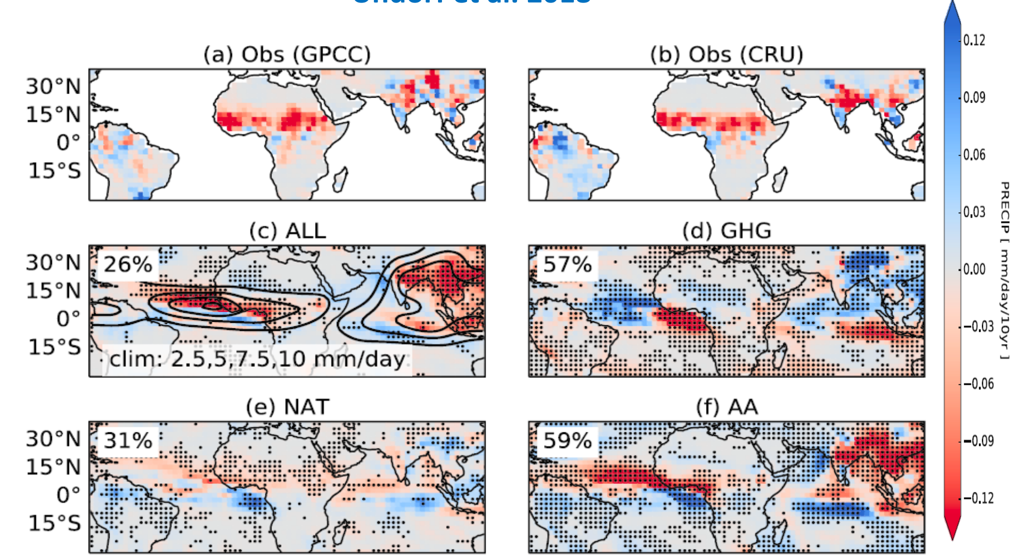

Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon
Massimo A. Bollasina *et al.*
*Science* **334**, 502 (2011);
DOI: 10.1126/science.1204994

**Bollasina, Ming and Ramaswamy Science, 2011**




Observed & simulated precipitation trends 1920-2005 (mm $day^{-1}$ $decade^{-1}$)

**Undorf et al. 2018**



# Overview

- IITM Earth System Model (IITM-ESM): CMIP6 historical simulation and future projection
- Sensitivity experiments using IITM-ESM – GHG versus aerosol forcing
- Need for high resolution: LMDZ telescopic zooming (grid < 35 km) over South Asia – Western Ghats, Precipitation Extremes
- Heavy monsoon precipitation areas Gujarat, Maharashtra, Mumbai e.g., Mid-tropospheric cyclones (MTC) of the Indian Monsoon
- Future plan for global high-resolution (27 km) atmospheric version of IITM-ESM
- Scientific challenges: Representation of monsoon wind and precipitation coupling, warm rain & moist processes, organized convection, etc

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Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1029/2017MS001262

**Long-Term Climate Simulations Using the IITM Earth System Model (IITM-ESMv2) with Focus on the South Asian Monsoon**

P. Swapna[1], R. Krishnan[1], N. Sandeep[1], A. G. Prajeesh[1], D. C. Ayantika[1], S. Manmeet[1], and R. Vellore[1]

[1]Centre for Climate Change Research, Indian Institute of Tropical Meteorology (IITM), Pune, India

**Key Points:**
- IITM-ESMv2 simulations show fidelity in capturing large-scale circulation and global climate drivers
- Significant improvement in the representation of South Asia monsoon and its variability
- First climate model from India contributing to the Intergovernmental Panel for Climate Change (IPCC) sixth assessment report (AR6)

**Supporting Information:**
- Supporting Information S1
- Table S1

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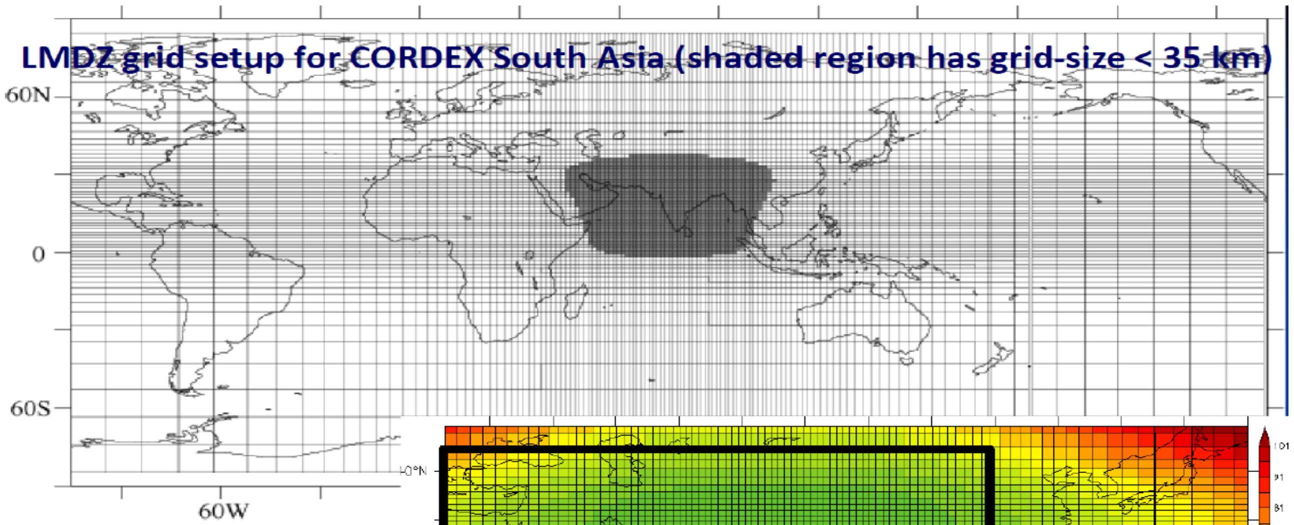
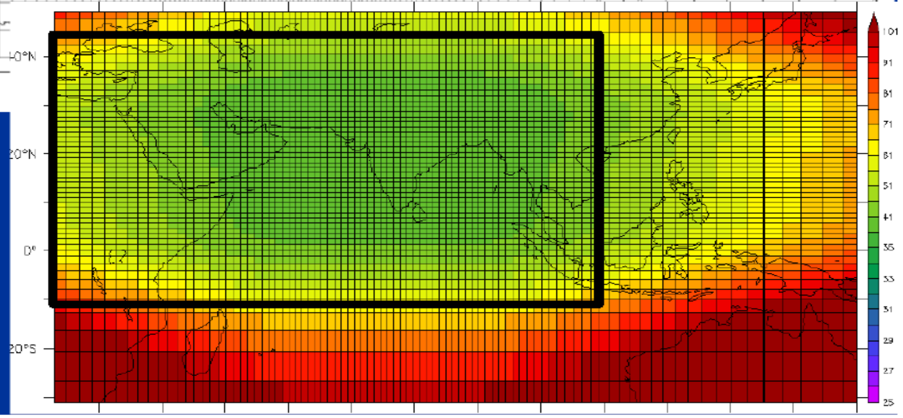
**Citation:**

**Abstract** Long-term climate simulations are performed using the IITM Earth System Model version 2 (IITM-ESMv2), a sequel to the earlier version (IITM-ESMv1), to assess climate variability and change with a special focus on the South Asian monsoon. Substantial improvements are incorporated in IITM-ESMv2 to obtain a radiatively balanced global climate modeling framework. The IITM-ESMv2 includes time-varying aerosol forcing and land-use land-cover changes. Multicentury simulations corresponding to preindustrial and present-day conditions show major improvements in capturing key aspects of time-mean atmosphere and ocean large-scale circulation. Representations of the Atlantic Meridional Overturning Circulation and poleward ocean heat transport, and major global climate drivers are superior to ESMv1. Teleconnections of the South Asian monsoon with climate drivers such as the El-Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are found to be more robust in IITM-ESMv2, thus leading to improved simulation of South Asian monsoon and its variability. The IITM-ESMv2 takes a novel pursuit from India to contribute in the Intergovernmental Panel for Climate Change (IPCC) sixth assessment report (AR6).




LMDZ global atmospheric model: Variable resolution with zooming capability

Source: Sabin, CCCR, IITM



# IITM-ESM for long-term climate change studies

Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune

**Atmosphere : GFS (Global Forecast System)**

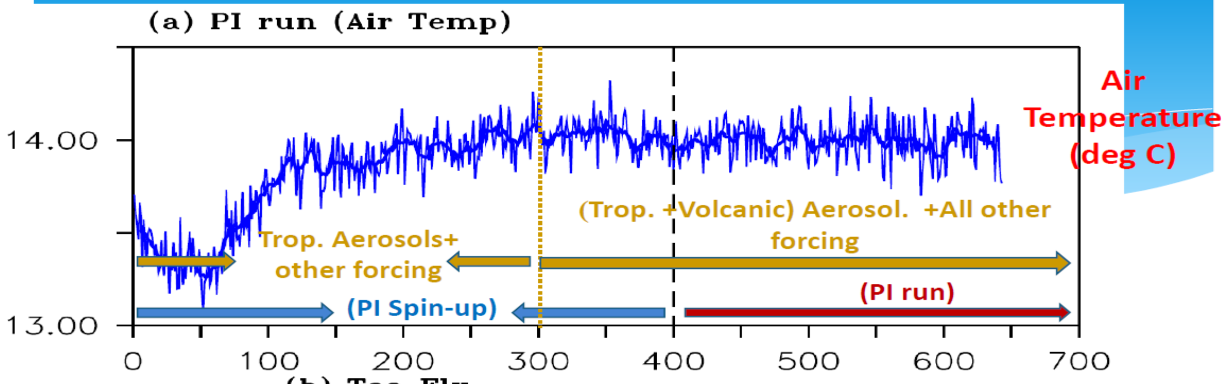
- T62 ; vertical: 64 sigma – pressure hybrid levels
- Resolution ~200 km
- Model top 0.2 mb
- Prescribed MAC-v2 aerosols

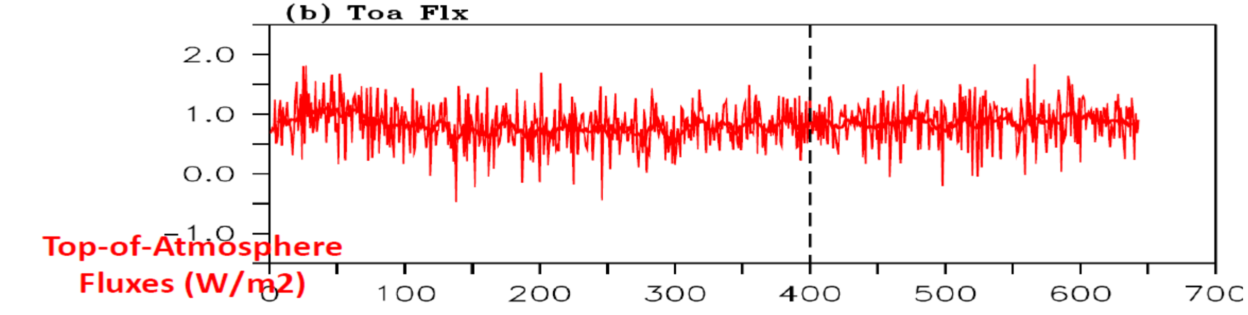
**Land surface : Noah LSM**

**Ocean: Modular Ocean Model v4p1 (MOM4p1)**

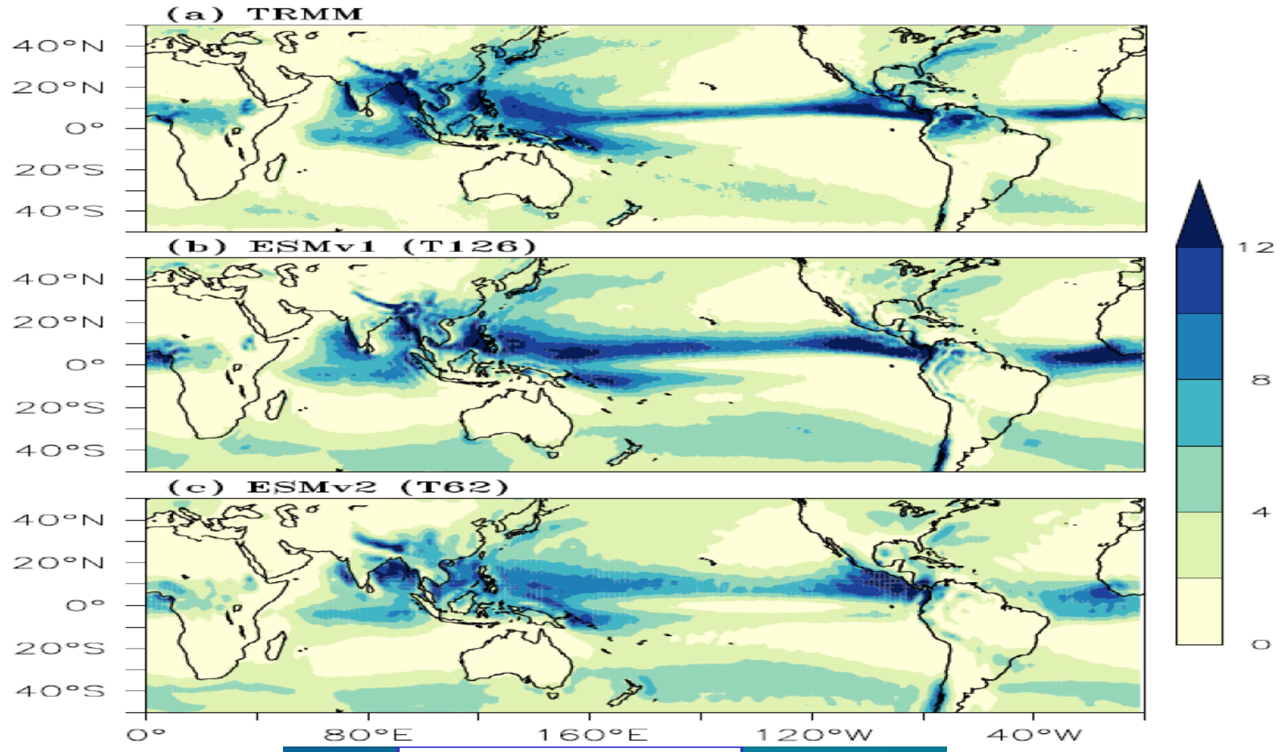
- Tripolar; 360x200 ; 1 deg poleward ; 0.33 deg near equator
- 50 levels ; Top grid cell 5m
- Ocean Biogeochemistry : TOPAZ
- Ice Model : Sea Ice Simulator

## Pre-industrial Control Simulation

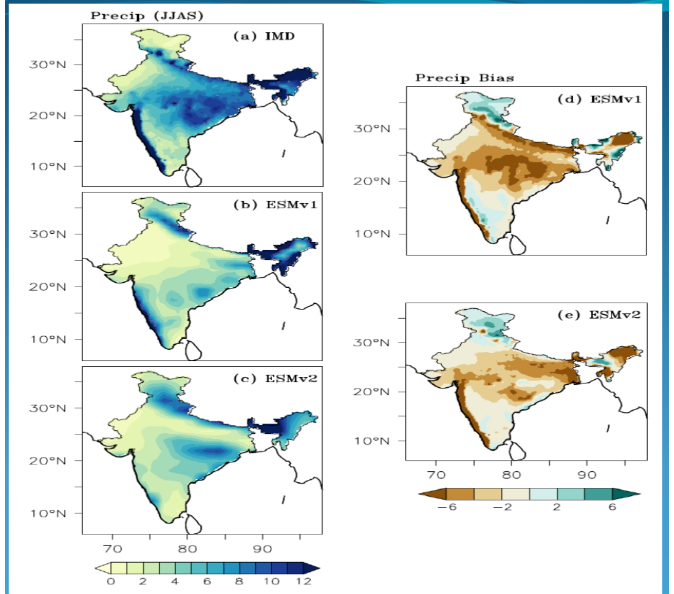



## Mean summer rainfall (June-Sept)

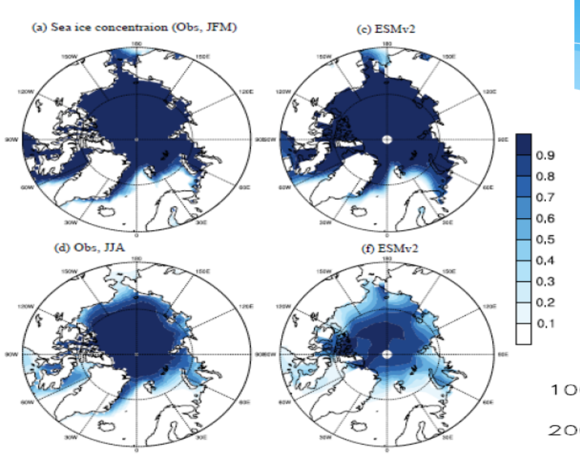



## Precipitation Bias (June-Sept)

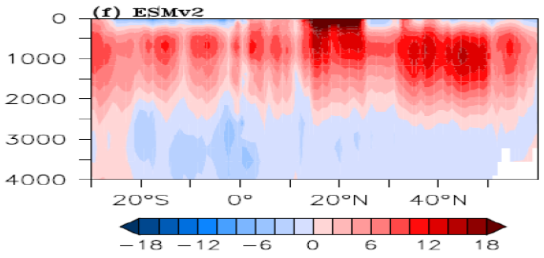



**Courtesy: Swapna**

## Sea-ice concentration IITM ESMv2

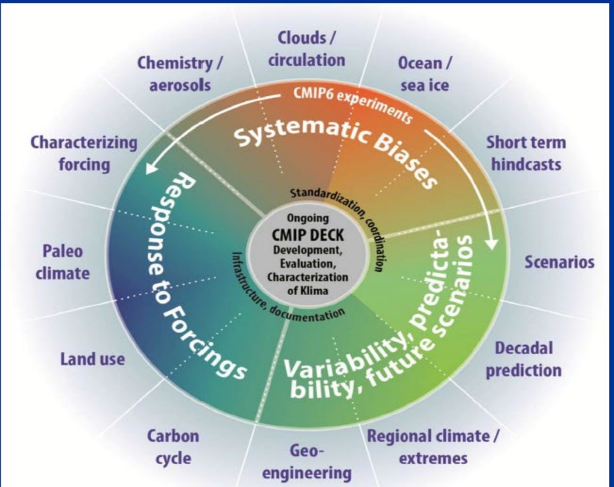



### Atlantic Meridional Overturning Circulation (AMOC)




## CMIP6 Schematic: Participation in the 6th Intergovernmental Panel for Climate Change (IPCC)

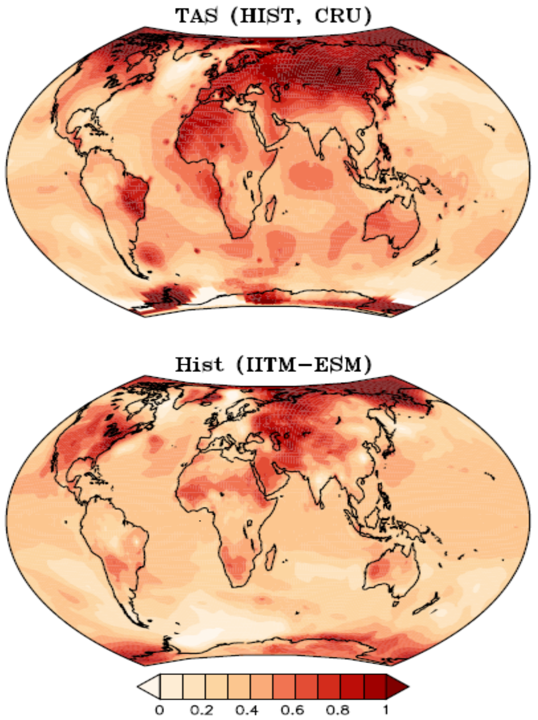
Initial proposal for the CMIP6 experimental design has been released



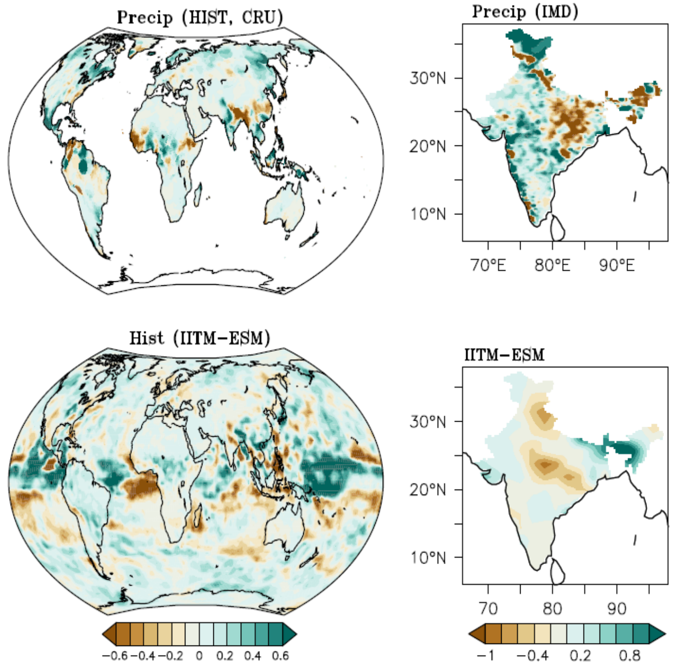

CMIP6 Concept: A Distributed Organization under the oversight of the CMIP Panel

IITM ESM will participate in the climate modeling CMIP6 experiments for the IPCC 6th Assessment Report

Spatial patterns of change in surface air temperature (°C) computed from trends during 1900-2014 **(a)** Observations **(b)** IITM-ESM (HIST)




Spatial patterns of change in JJAS precipitation (mm day$^{-1}$) computed from trends during 1950-2014 **(a)** Observations **(b)** IITM-ESM (HIST)

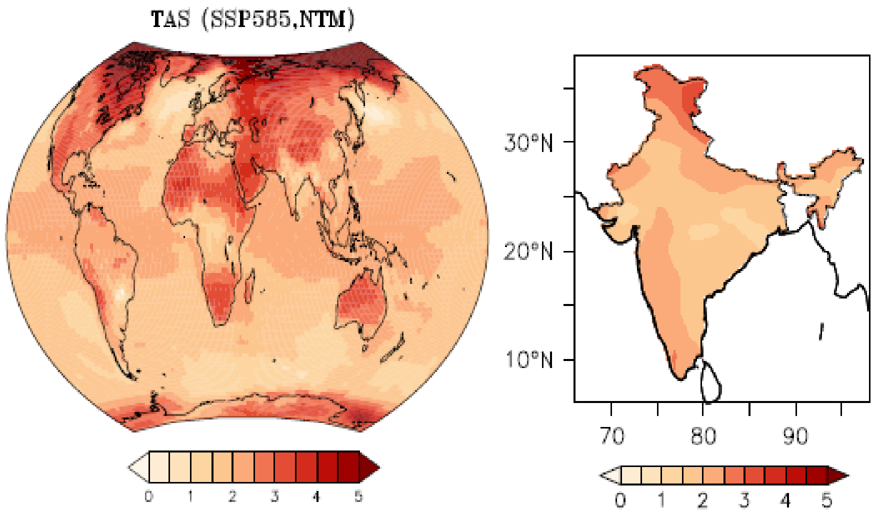


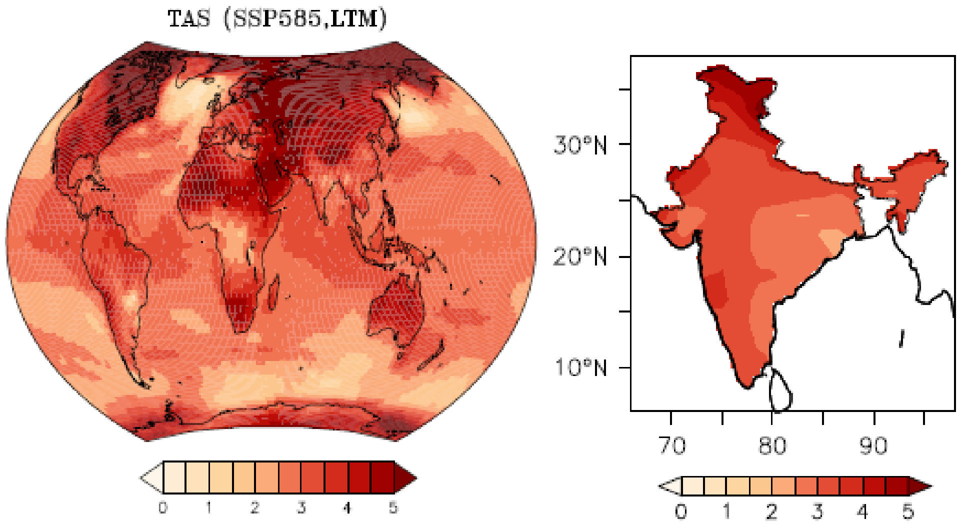

**Courtesy: Swapna**

# Surface temperature and precipitation response in IITM-ESM (SSP8.5) – CMIP6

**Near-term (2041-2069) minus PI-CTL (1850-1900)**

**Long-term (2071-2099) minus PI-CTL (1850-1900)**



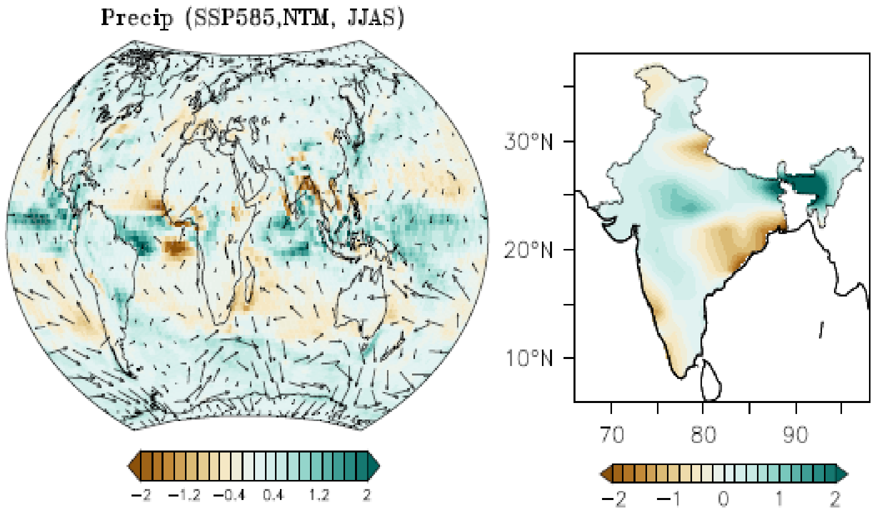



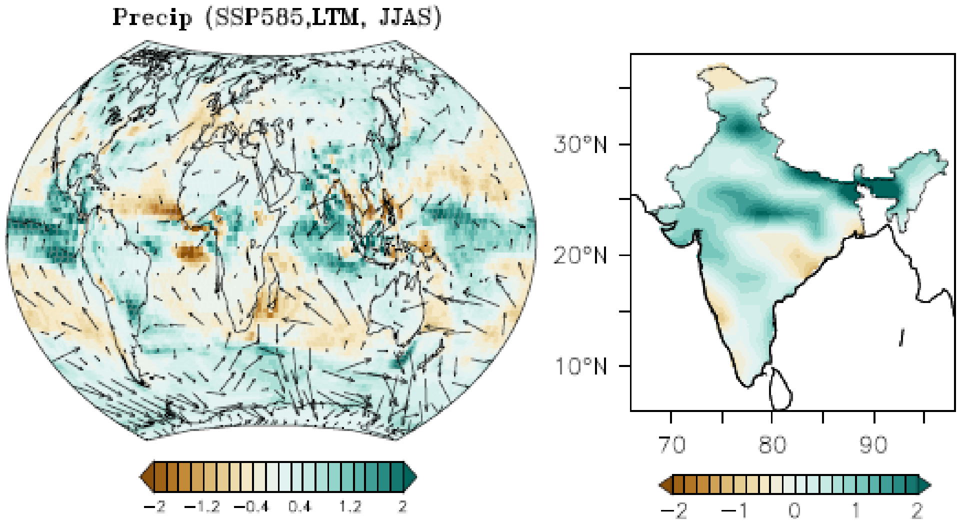

## *The Water Vapor Feedback*

*Temp dependence of saturation vapor pressure*

$$e_s : e^{-5400/T}$$

$$\frac{d \ln e_s}{dT} = \frac{5400}{T^2} \approx 0.06 \quad to \quad 0.1 \quad per \quad K$$



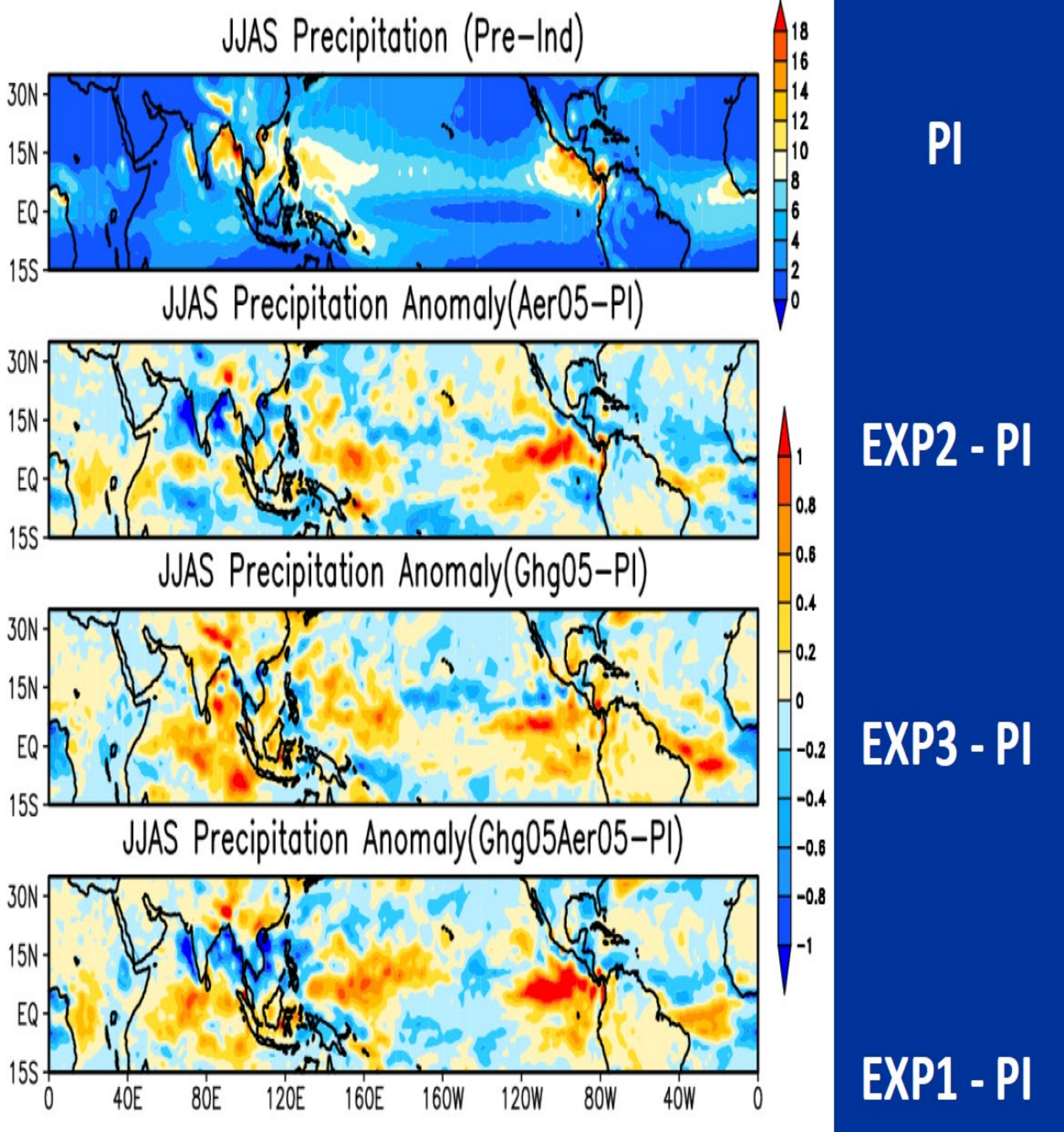

**Courtesy: Swapna**

# Indian summer monsoon response to GHG & Aerosol forcing

## Sensitivity experiments using the IITM ESMv2

| Experiment | $CO_2$ | Aerosol | Integration |
|---|---|---|---|
| PI-CTL (1850 conditions) | 284.2 ppmv | Natural | 500 years |
| EXP1_(GHG2005+ AERO2005) | 367.5 ppmv | Natural + Anthrop | 50 years |
| EXP2_(AERO_2005) | 284.2 ppmv | Natural + Anthrop | 50 years |
| EXP3(GHG_2005) | 367.5 ppmv | Natural | 50 years |

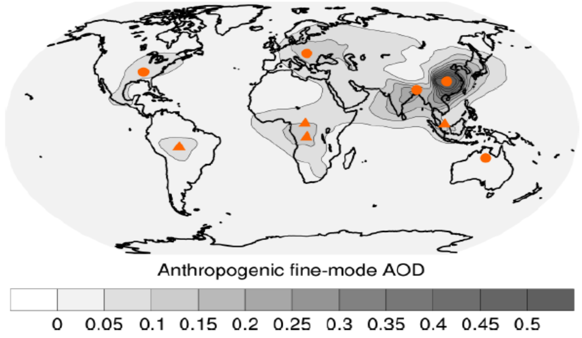
Ayantika Dey Choudhury, R. Krishnan, Manmeet Singh, P. Swapna, N. Sandeep, A.G. Prajeesh, R. Vellore, T.P. Sabin (2019) – Under preparation



# MACv2-SP: a parameterization of anthropogenic aerosol optical properties and an associated Twomey effect for use in CMIP6

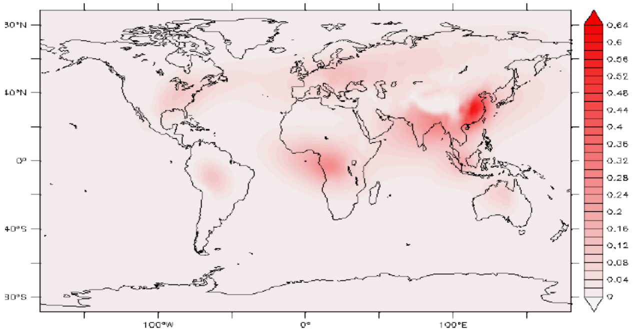
**Bjorn Stevens[1], Stephanie Fiedler[1], Stefan Kinne[1], Karsten Peters[1], Sebastian Rast[1], Jobst Müsse[1], Steven J. Smith[2], and Thorsten Mauritsen[1]**

[1]Max Planck Institute for Meteorology, Hamburg, Germany
[2]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, USA




| No. | Source region | Lat. | Long. | Type | Main features of annual cycle |
|---|---|---|---|---|---|
| 1 | Europe | 49.4 | 20.6 | Industrial | Amplitude 25 %, May max |
| 2 | North America | 40.1 | 277.5 | Industrial | Amplitude 30 %, July max |
| 3 | East Asia | 30.0 | 114.0 | Industrial | Amplitude 15 %, biharmonic, Oct and Apr max |
| 4 | South Asia | 23.3 | 88.0 | Industrial | Amplitude 10 %, maximum in mid-July |
| 5 | North Africa | 3.5 | 22.5 | Biomass | Non-harmonic, Dec max, Mar–Oct min |
| 6 | South America | −10.3 | 298.0 | Biomass | Non-harmonic, Sep max, Jan–Jun min |
| 7 | Maritime Continent | −1.0 | 106.0 | Biomass | Non-harmonic, Sep max, Jan–Jun min |
| 8 | South central Africa | −3.5 | 16.0 | Biomass | Non-harmonic, Aug max, Jan–Dec min |
| 9 | Australia | −20.0 | 135.0 | Industrial | Amplitude 60 %, Sep max |

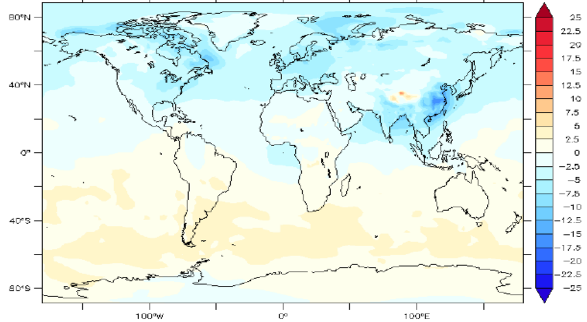
**Figure 1.** Global distribution of annually averaged anthropogenic aerosol optical depth $\tau_a$ at 550 nm. Also indicated are the locations of MACv2-SP plume centers. Industrial and biomass plumes are distinguished by the choice of symbol: circles for industrial plumes and triangles for biomass plumes.



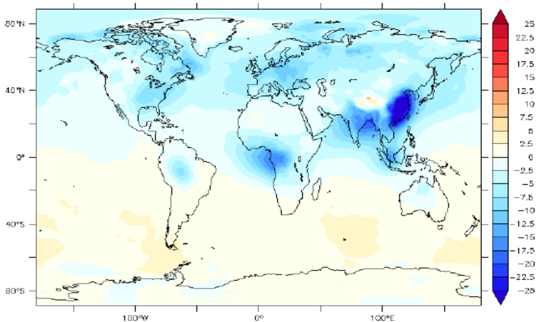
**Anthropogenic Aerosol Optical Depth (550 nm)**

**Courtesy: Ayantika, Manmeet**

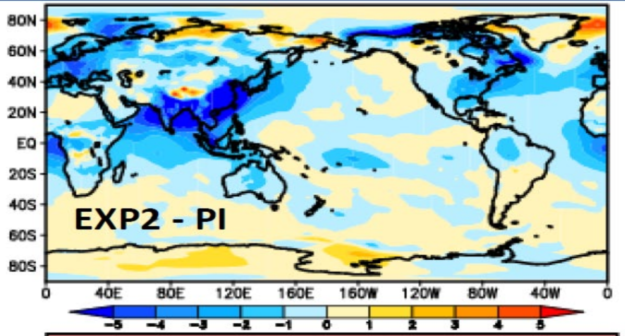
**Anthropogenic Aerosol RF at TOA**

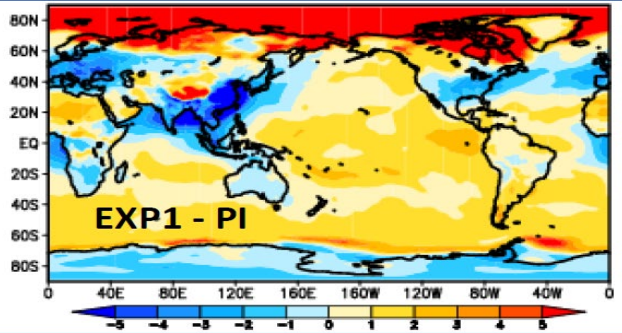


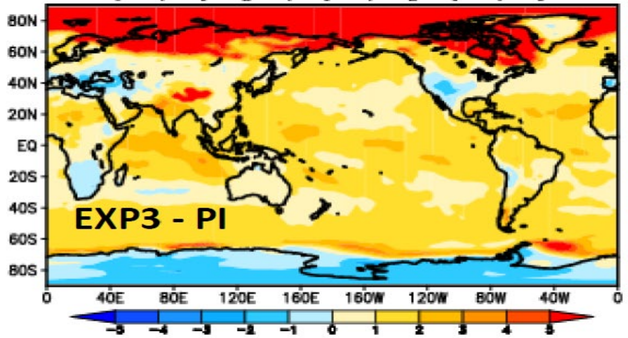
**Anthropogenic Aerosol RF at Surface**



## Changes in Clear Sky Radiative Forcing (RF) @ TOA: (JJAS)

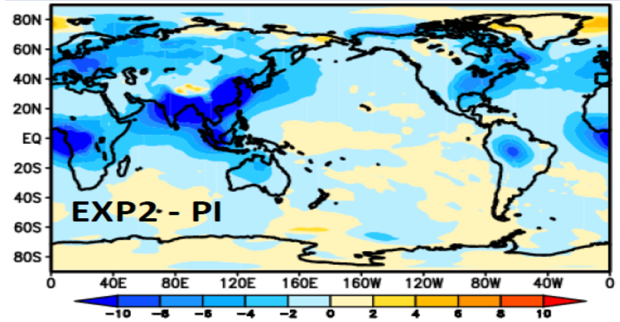


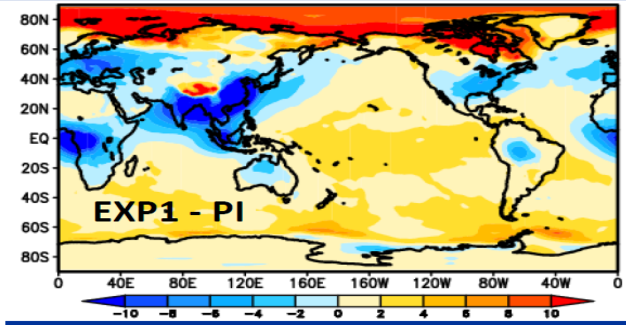



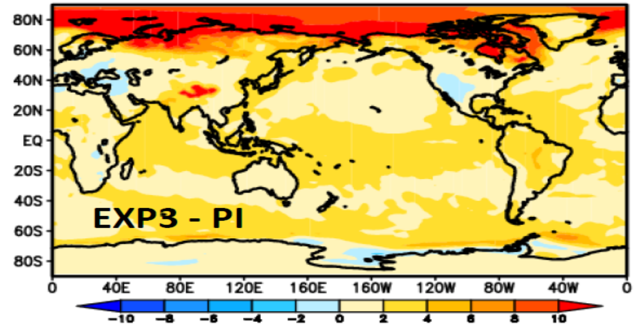




**Courtesy: Ayantika**

## Changes in Clear Sky Radiative Forcing (RF) @ SFC: (JJAS)

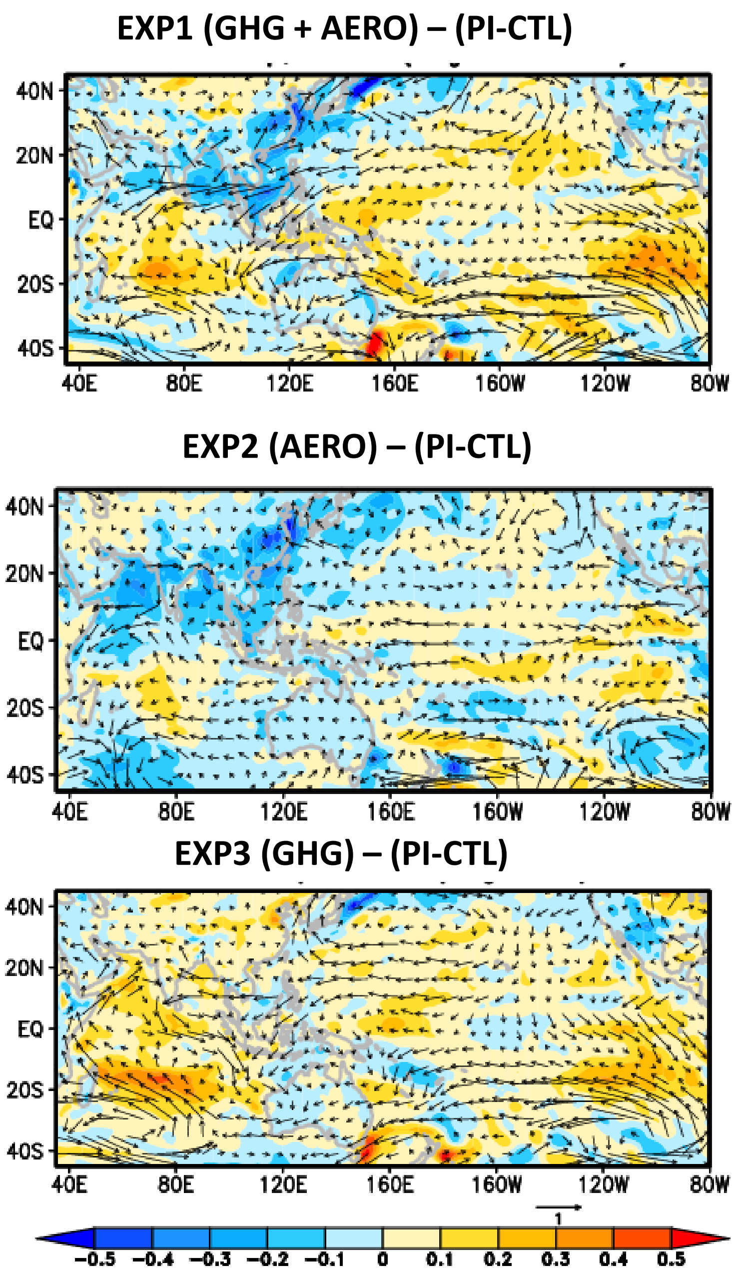


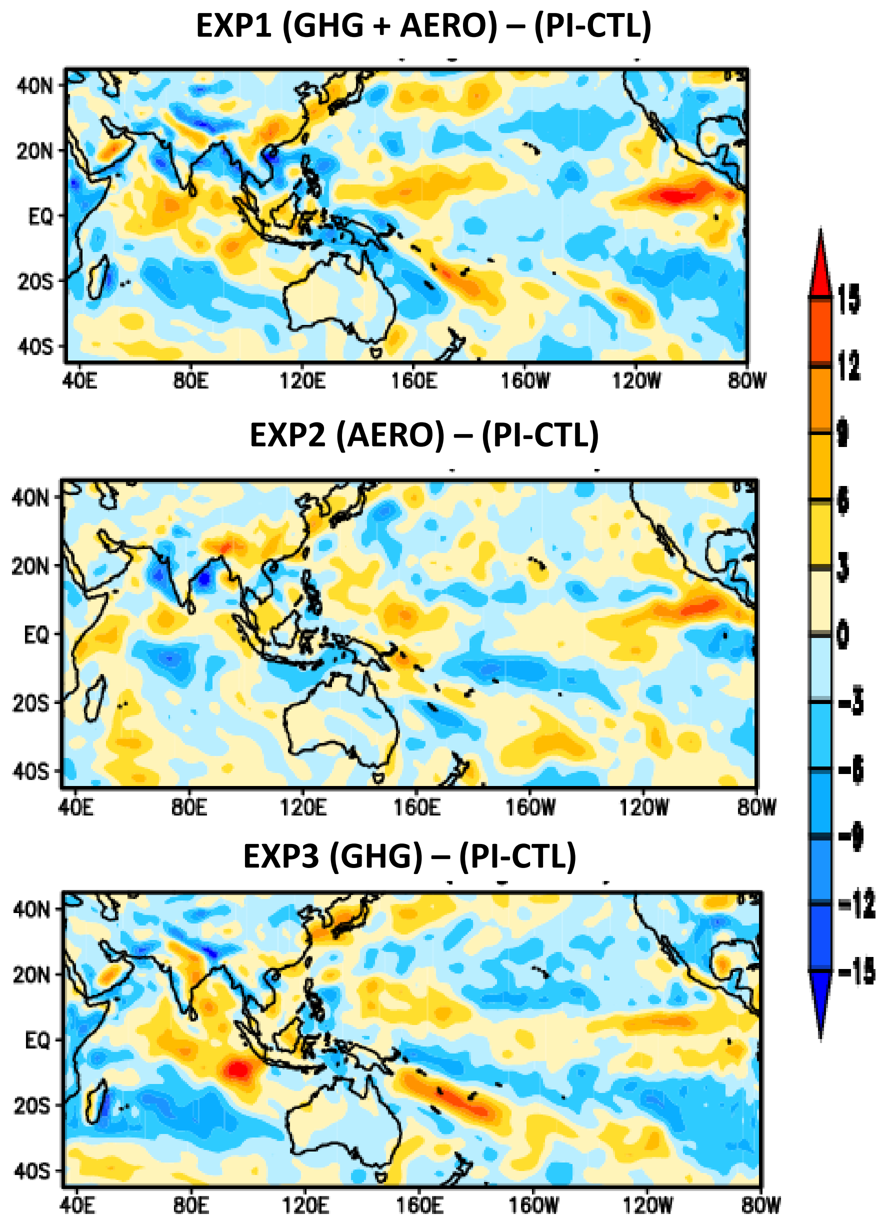




**Courtesy: Ayantika**

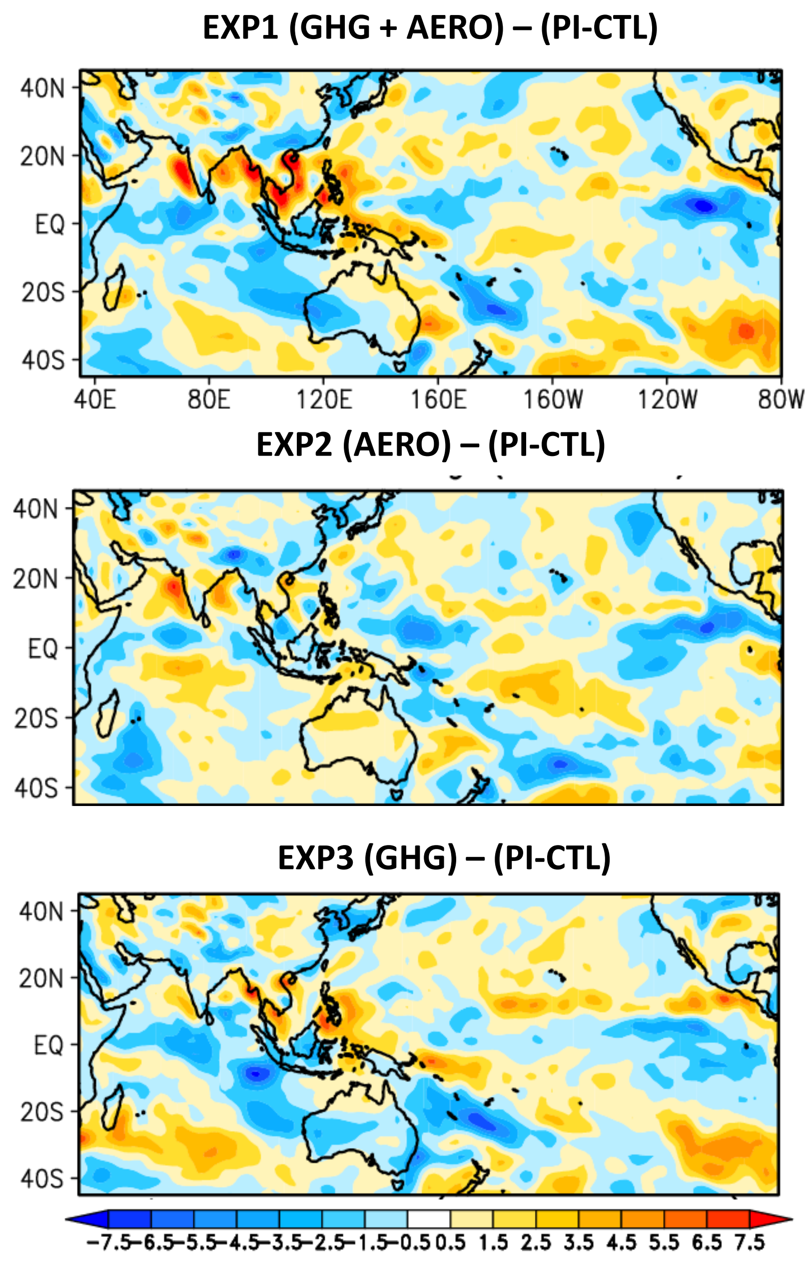
## Evaporation & winds 850 hPa: JJAS



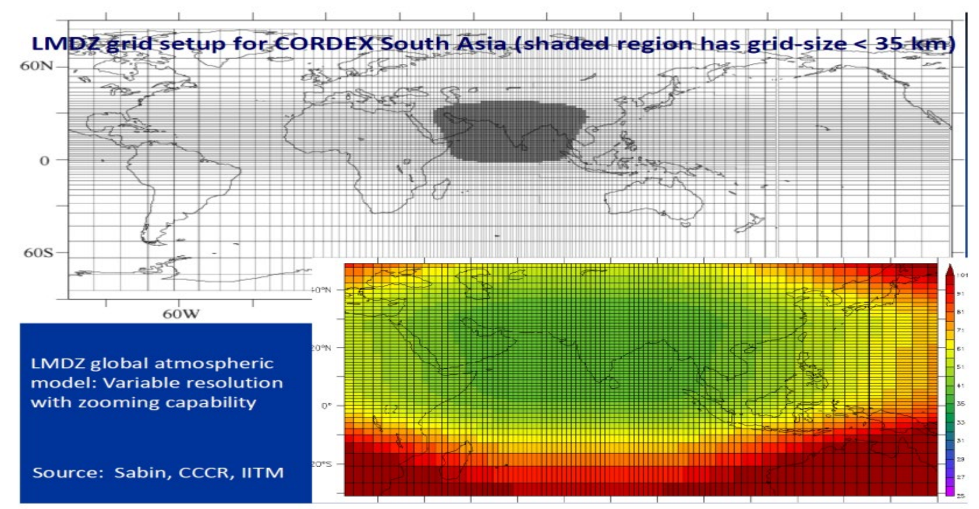

## Vertically integrated moisture convergence



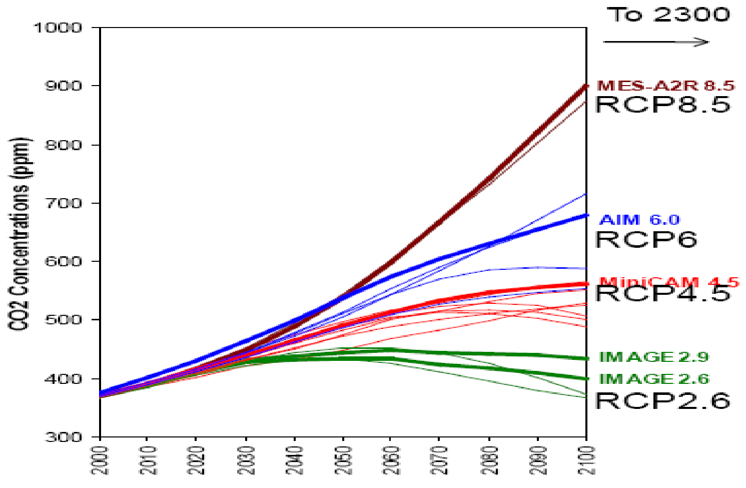

## Mid-level vertical velocity



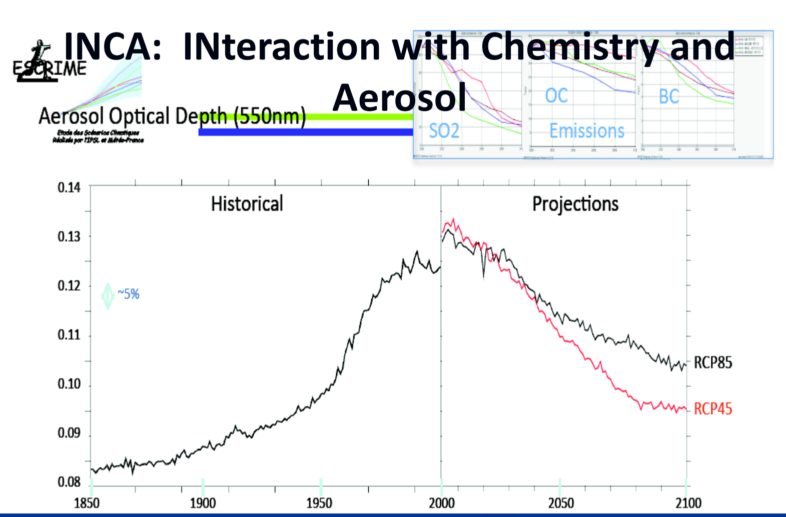
High-Resolution (~ 35 km)
Climate Change Simulations




CO2 concentration in the future IPCC AR5 scenarios




Aerosol distribution from IPSL ESM




***Historical (1886-2005):*** *Includes natural and anthropogenic (GHG, aerosols, land cover, …) forcing*

***Historical Natural (1886 – 2005):*** *Includes only natural climate forcing for the historical period*

***GHG-Only (1951-2005):*** *Includes GHG only forcing. Other forcing set to pre-industrial values*

***Aerosol-Only (1951– 2005):*** *Includes Aerosol only forcing. Other forcing set to pre-industrial values*

***RCP 4.5 scenario (2006-2100) ~ 95 yrs:***

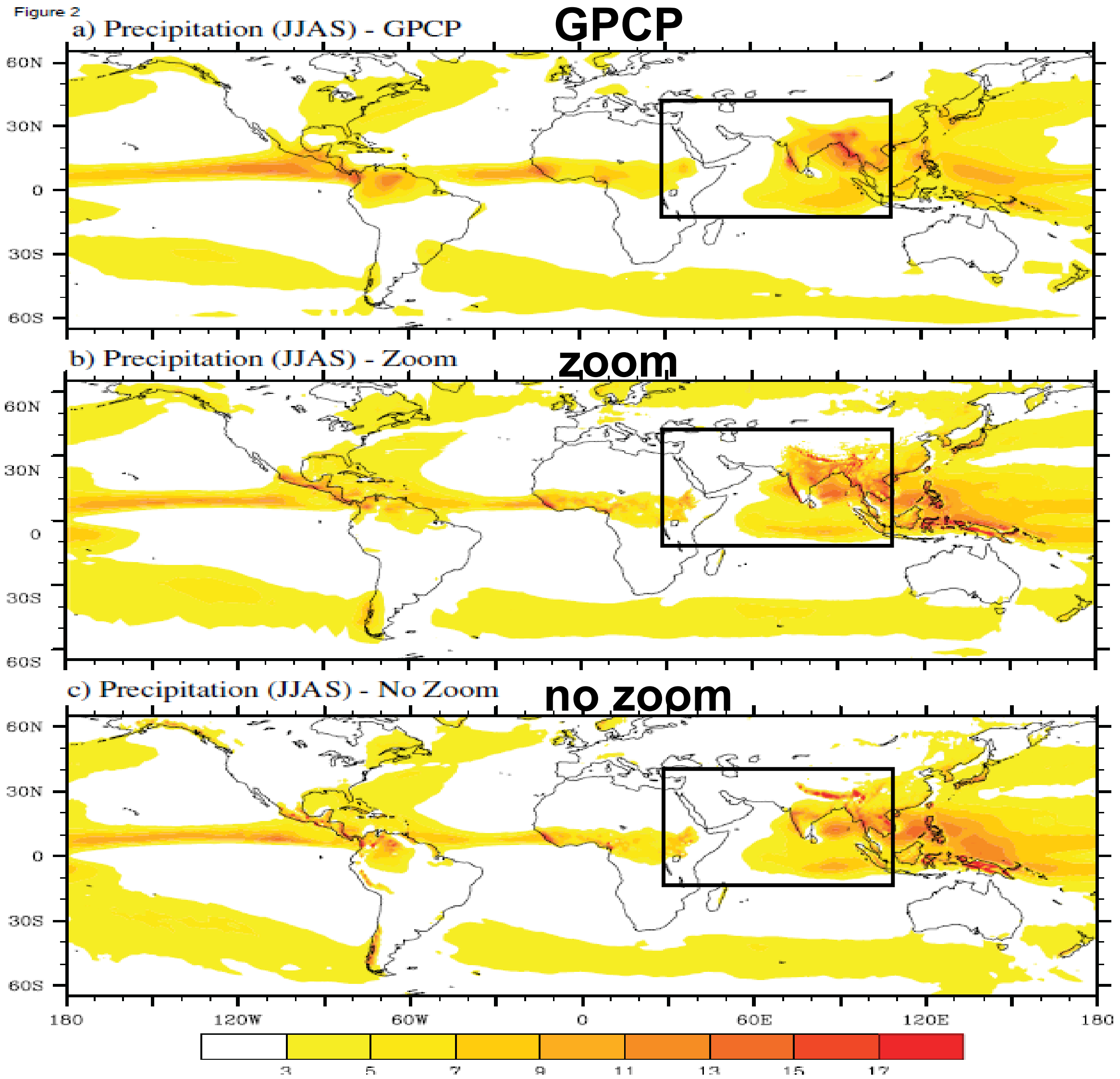
*Future projection run which includes both natural & anthropogenic forcing based on the IPCC AR5 RCP4.5 climate scenario. The evolution of GHG & anthropogenic aerosols in RCP4.5 produces a global radiative forcing of + 4.5 W m$^{-2}$ by 2100*

**Courtesy: Sabin Simulations performed on PRITHVI, CCCR-IITM**

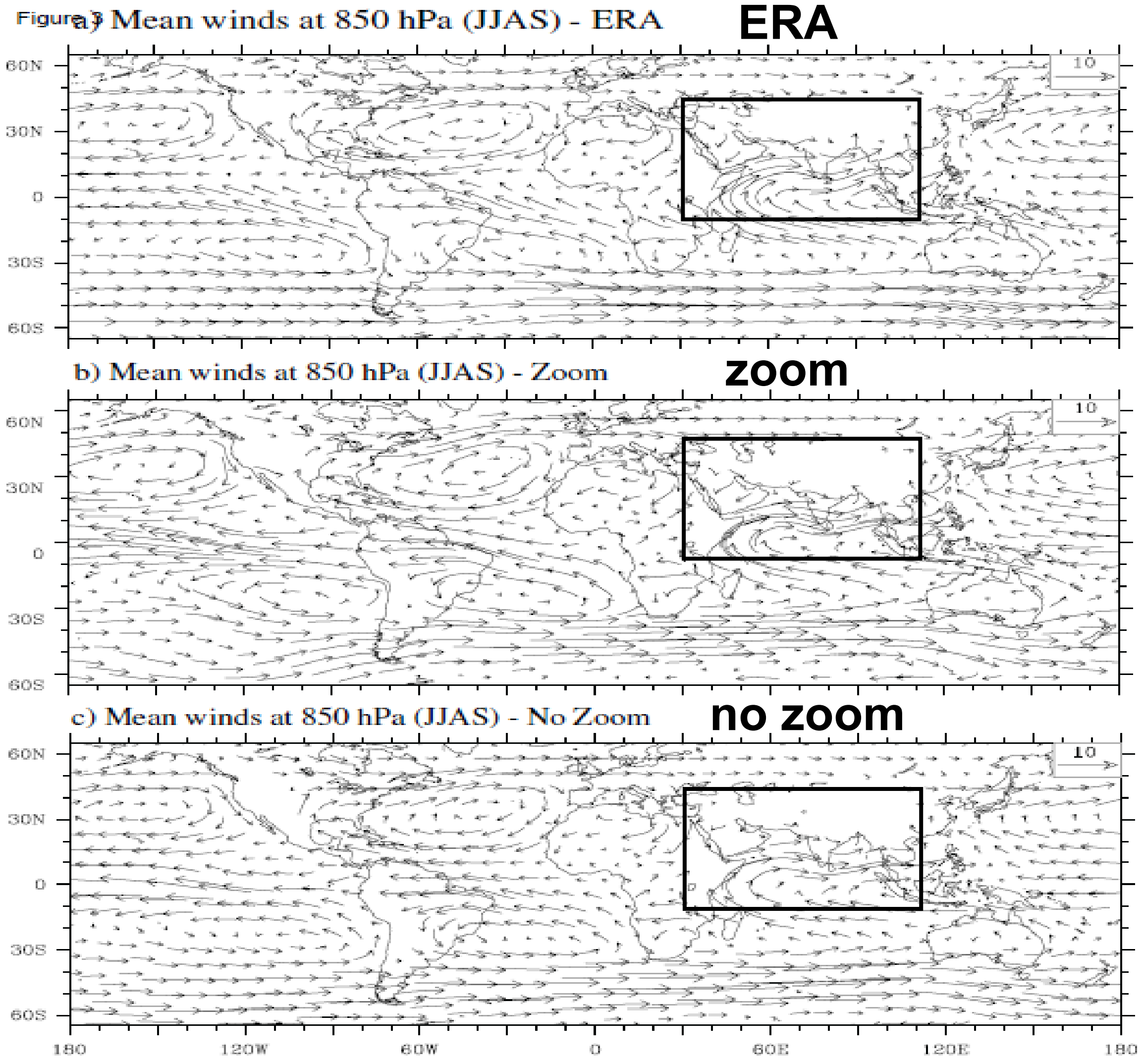
# Global climate

**No zoom**: 1°x1° ; **Zoom**: same number of points, with resolution ≈35 km over west Asia

precip JJAS (mm/day)

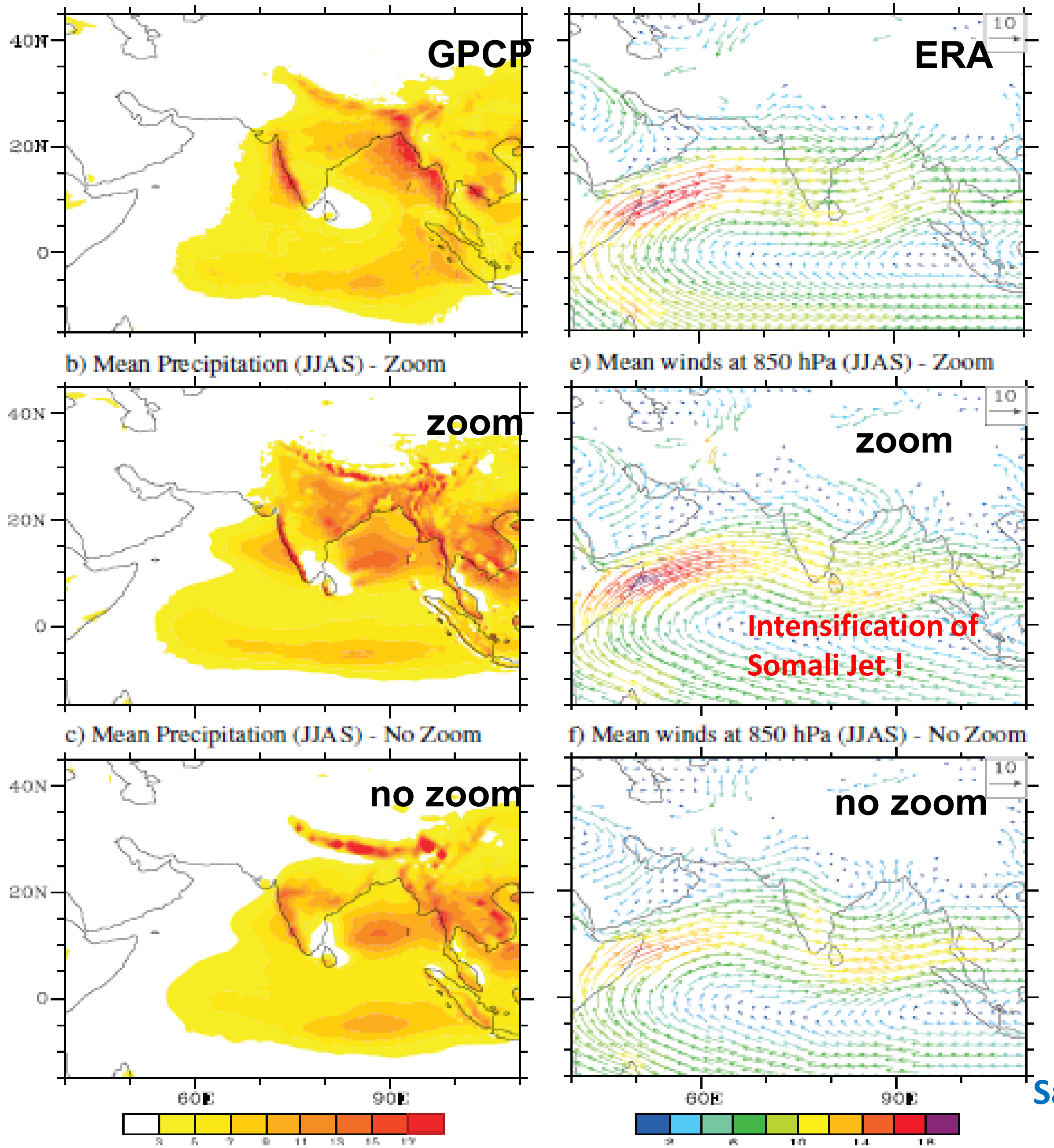



Mean winds at 850 hPa (JJAS)



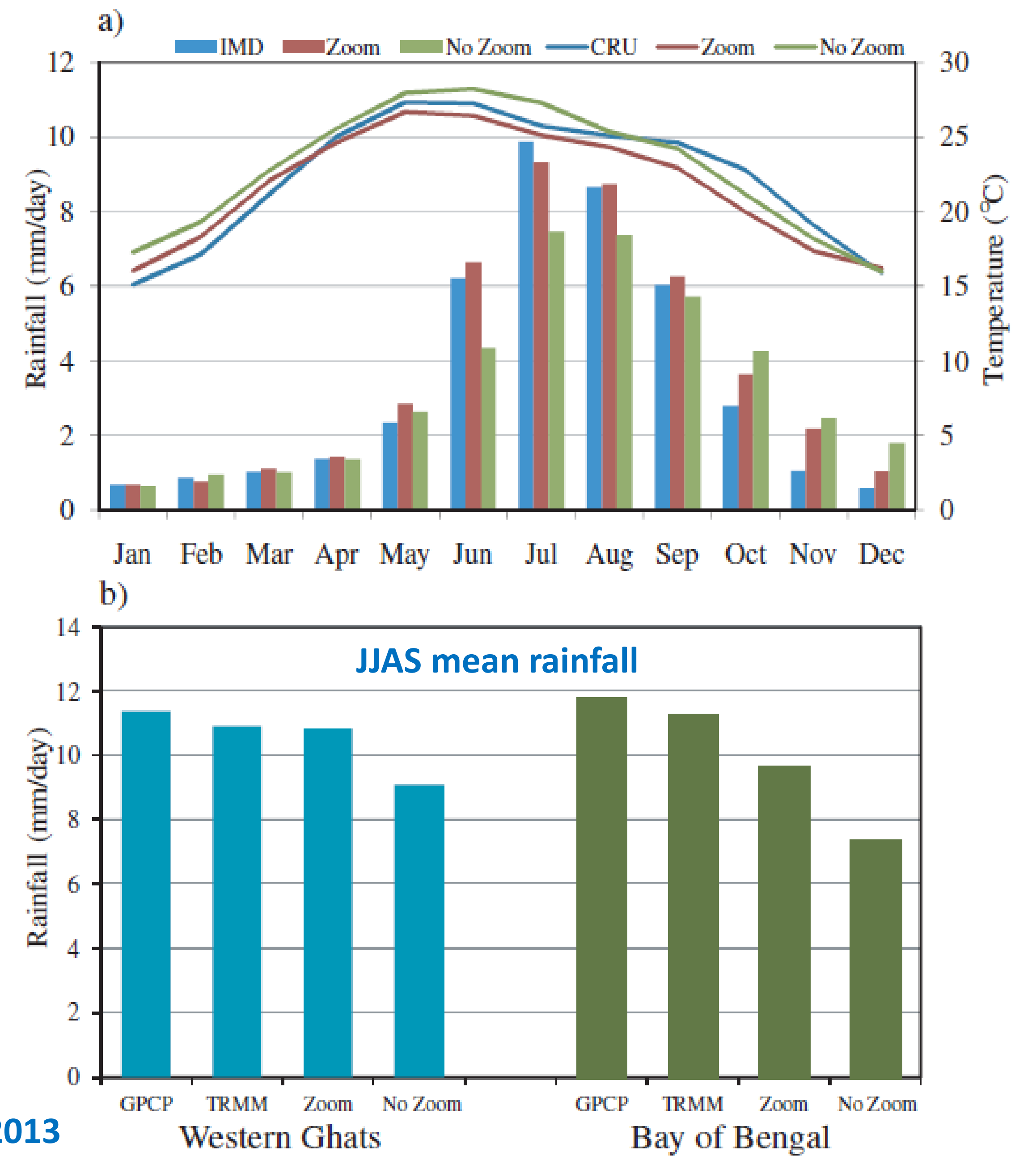

Sabin et al. 2013

Precip JJAS (mm/day) | Mean winds at 850 hPa

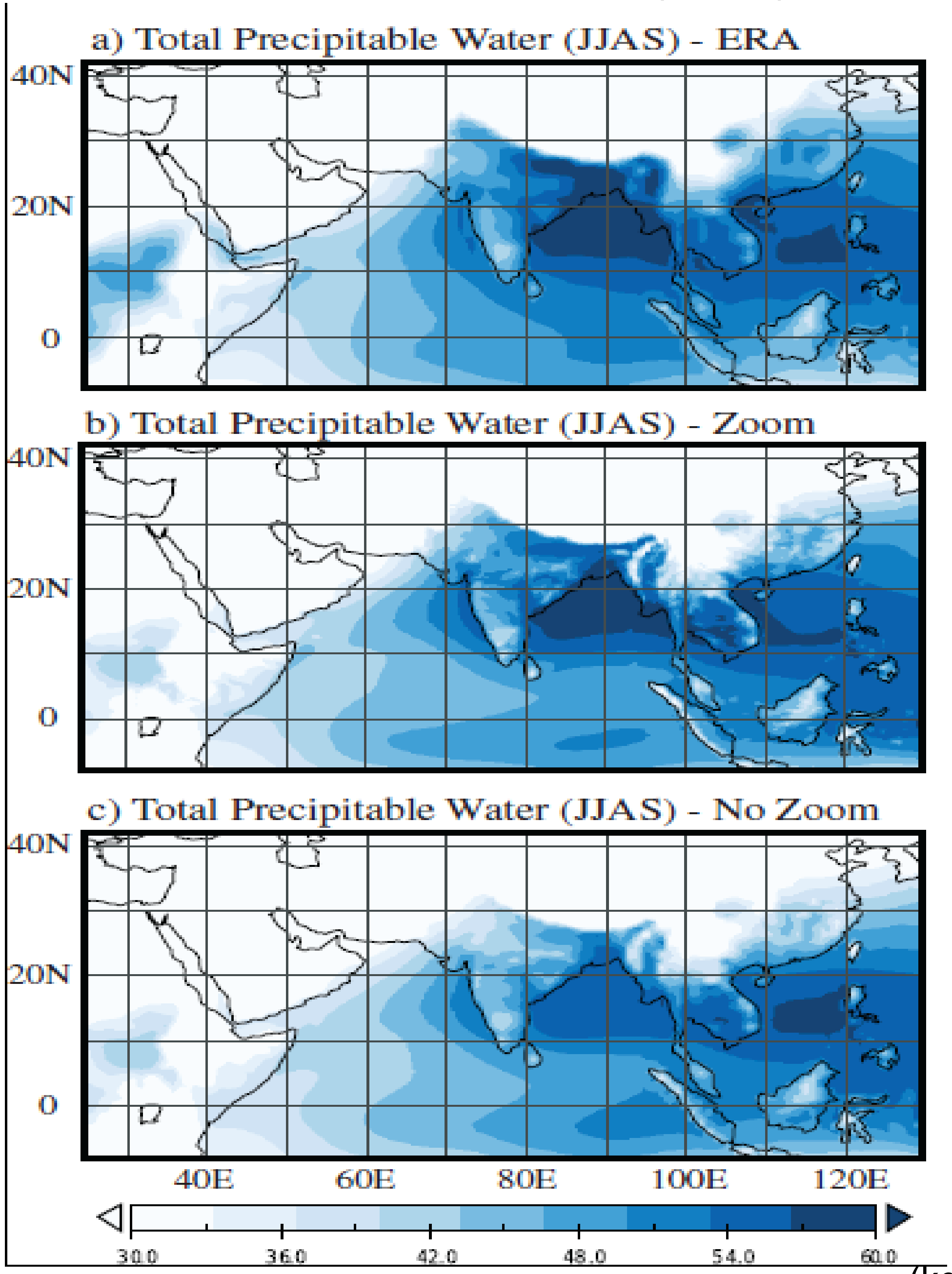



Sabin et al. 2013

## Rainfall & surface temperature over the Indian landmass

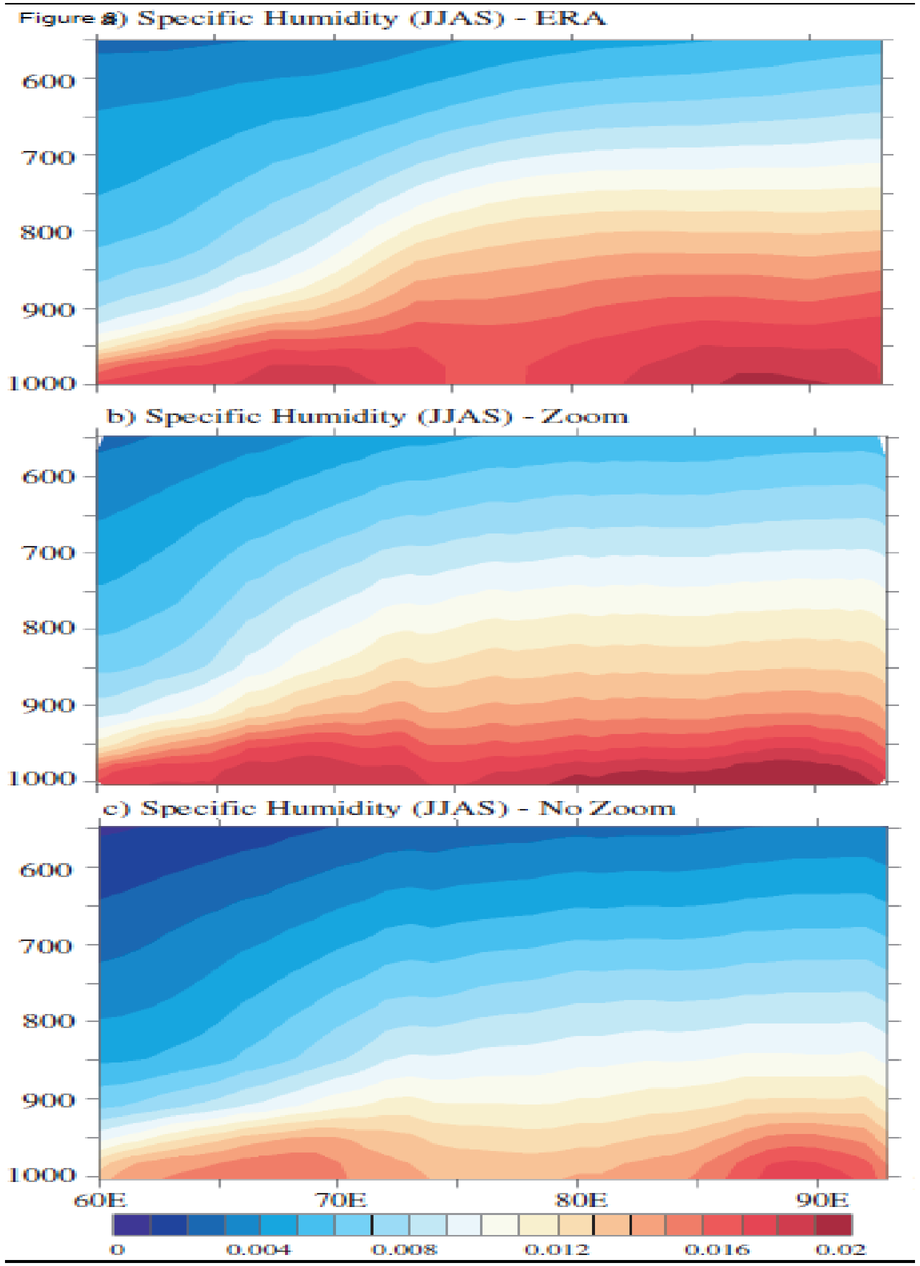


## Total precipitable water (JJAS)




(kg.m$^{-2}$)

## Specific humidity (JJAS)



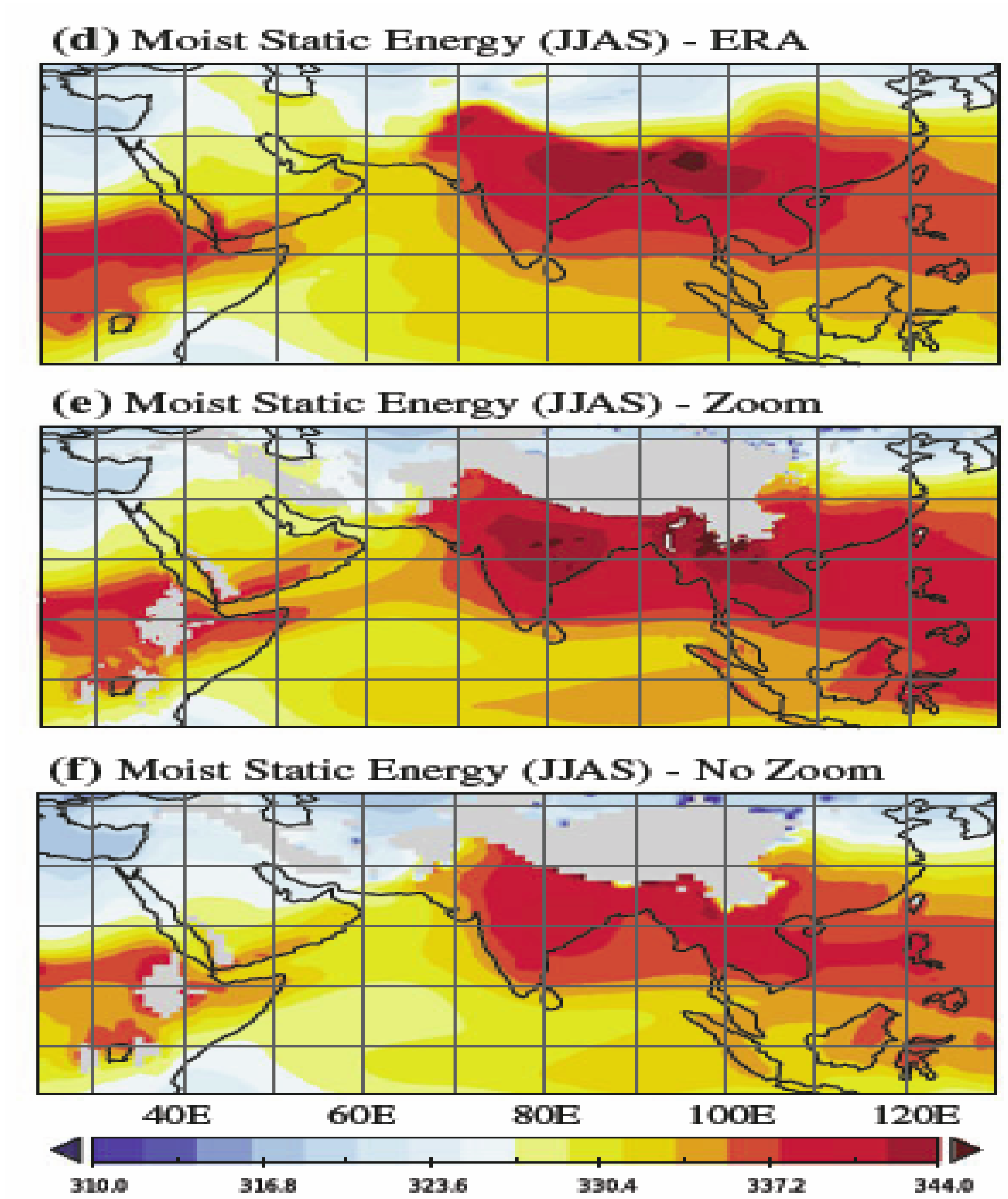

**ERA**

**zoom**

**no zoom**

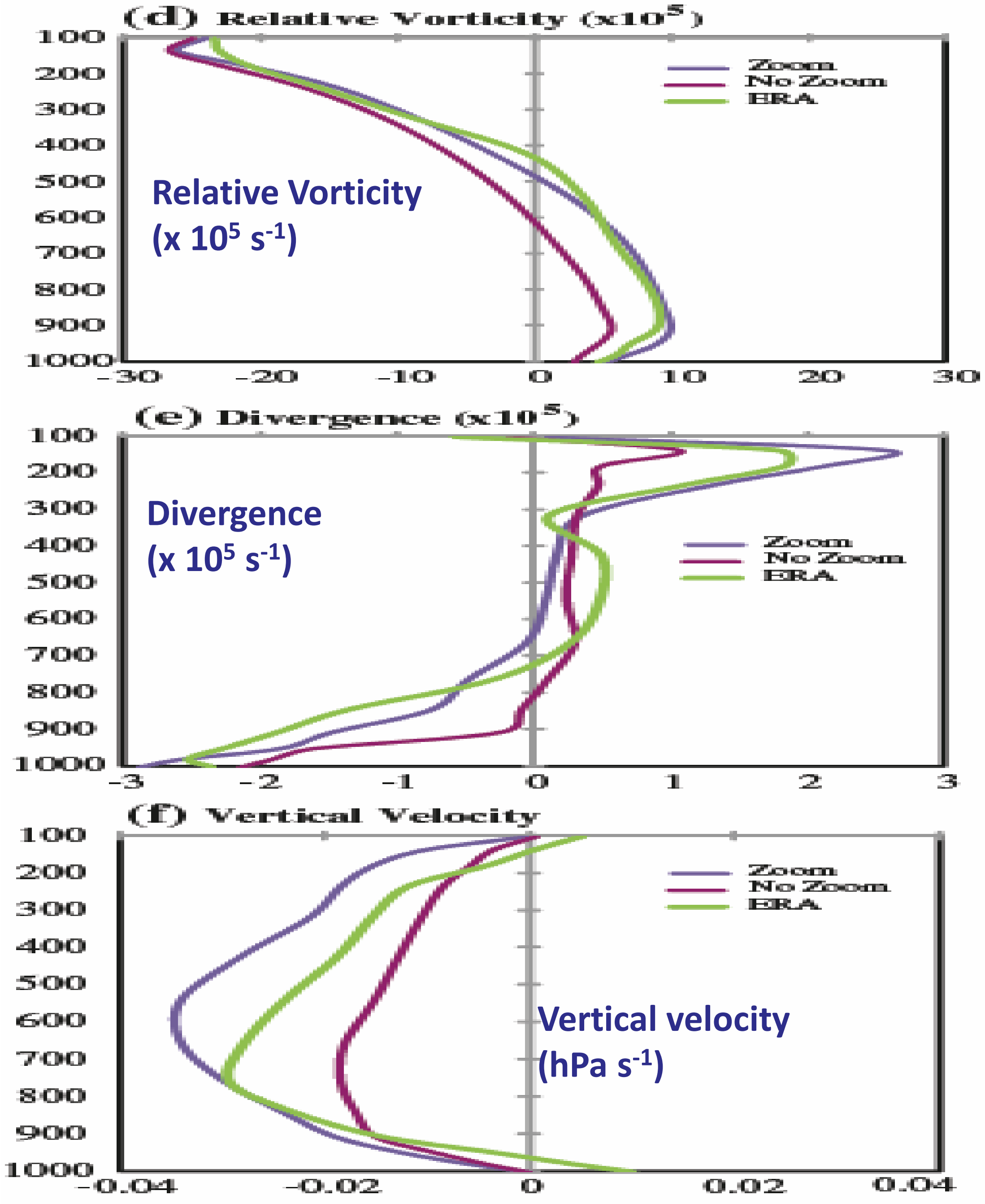
(kg.kg$^{-1}$)

## Moist Static Energy (x $10^3$ $Jm^{-2}$)



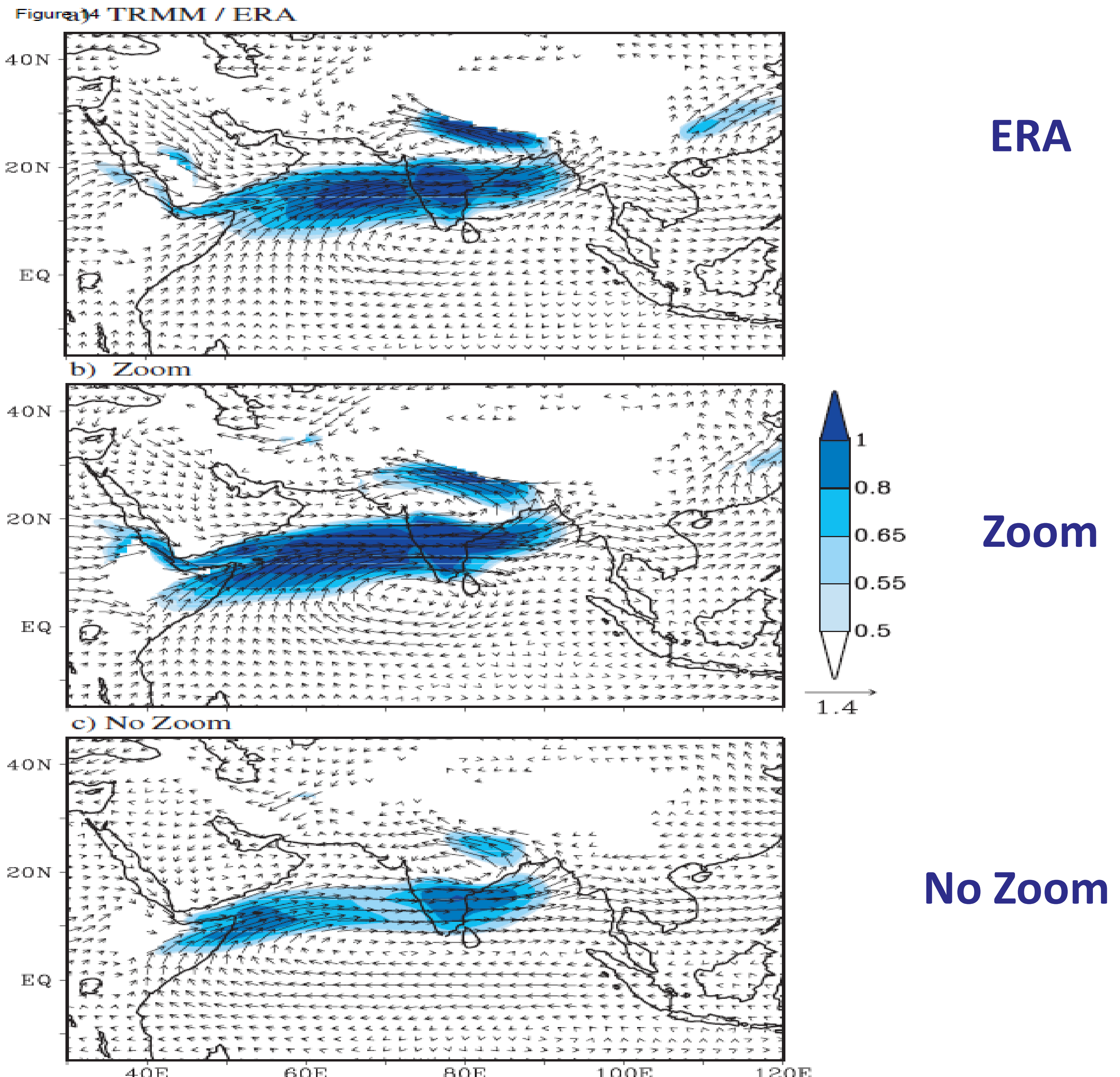

Sabin et al. 2013

## Vertical profiles [16N-28N, 65E 100E]



Patterns generated by regressing the 850 hPa winds on the index of frequency count (FC) of moderate-to-heavy rainfall over the monsoon trough (70E-90E, 16N-28N). Shading corresponds to magnitude of regression. Unit of regression is $ms^{-1}$ (std.dev FC)$^{-1}$.

Precipitation thresholds for moderate and heavy rainfall at each grid point correspond to the 75$^{th}$ and 95$^{th}$ percentile of daily rainfall.

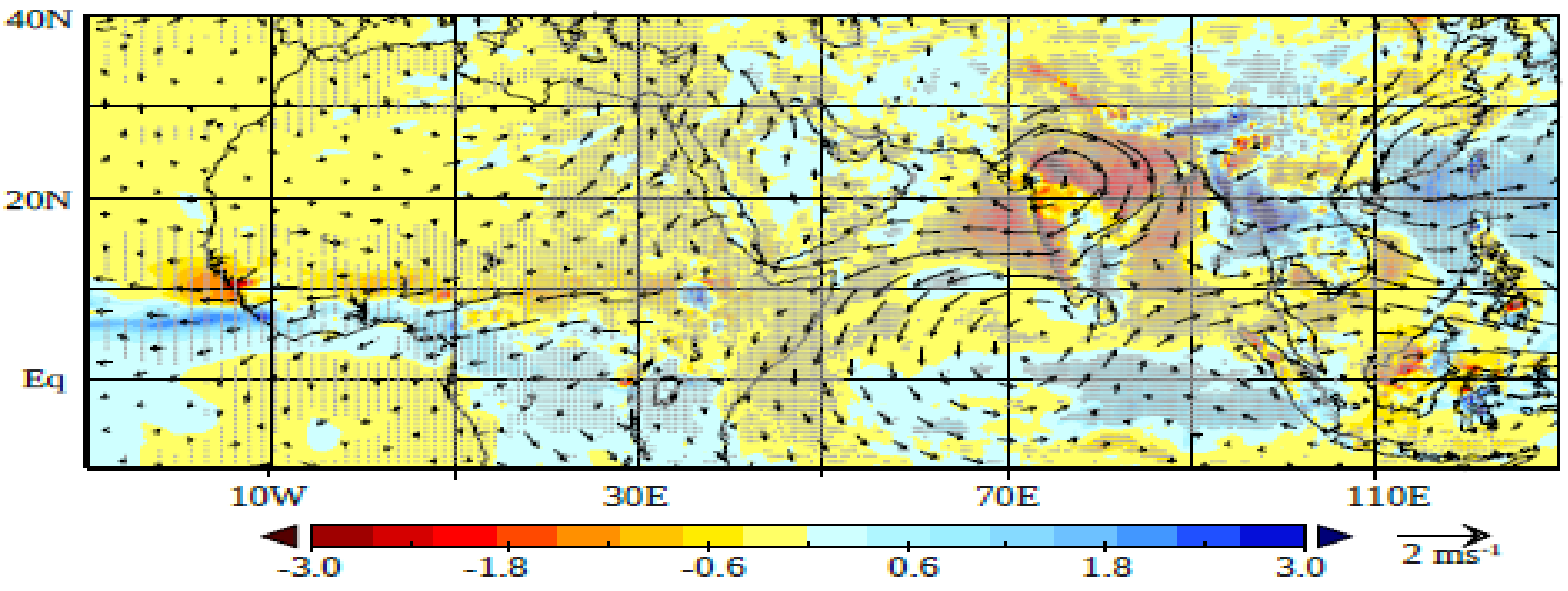



**Sabin et al. 2013**

# Weakening Response of Indian Monsoon to Climate Change

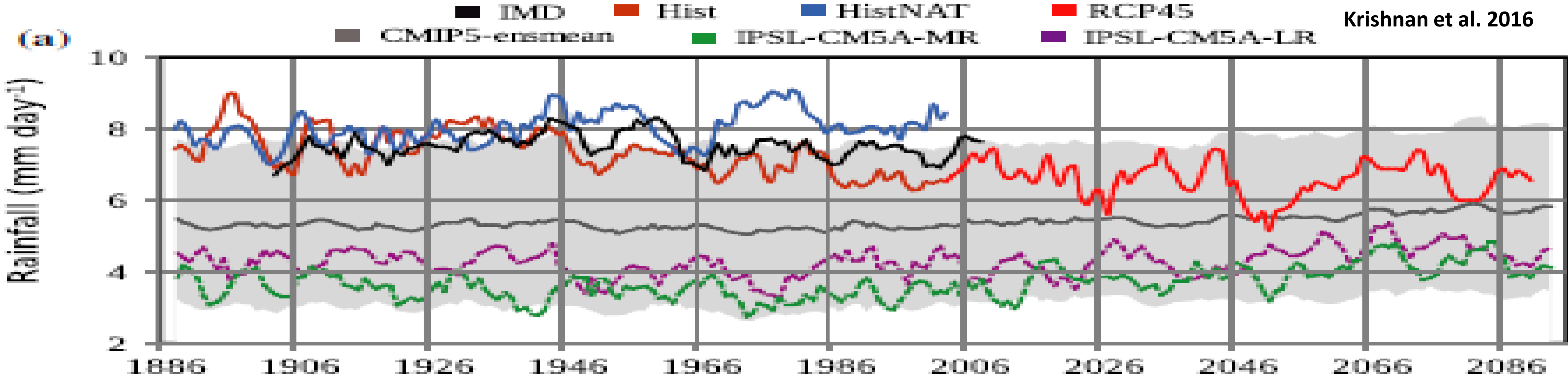
**Difference (HIST - HISTNAT): 1951-2005**

**Mean JJAS rainfall & 850 hPa winds**

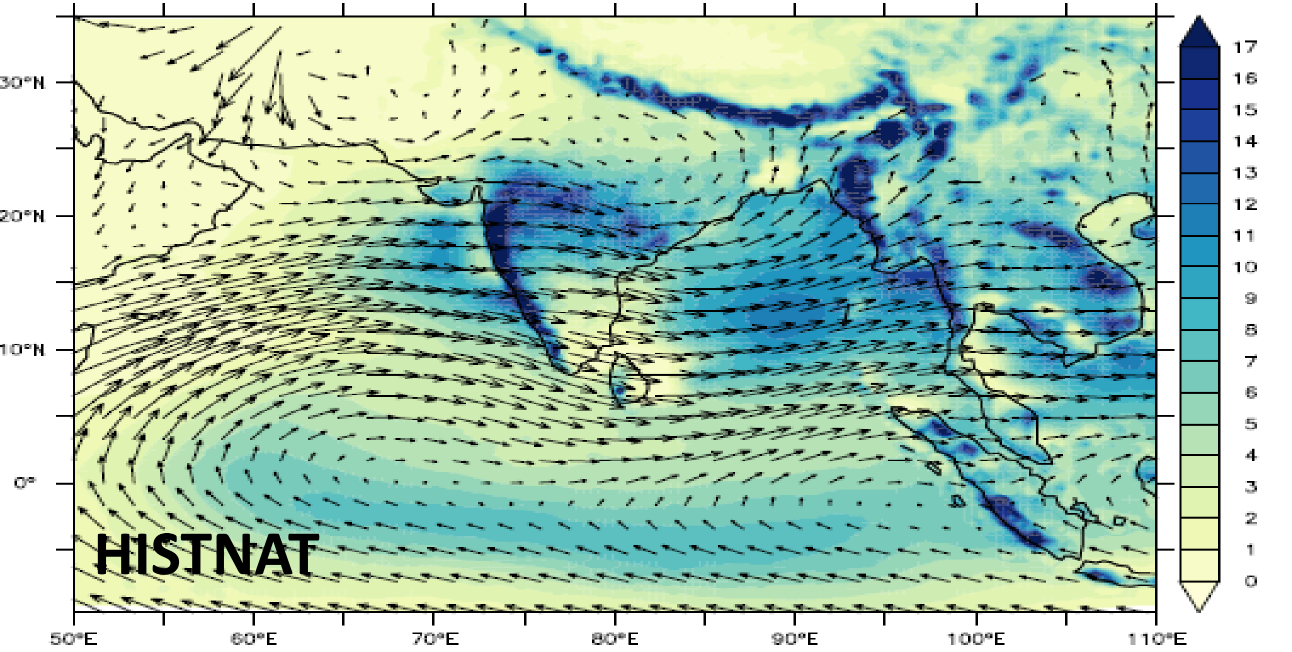


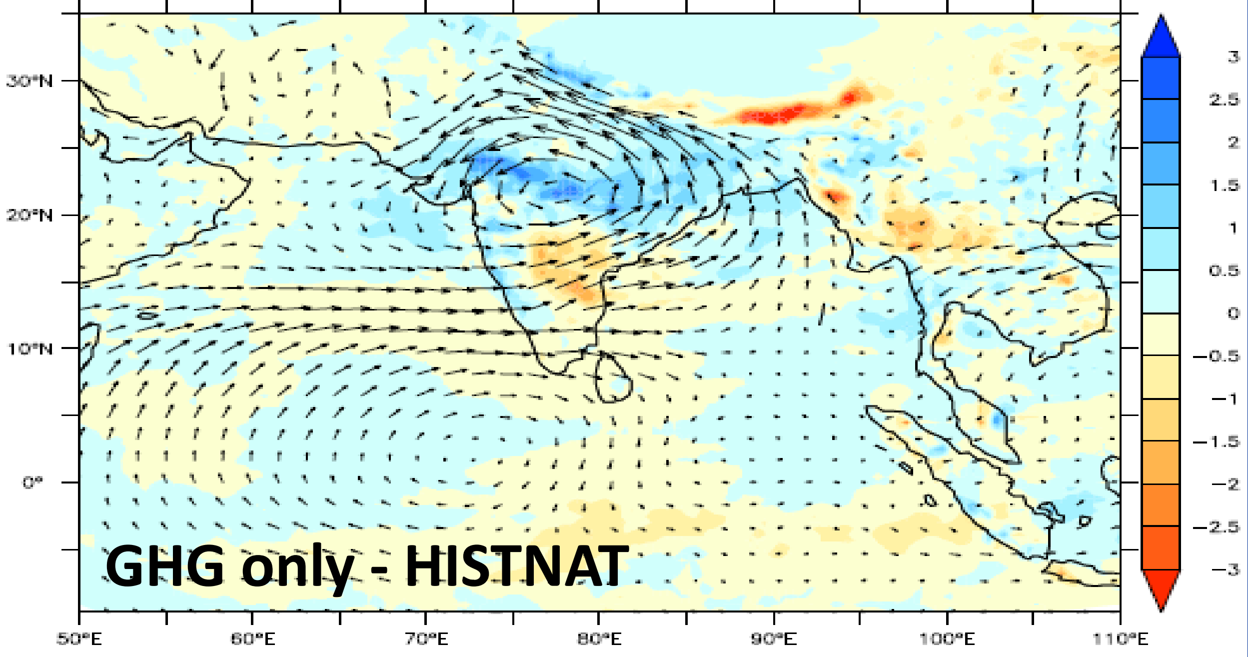

Monsoon rainfall (JJAS) averaged over Indian region

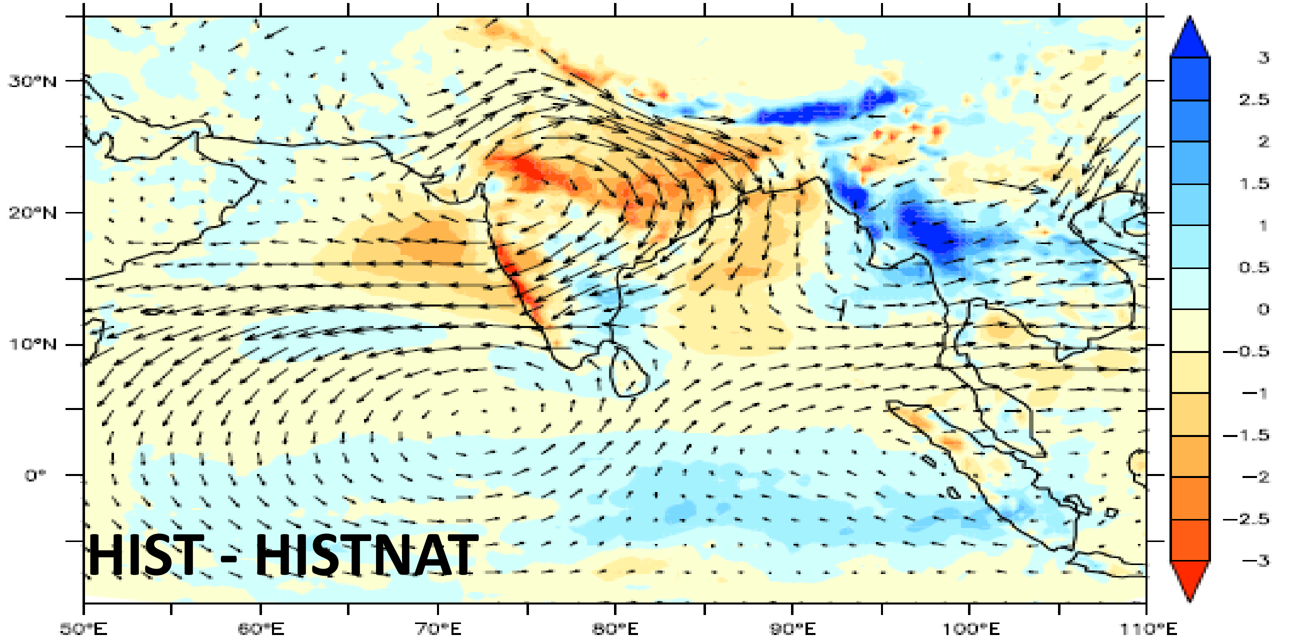
Krishnan et al. 2016

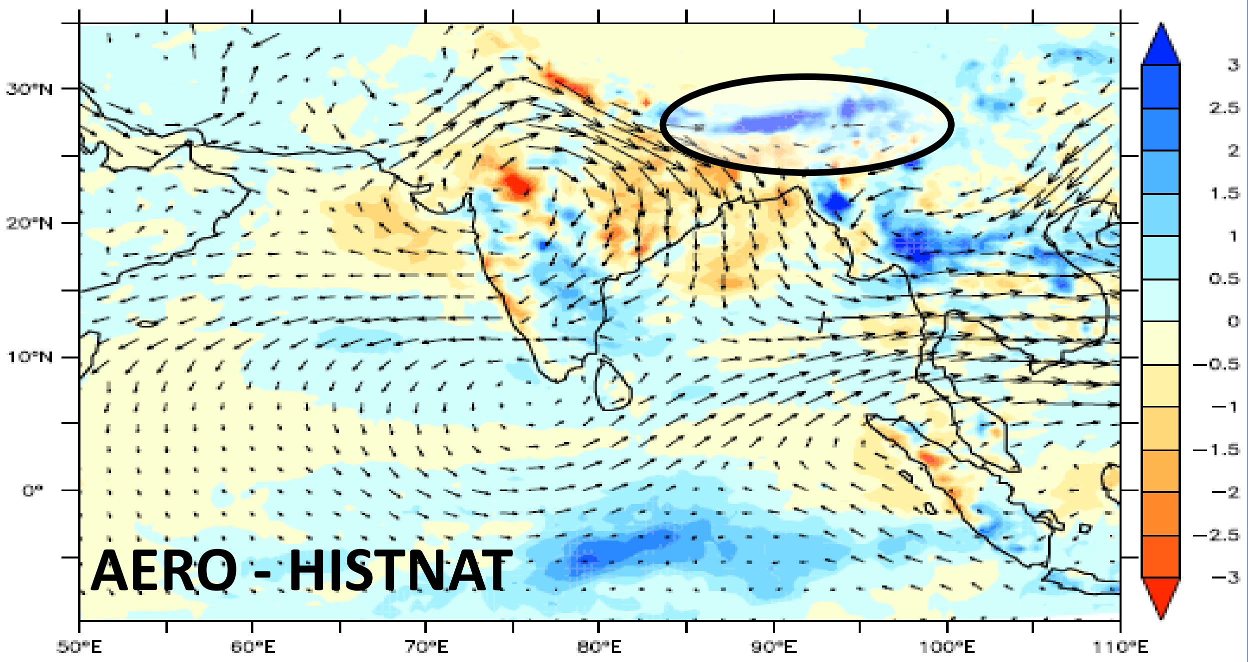


# Simulation of summer monsoon precipitation & 850 hPa circulation

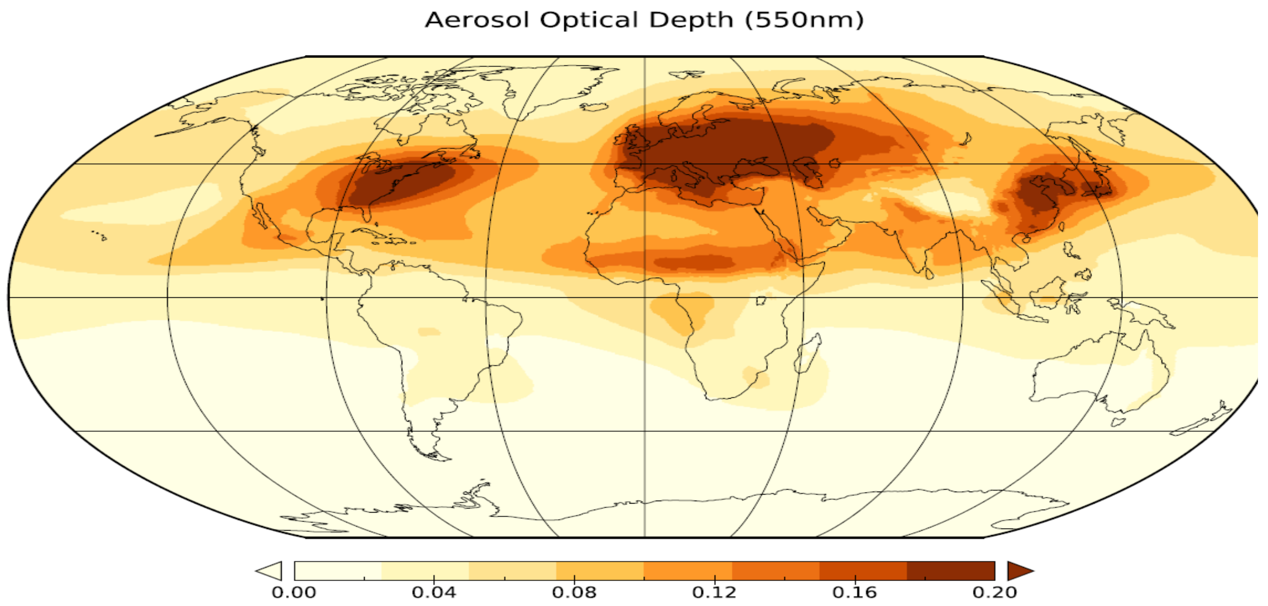


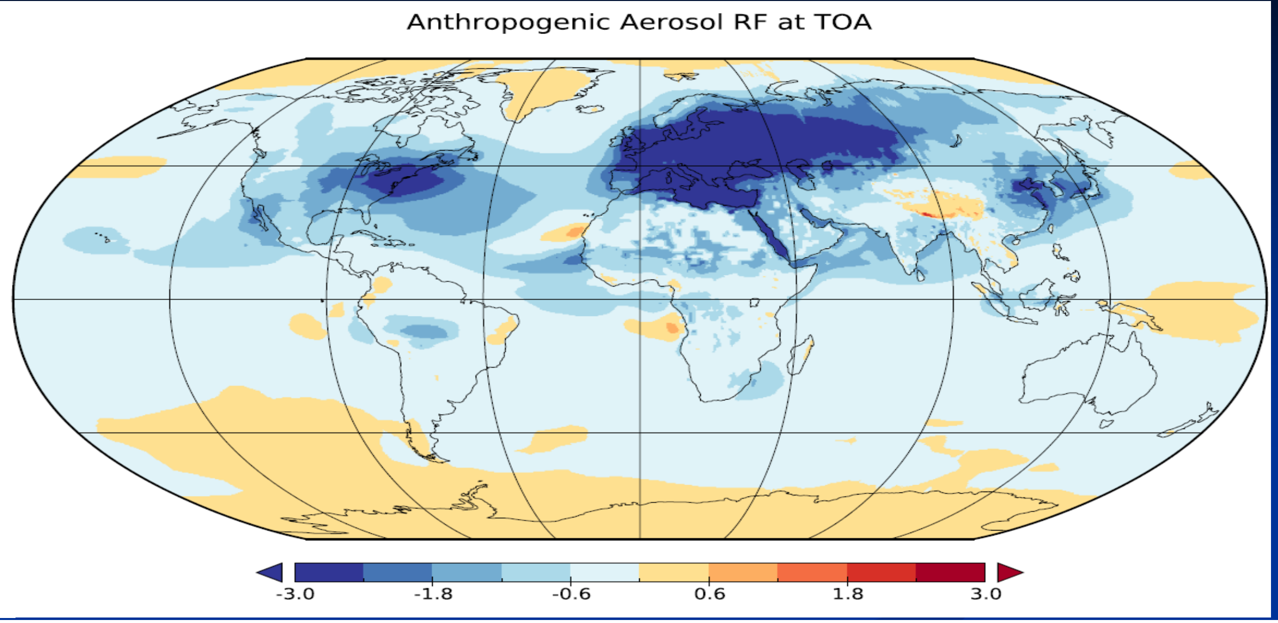



## Anthropogenic AOD

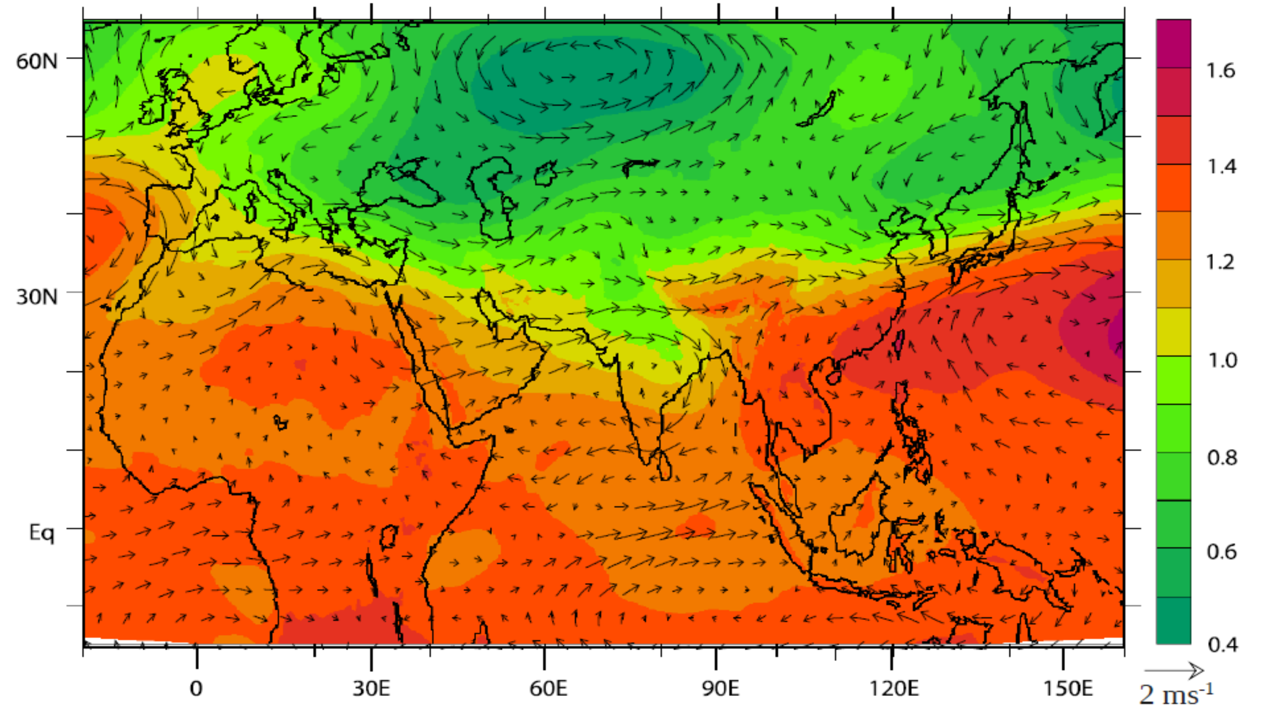



## Anthropogenic Aerosol Radiative Forcing: TOA



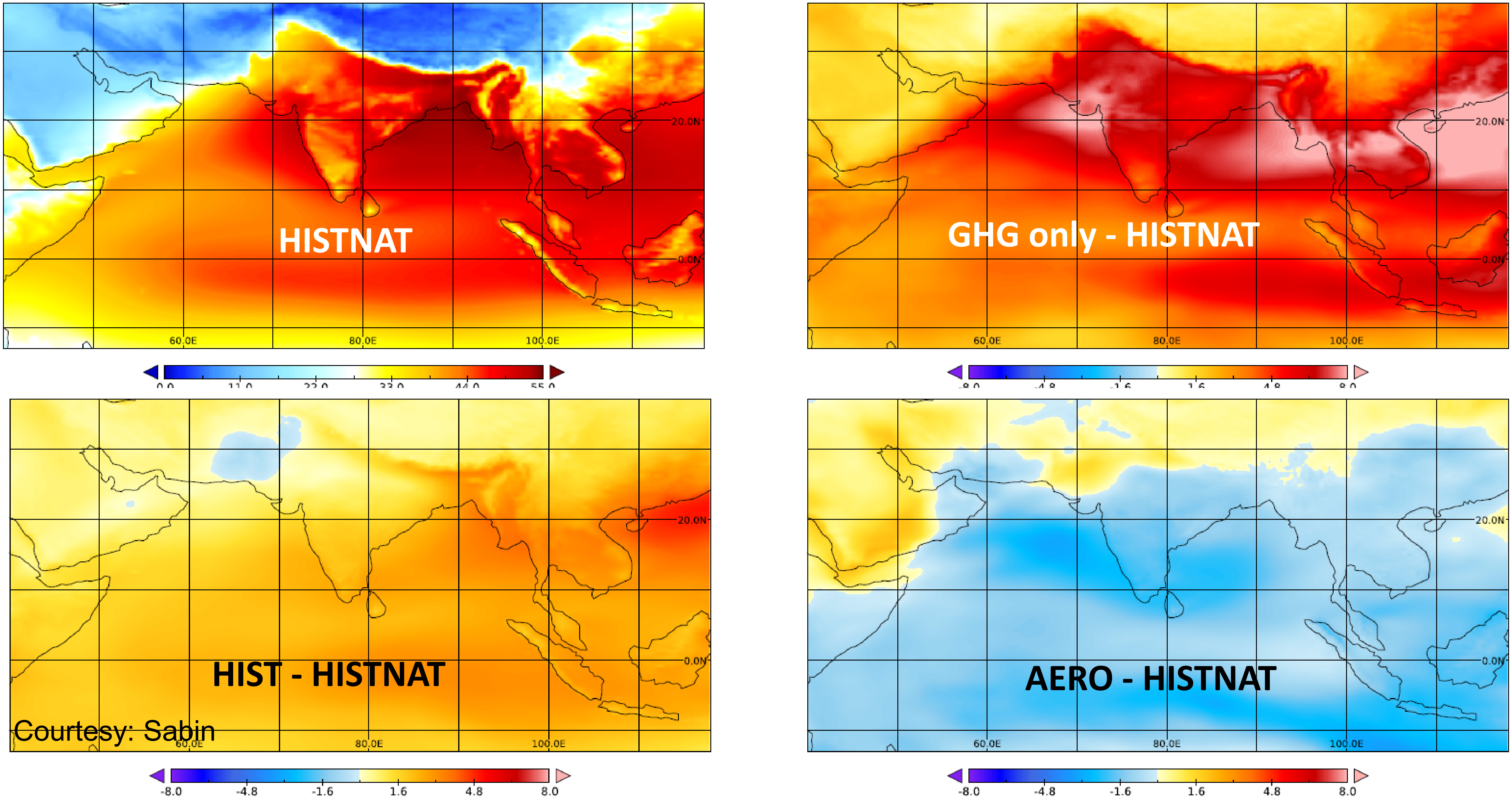

Response of tropospheric temperature & large-scale circulation to anthropogenic forcing

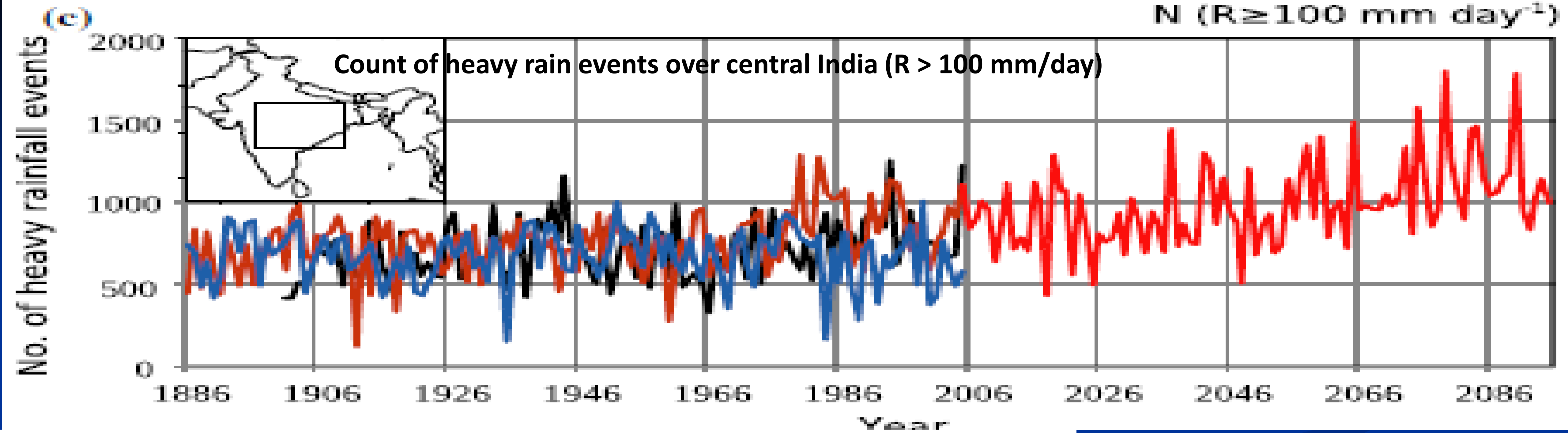
**HIST minus HISTNAT (1951 – 2005): Winds & temperature vertically averaged 600-200 hPa**

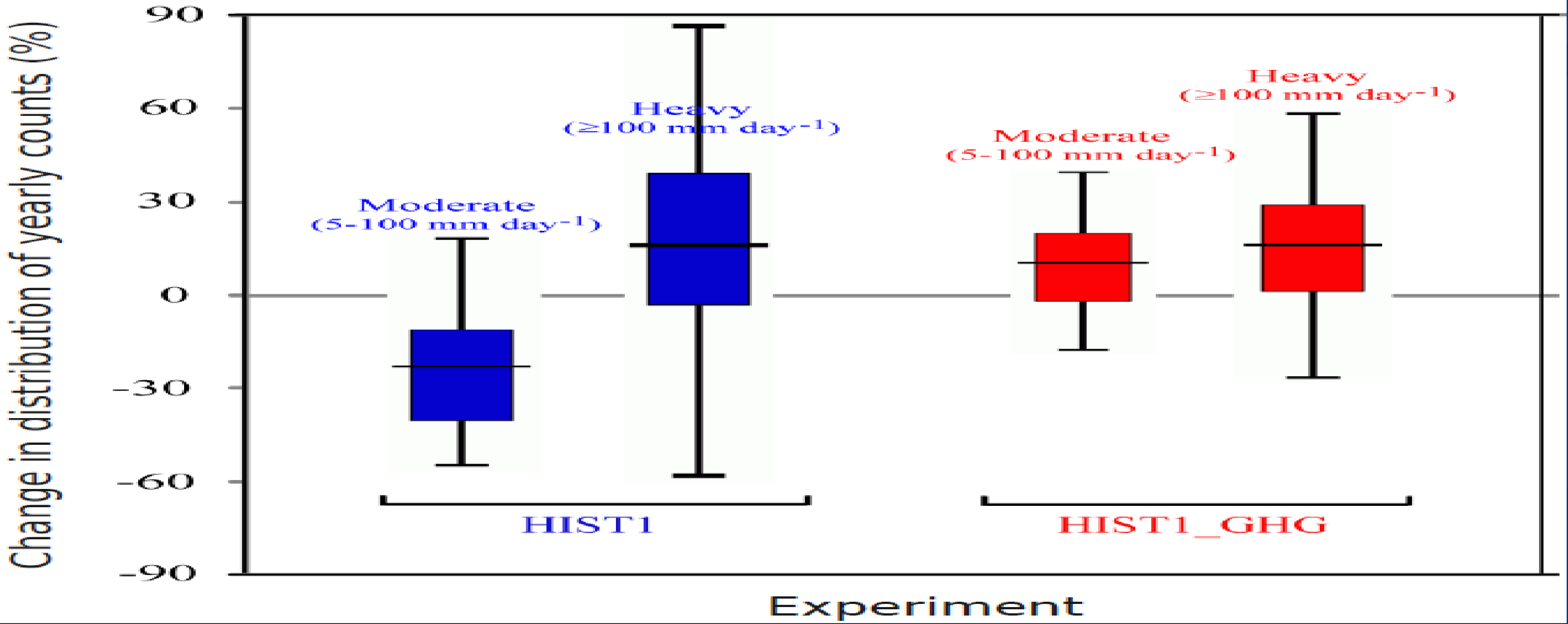



Courtesy: Sabin

# Change in precipitable water w.r.t HISTNAT





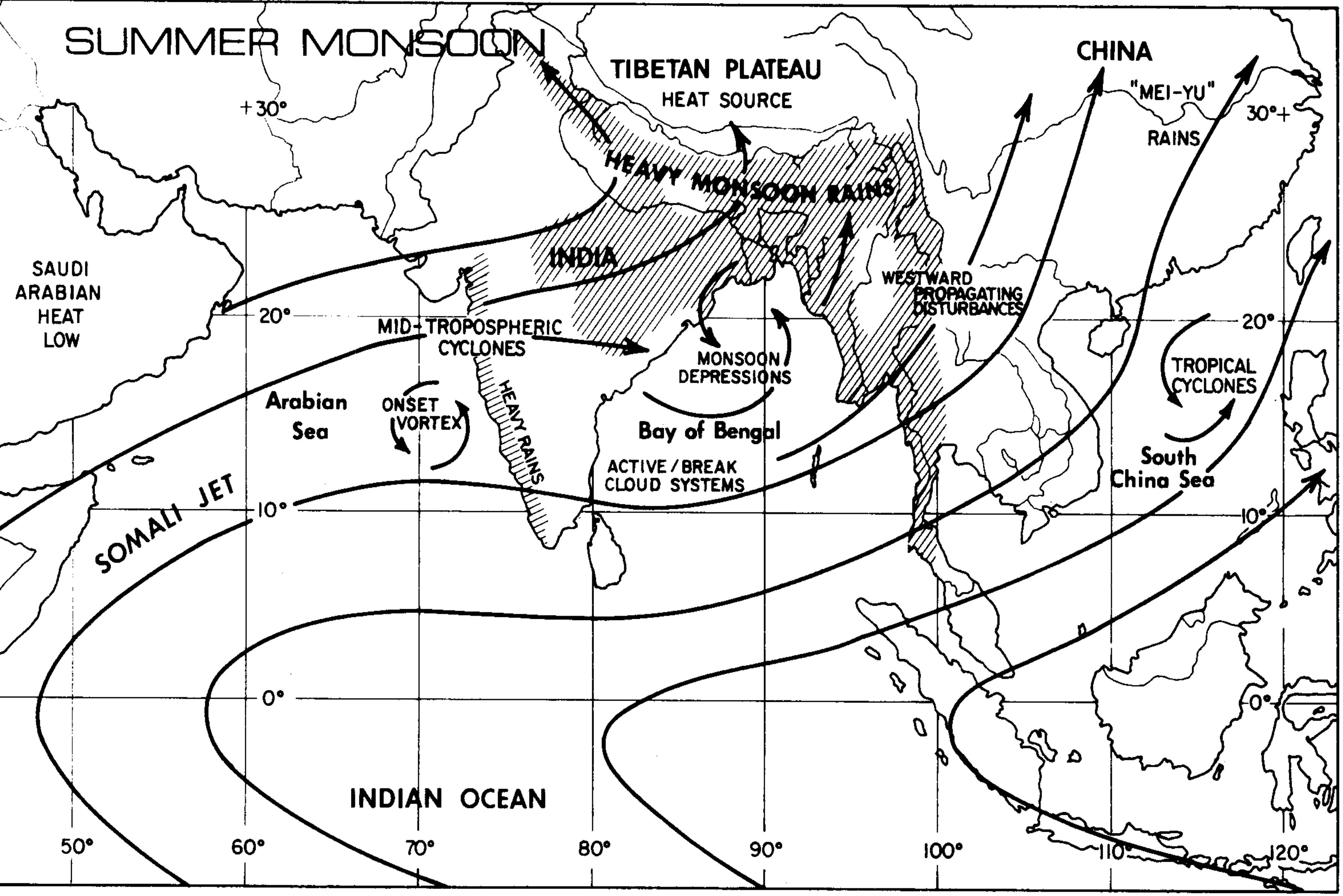



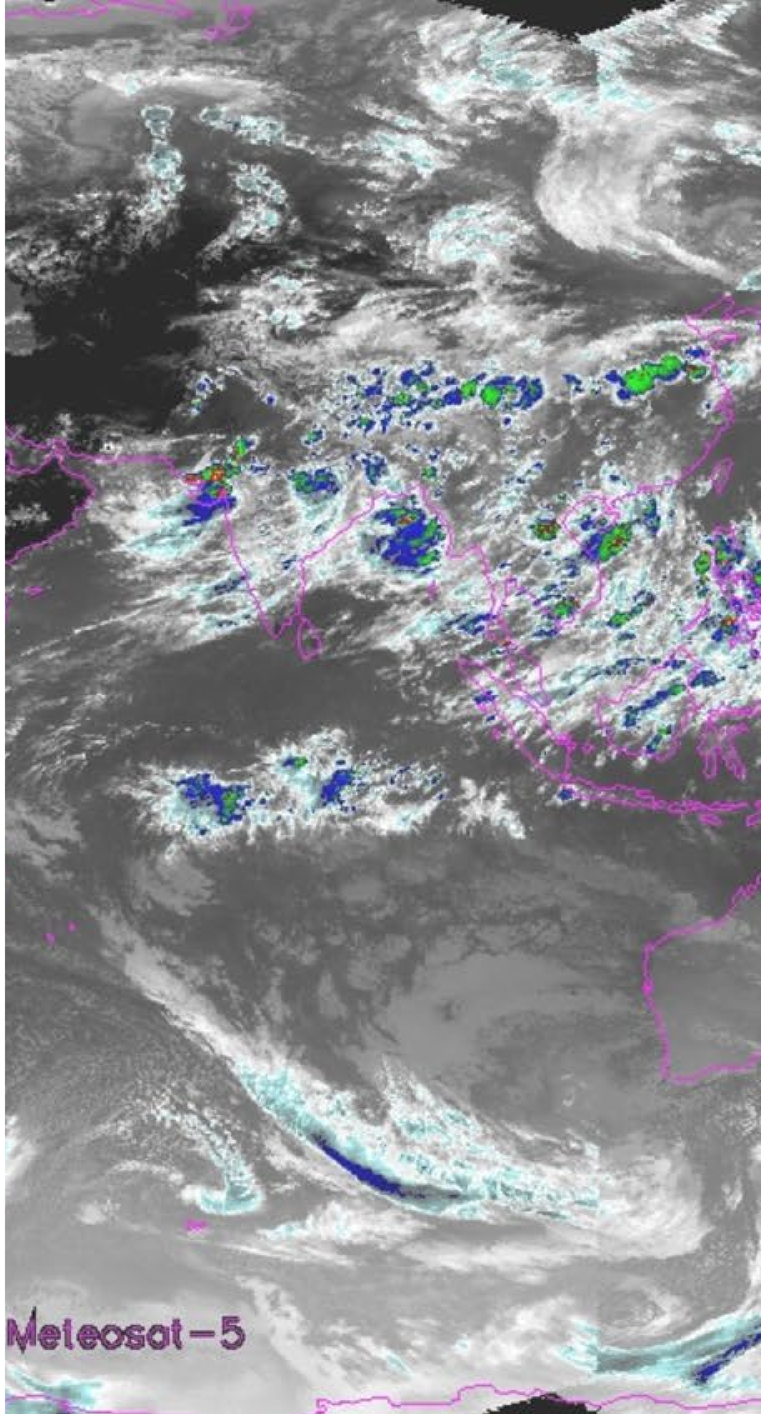

Changes in Heavy & Moderate precipitation types to GHG & regional forcing

Central India: 74.5°E – 86.5°E, 16.5°N - 26.5°N

Period:1951-2000

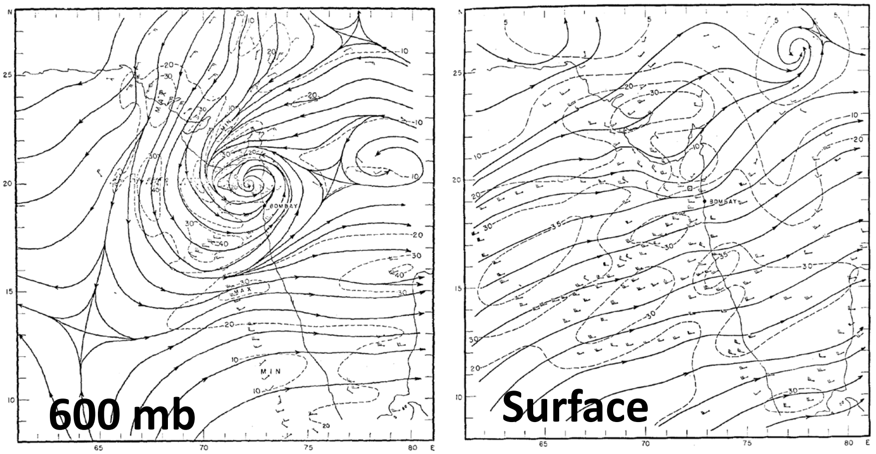
Krishnan et al. 2016



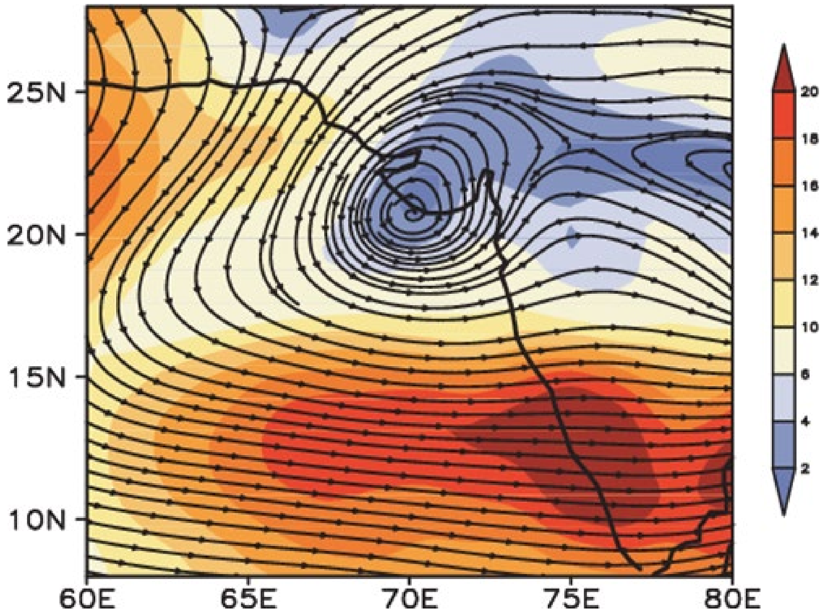




**Primary synoptic and smaller-scale circulation features that affect cloudiness and precipitation in summer monsoon region**. Locations of June to September rainfall exceeding 100 cm over the land west of 100$^{o}$E associated with the southwest monsoon are indicated (from Rao, 1981). (Adapted from Johnson, R. H., and R. A. Houze, Jr., 1987)

2-10 July 1963 MTC (Miller and Keshavamurty 1968)



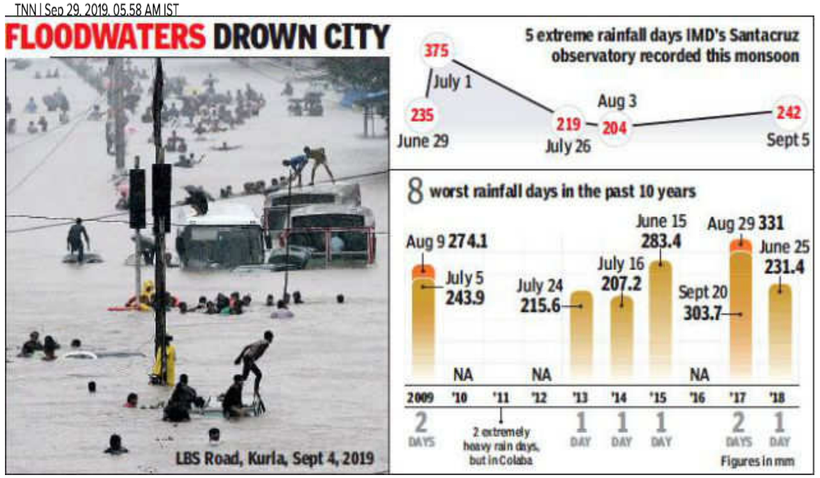

31 Jul-7 Aug 2007 MTC
600 hPa circulation




THE TIMES OF INDIA

## Mumbai: Five extremely heavy rain days in Monsoon 2019 alone, eight in past decade

TNN | Sep 29, 2019, 05.58 AM IST




The city recorded as many as five "extremely heavy" rain days this monsoon when over 200 mm of downpour lashed the city within a 24-hour span and disrupted daily life

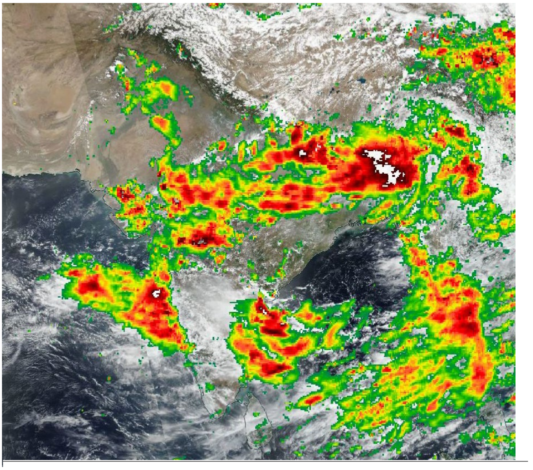
During 29th June, 1st July, 5th September extreme rainfall days a quasi-stationary mid-level cyclonic circulation was located over north Konkan and adjoining south Gujarat region

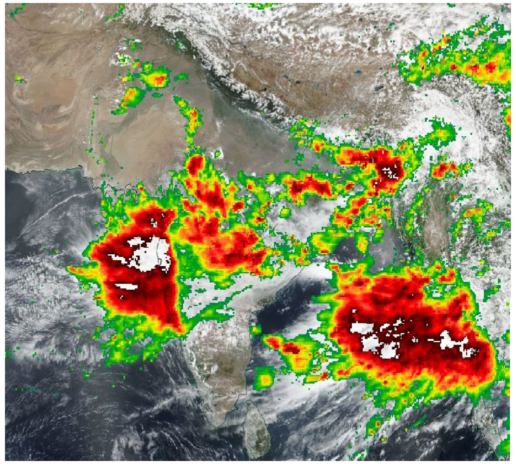
| No. | MTC case | No. of days | Mean rainfall accumulation (cm) | MTC selection |
|---|---|---|---|---|
| 1 | 15–22 Aug 1988 | 8 | 25 | ✓ |
| 2 | 20–25 Aug 1989 | 5 | 33 | ✓ |
| 3 | 11–15 Sep 1989 | 5 | 4 | |
| 4 | 26–30 Jun 1990 | 5 | 44 | ✓ |
| 5 | 13–22 Aug 1991 | 10 | 21 | |
| 6 | 18–25 Jul 1992 | 8 | 58 | ✓ |
| 7 | 18–29 Aug 1993 | 12 | 10 | |
| 8 | 22–30 Aug 1994 | 9 | 46 | ✓ |
| 9 | 14–22 Sep 1994 | 9 | 5 | |
| 10 | 4–8 Jul 1995 | 5 | 4 | |
| 11 | 11–23 Jul 1995 | 13 | 70 | ✓ |
| 12 | 10–20 Aug 1995 | 11 | 6 | |
| 13 | 6–11 Sep 1995 | 6 | 5 | |
| 14 | 20–24 Jul 1996 | 5 | 91 | ✓ |
| 15 | 4–9 Jul 1997 | 6 | 44 | ✓ |
| 16 | 6–11 Sep 1997 | 6 | 19 | |
| 17 | 30 Aug–4 Sep 1998 | 6 | 9 | |
| 18 | 4–8 Aug 1999 | 5 | 27 | ✓ |
| 19 | 2–6 Sep 1999 | 5 | 9 | |
| 20 | 27 Jun–15 Jul 2000 | 19 | 57 | ✓ |
| 21 | 18–24 Aug 2000 | 7 | 22 | |
| 22 | 6–11 Aug 2002 | 6 | 55 | ✓ |
| 23 | 18–27 Sep 2002 | 10 | 3 | |
| 24 | 1–8 Jul 2003 | 8 | 41 | ✓ |
| 25 | 12–19 Jul 2003 | 8 | 40 | ✓ |
| 26 | 1–13 Aug 2003 | 13 | 34 | ✓ |
| 27 | 13–26 Sep 2003 | 14 | 12 | |
| 28 | 29 Jun–8 Jul 2004 | 10 | 28 | ✓ |
| 29 | 12–19 Sep 2004 | 8 | 5 | |
| 30 | 24 Jun–3 Jul 2005 | 10 | 150 | ✓ |
| 31 | 23 Aug–1 Sep 2005 | 10 | 7 | |
| 32 | 28 Jun–4 Jul 2006 | 7 | 83 | ✓ |
| 33 | 31 Jul–7 Aug 2007 | 8 | 91 | ✓ |
| 34 | 27 Jul–5 Aug 2008 | 10 | 54 | ✓ |
| 35 | 12–18 Sep 2008 | 7 | 72 | ✓ |

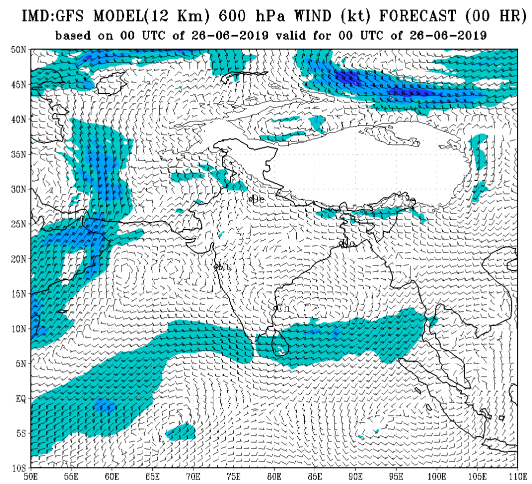
Choudhury et al. 2018, J.Atmos.Sci

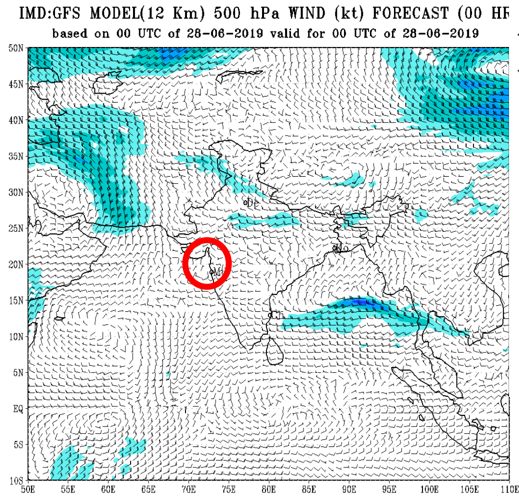
**Courtesy: Ayantika Dey Choudhury**

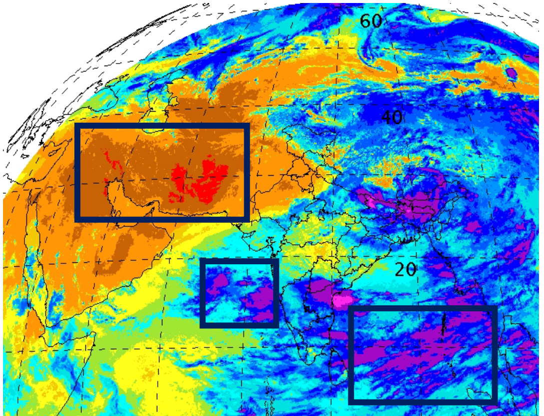
**26th June 2019** | **28th June 2019**

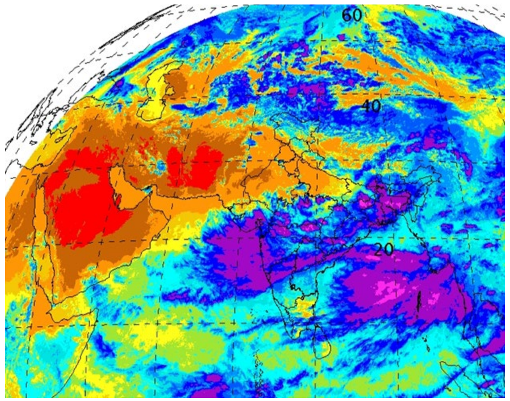




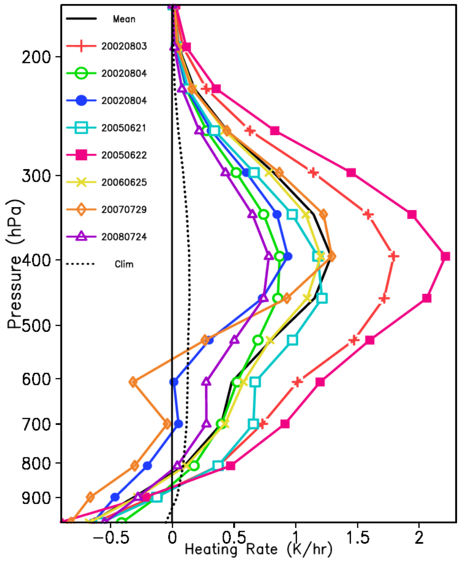


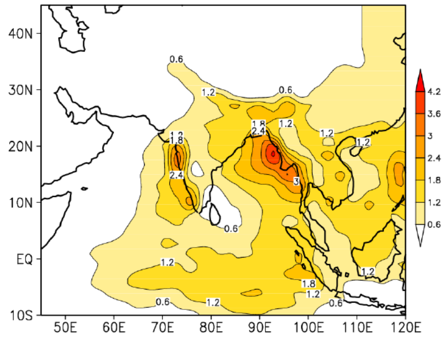

## Snapshots of CSH latent heating over Arabian Sea and Western Ghats (day -3, -2, -1)



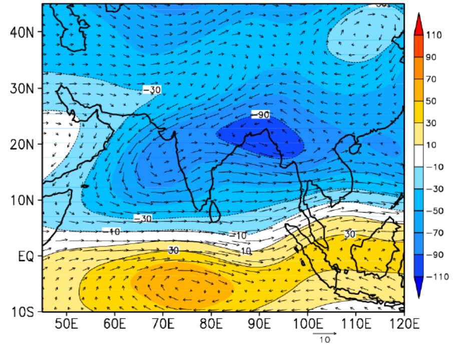

**Choudhury et al. 2018**

# Simplified Atmospheric GCM experiments

Vertically averaged JJAS latent heating derived from TRMM 3A25 rainfall



Control experiment
Mid-tropospheric circulation response

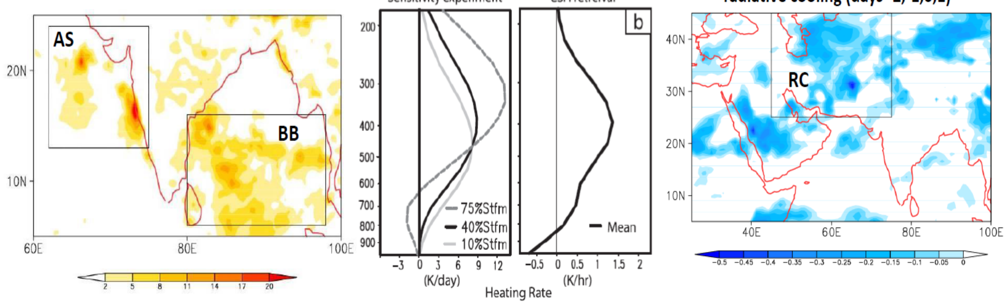


- Heating maxima over Western Ghats and head Bay of Bengal off Myanmar coast
- Enhanced heating in the 10-25 N latitude belt associated with large-scale monsoon convection
- East-west oriented mid-tropospheric cyclonic circulation over monsoon region, with maxima over head Bay

## Phenomenological model synthesis for MTC genesis

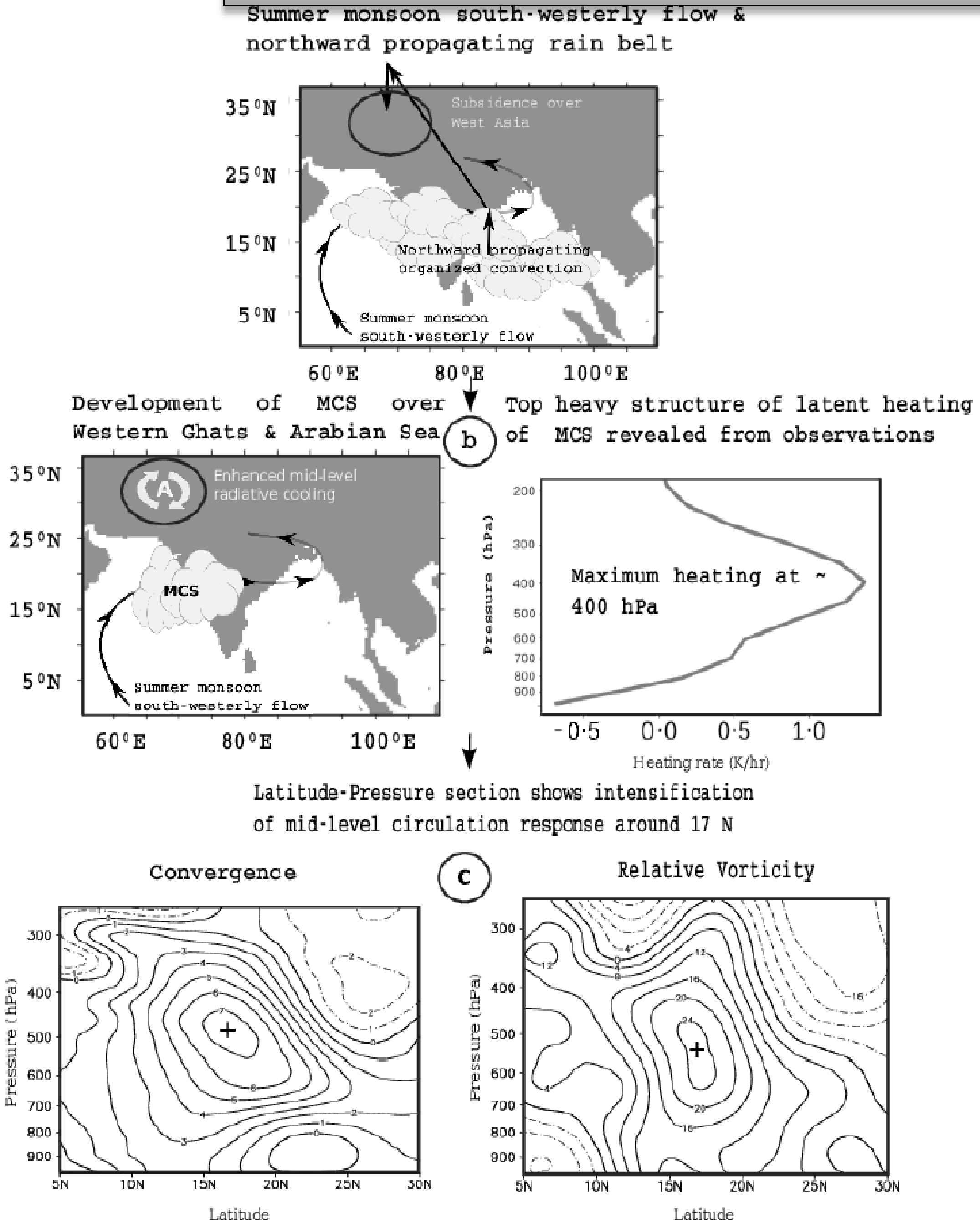
### Model sensitivity experiments

Anomaly composite of rainfall (days -3,-2,-1) | Vertical structure of heating | Anomaly composite of mid-level radiative cooling (days -2,-1,0,1)




| Exp | Heating anomaly superposed on JJAS Climatological Heating |
|---|---|
| AS | Enhanced Arabian Sea MCS LH (40 % stratiform) |
| ASRC | Enhanced Arabian Sea MCS LH + West Asia RC anomaly |
| ASRCBB | Enhanced Arabian Sea MCS LH + West Asia RC anomaly + Enhanced Bay of Bengal MCS LH |

# A conceptual sequence of mechanisms /processes leading to development of MTC




Formation of MTCs have a dependence on slow northward propagating monsoon rain belt enriched with mesoscale precipitating systems

Top heavy heating from stratiform precipitating systems plays a pivotal role

Maximum vertical gradient of heating at mid tropospheric levels generate a mid tropospheric cyclonic vortex directly, thereafter intensification occurs through mid-level convergence and stretching

*Journal of Atmospheric Sciences, September 2018*

## Future Plans: High resolution (27 km grid) global climate model (T574)

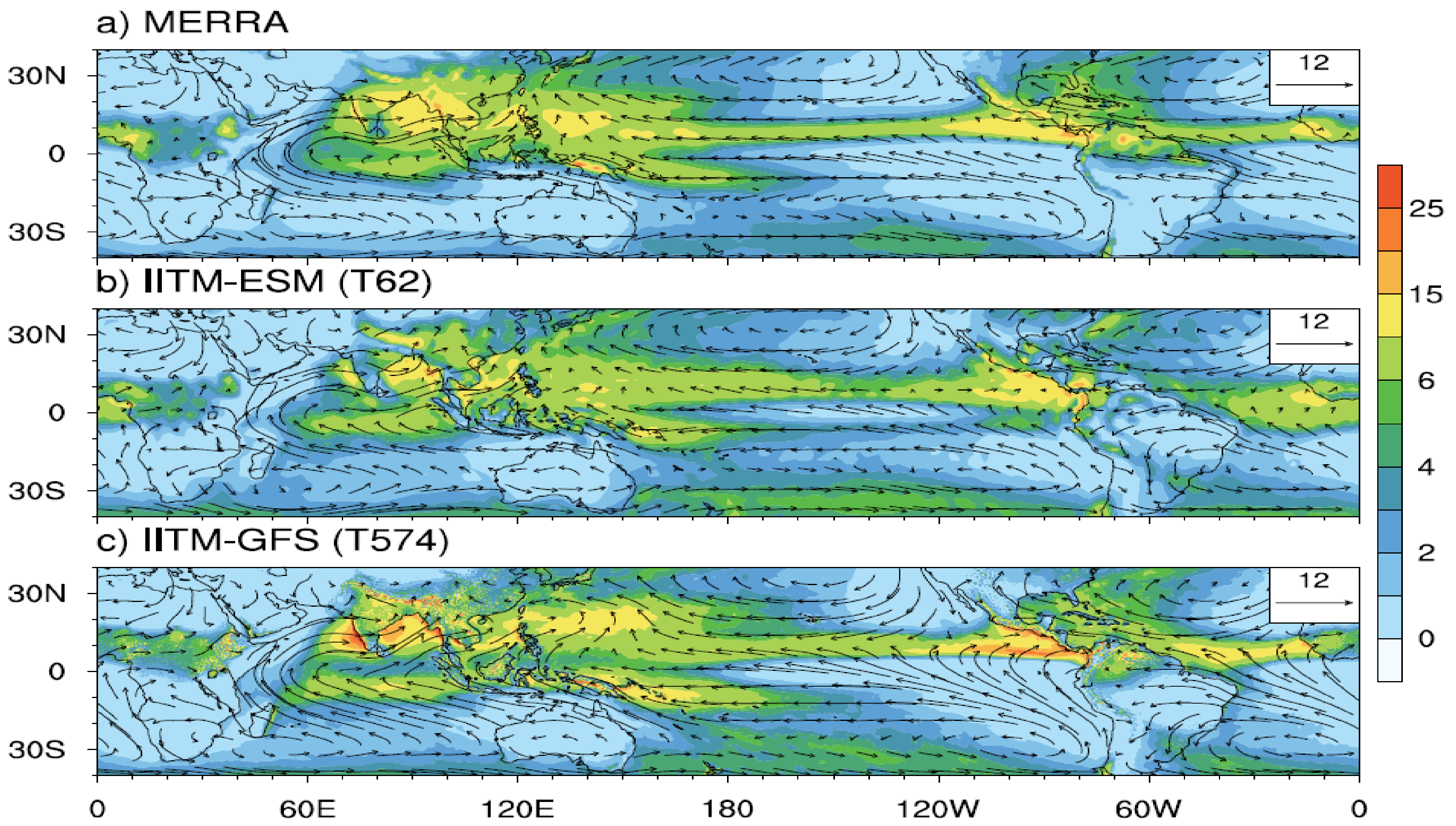
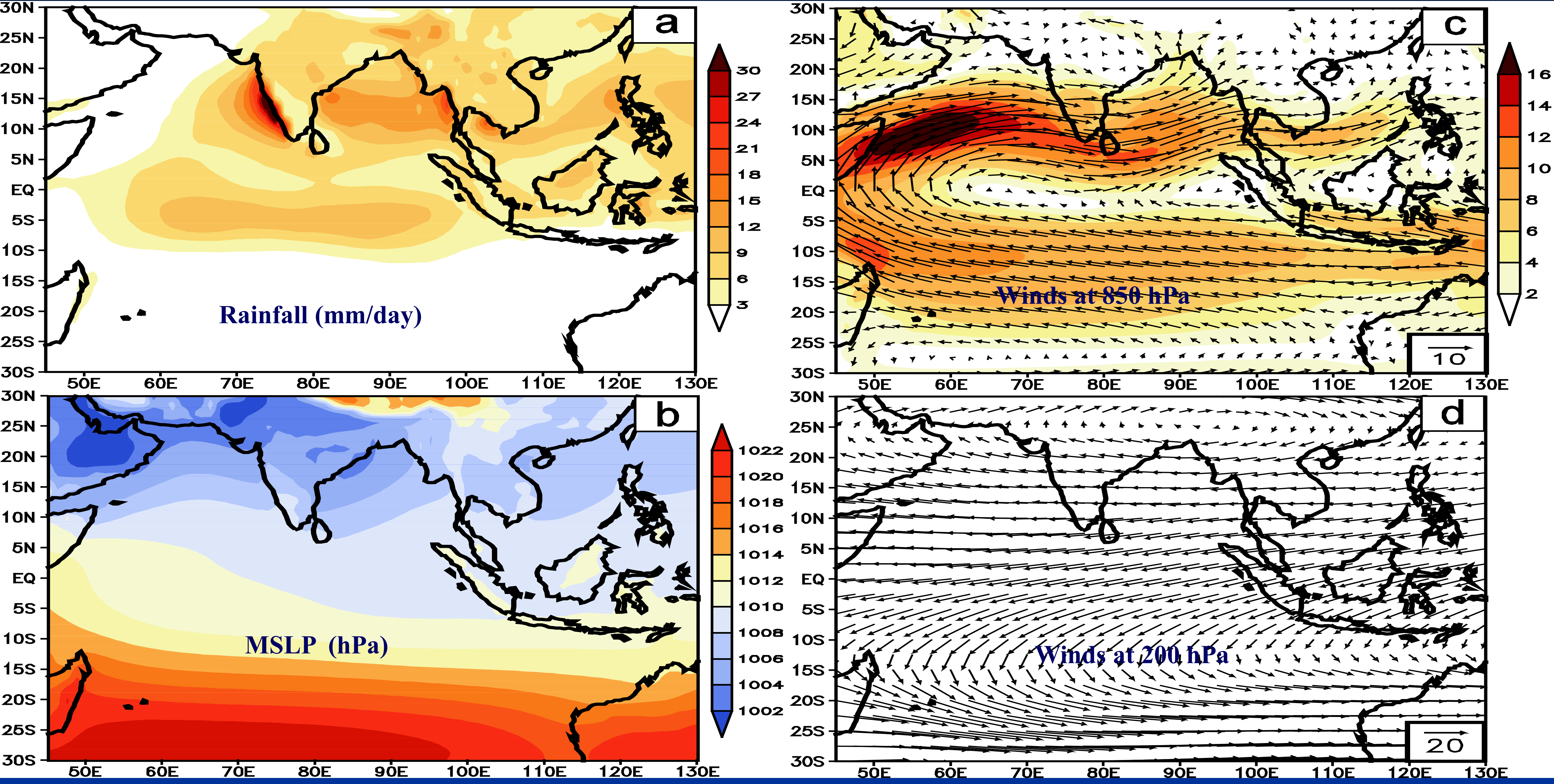



**Figure.** Spatial maps of climatological mean precipitation (mm day$^{-1}$) and 850 hPa winds during the boreal summer monsoon (June – September) season **(a)** TRMM precipitation and MERRA reanalysis winds **(b)** IITM-ESMv2 (PI control simulation) and **(c)** High-resolution (T574: 27 km grid) atmospheric-only version of IITM-ESMv2. The simulated means are based on the last 50 years of the PI Control experiment and 10 years from high-resolution atmospheric-only version of IITM-ESMv2.

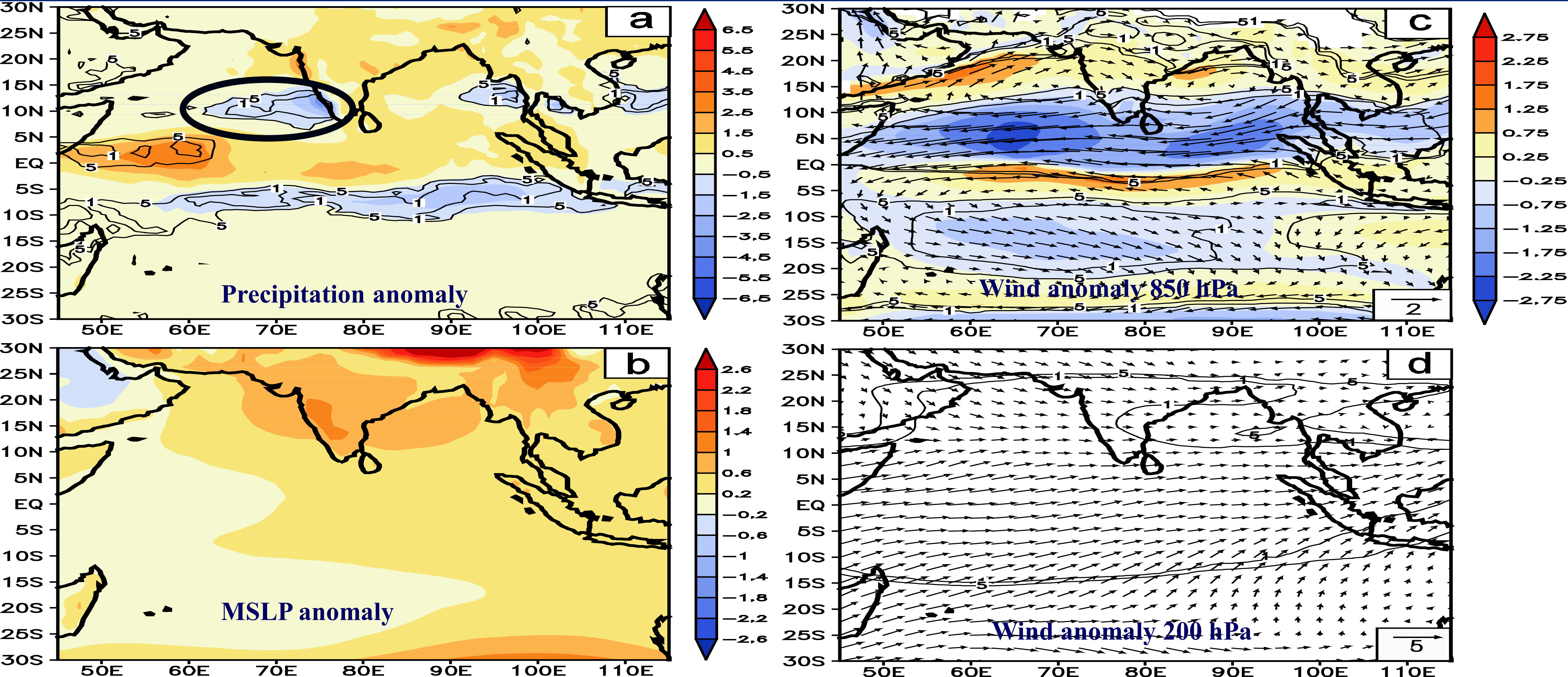
# Simulation of present-day monsoon climate (PDC): MRI 20-km global model (Kitoh and Kusunoki, 2009, Krishnan et al. 2013)



# Simulated changes in South Asian Monsoon: A1B scenario (MRI 20-km GCM)

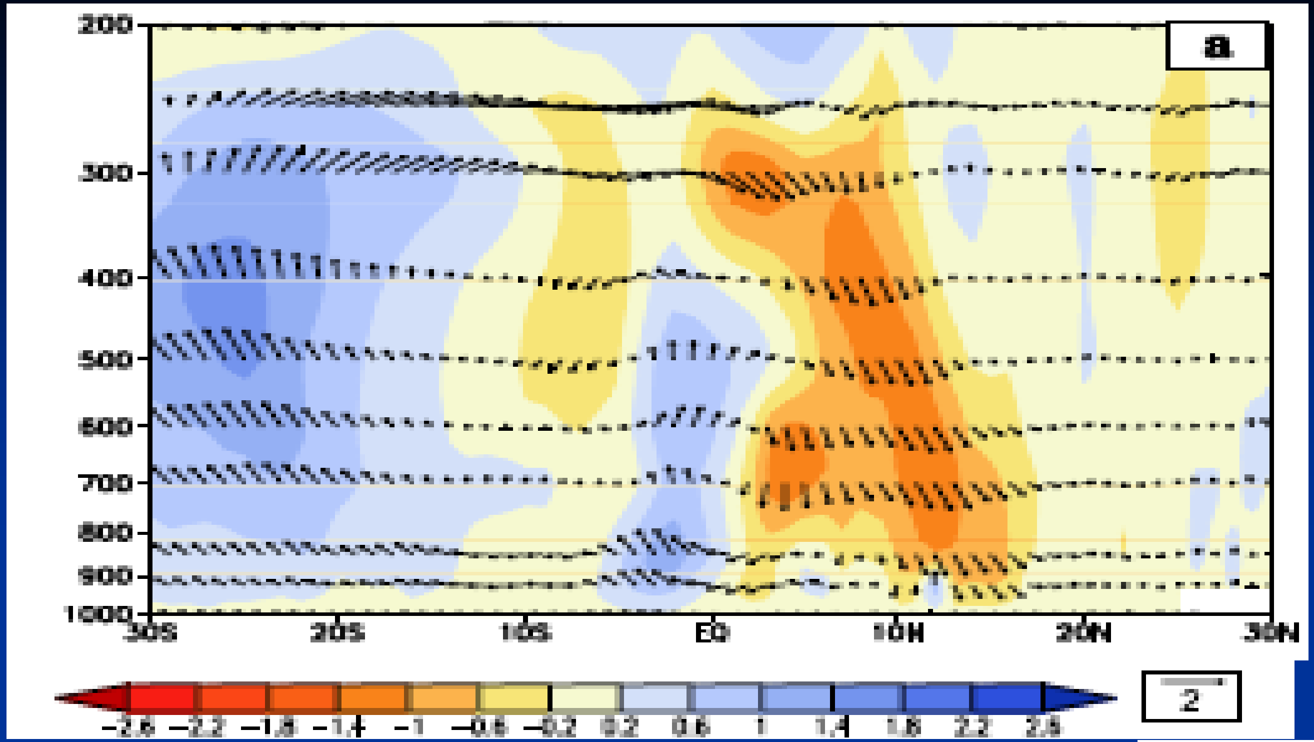
## Future (2075 – 2100) – Present (1979 – 2003)

**Weakening of monsoon winds and decrease of precipitation over southern Western Ghats**



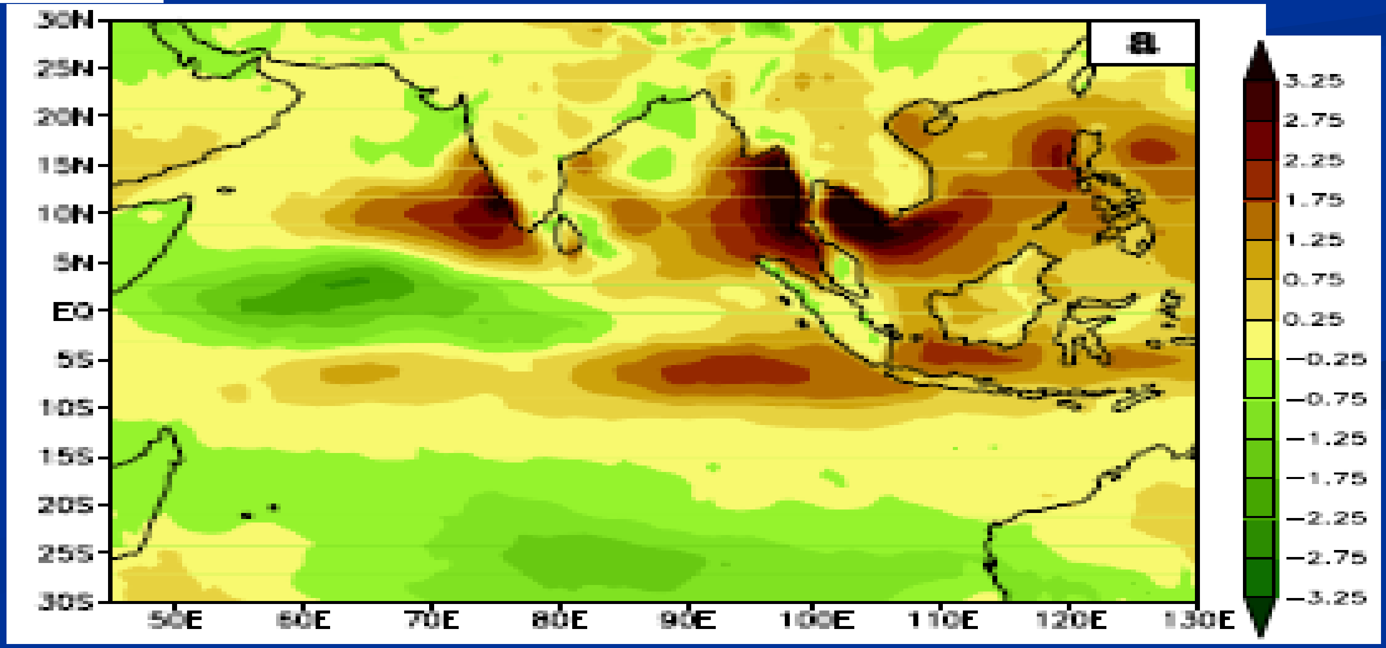
# Large-scale circulation changes

# Future (GWC) – Present (PDC)

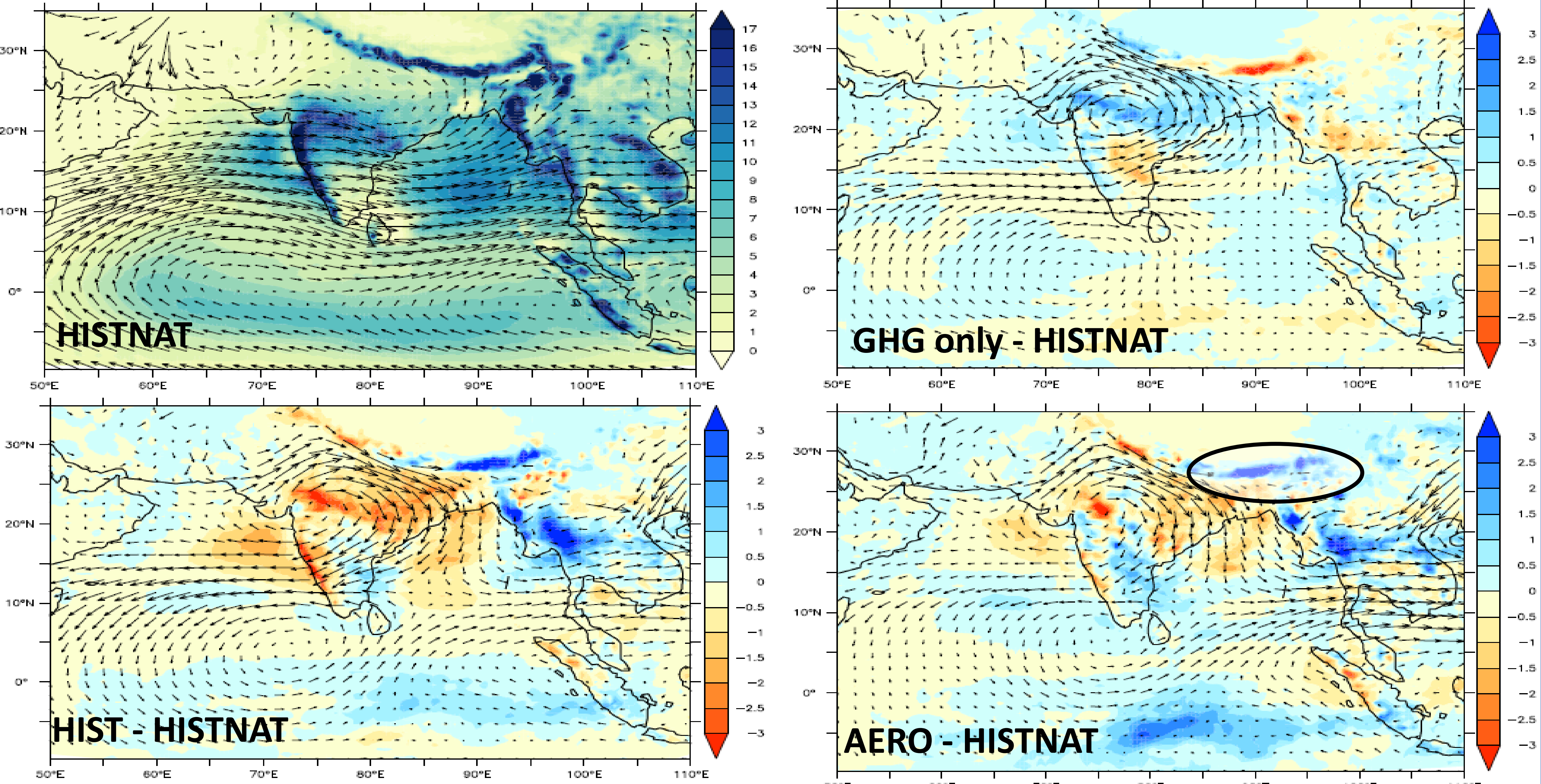



Weakening of the Monsoon Hadley-type circulation (60 E – 100E). Shading is for change in vertical velocity (–ω x 100)

Vertical velocity (+ω x 100) at 500 hPa. Weakening of vertical motions



# Simulation of summer monsoon precipitation & 850 hPa circulation (LMDZ – Zoom setup grid < 35 km)



## Shige et al. 2017 : Role of orography, diurnal cycle and intraseasonal oscillation in summer rainfall over the Western Ghats and Myanmar Coast

JJA mean precipitation (mm month$^{-1}$) TRMM PR 2A25 V7

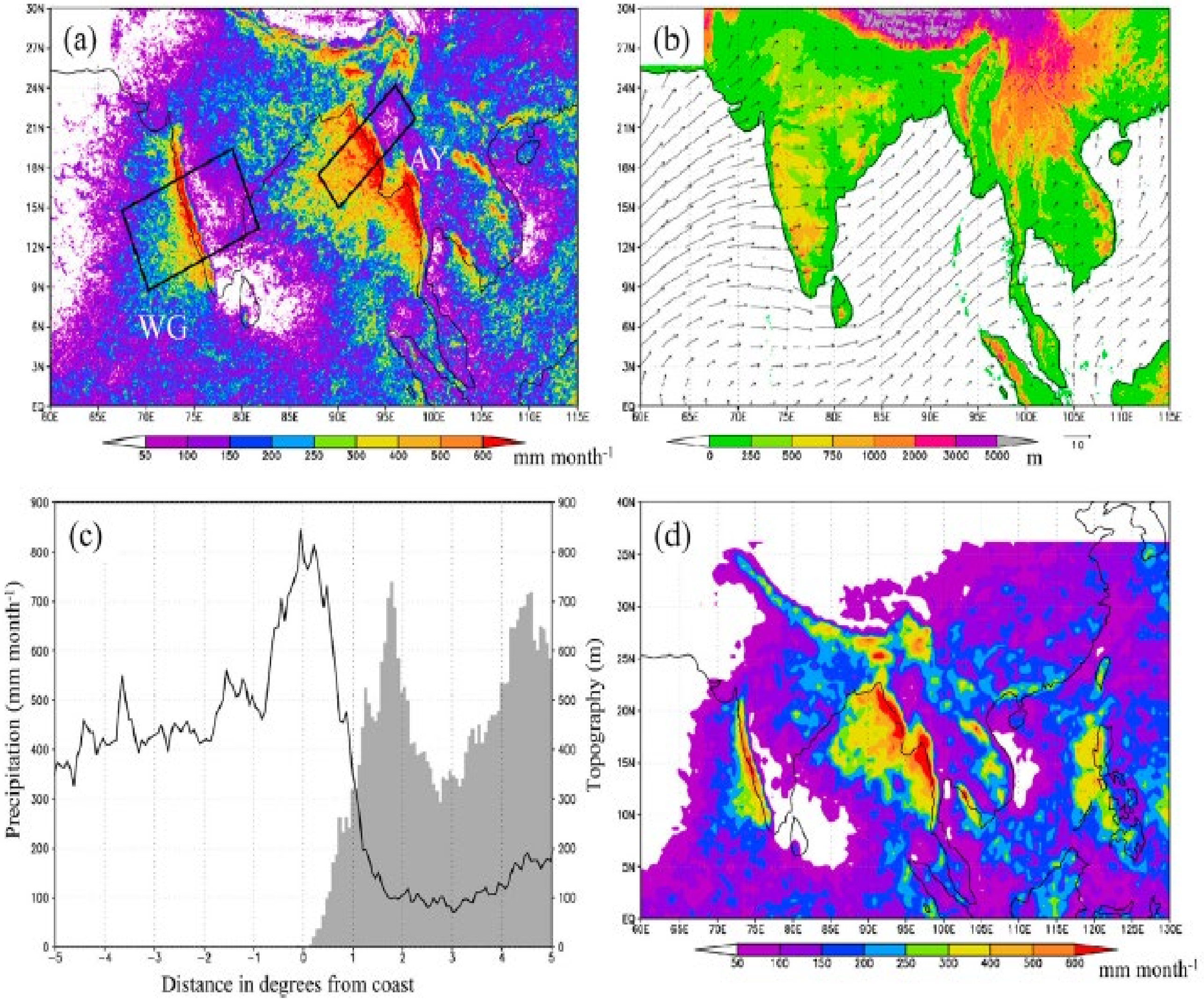
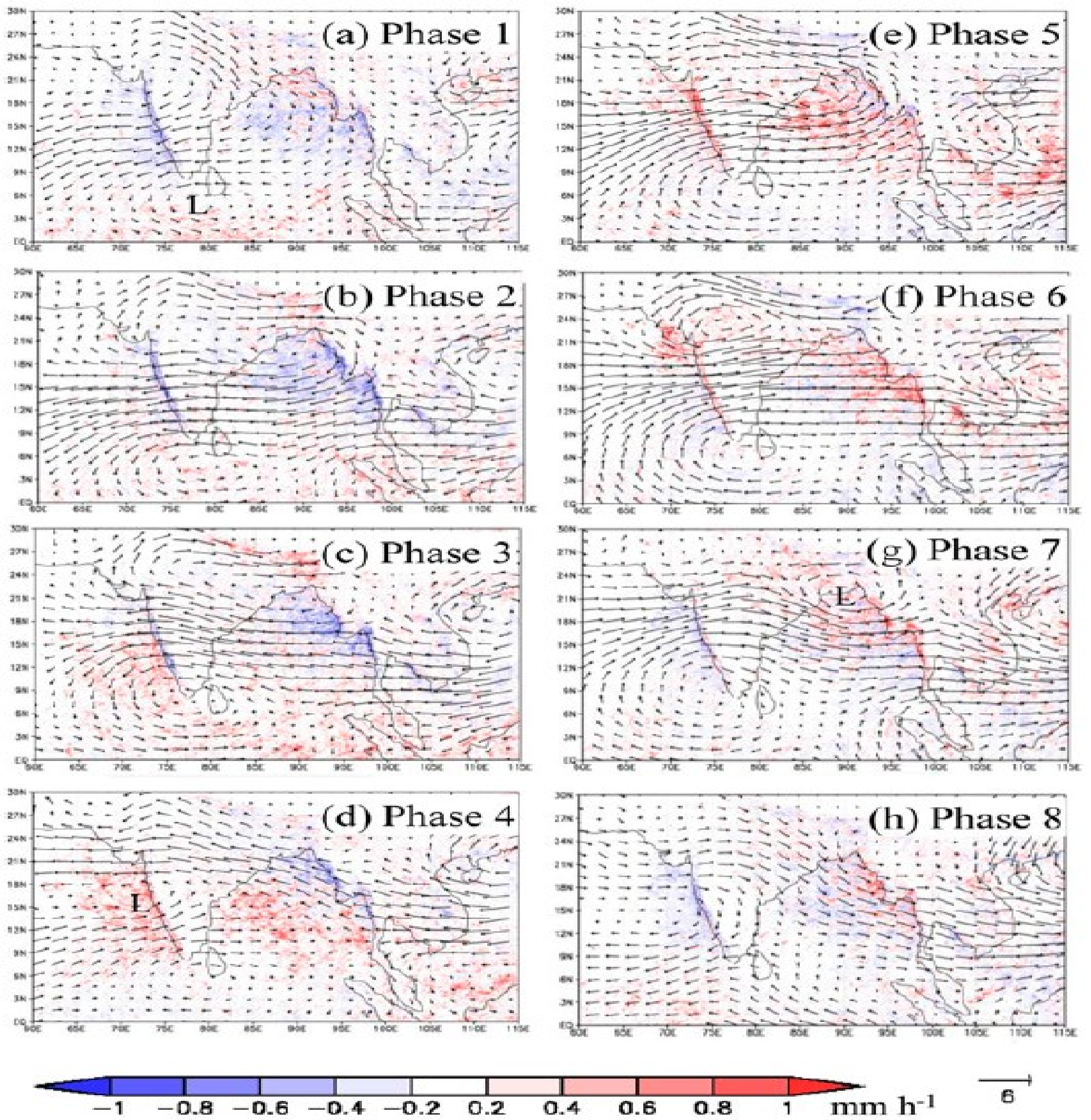



FIG. 1. June–August climatologies of (a) surface precipitation (mm month$^{-1}$) at 0.05° resolution using the TRMM PR 2A25 V7 data and (b) 850-hPa wind vectors (m s$^{-1}$) from ERA-Interim with orography (m) for a 16-yr period (1998–2013). The coastal regions of western India [Western Ghats (WG)] and Myanmar [Arakan Yoma (AY)] are indicated by the black boxes in (a). (c) Cross-shore distributions of precipitation (black line; mm month$^{-1}$) and topography (gray bars; m) averaged across the AY region. (d) The 7-yr (1998–2004) averaged June–August climatologies of surface precipitation at 0.5° resolution from the TRMM PR 2A25 V6 data.




Anomalies of PR-rainfall and 850 ERA-Interim wind vectors during the eight phases of the BSISO

# Summary

•Influence of climate change on the Indian summer monsoon ?

•Observations indicate a decreasing trend of summer monsoon precipitation averaged over whole of India about 7%, with notable decrease over the Indo-Gangetic plains and Western Ghats, since 1950 and a clear increasing trend in the occurrence of localized heavy rainfall ( > 100 mm $day^{-1}$) over Central India.

•Emerging consensus from climate model simulations and multiple datasets that NH anthropogenic aerosol forcing have largely influenced the recent decline of monsoon precipitation by offsetting the expected increase in precipitation due to GHG warming.

•Aerosols induce large-scale cooling over NH & continental Eurasia. Energy imbalance weakens the monsoon via mid-latitude circulation anomalies.

•Increase in frequency of heavy precipitation (R > 100 mm/day) occurrences over Central India is projected in response to increasing atmospheric moisture in a globally warming world.

•**Challenges ahead:** **(a)** Monsoon: Multi-scale interactive phenomenon **(b)** Strong internal variability **(c)** Large uncertainties in model projections **(c)** Monsoon precipitation extremes strong links to circulation, organized convection, remote teleconnections, etc.

•**Way forward:** Improve representation of organized monsoon convection in climate models, warm rain processes, orographic precipitation over WG, Myanmar, Himalayas, moist-convective processes, interactive feedbacks: clouds-aerosols-radiation-precipitation, latent heating and circulation, atmosphere-ocean-land coupling, among others.

**Thanks for your kind attention!**