Indian Monsoon
Basic Drivers and Variability

GOTHAM International Summer School

PIK, Potsdam, Germany, 18-22 Sep 2017

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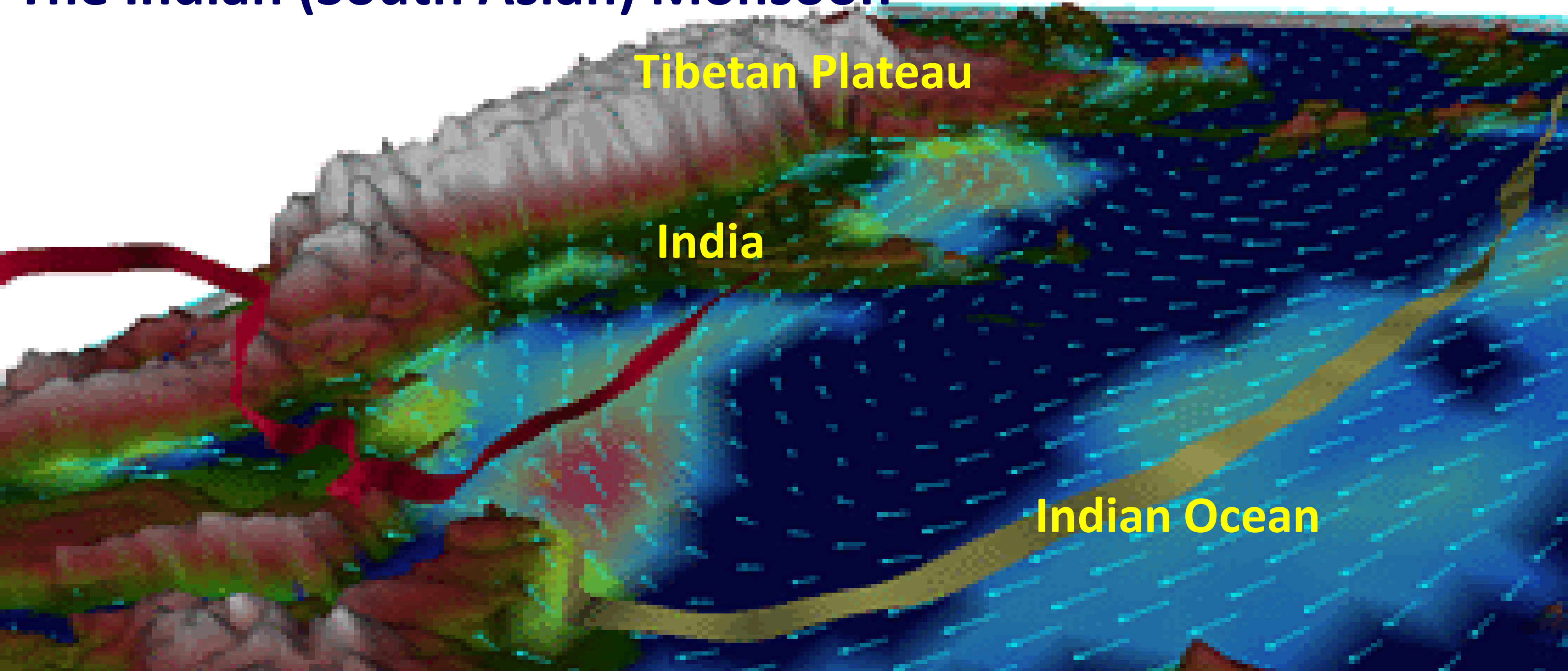
Indian Institute of Tropical Meteorology, Pune, India

The Indian (South Asian) Monsoon

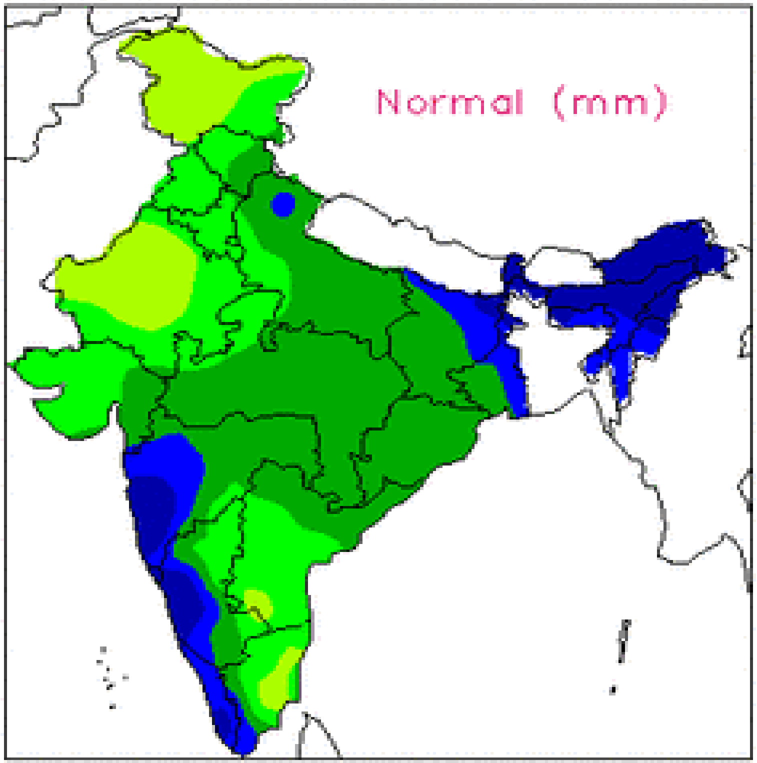


Monsoon circulation and rainfall: **A convectively coupled phenomenon**

Requires a thermal contrast between land & ocean to set up the monsoon circulation

Once established, a positive feedback between circulation and latent heat release maintains the monsoon

The year to year variations in the seasonal (June – September) summer monsoon rains over India are influenced internal dynamics and external drivers

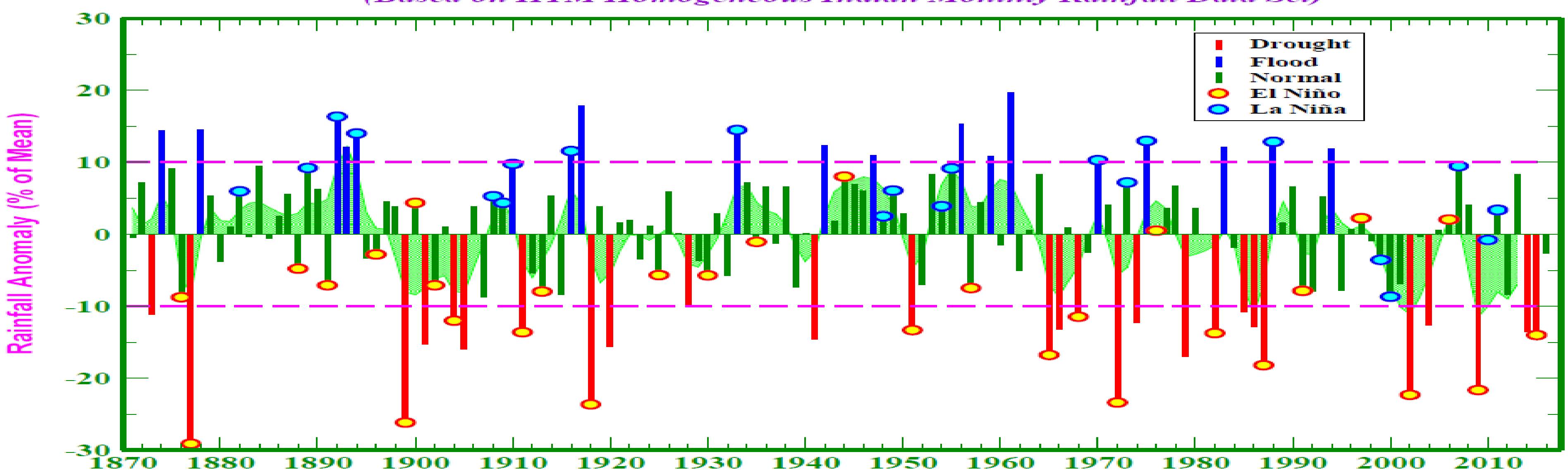


Long-term climatology of total rainfall over India during (1 Jun - 30 Sep) summer monsoon season (http://www.tropmet.res.in)

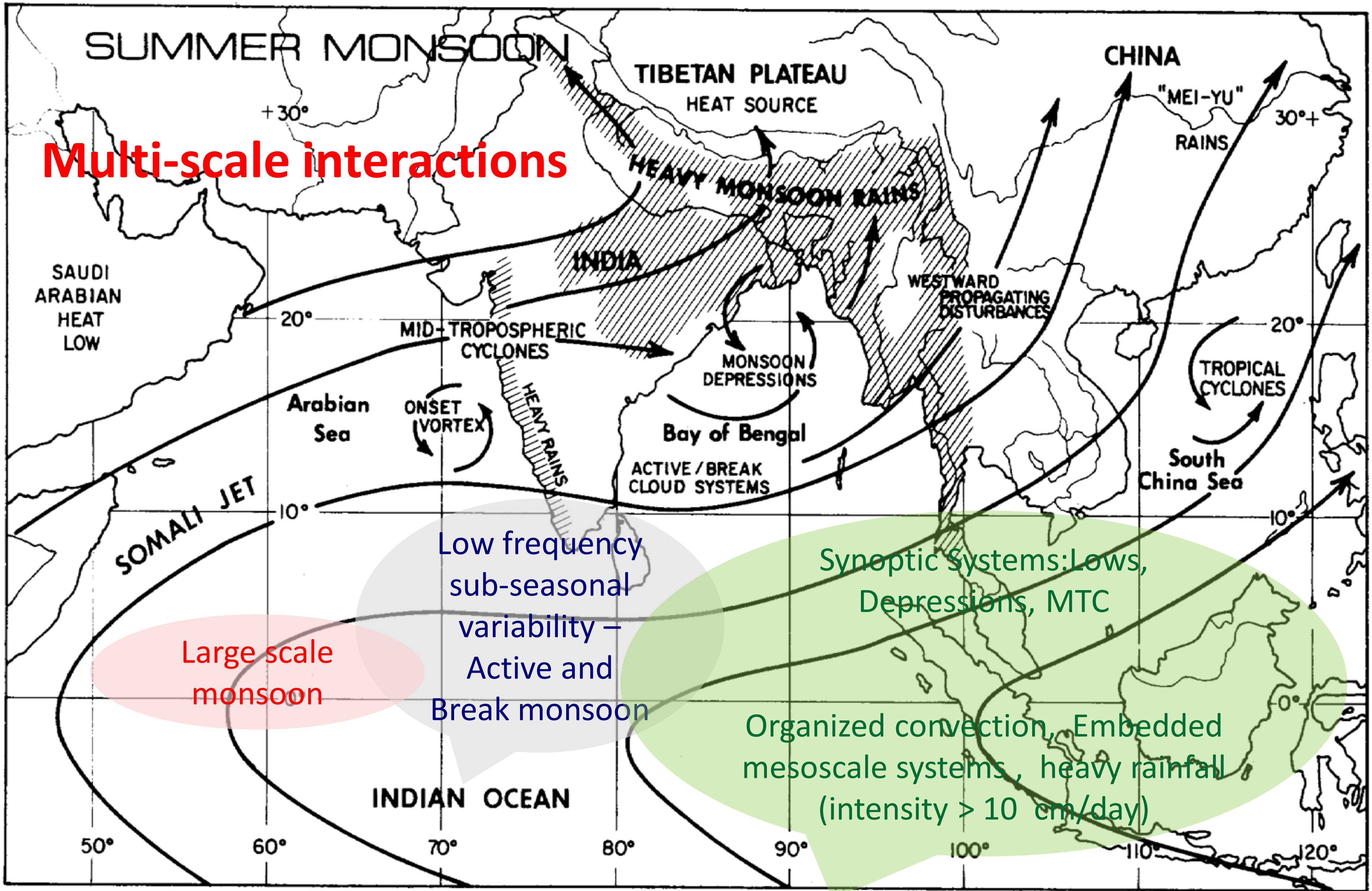
Interannual variability of the Indian Summer Monsoon Rainfall

All-India Summer Monsoon Rainfall, 1871-2016

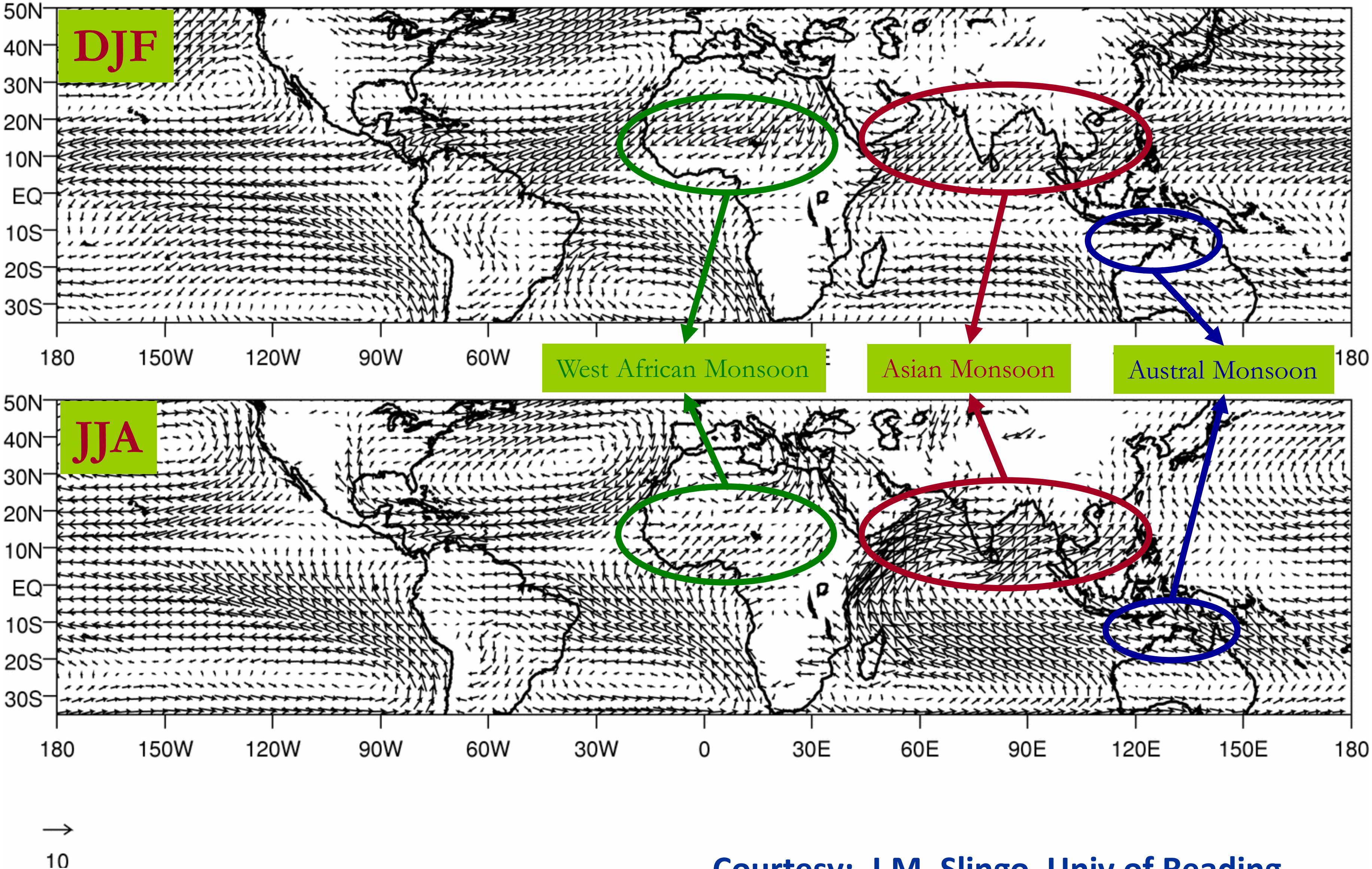
(Based on IITM Homogeneous Indian Monthly Rainfall Data Set)



Primary synoptic & smaller scale circulation features that affect cloudiness & precipitation. Locations of **June to September** rainfall exceeding 100 cm over the land west of 100°E associated with the southwest monsoon are indicated (**Source: Rao, 1981**).

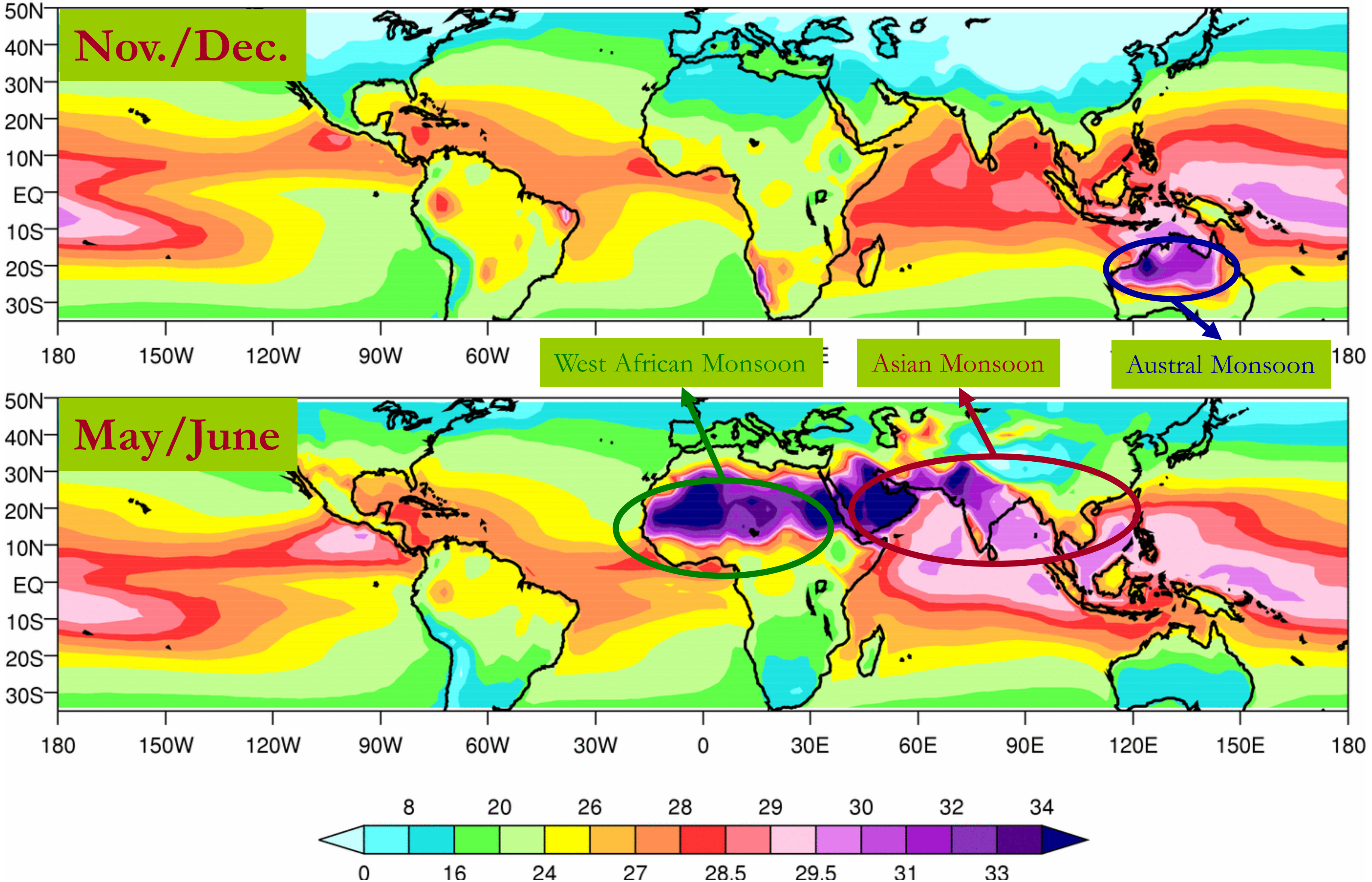


Winds at 925hPa



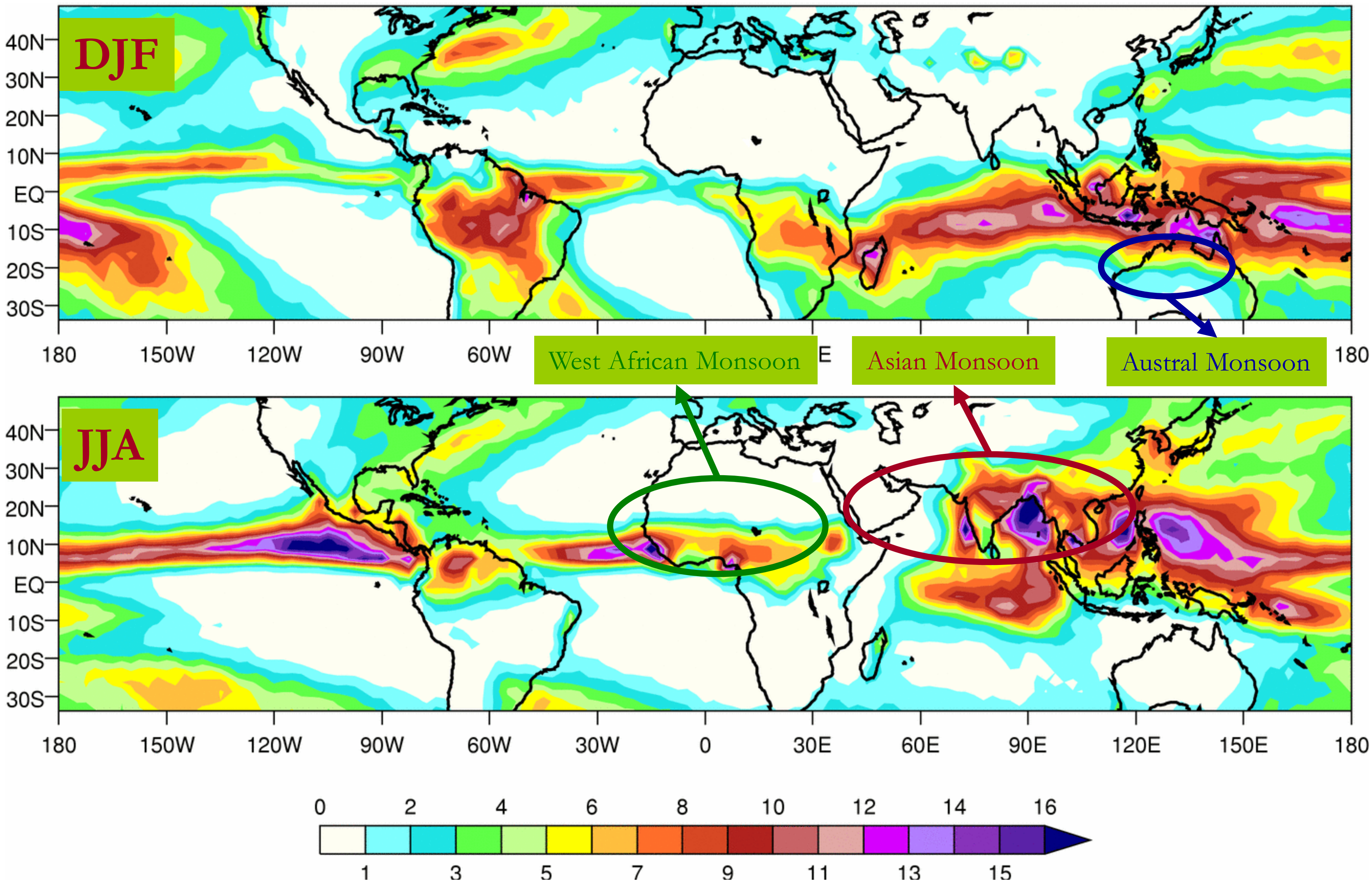
Courtesy: J.M. Slingo, Univ of Reading

Land/Sea Temperature contrasts



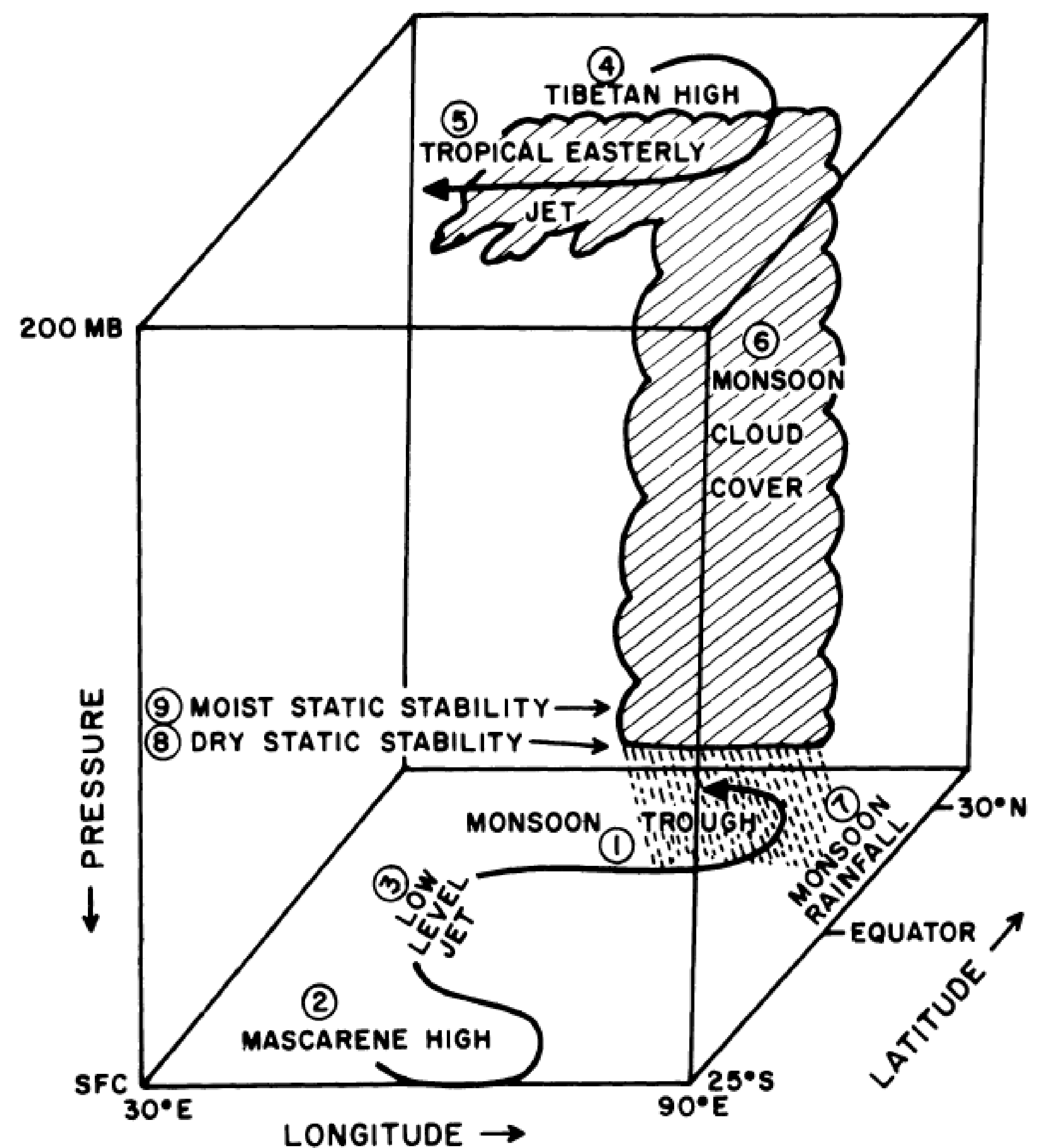
Courtesy: J.M. Slingo, Univ of Reading

Rainfall (mm/day)

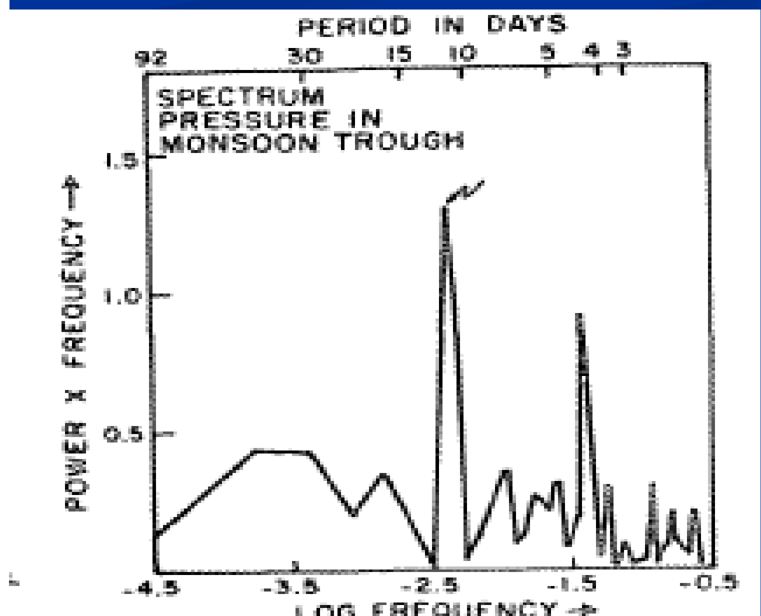


Courtesy: J.M. Slingo, Univ of Reading

Krishnamurti and Bhalme (1976): Schematic diagram of the salient elements of the monsoon system



A quasi biweekly oscillation can be seen in almost all the elements of the Monsoon system

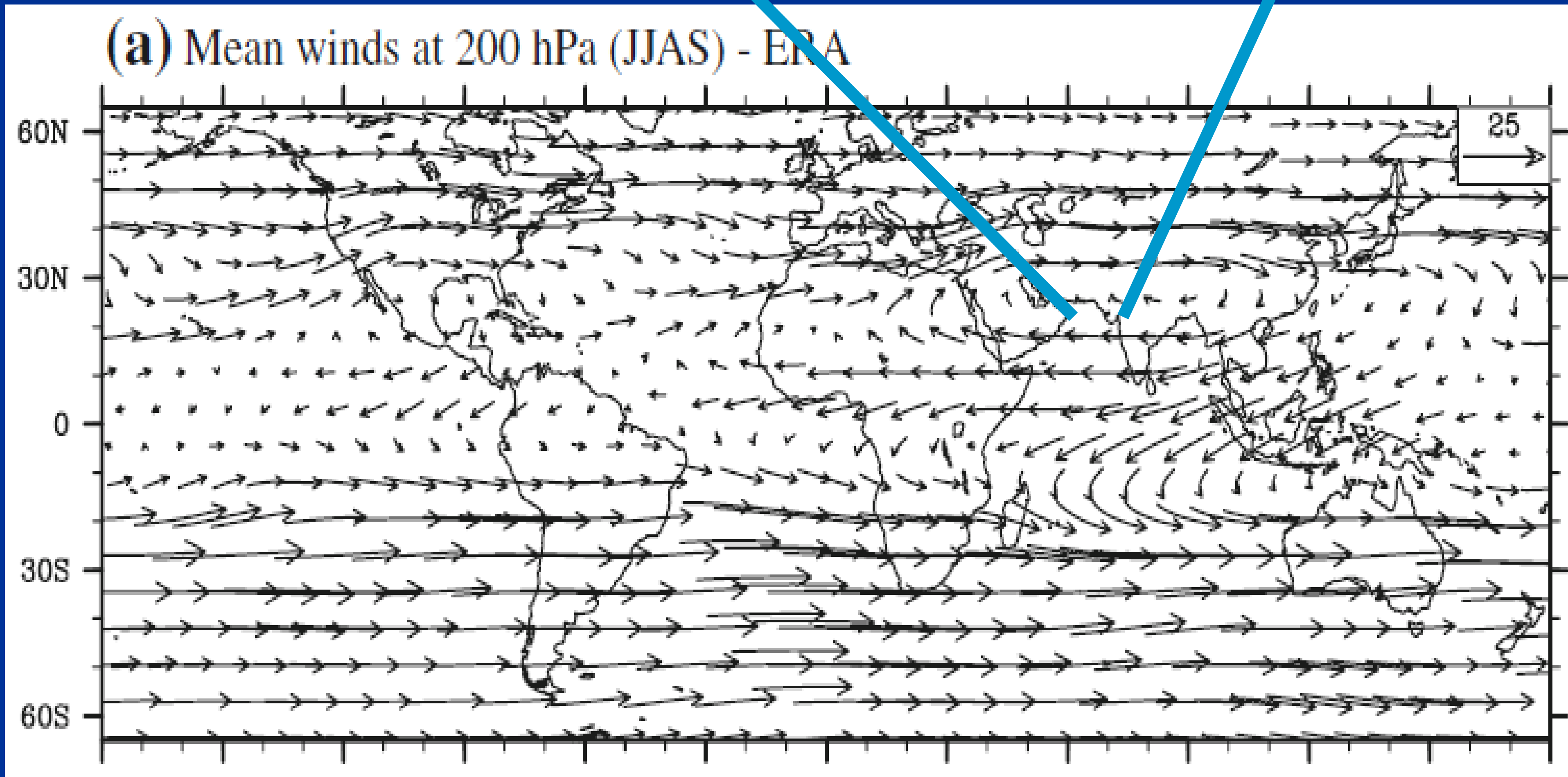


Planetary scale structure of the northern summer monsoon circulation at 200 hPa (upper troposphere)

Global scale divergent circulation identified by TN Krishnamurti (1971)

Tibetan Anticyclone

Tropical Easterly Jet

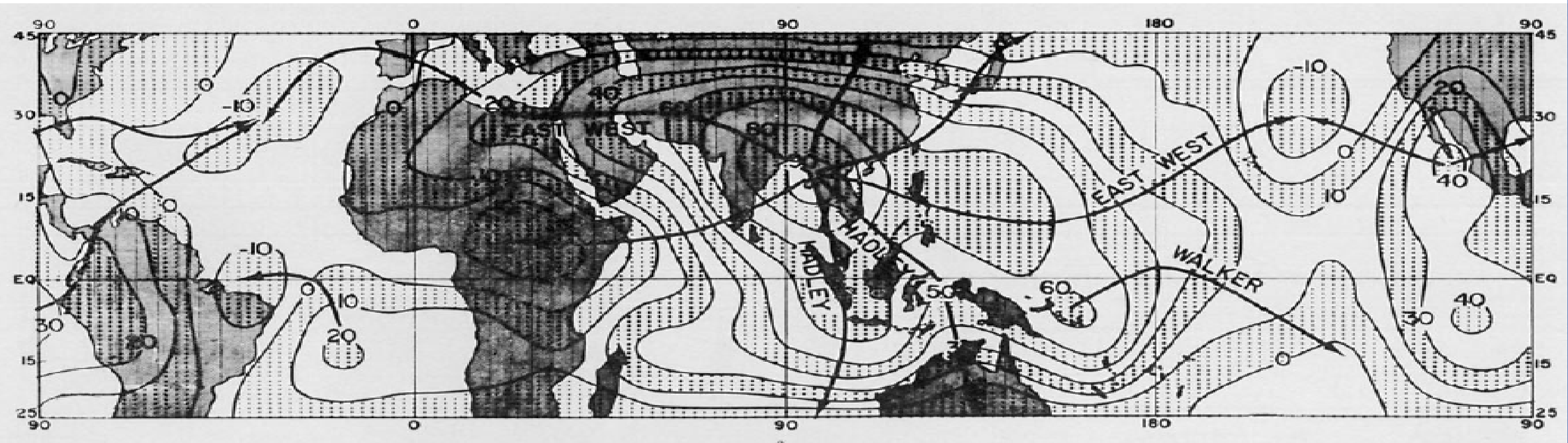


TN.Krishnamurti (1971): Tropical East-West Circulations during the Northern Summer. JAS

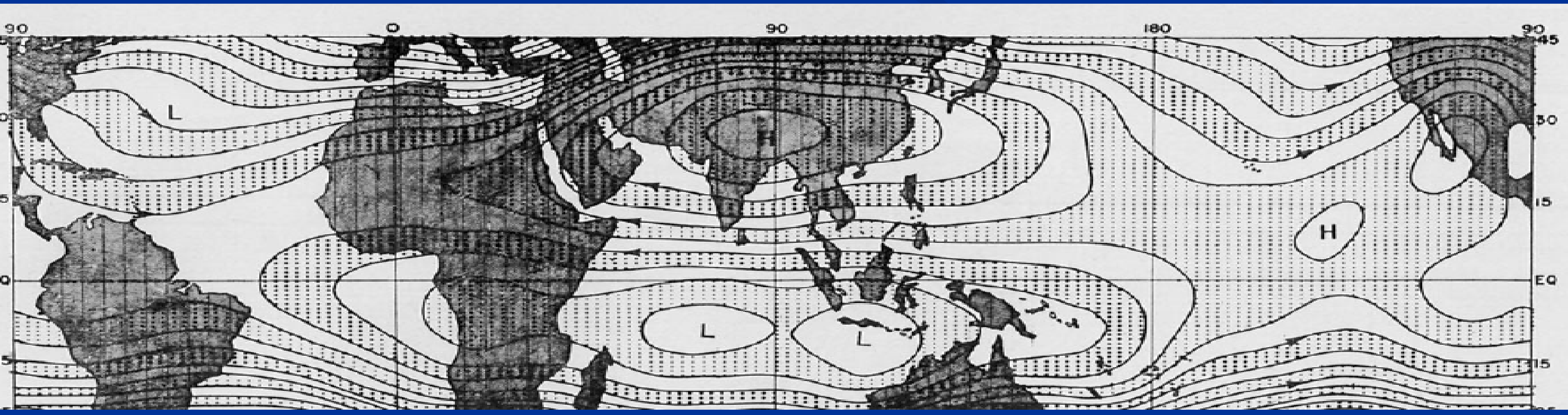
Helmoltz decomposition of wind field into rotational & divergent components

$$\mathbf{V} = \mathbf{k} \times \nabla\psi + \nabla\chi,$$

Velocity Potential at 200 hPa depicting Divergent component of summer monsoon circulation

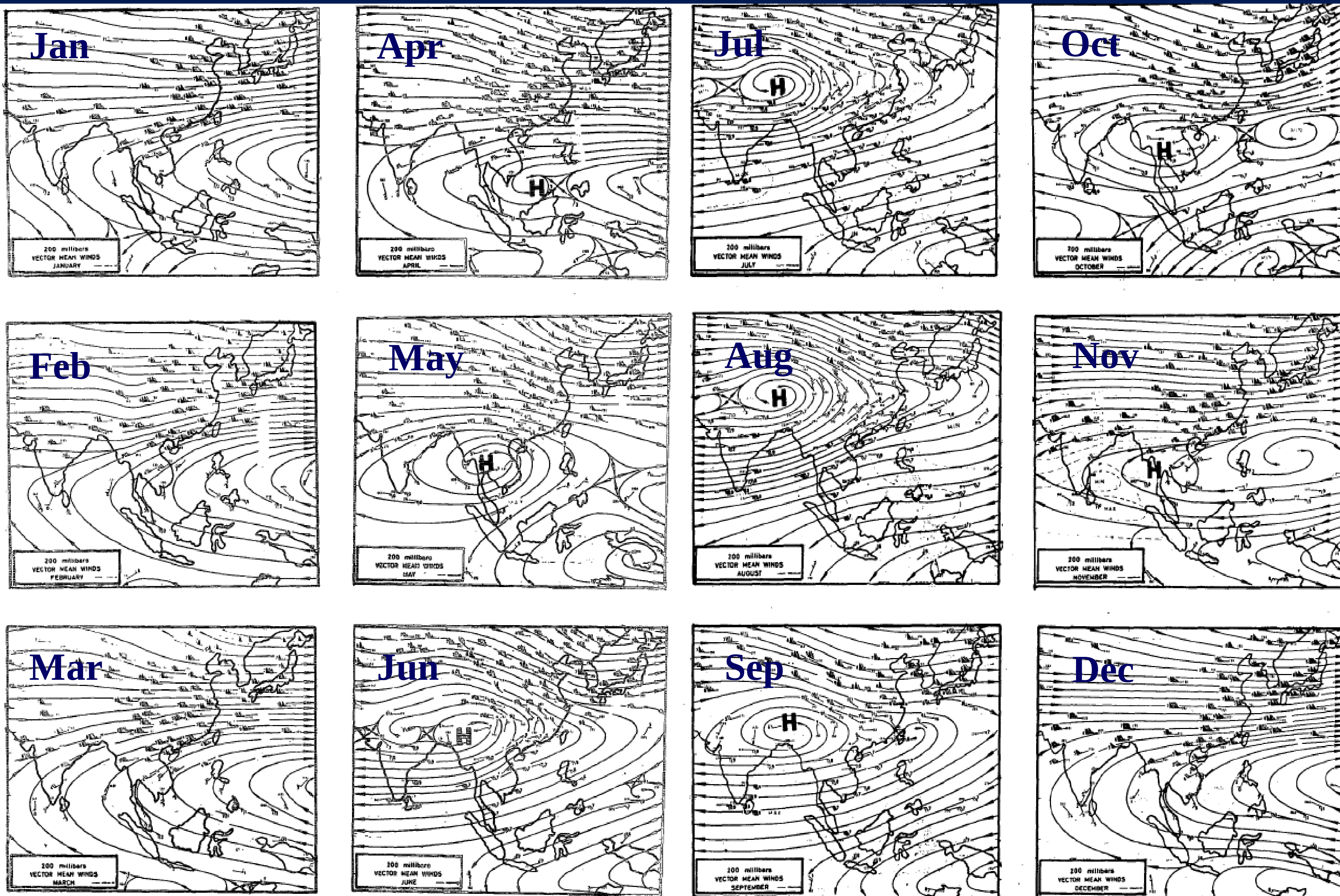


Streamfunction at 200 hPa depicting Rotational component of summer monsoon circulation

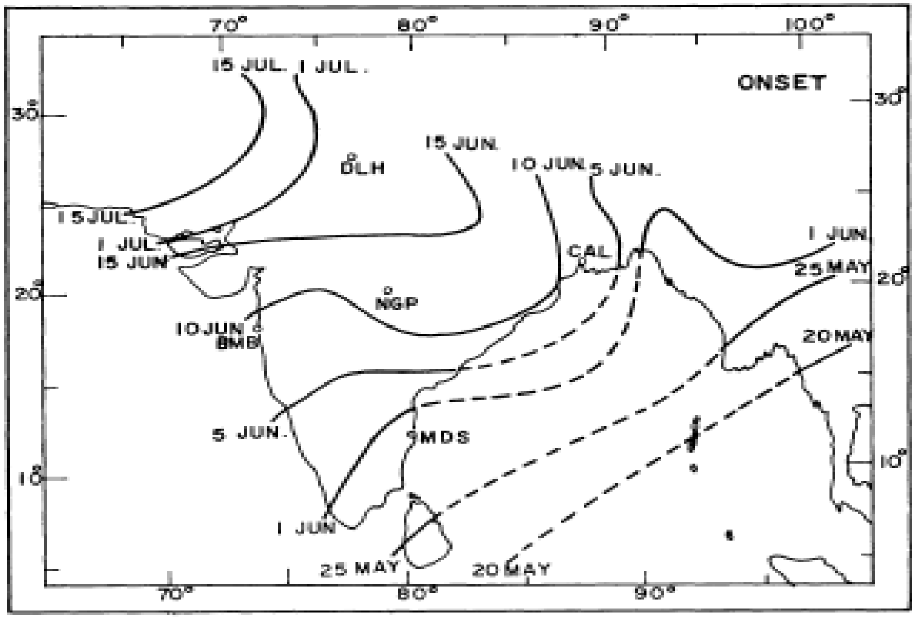


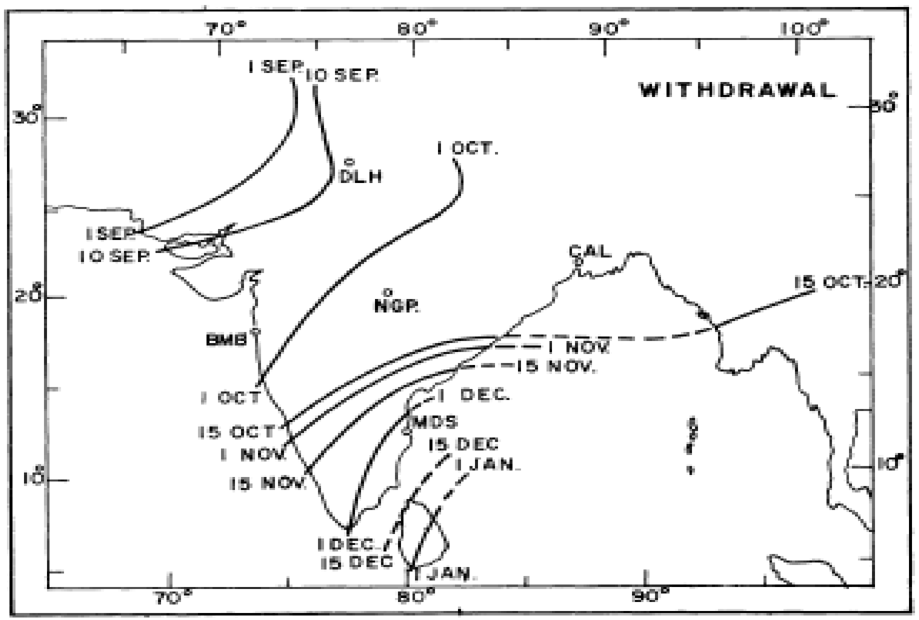
Seasonal evolution of upper tropospheric anticyclone: Convectively coupled process

Monthly mean 200 hPa wind field over Asia. Chin & Lai (1974); Krishnamurti & Bhalme (1976)

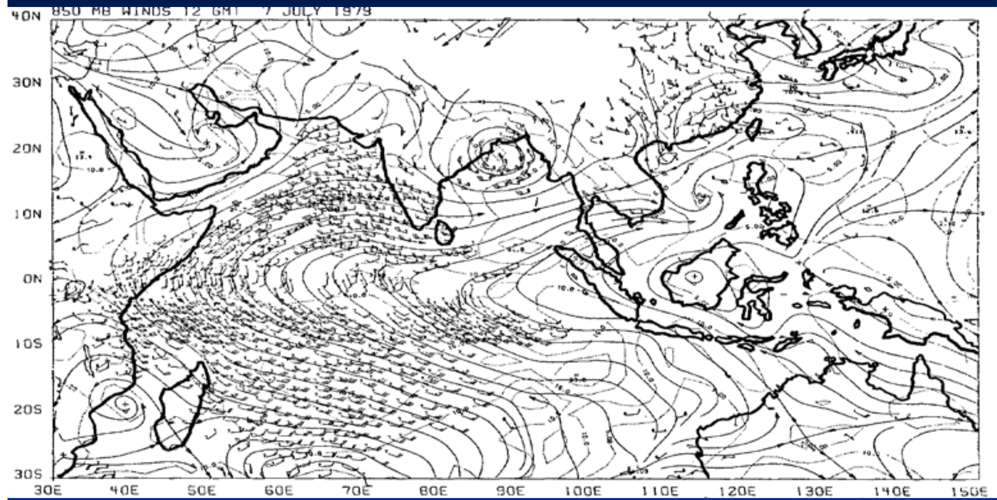


Progression of onset and withdrawal of the southwest monsoon –Ananthakrishnan, 1977

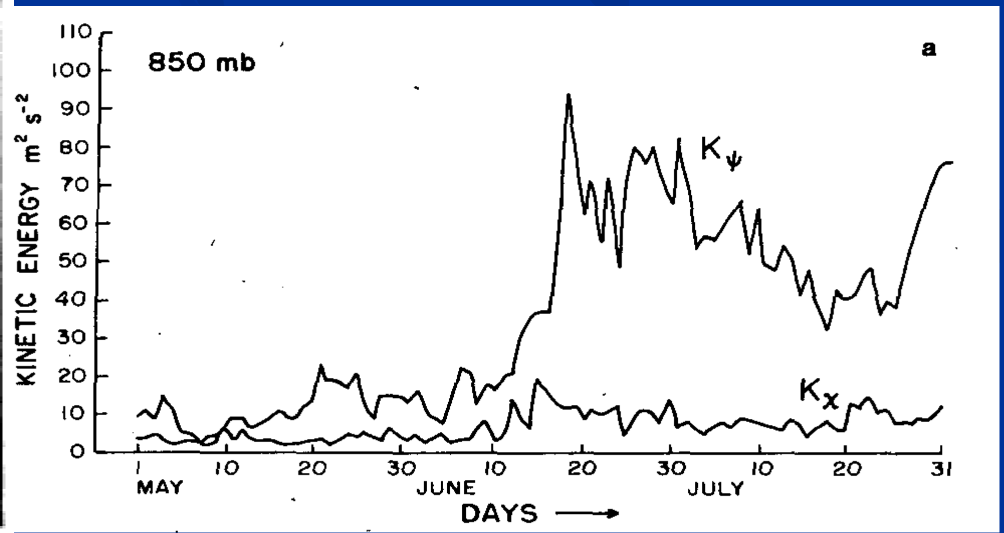




Krishnamurti & Ramanathan, 1982: Sensitivity of monsoon onset to differential heating (MONEX)



Large increase in kinetic energy of total flow & rotational flow over Arabian Sea one week prior to onset of monsoon rains over Central India



Monsoon Interannual & Decadal variability

(Links with ENSO, Indian Ocean and PDO)

ENSO – Monsoon teleconnection

Observational documentation

(Examples: Walker (1924), Walker and Bliss (1937), Normand (1953), Troup (1965), Berlage (1966), Kanamitsu and Krishnamurti, 1978; Sikka, 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983; Rasmusson and Wallace, 1983; Shukla and Paolino, 1983; Bhalme and Jadhav, 1984; Ropelewski and Halpert, 1987; Parthasarathy et al., 1988, Yasunari, 1990, Yasunari and Seki, 1992, Joseph et al., 1994 and many others)

Atmospheric Model Simulation Experiments / Coupled Models

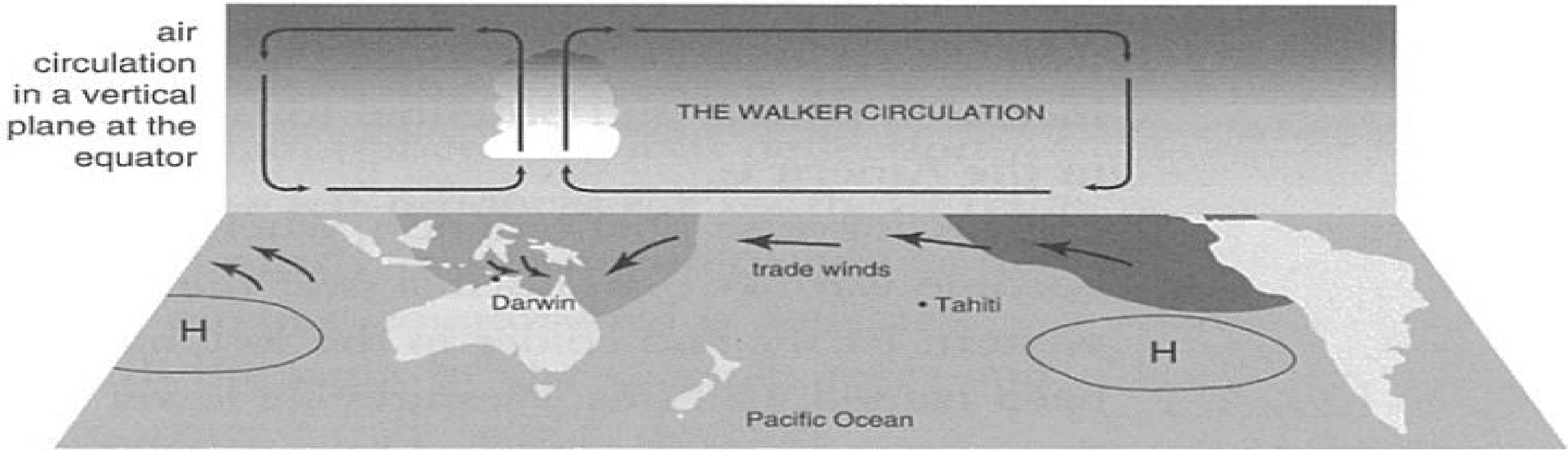
(Examples: Keshavamurty, 1982; Shukla and Wallace, 1983; Krishnamurti et al., 1989 ; Palmer et al., 1992; Webster and Yang, 1992 ; Nigam, 1994; Chen and Yen, 1994; Ju and Slingo, 1995; Soman and Slingo, 1997; Sperber and Palmer, 1996; Krishnan et al., 1998; Meehl and Arblaster, 1998; Krishna Kumar et.al., 2005, 2006; Mujumdar et al., 2007, Krishnamurthy et al. 2011, G. George et al. 2016 and many others)

Monsoon links with other boundary forcing (eg., Eurasian Snow Cover, Soil Moisture etc.

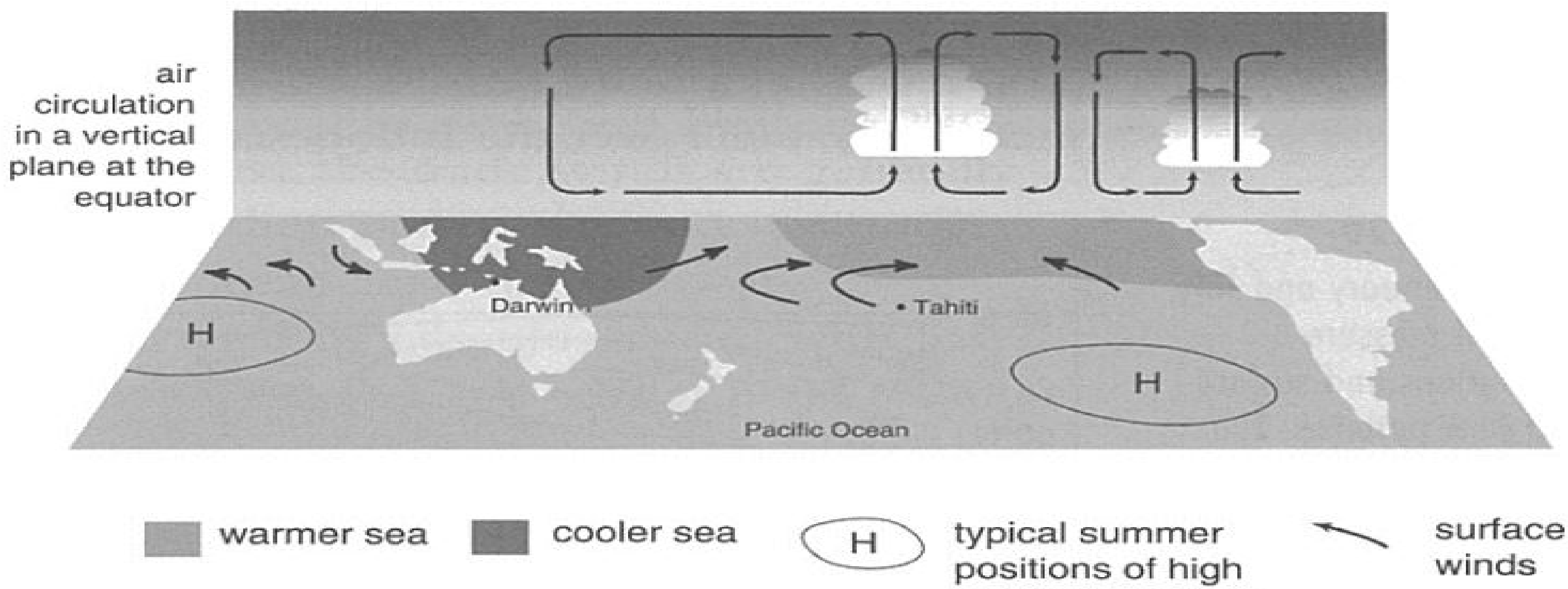
Atmospheric Model Simulation Experiments

(Examples: Barnett et al., 1989; Yasunari et al., 1991, Zwiers et al., 1993, Fennessy et al., 1994; Vernekar et al., 1994, Fennessy and Shukla, 1999; Douville and Chauvin, 2000; Becker et al., 2001, Dash et al., 2005)

Typical Walker circulation pattern

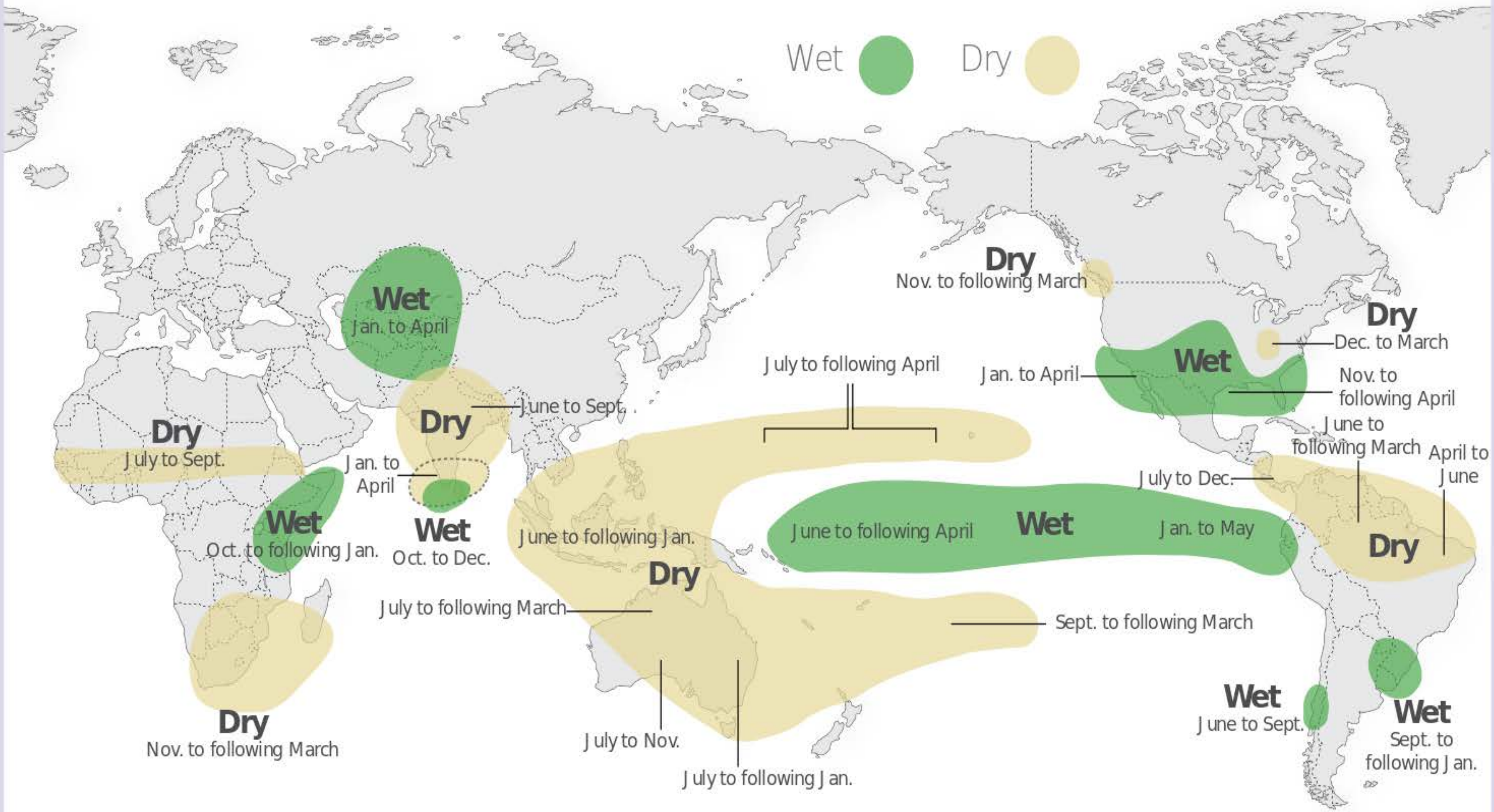


Walker circulation during an El Niño



El Niño and Rainfall

El Niño conditions in the tropical Pacific are known to shift rainfall patterns in many different parts of the world. Although they vary somewhat from one El Niño to the next, the strongest shifts remain fairly consistent in the regions and seasons shown on the map below.

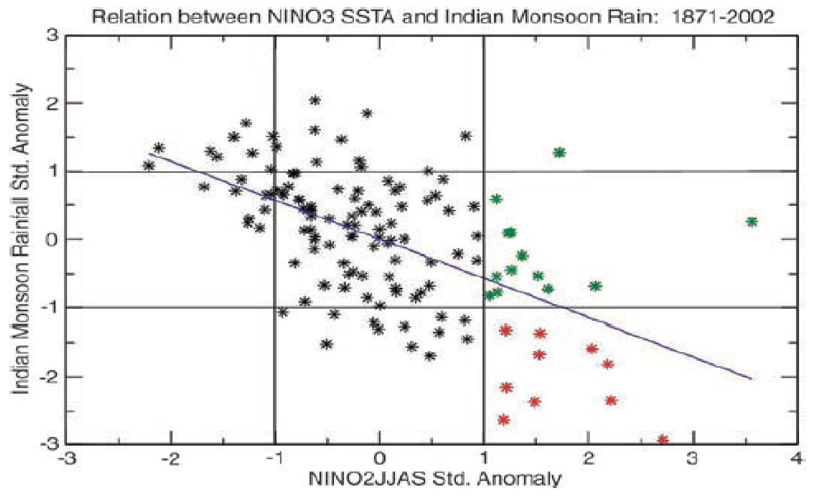


For more information on El Niño and La Niña, go to: http://iri.columbia.edu/ENSO

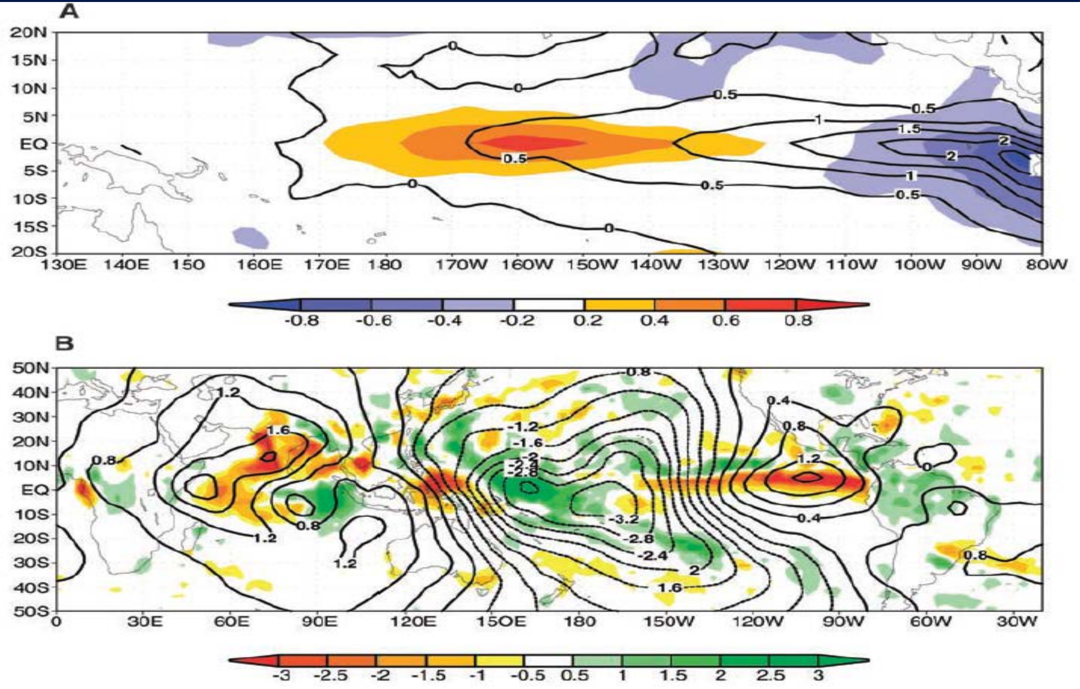
Sources: Ropelewski, C. F. and M. S. Halpert, 1989: Precipitation patterns associated with the high index phase of the Southern Oscillation. J. Climate, 2, 268-284.
Mason and Goddard, 2001. Probabilistic precipitation anomalies associated with ENSO. Bull. Am. Meteorol. Soc. 82, 619-638

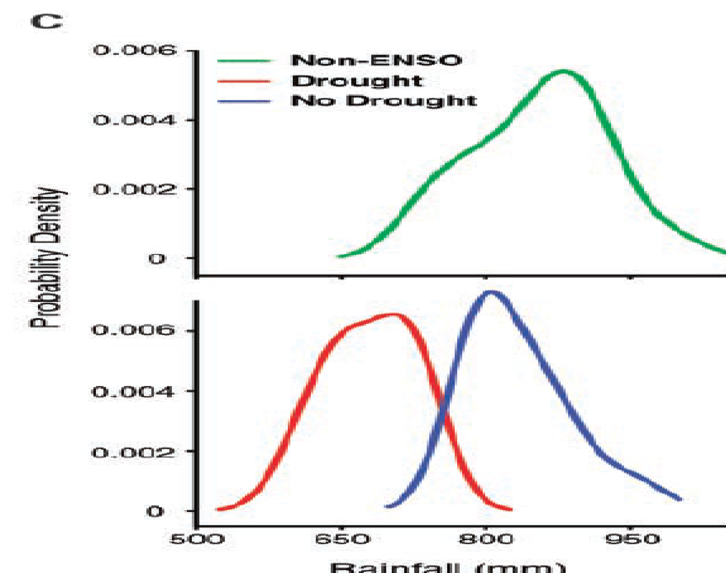
https://www.climate.gov/sites/default/files/IRI_ENSOimpactsmap_lrg.png

K. Krishna Kumar et al. 2006: Unraveling the mystery of Indian monsoon failure during El Nino (Science)



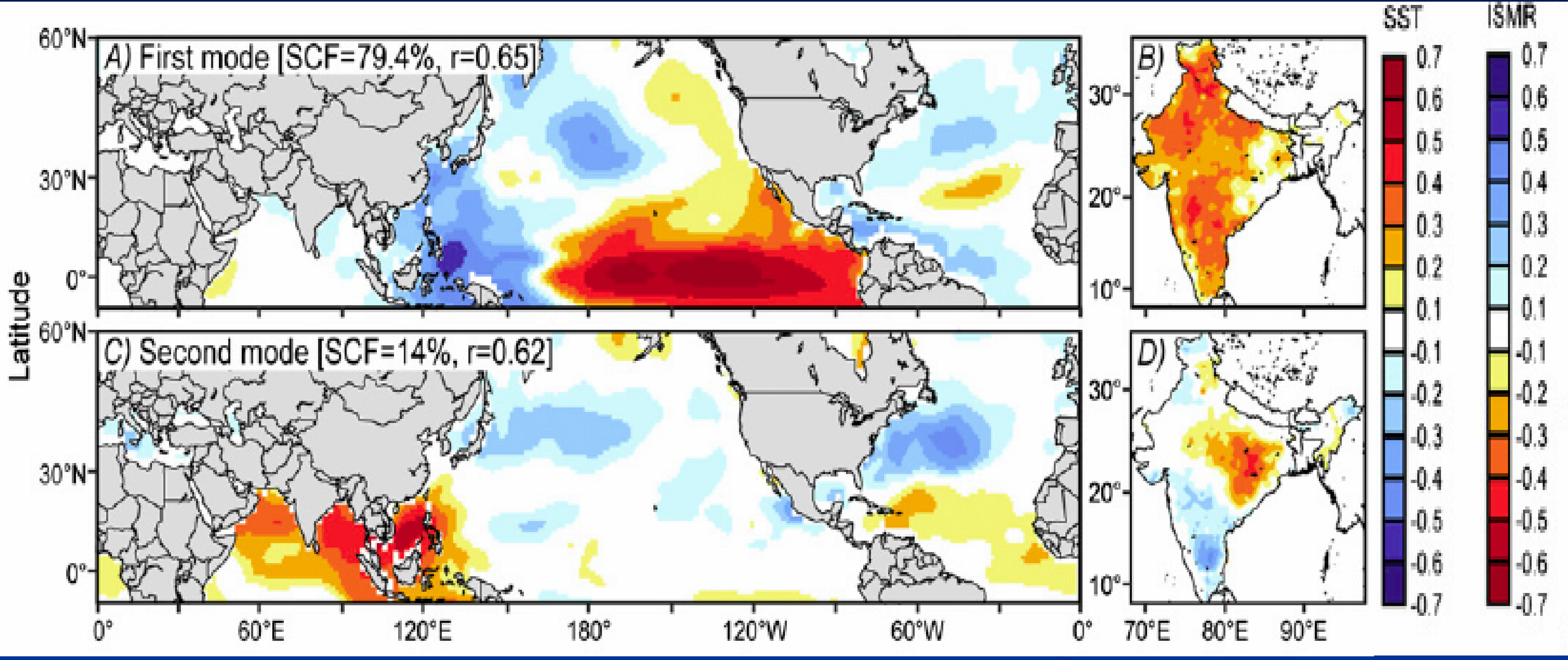
Plot of standardized all-India summer (JJAS) monsoon rainfall and summer NINO3 anomaly index. Severe drought and drought-free years during El Nino events (standardized NINO3 > 1) are shown in red and green respectively



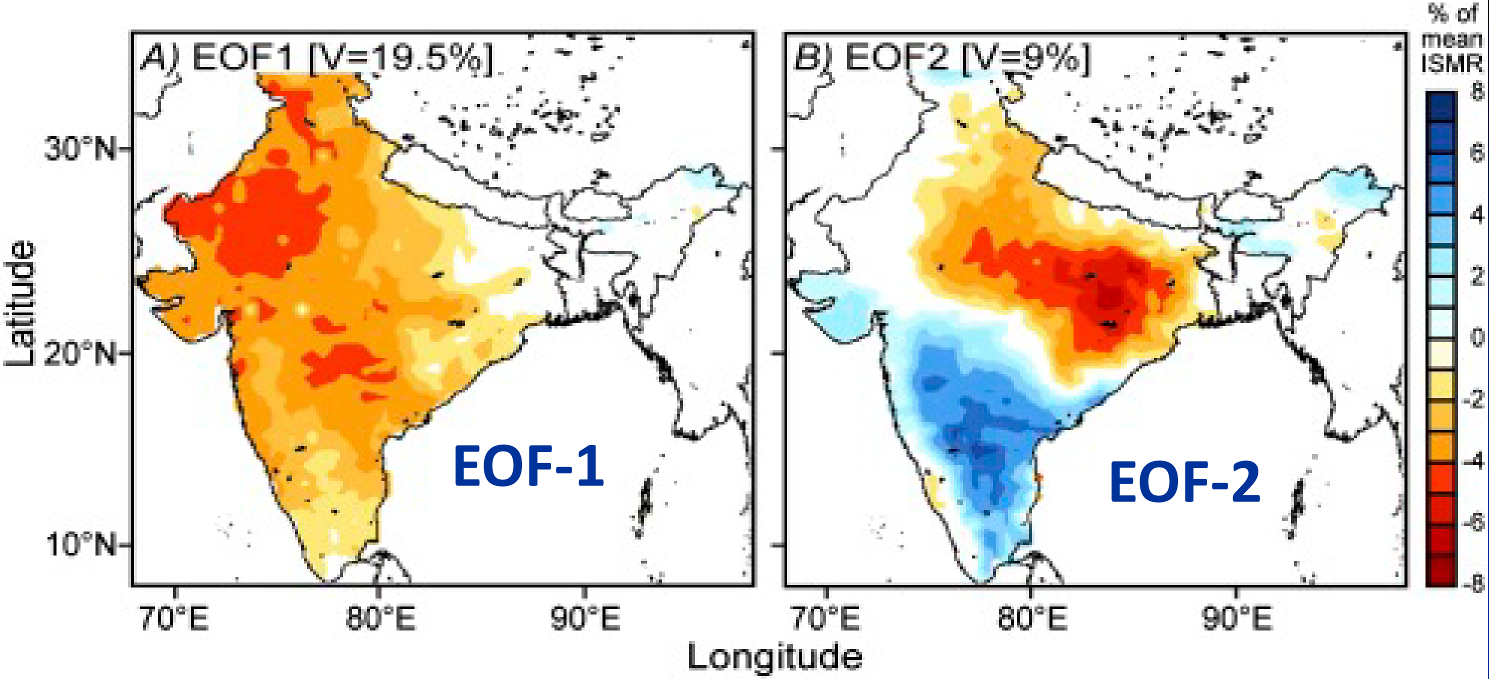


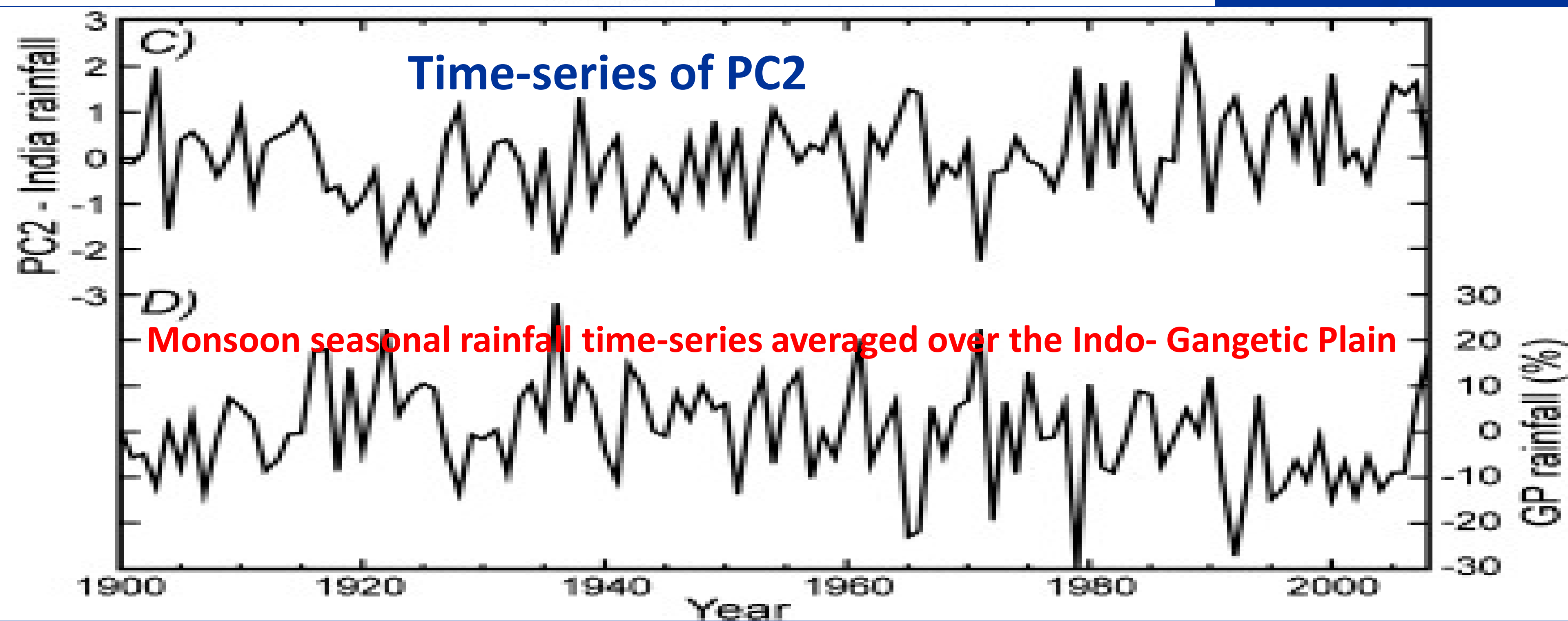
El Nino events with warmest SST anomalies in the central equatorial Pacific are more effective in focusing drought-producing subsidence over India than events with the warmest SSTs in the eastern equatorial Pacific

Vimal Mishra, B.V. Smoliak, D.P. Lettenmaier, J.M. Wallace, PNAS 2012

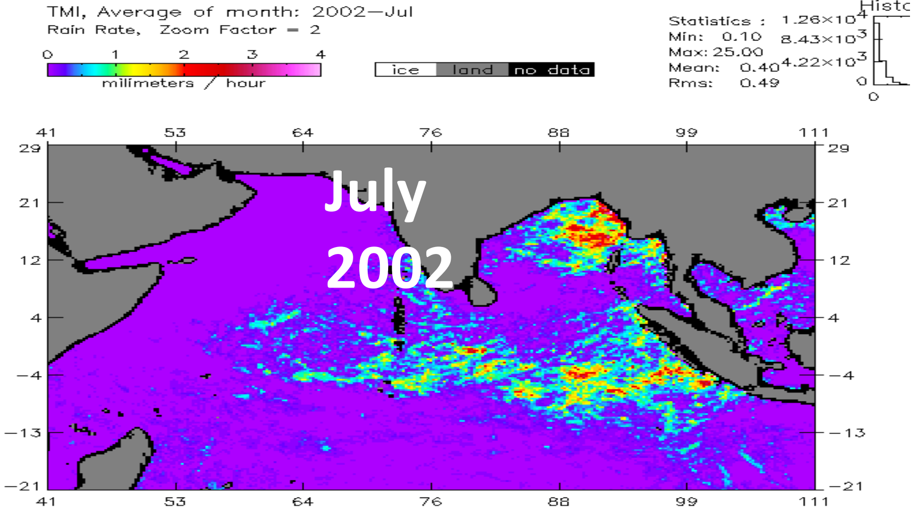


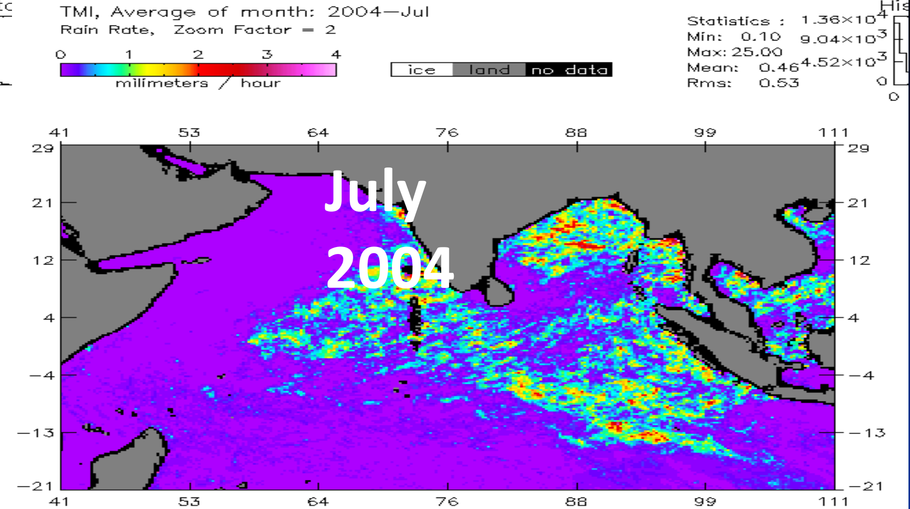
Coupled patterns of SST and JJAS ISMR variability estimated by performing maximal covariance analysis (MCA) from 1900 to 2008. The patterns indicated by colored shading are the heterogenous correlation coefficients between the ISMR expansion coefficient time-series and the SST departure field at each grid point and vice versa. (A-D) leading two modes for the global SST domain





Vimal Mishra et al. 2012, PNAS



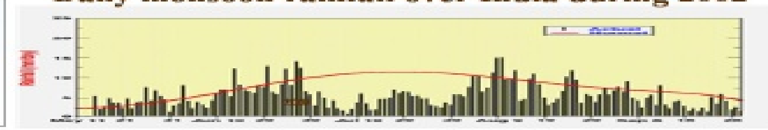


Indian Ocean - Monsoon Coupled interactions & Droughts over India

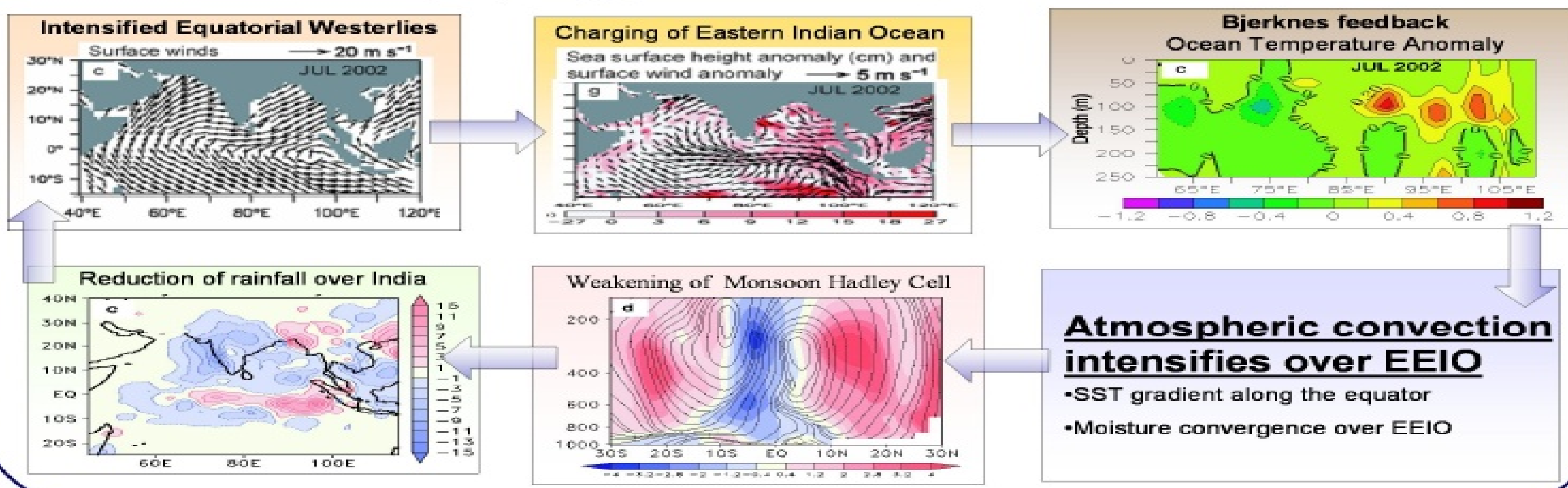
Long-standing scientific question

Can the Indian Ocean dynamics influence the occurrence of long-lasting "breaks" in the monsoon rainfall over the Indian subcontinent ?

Daily monsoon rainfall over India during 2002

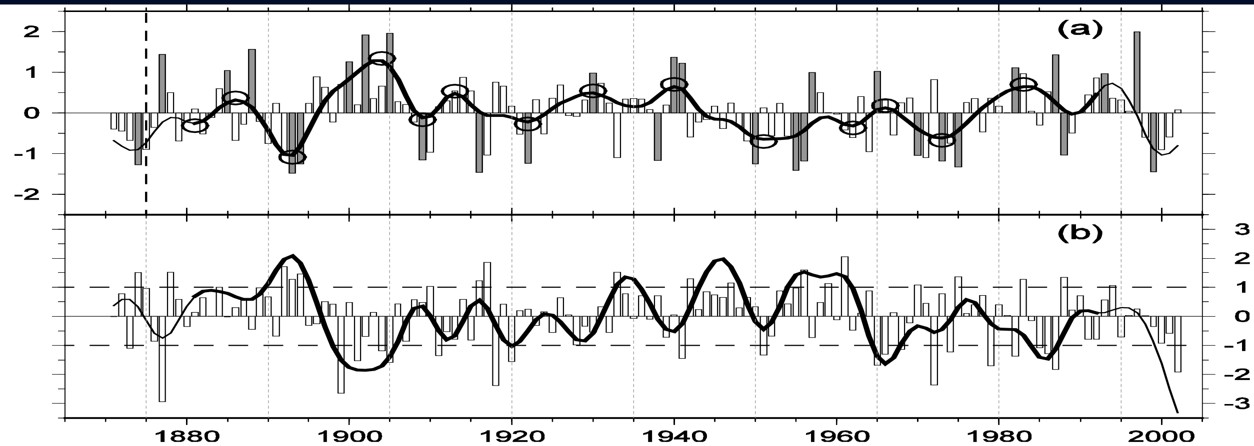


Reference: Krishnan, R. et al., (2006): *Geophysical Research Letters*, 33, L08711, doi:10.1029/ 2006GL025811



Krishnan R., et al GRL 2006

Pacific Decadal Oscillation (PDO) and Indian summer monsoon rainfall: Krishnan and Sugi (2003)

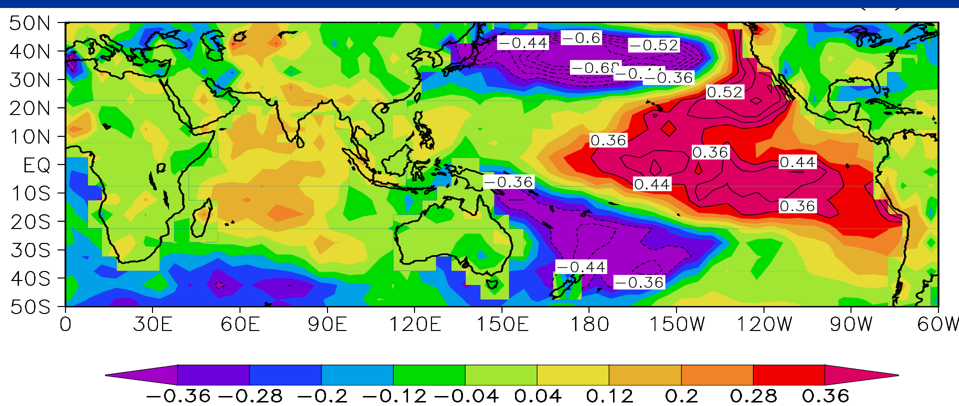


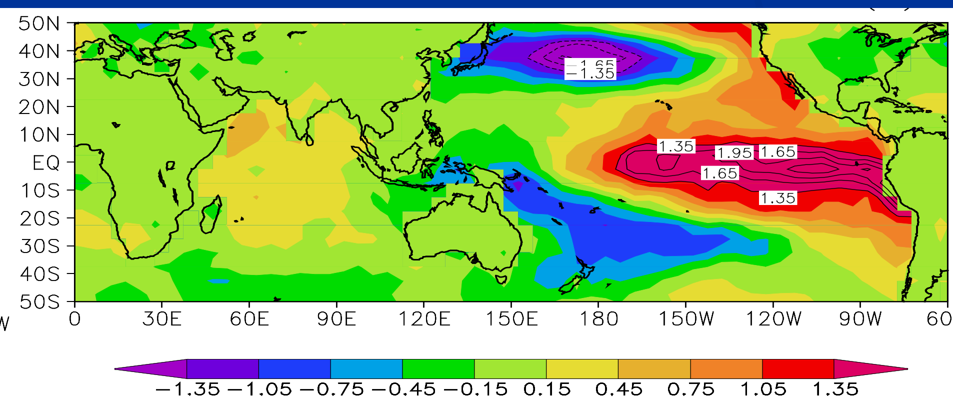
Top: Time-series of PC1 of detrended and low-pass filtered (> 8 yr) SST in the Pacific Ocean domain (120ºE – 90ºW ; 45ºS – 45ºN) for the period (1871-2002). The bar-graph is the first PC of unfiltered SST in the Pacific Ocean.

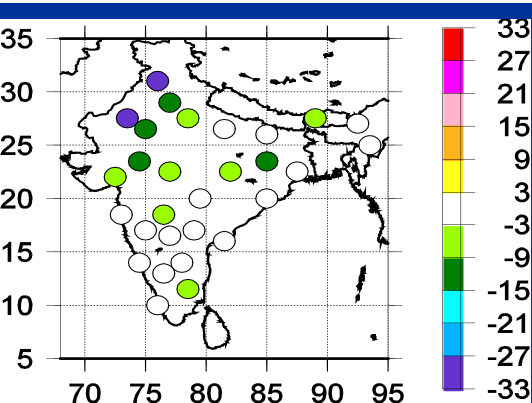
Bottom: Bar-graph is the time-series of All India Summer Monsoon Rainfall (AISMR) anomalies (1871-2002) and the thick line is the low-pass filtered time-series of AISMR.

Decadal pattern: Warm minus cold composite of surface temperature based on 7 warm and 7 cold points of PDO index.

Interannual pattern: Warm minus cold composite of surface temperature based on 15 warm and 15 cold points of ENSO index







Warm minus cold composite of JJAS rainfall over 29 subdivisions of India based 7 warm and 7 cold points of PDO index. Anomalies are % departures from normal

<u>**Summary:**</u>

•Inverse relationship is noted between the Pacific SST variations associated with the PDO and the Indian monsoon rainfall

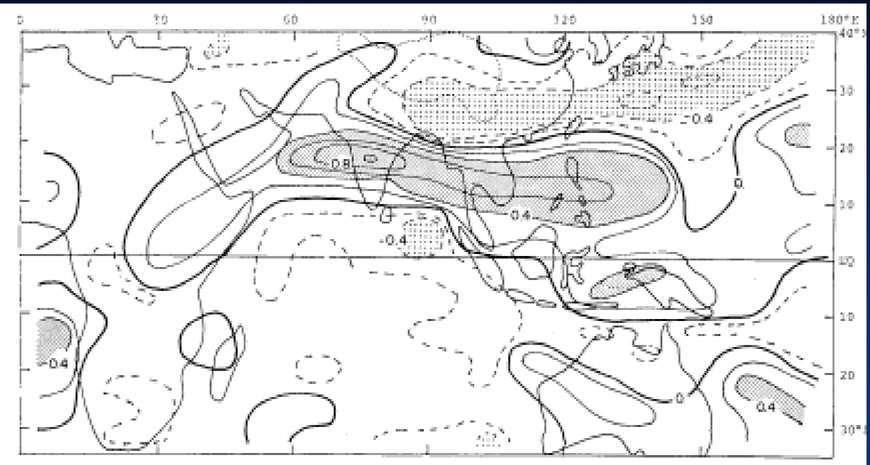
•Majority of dry monsoons have occurred when El Nino events occurred during warm phase of PDO

•Several wet monsoons have occurred when La Nina events occurred during cold phase of PDO

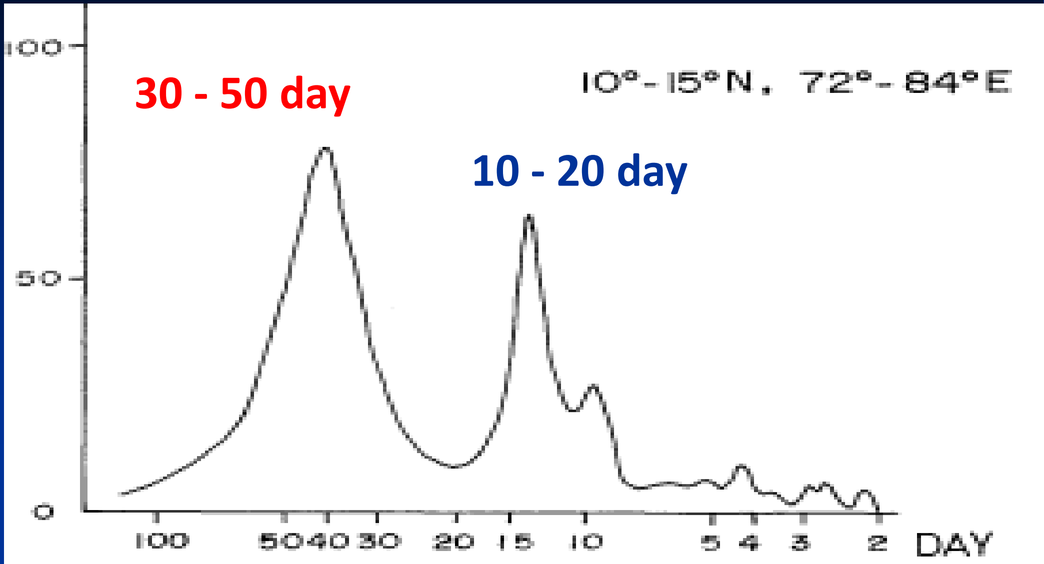
Summer Monsoon Sub-seasonal / Intra-seasonal) variability

(Active and Break Monsoon Spells)

Sub-seasonal cloudiness fluctuations over India: T. Yasunari 1979, J. Met.Soc. Japan



Spatial map of correlation coefficients of cloudiness with reference point over central India (17.5N, 78E). Values > 0.4 are Shaded and those less than -0.4 are dotted



Power spectra of cloudiness fluctuations over 10N-15N, 72-84E. Units: (Cloudiness values)^2 .day

10-20 day oscillation: Westward propagation in the Asian summer monsoon

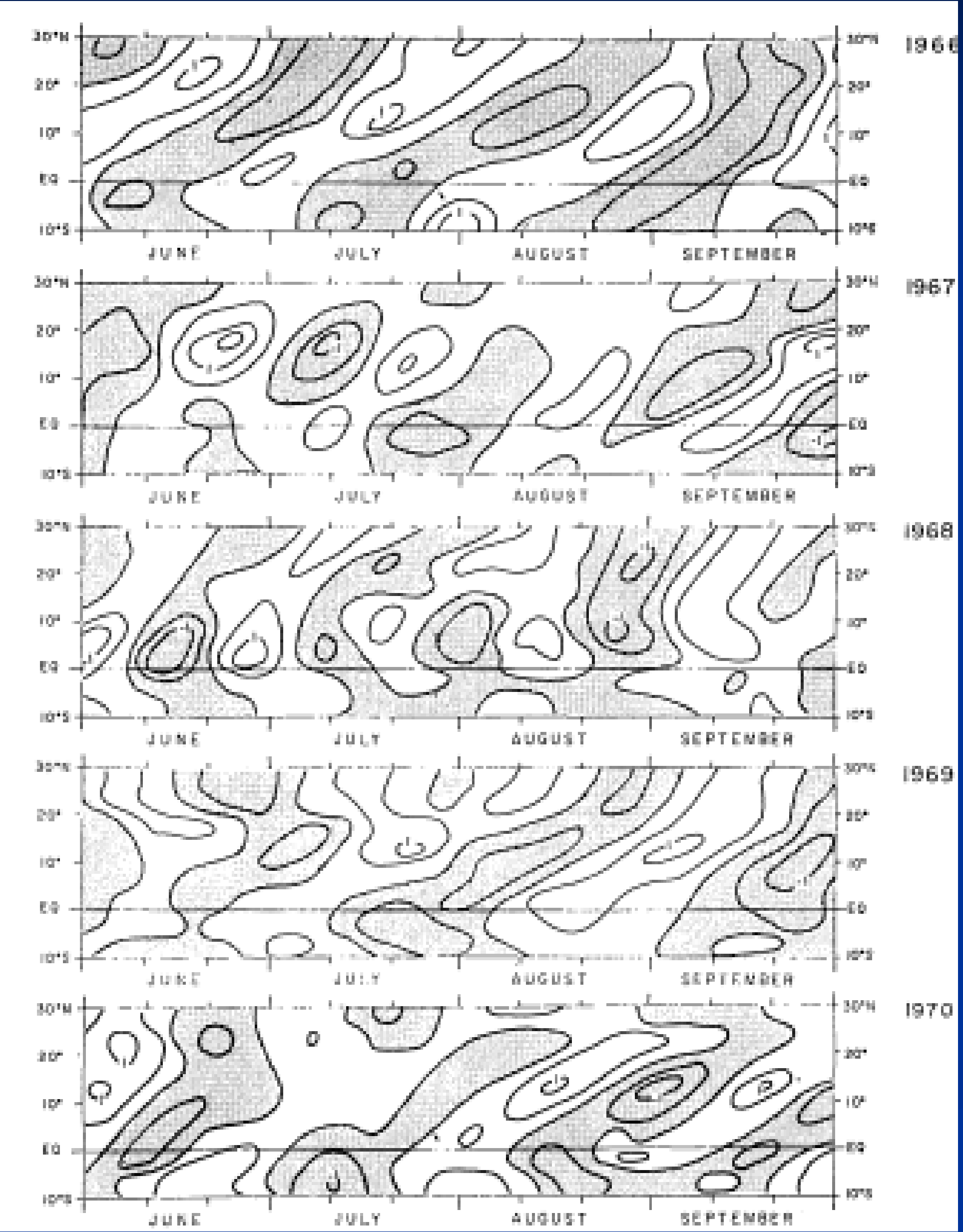
Keshavamurty 1973, Murakami, 1977 – Meridional winds, Krishnamurti et al. 1973: Spectrum of Tibetan High; Krishnamurti and Bhalme (1976); Murakami & Frydrych (1974), Murakami (1975), Krishnamurti et al. (1977), Krishnamurti & Ardanuy (1980), Yasunari (1978, 1980) and others

30-50 day oscillation: Slow northward propagation over the Indian monsoon region

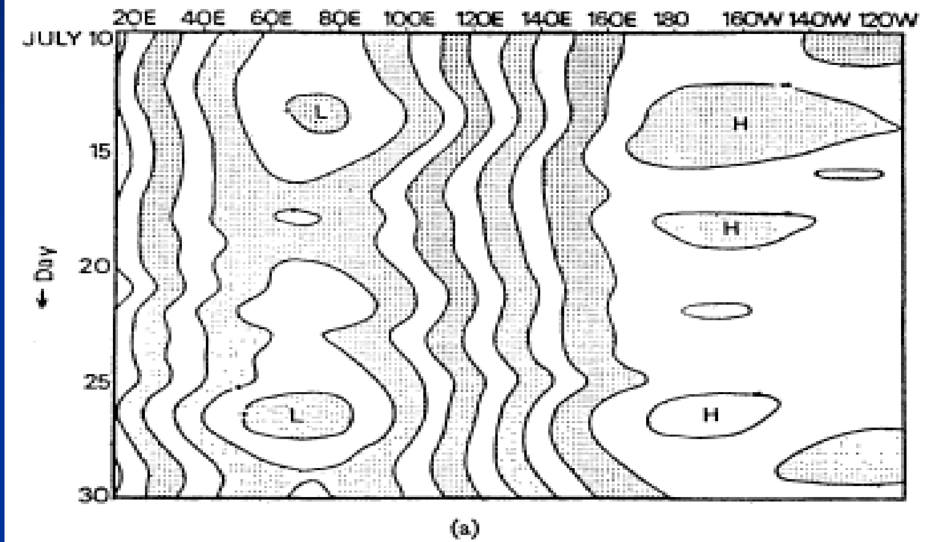
Dakshinamurty & Keshavamurty, 1976; Yasunari (1979, 1980), Sikka and Gadgil (1980) – Northward movement of cloud bands, Krishnamurti and Subrahmanyam (1982), Hartmann and Michelsen (1980), Madden and Julian (1994) and others

Northward propagation of cloudiness fluctuations (30-50 day) over the Indian summer monsoon region: Yasunari (1980)

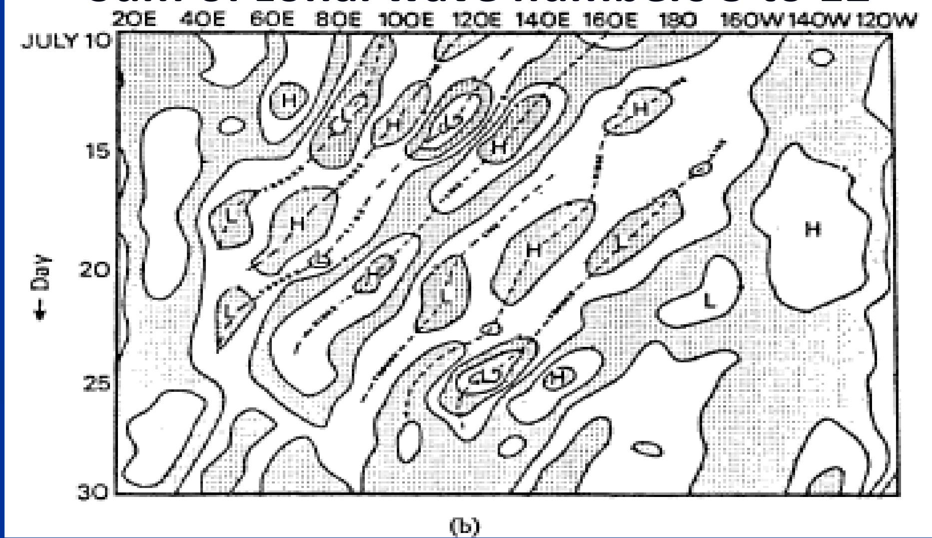
Westward propagation of sea level pressure at 20N latitude during July 1965 : Krishnamurti et al. 1977



Sum of zonal wave numbers 1 & 2



Sum of zonal wave numbers 3 to 12



The 30-50 day mode at 850 mb during MONEX : Krishnamurti & Subrahmanyam (1982)

Meridional propagation of a train of troughs and ridges from near the equator and dissipate near the Himalayas, based on winds at 850 hPa. The meridional scale of this mode Is around 3000 km and its meridional speed of Propagation is ~0.75 deg latitude per day. The amplitude of wind for this mode is around 3-6 ms^{-1}

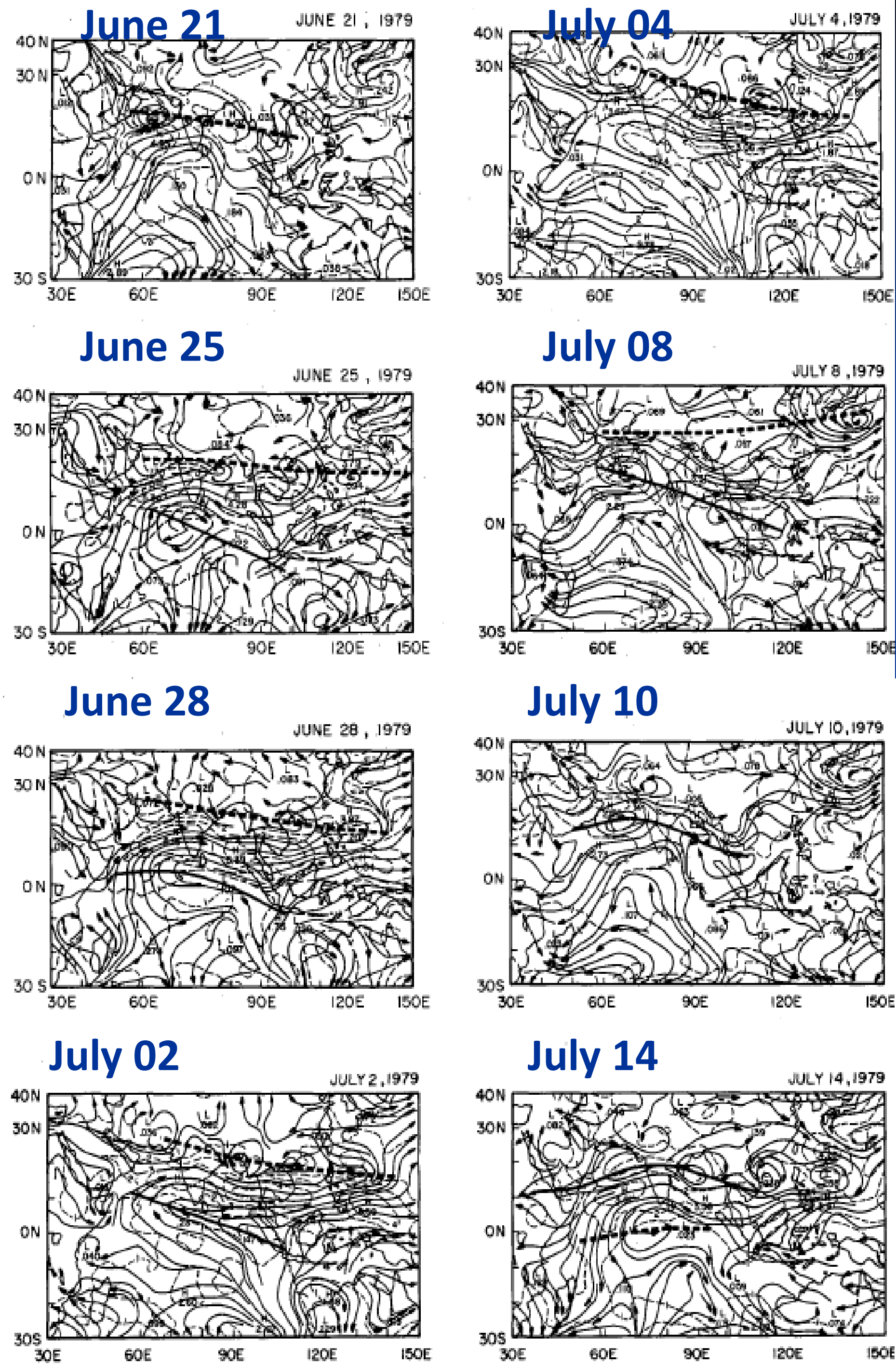
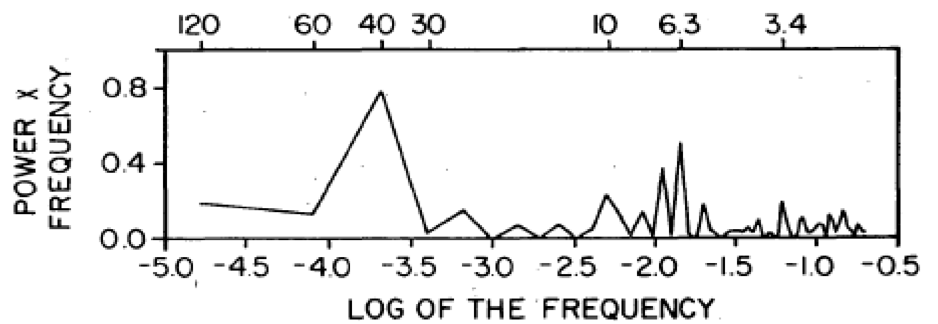
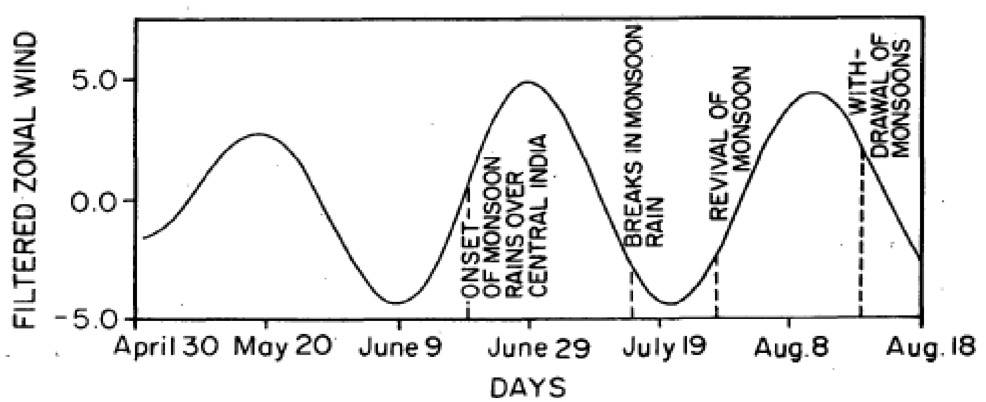
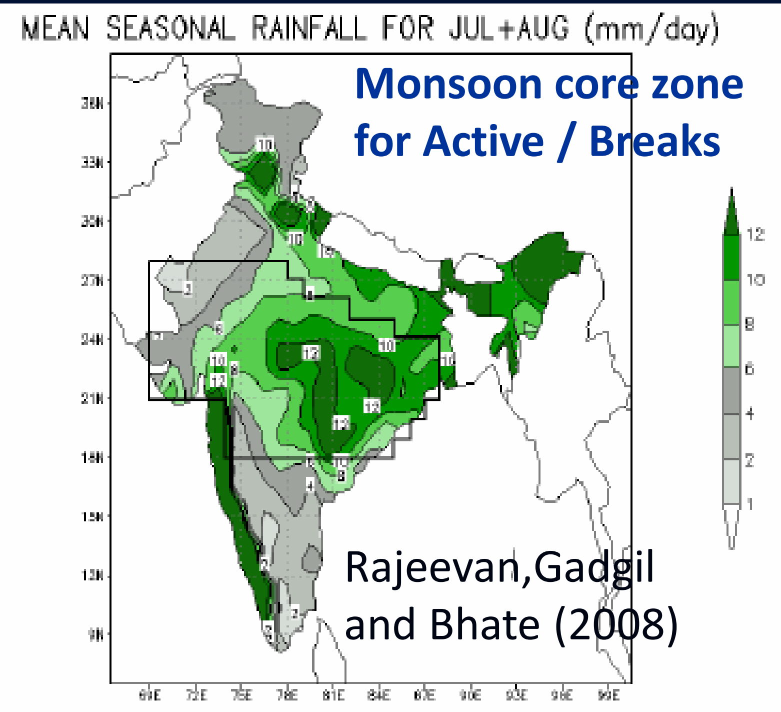


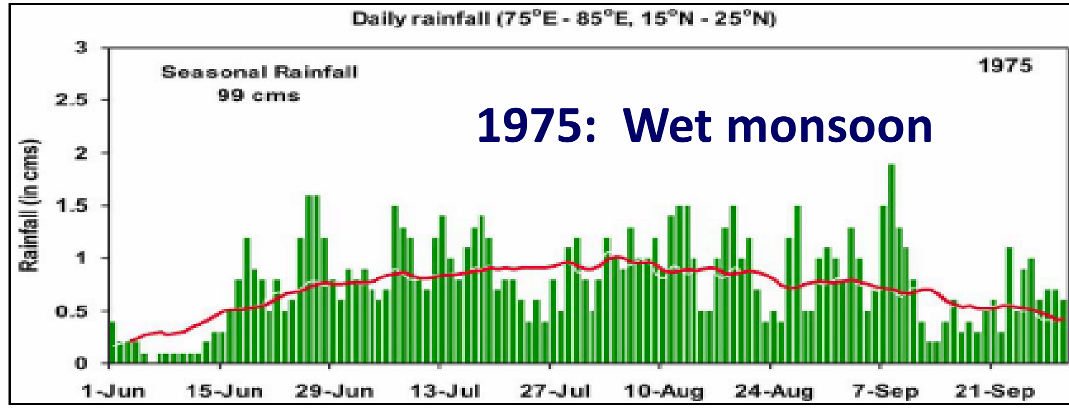
FIG. 3. (Continued)

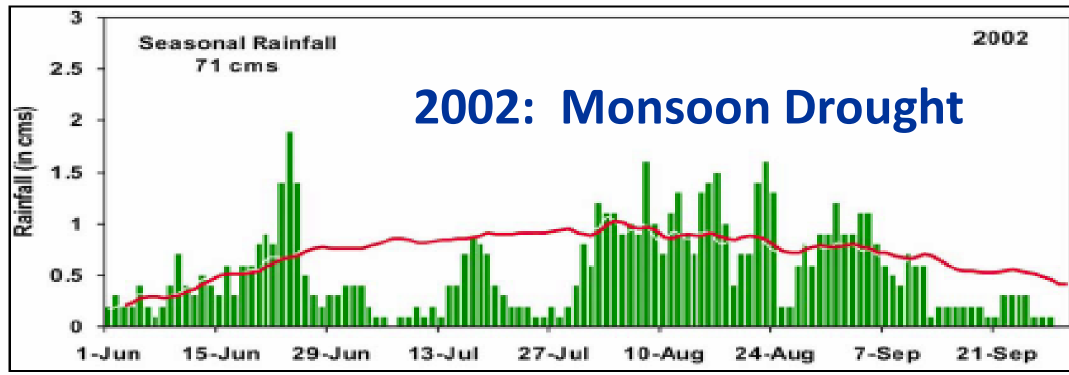


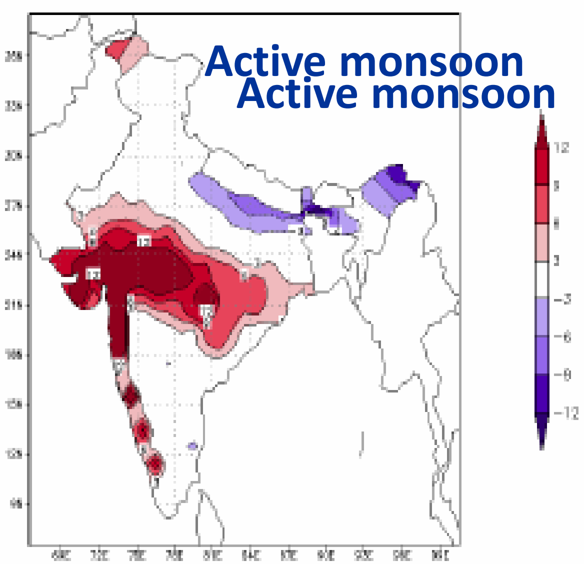


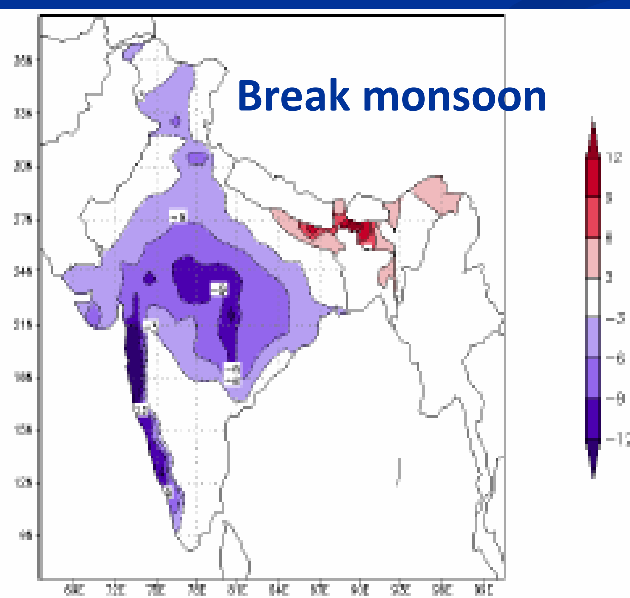
Mean rainfall during July & August

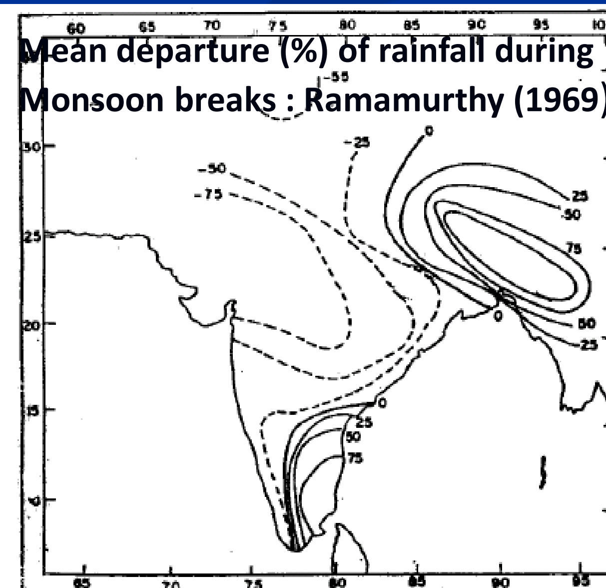


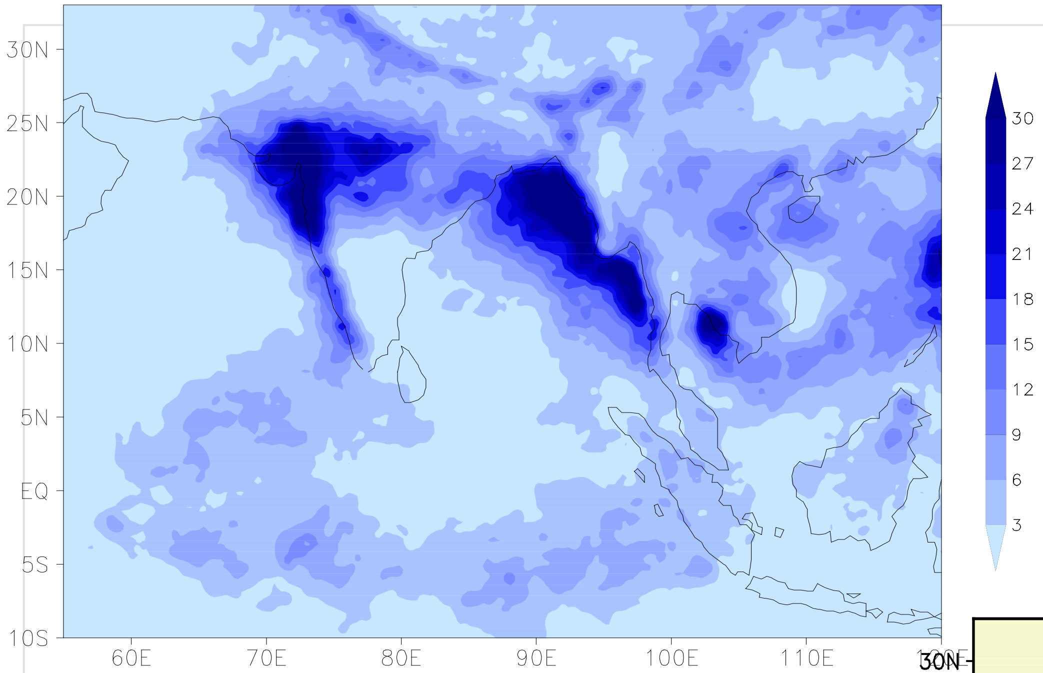










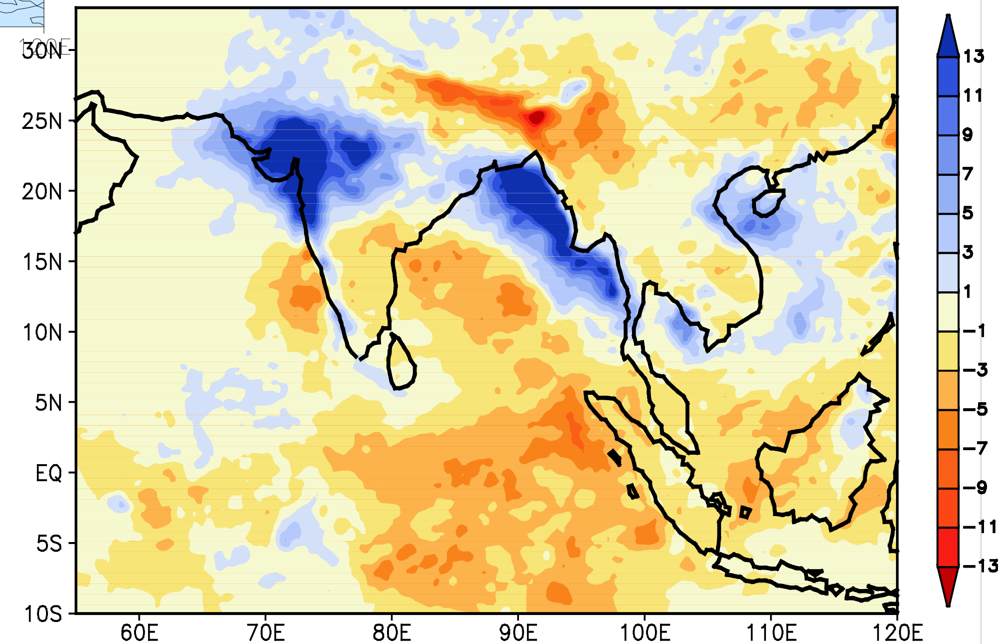


Composite map of rainfall (mm day $^{-1}$) based on active monsoon days. The data is from TRMM 3B42 daily rainfall dataset. The active monsoon dates are from Rajeevan et al. (2008)

Large-scale organization of meso-scale convective systems MCS (3000-4000 km)

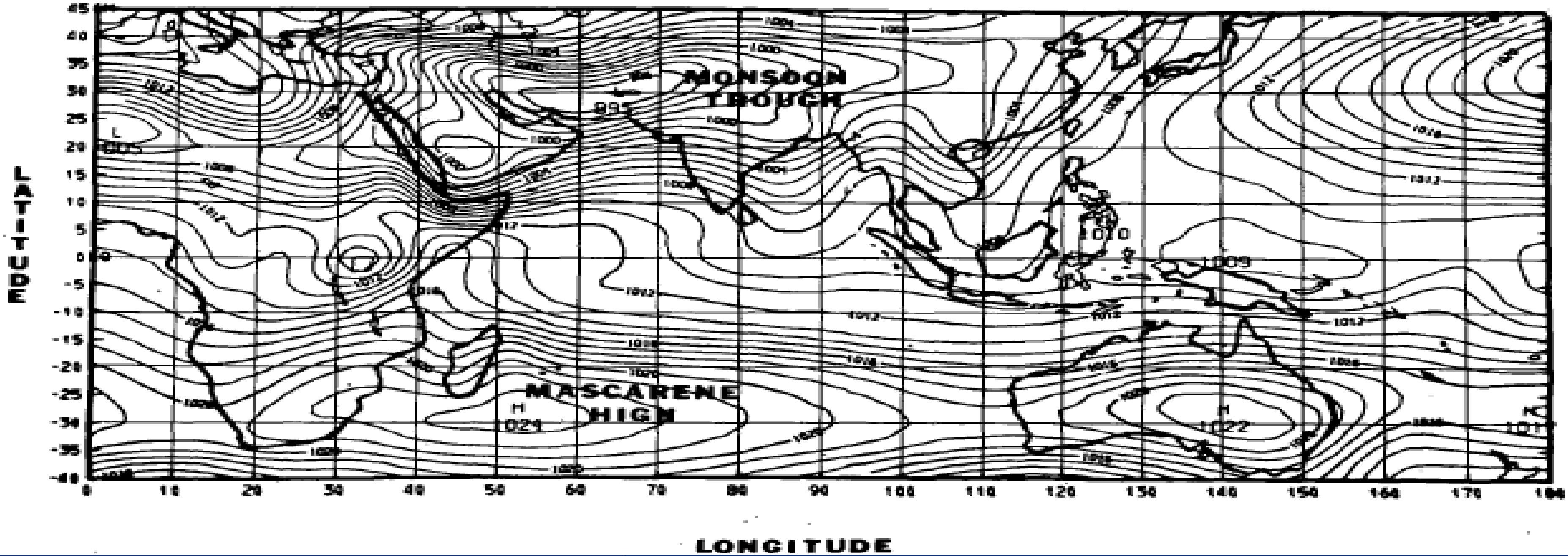
Active Monsoon

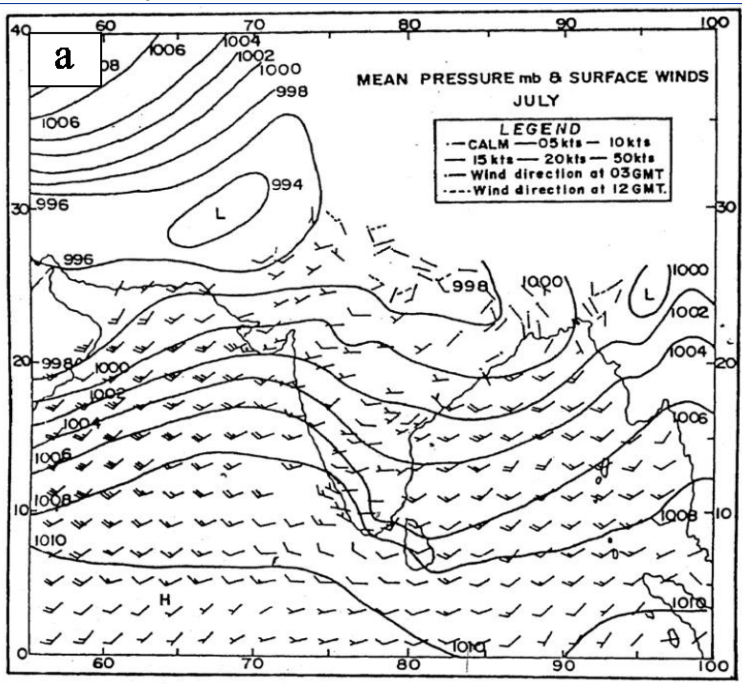
Composite map of rainfall anomaly (mm day $^{-1}$) based on active monsoon days.



Ayantika Dey Choudhury and R. Krishnan (2011): Dynamical response of the South Asian monsoon trough to latent heating from stratiform and convective precipitation, *J. Atmos. Sci*, 68, 1347-1363.

MSLP July (Courtesy: Henry Van de Boogard) – Adapted from Krishnamurti & Bhalme (1976)





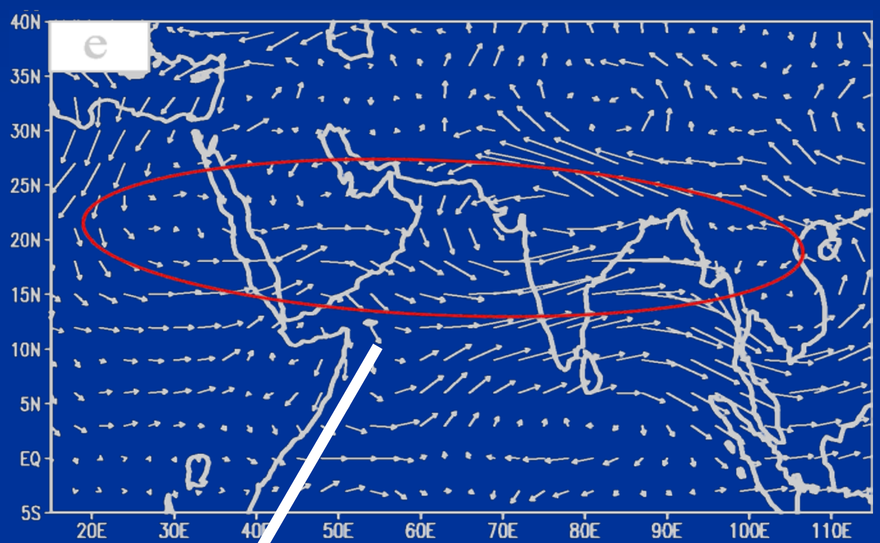
South Asian Monsoon Trough

July mean SLP (hPa) & surface wind (knots)
(Sikka and Narasimha 1995)

Dynamical response of monsoon trough during active monsoons

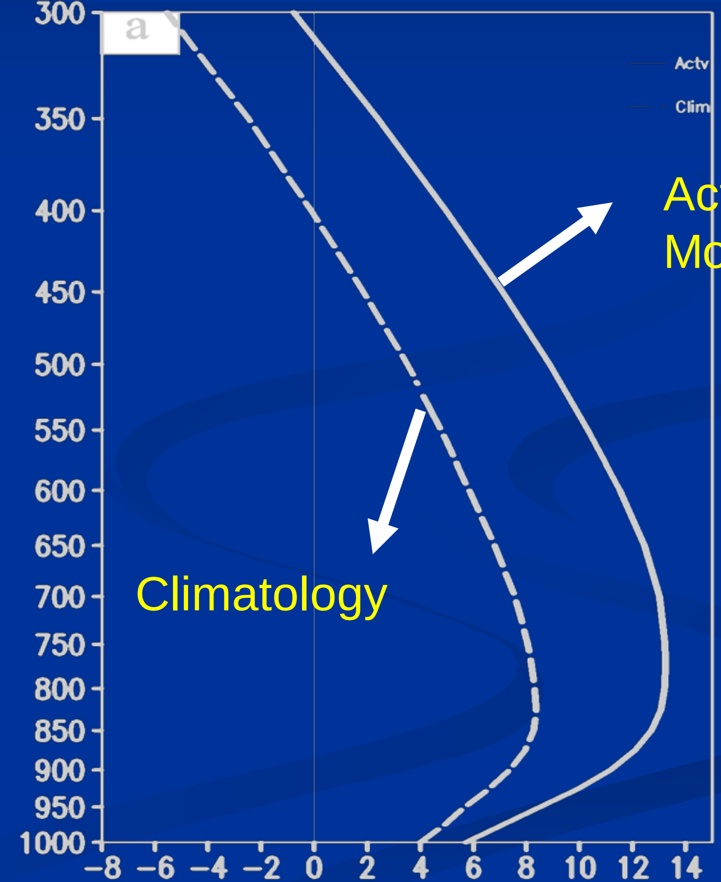
Vertical development of cyclonic circulation well above the mid-troposphere !

Wind anomaly at 500 hPa during active monsoons

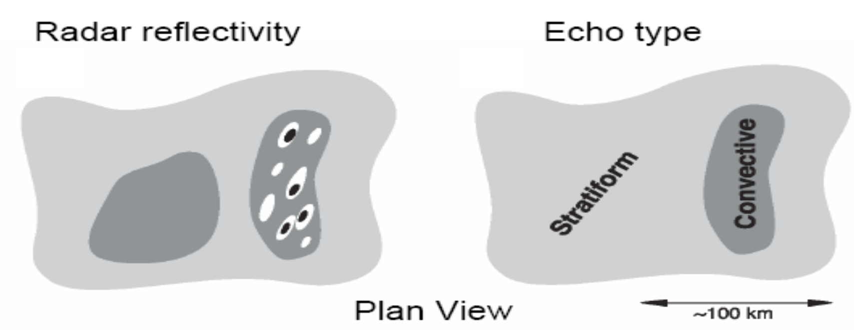


Large-scale mid–level circulation anomalies extending into the African ITCZ region

Relative vorticity ($x10^{-6}$ s^{-1}) profiles averaged over monsoon trough



Ayantika Dey Choudhury and R. Krishnan (2011): Dynamical response of the South Asian monsoon trough to latent heating from stratiform and convective precipitation, *J. Atmos. Sci*, 68, 1347-1363.



TRMM algorithm to separate convective and stratiform echoes :

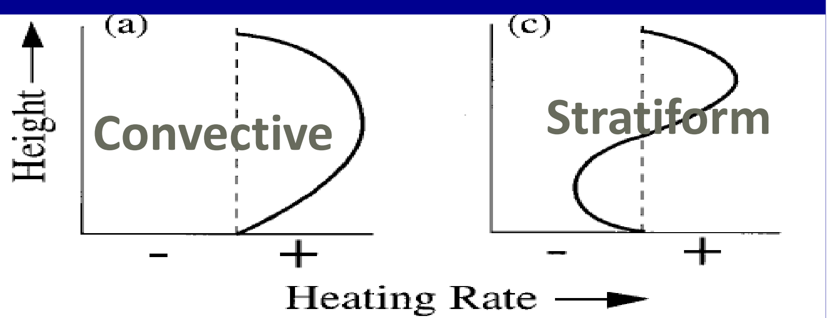
Convective-

- ✓Young, active convection
- ✓w ~ several m/s
- ✓Single mid-tropospheric heating peak

Stratiform–

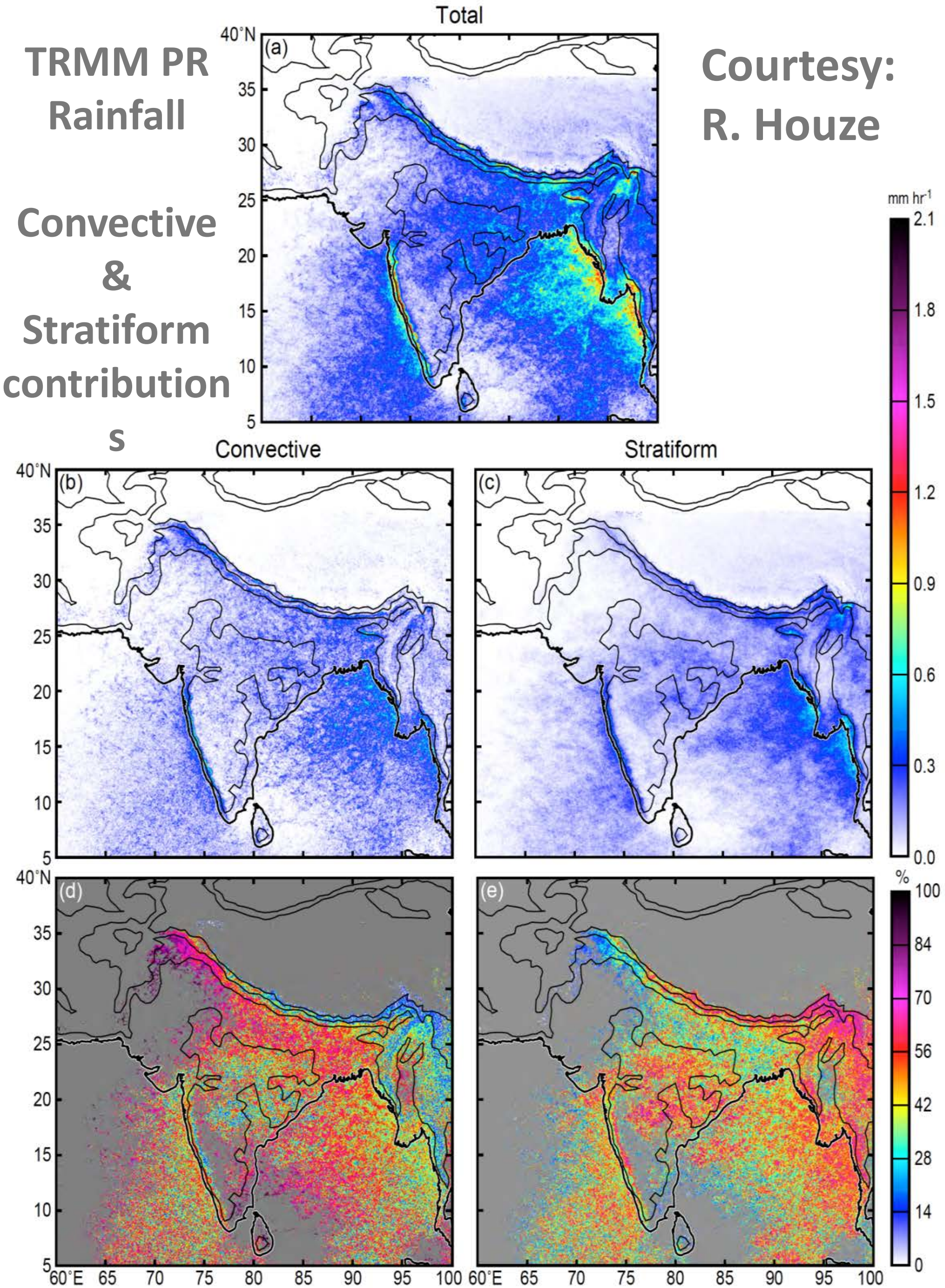
- ✓Older and less active convetion
- ✓w~ <1-2m/s
- ✓Heating upper & cooling lower levels

Vertical profiles of latent heating



TRMM PR Rainfall

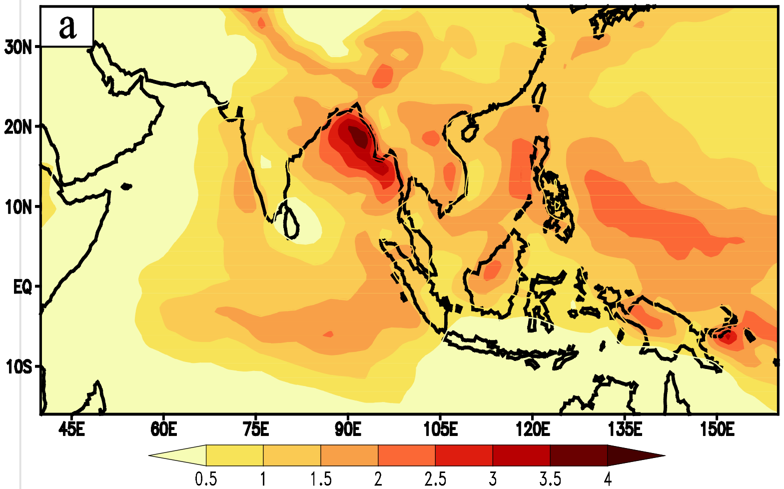
Convective & Stratiform contributions

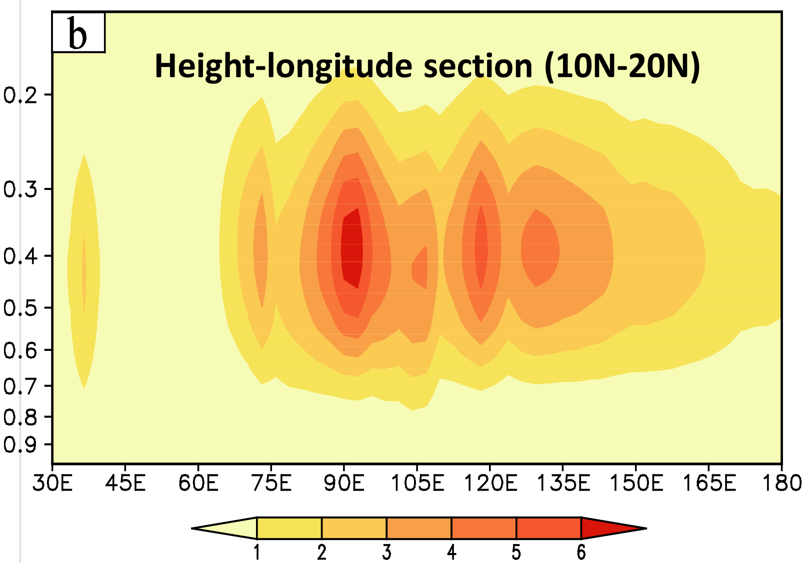


Courtesy: R. Houze

Climatological JJAS latent heating derived from TRMM rainfall

Vertically averaged heating



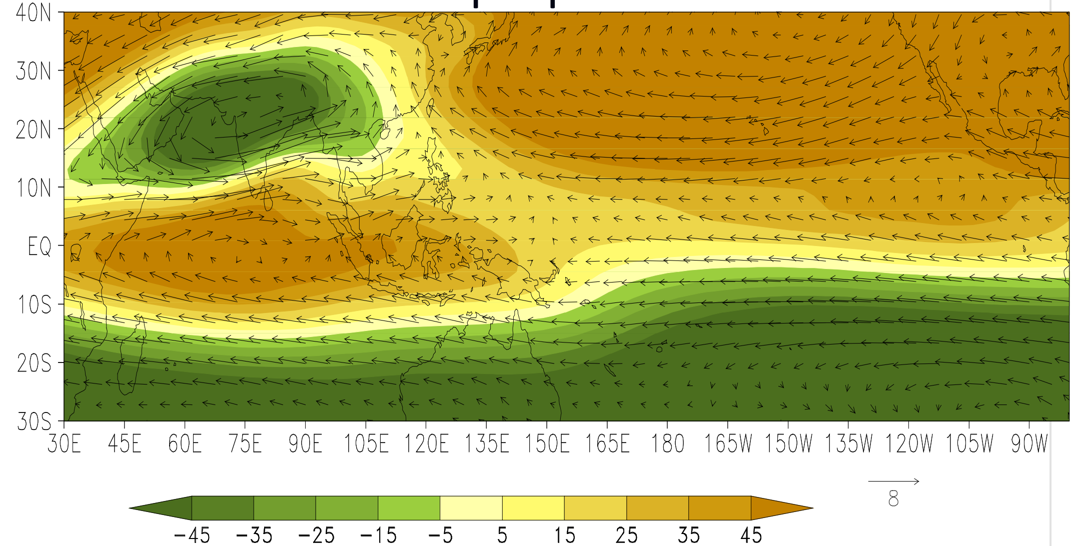


(Algorithm from Schumacher 2004)

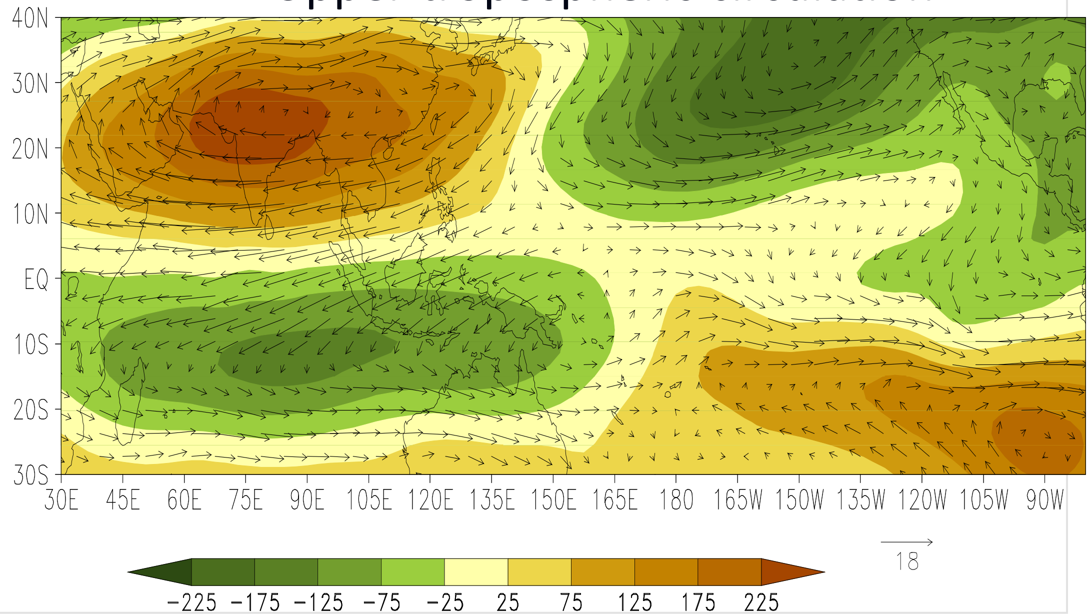
Choudhury and Krishnan (2011)

Dry model response to prescribed heating: Control (CTL) experiment

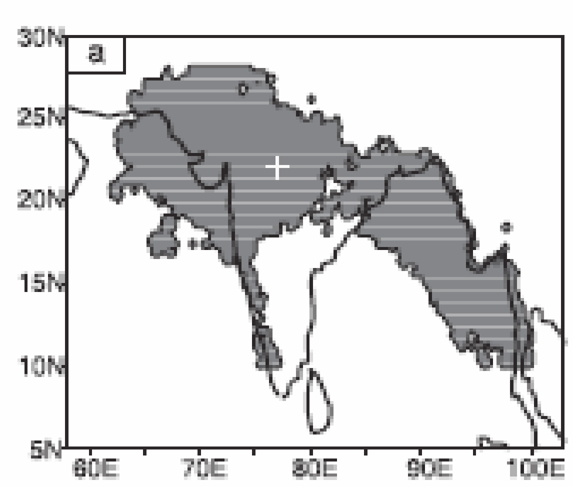
Lower tropospheric circulation



Upper tropospheric circulation



Sensitivity of circulation response to varying population of convective and stratiform rain anomalies over the monsoon trough zone during active monsoon spells



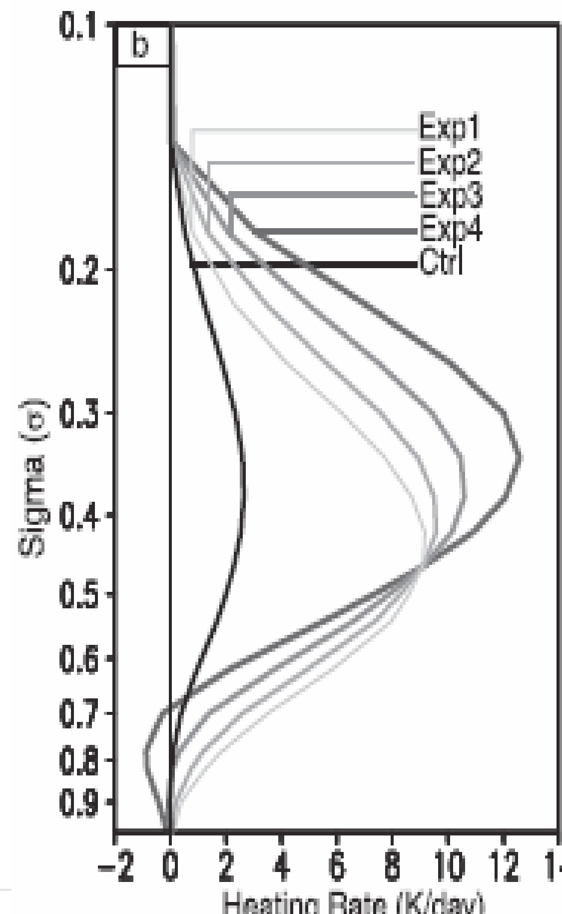
Shaded area: Monsoon trough (MT) zone

Stratiform (SF) and convective fractions (CF) of rainfall anomaly is assumed to be fixed at all grid points over the MT zone for any particular experiment

Total Rain = Clim Rain + Anom Rain

Spatial variation of CF and SF for the total rainfall over the MT zone is allowed

Heating profiles for sensitivity experiments computed based on Schumacher et al. 2004



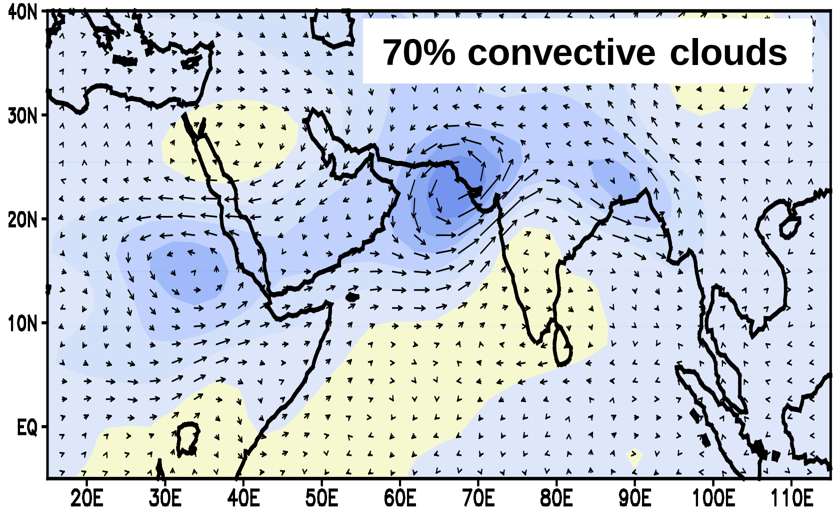
Model sensitivity experiments

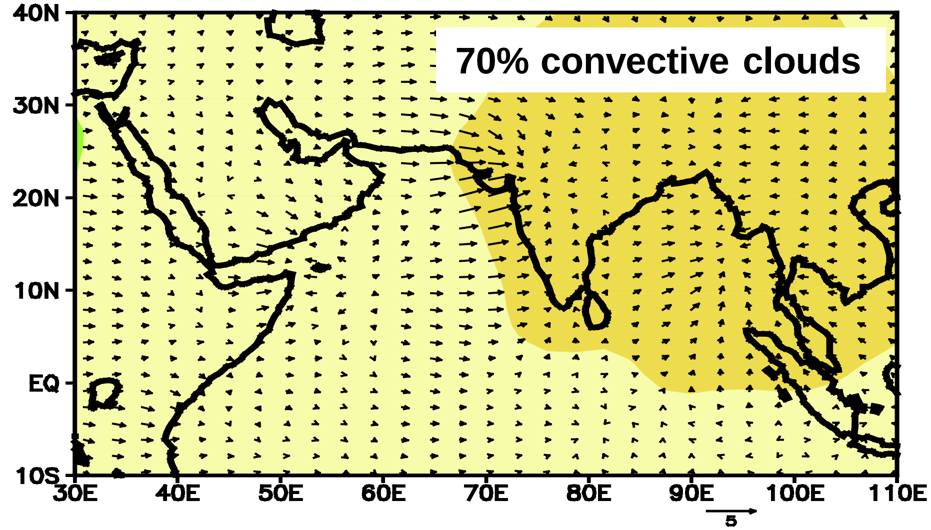
Experiment	Stratiform and convective fractions of rain anomaly during active monsoon period		Active period rain anomaly	
	Stratiform Fraction (SF)	Convective Fraction (CF)	Stratiform anomaly	Convective anomaly
Exp 1	0%	100%	0.0 % of Rain anomaly	100 % of Rain anomaly
Exp 2	30%	70%	30 % of Rain anomaly	70 % of Rain anomaly
Exp 3	50%	50%	50 % of Rain anomaly	50 % of Rain anomaly
Exp 4	70%	30%	70 % of Rain anomaly	30 % of Rain anomaly

Mid-level anomalous circulation response

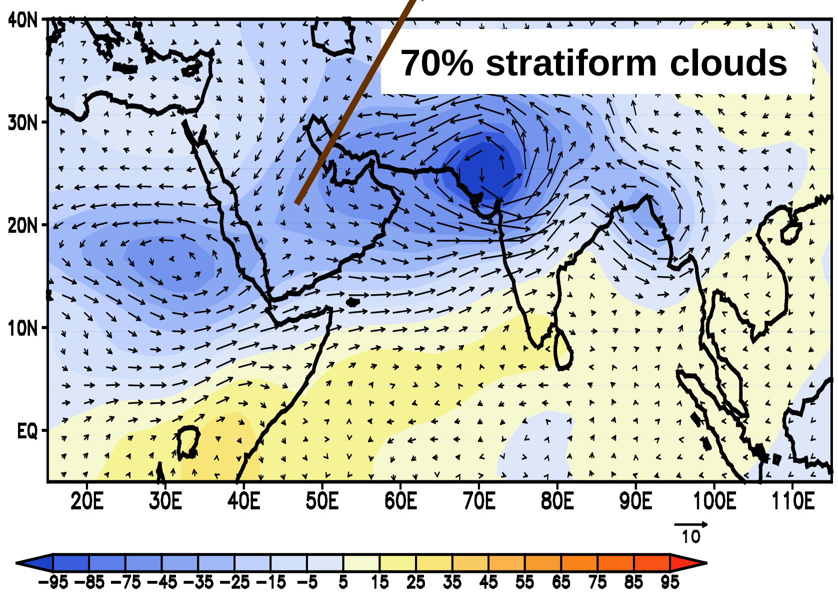
Streamfunction

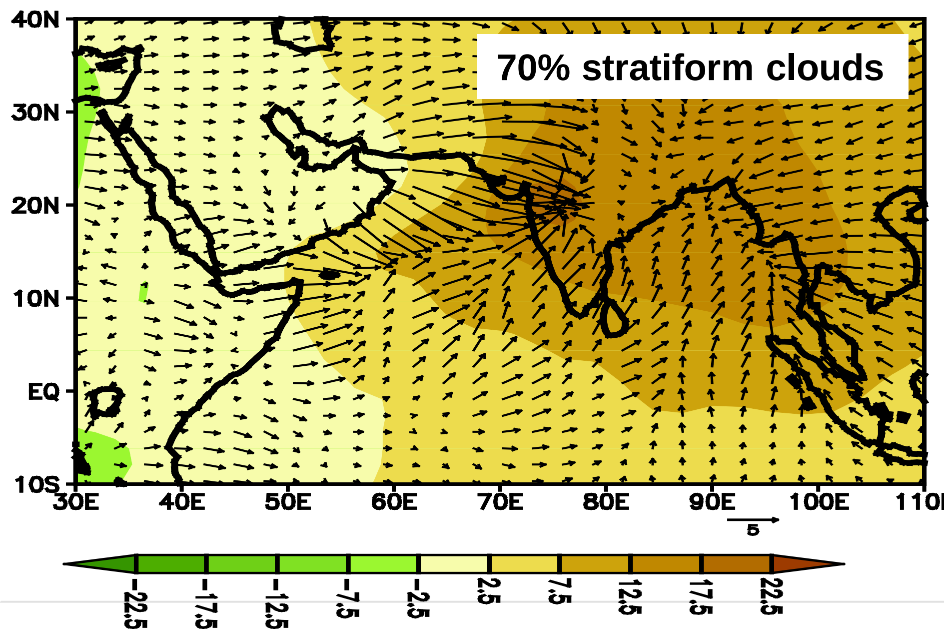
Velocity potential

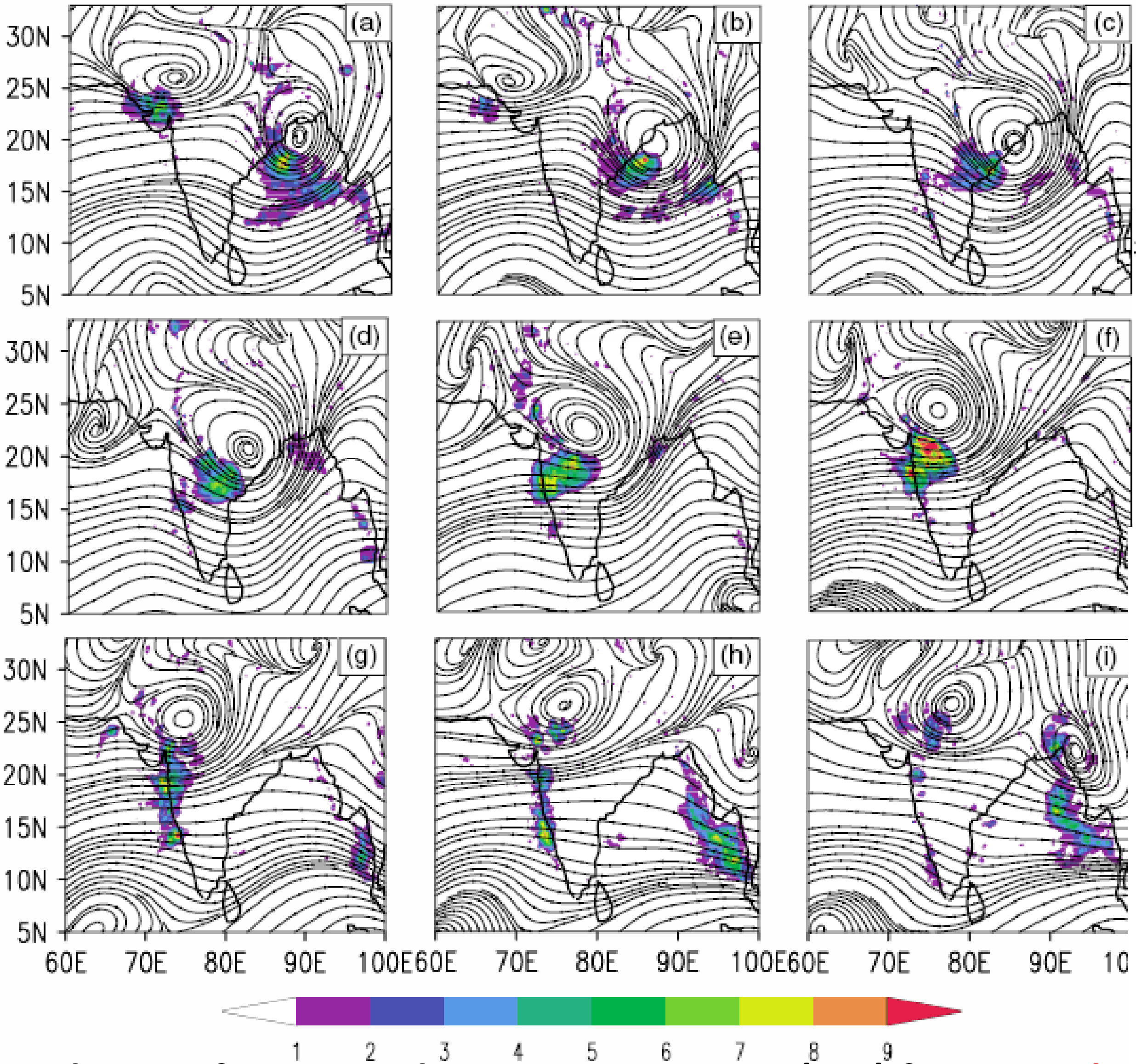




Large scale structure of mid-level cyclonic response extending into African ITCZ region

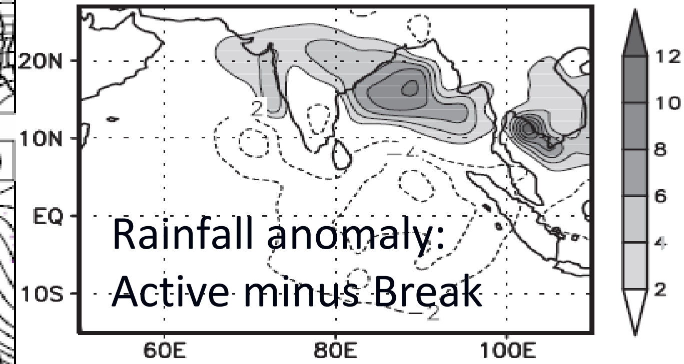


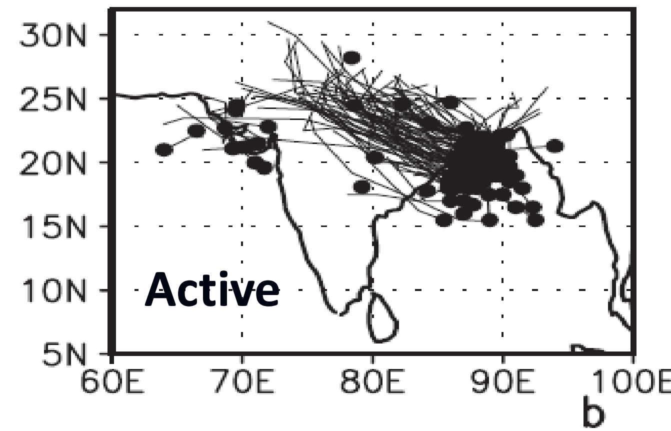


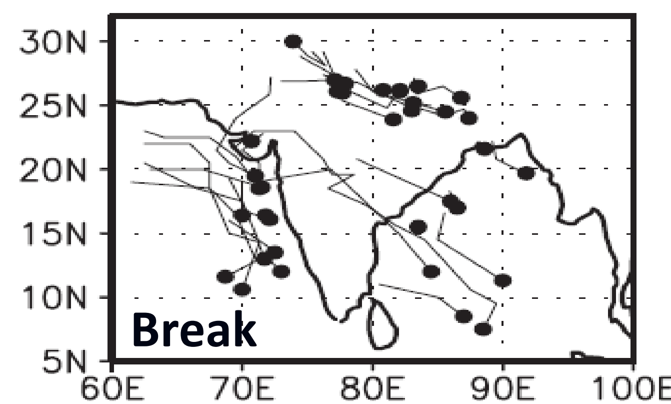


Evolution of monsoon low pressure system (LPS) from 31 July to 8 August, 2006: Streamlines at 850 hPa and rainfall from TRMM Microwave Imager (TMI) Krishnan et al. 2011

Clustering of synoptic activity by monsoon intraseasonal oscillations: Goswami et al. 2003, GRL

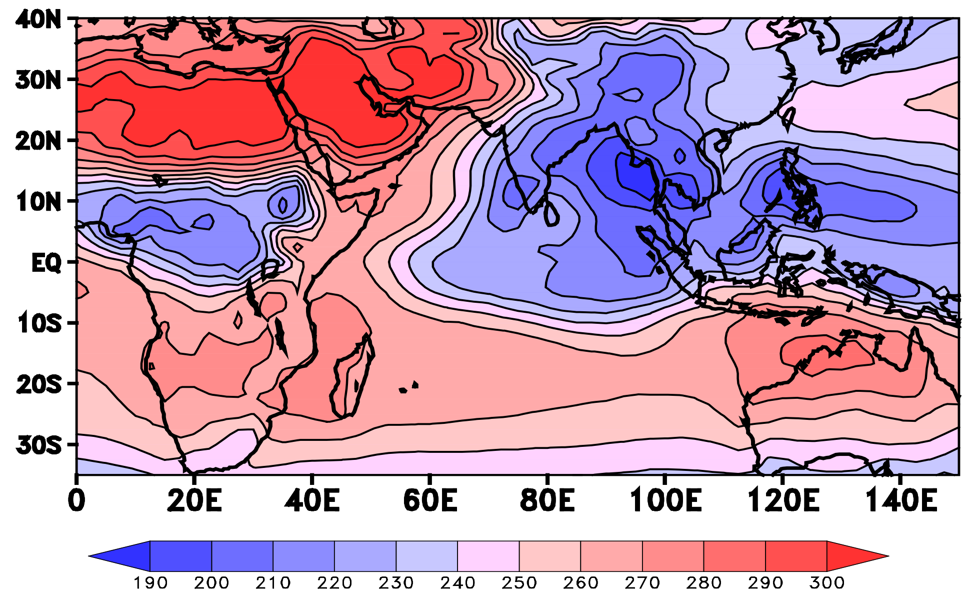




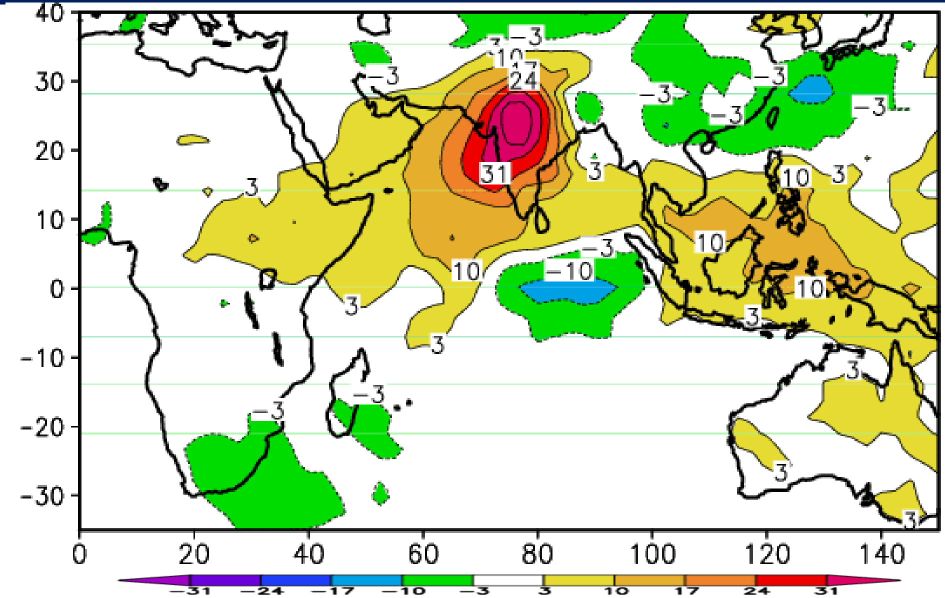


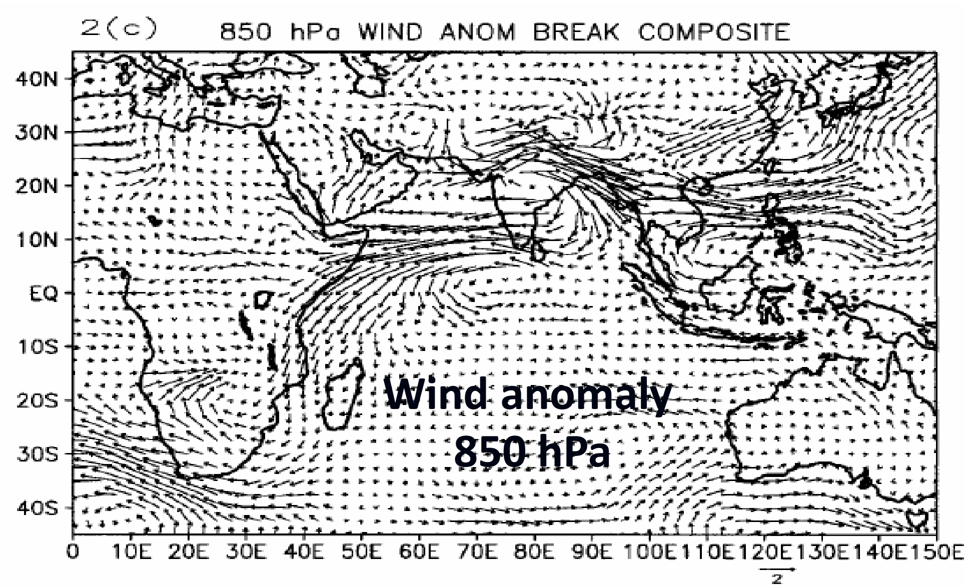
Monsoon Breaks: Large-scale structure of anomalies

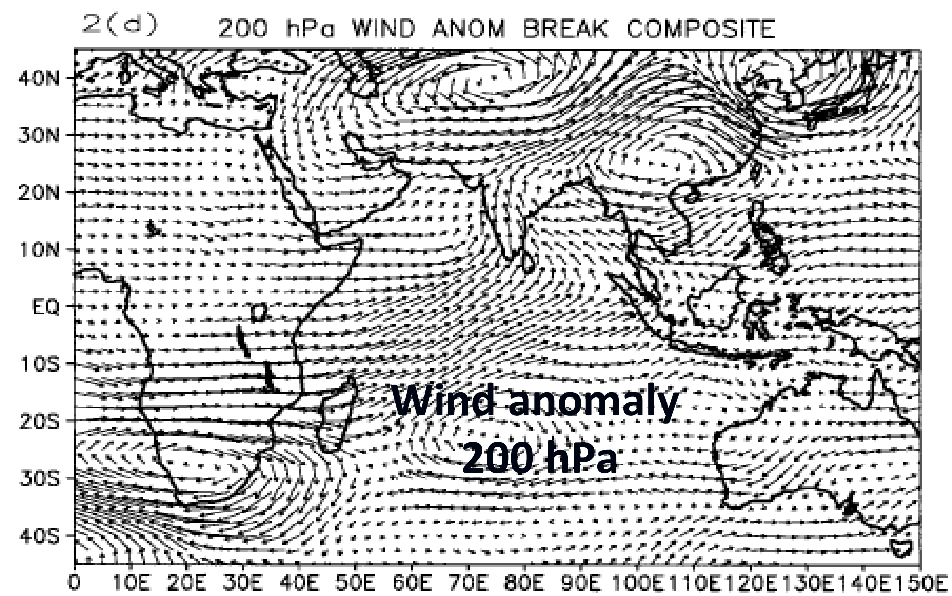
Mean OLR (June – September) NOAA satellite
Good proxy for tropical convection

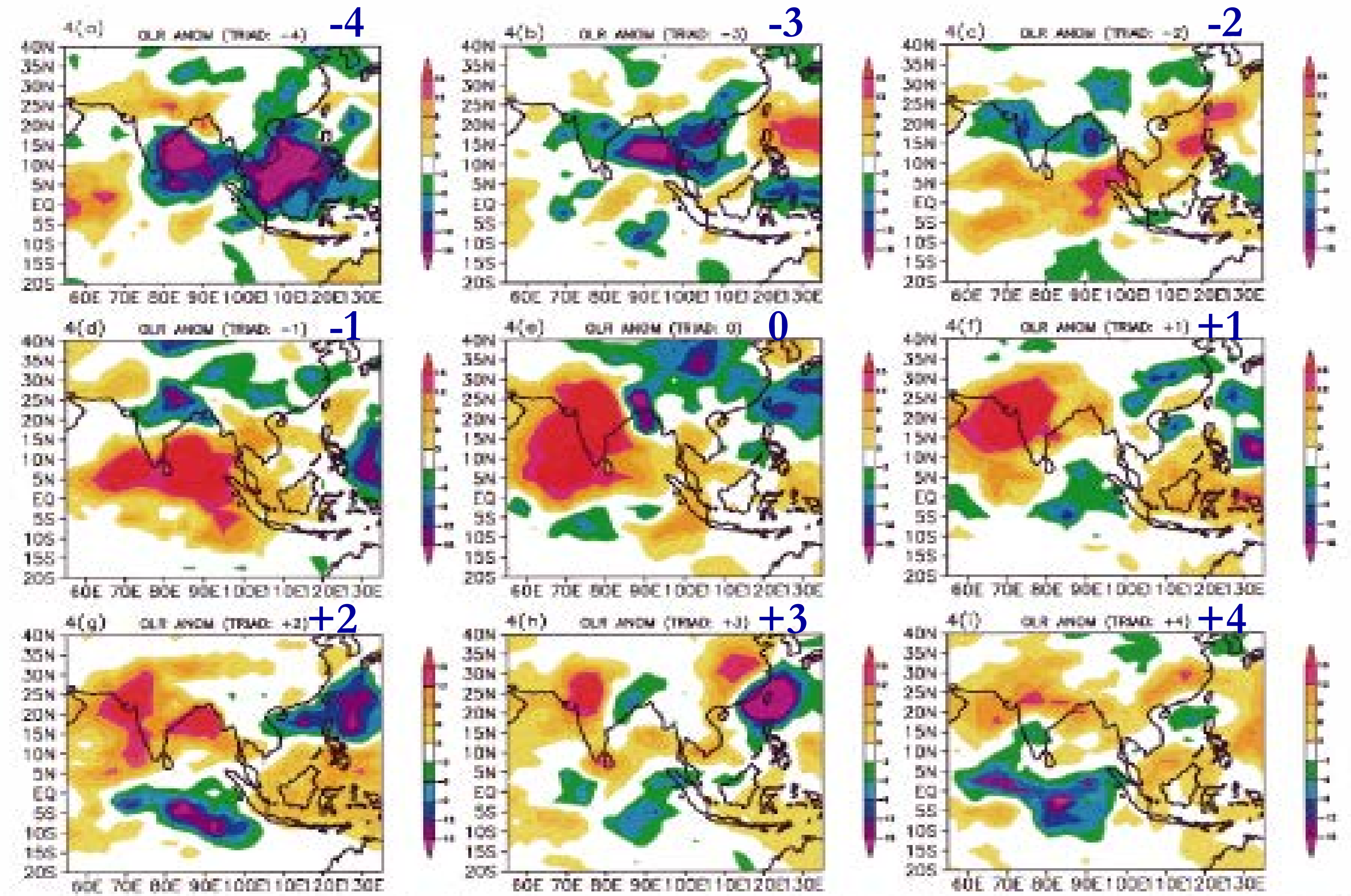


Composite OLR anomaly during monsoon Breaks – Krishnan, Zhang, Sugi (2000) JAS



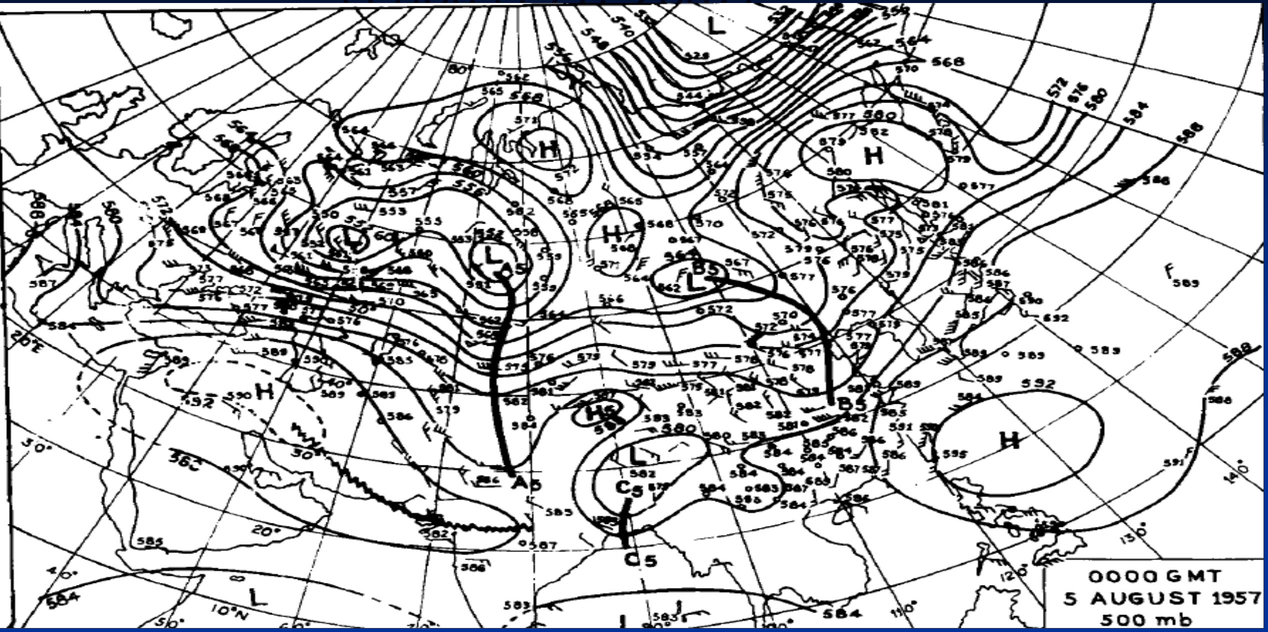






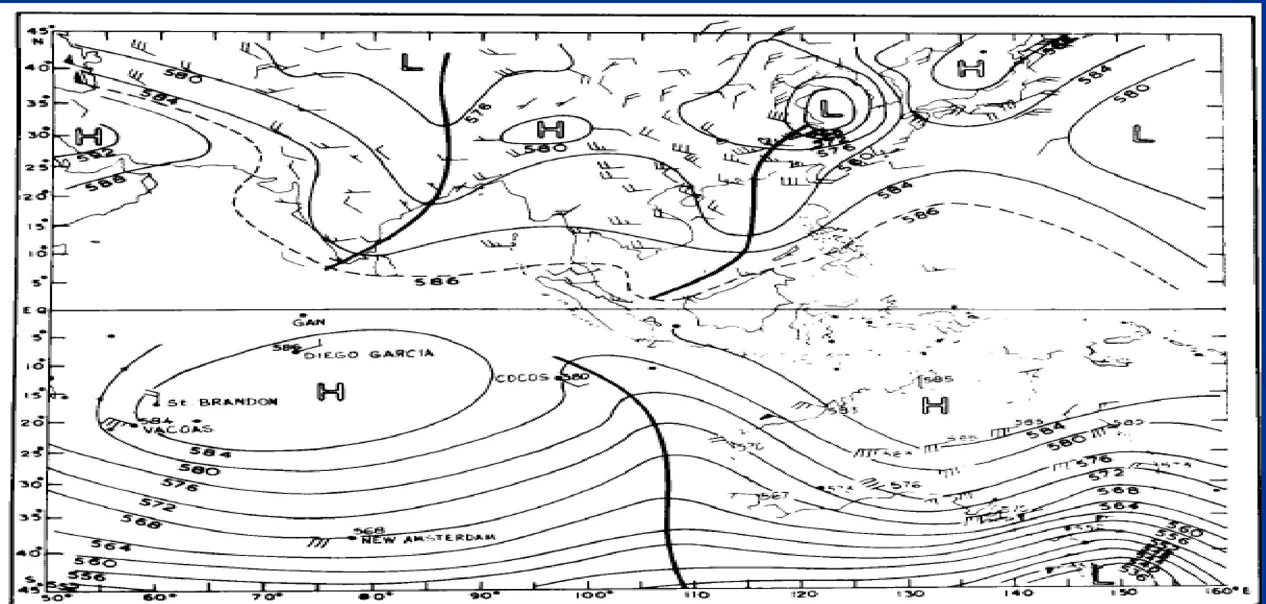
Sequence of composited OLR anomalies during evolution of breaks (a) Triad -4 (b) Triad -3 (c) Triad -2 (d) Triad -1 (e) Triad 0 (f) Triad +1 (g) Triad +2 (h) Triad +3 (i) Triad +4

C. Ramaswamy (1962): Breaks in the Indian summer monsoon as a phenomenon of interaction between the easterly and sub-tropical westerly jet streams - Tellus



500 hPa chart - 05 Aug 1957

Ramaswamy & Pareekh (1978) Development of westerly circulation in both Hemispheres

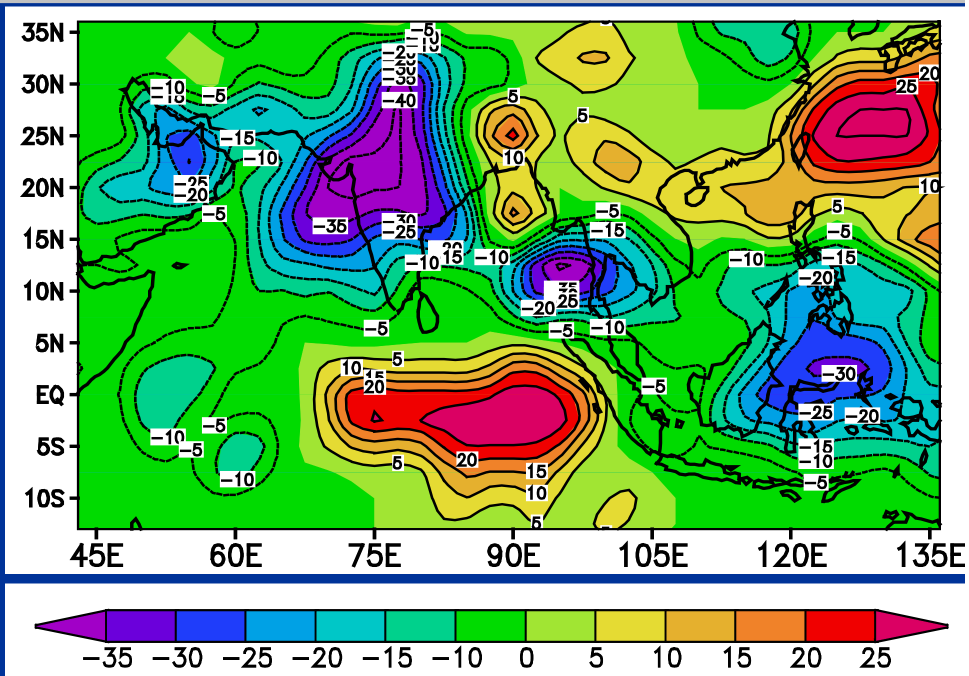


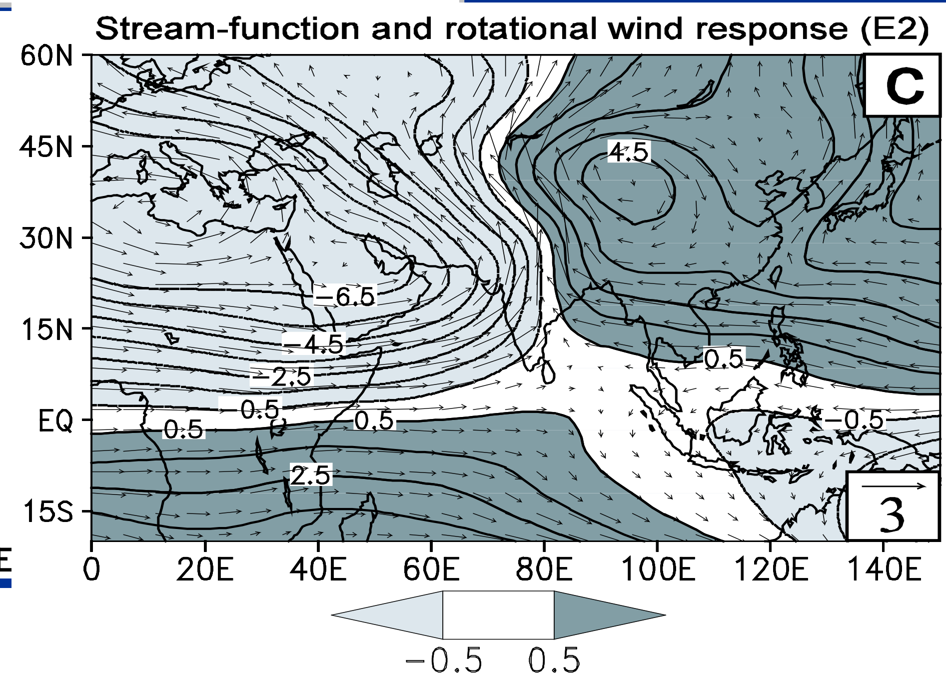
500 hPa chart - 26 July 1972 : A peak phase of monsoon break

Anomalous southward intrusion of mid-latitude westerly troughs in middle and upper levels during breaks

$$\frac{\partial \xi}{\partial t} + V.\nabla(\xi + f) = -(\xi + f)\nabla .V + F$$

Forced divergent barotropic vorticity equation

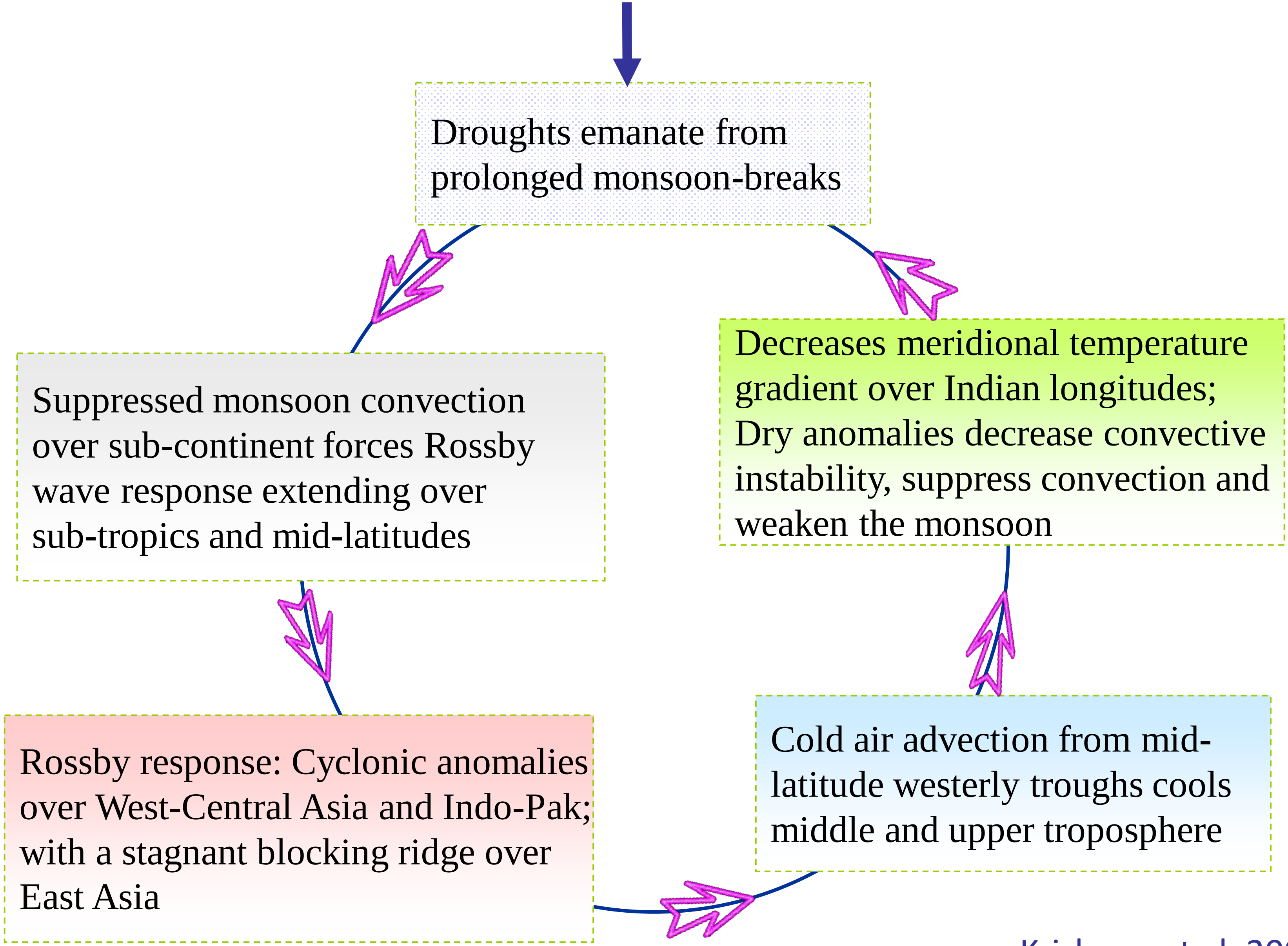




Divergence anomalies at 200 hPa during monsoon breaks - estimated using OLR : Krishnan et al. 2009

Simulated Rossby wave response to forcing from upper-tropospheric (200 hPa) divergence anomalies Note that thee simulated circulation response extends from the monsoon region into the midlatitudes

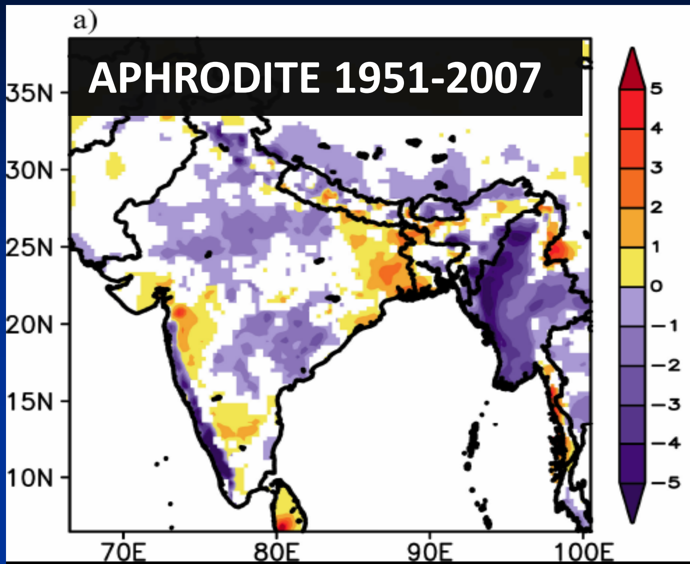
Monsoon-midlatitude interactions during droughts over India



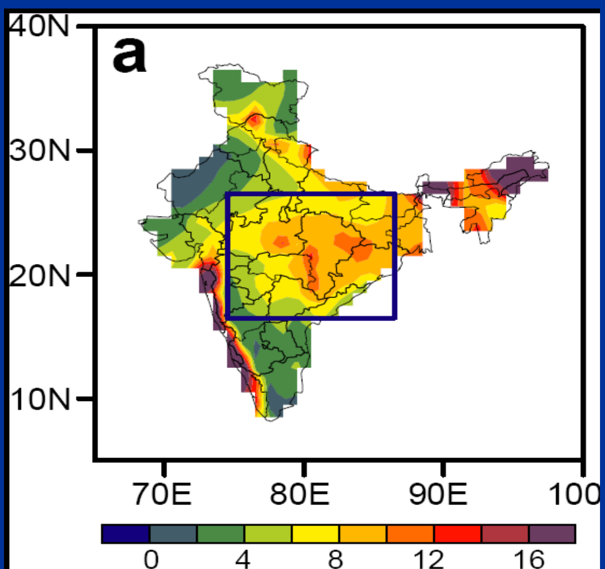
Krishnan et al. 2009

Changes in monsoon precipitation over India since 1950s

Spatial map of linear trend of JJAS rainfall (1951 – 2007)

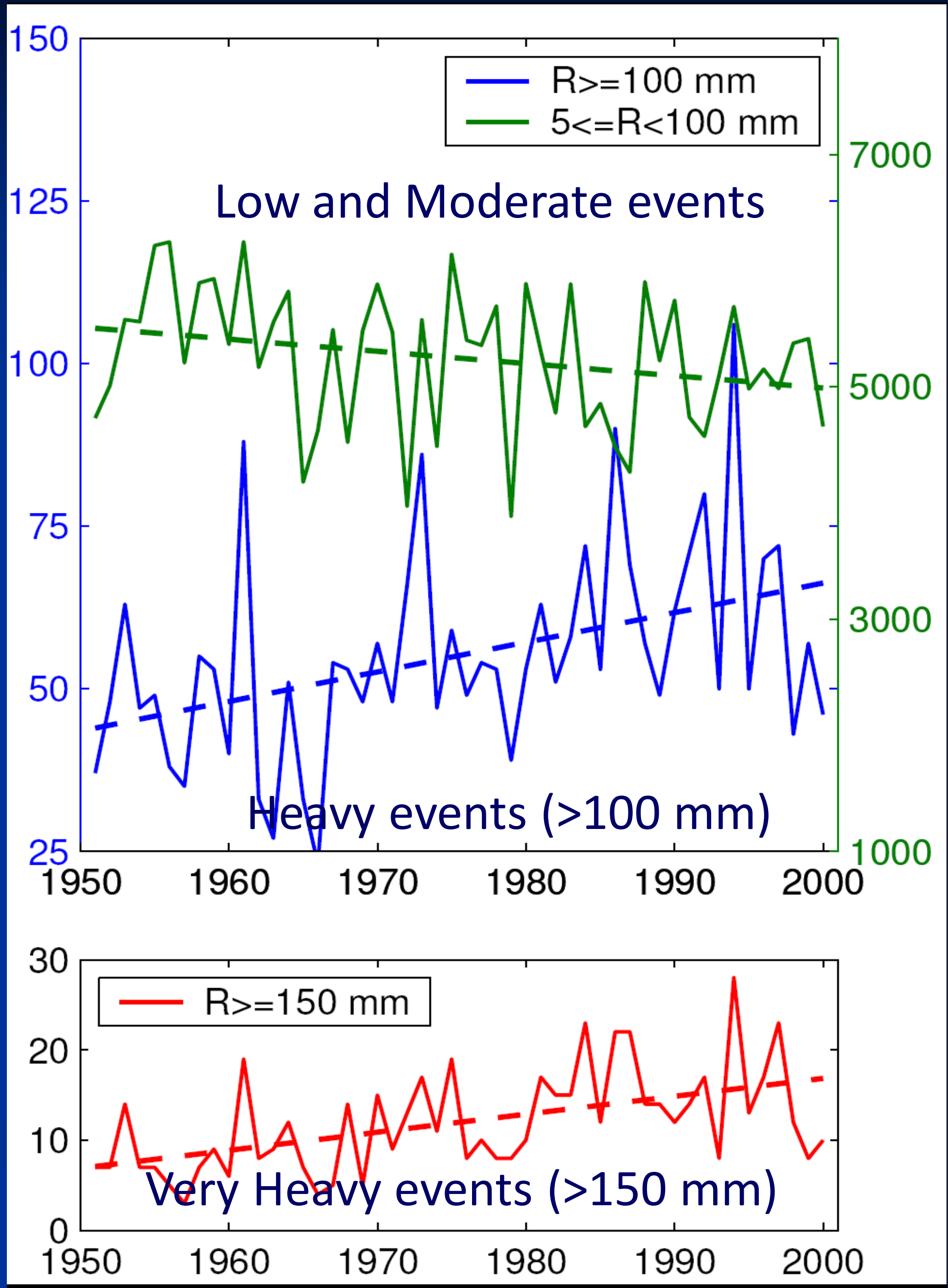


Increasing Trend of Extreme Rain Events over India in a Warming Environment

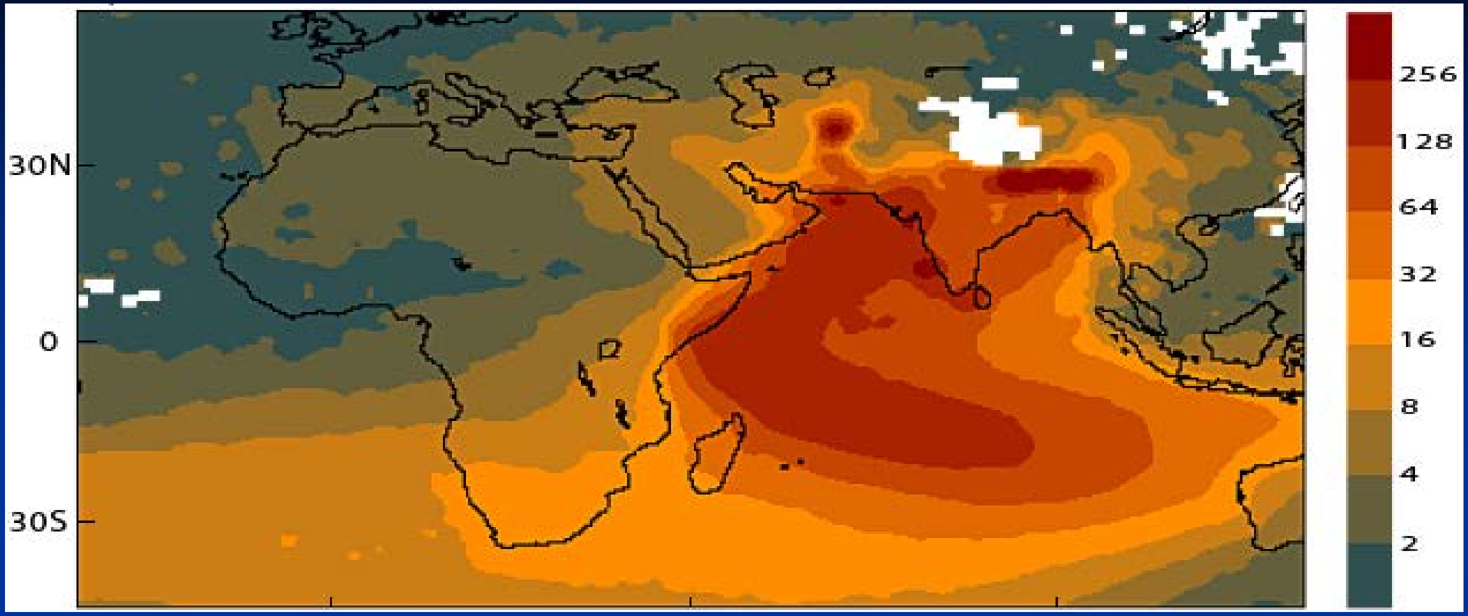


Goswami et al. 2006, Science

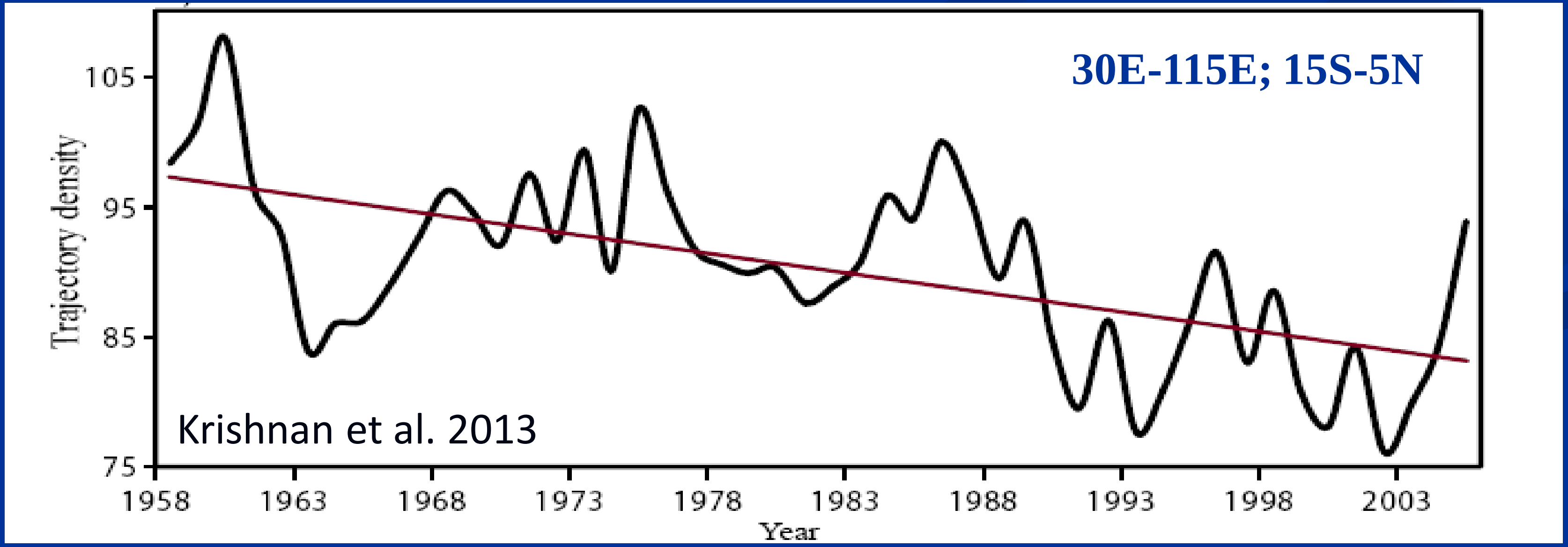
Time series of count over Central India

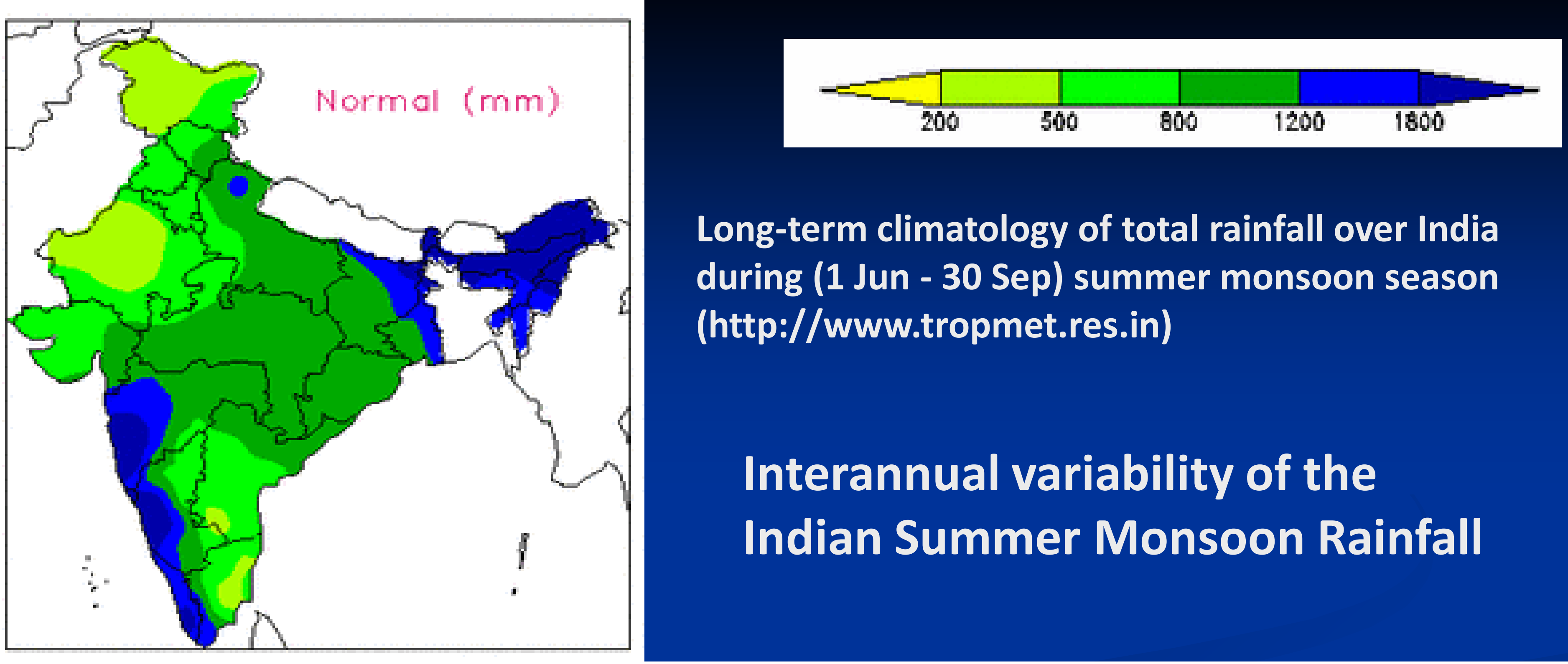


Climatological mean density of back-trajectories of monsoon flows reaching Indian region



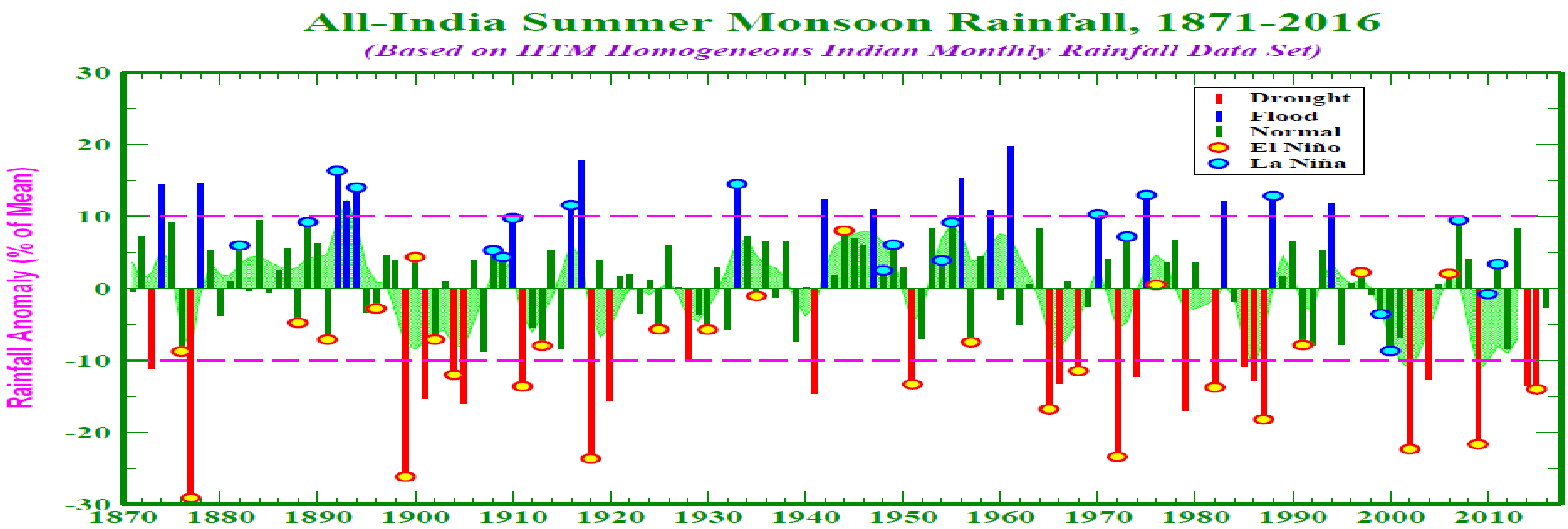
Interannual variability of JJAS seasonal mean trajectory density (1958 – 2006)



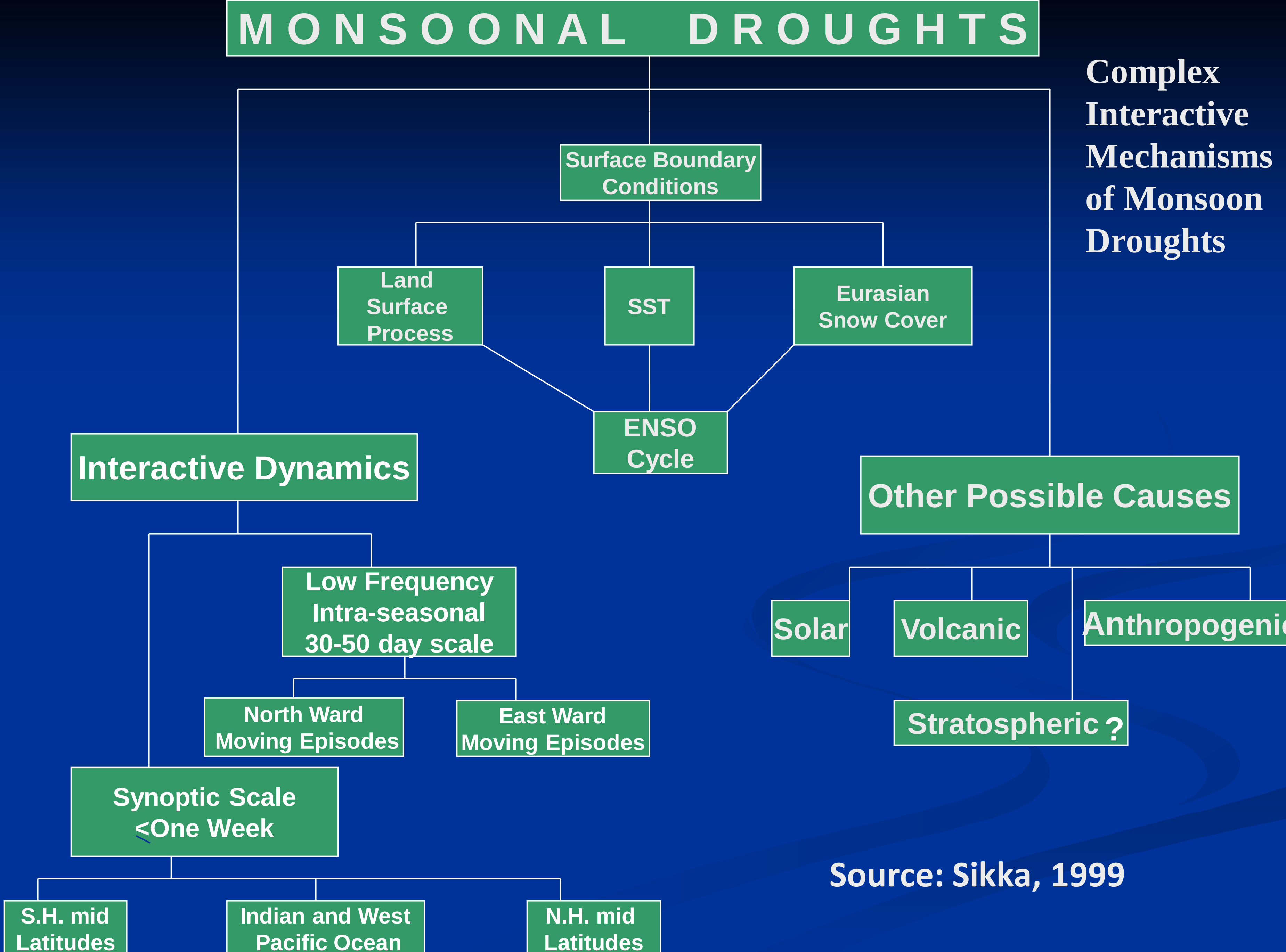


Long-term climatology of total rainfall over India during (1 Jun - 30 Sep) summer monsoon season (http://www.tropmet.res.in)

Interannual variability of the Indian Summer Monsoon Rainfall



Complex Interactive Mechanisms of Monsoon Droughts

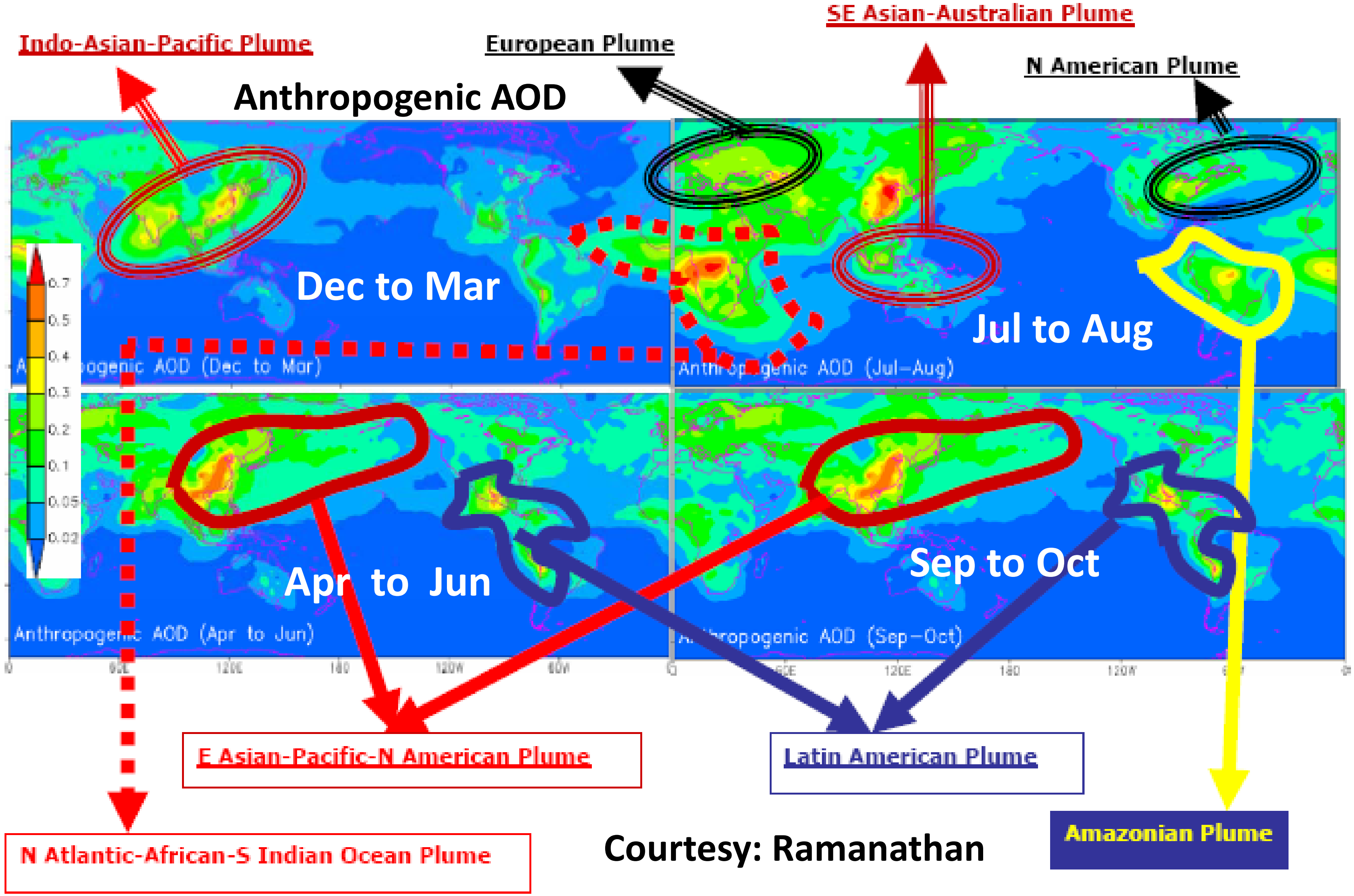


Source: Sikka, 1999

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

Ramanathan et al. JGR-2007

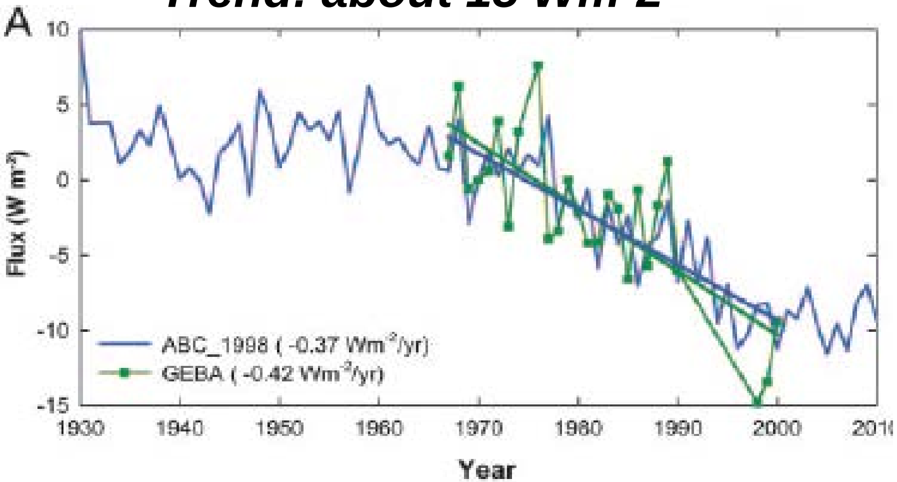
ABCs (eg. sulfate, organics, black carbon, ash, dust, sea-salt, etc) alter absorption and reflection of solar radiation and influence climate



Courtesy: Ramanathan

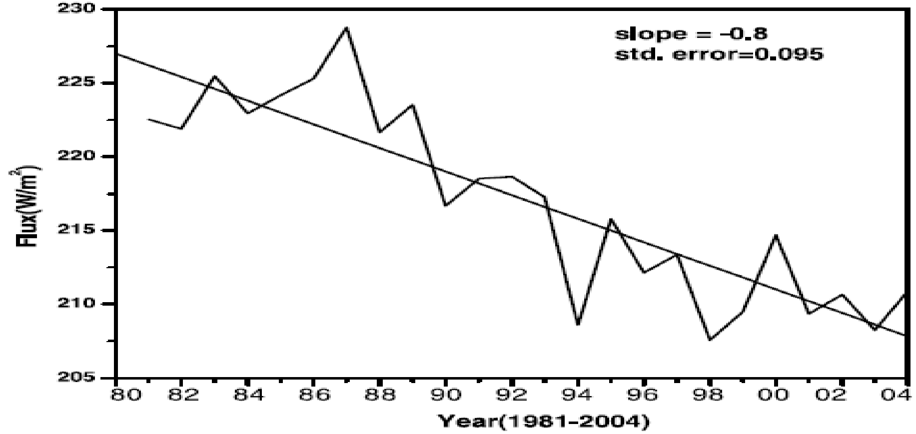
Ramanathan et al PNAS 2005

1970 to 2005: Surface Dimming-India
Trend: about 15 Wm-2



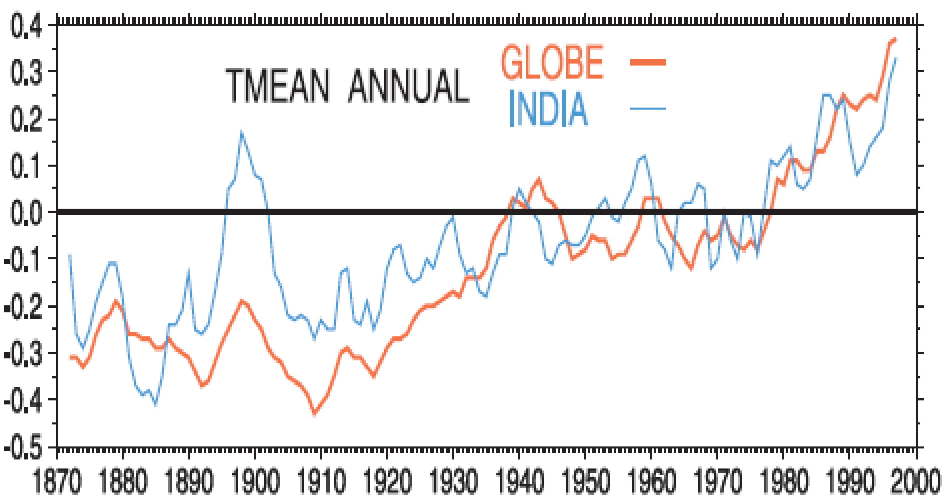
Padma Kumari et al, GRL 2007

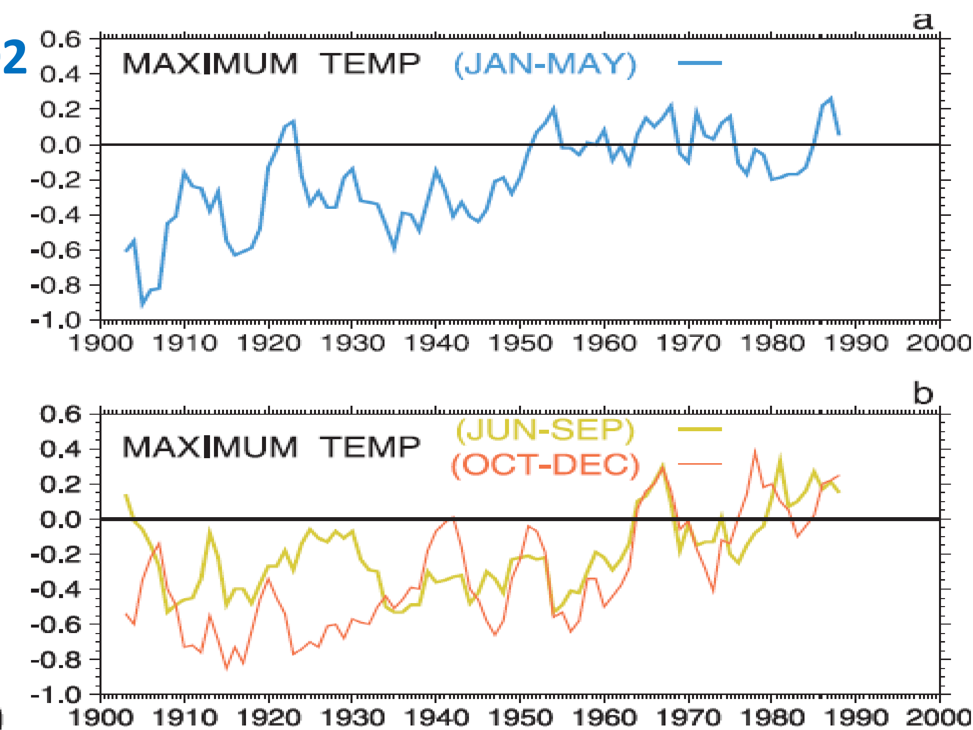
1980 to 2004: Surface Dimming-India
Trend 19 Wm^{-2}



R. Krishnan and V. Ramanathan, GRL 2002

Evidence of surface cooling from absorbing aerosols

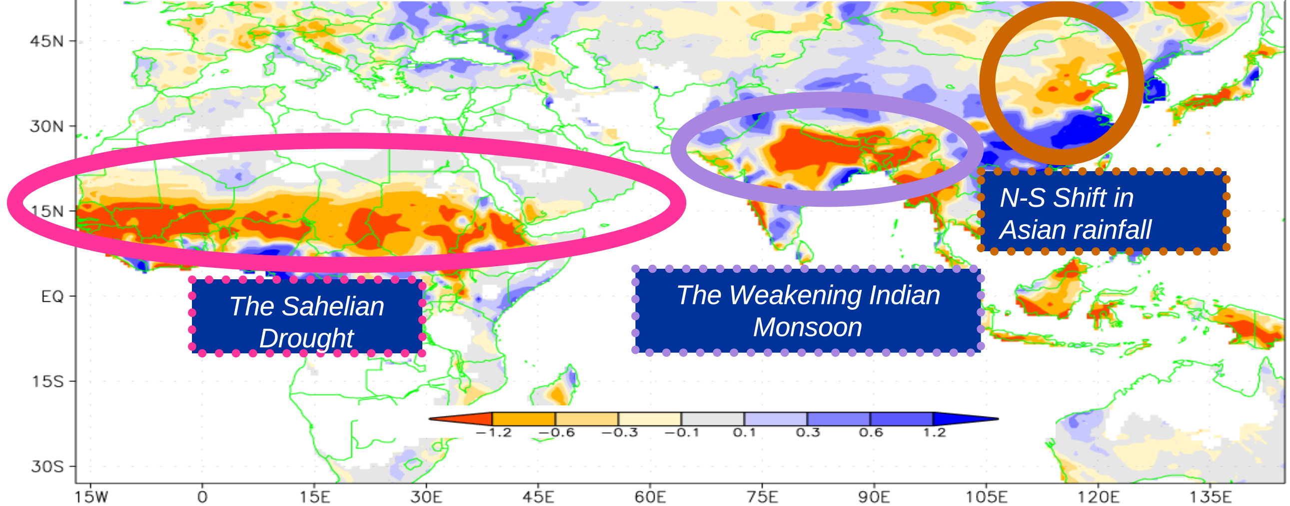




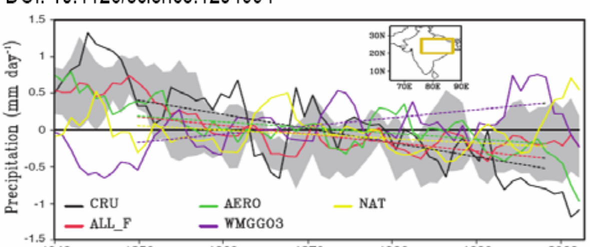
Weakening of North Indian SST Gradients and the Monsoon Rainfall in India and the Sahel

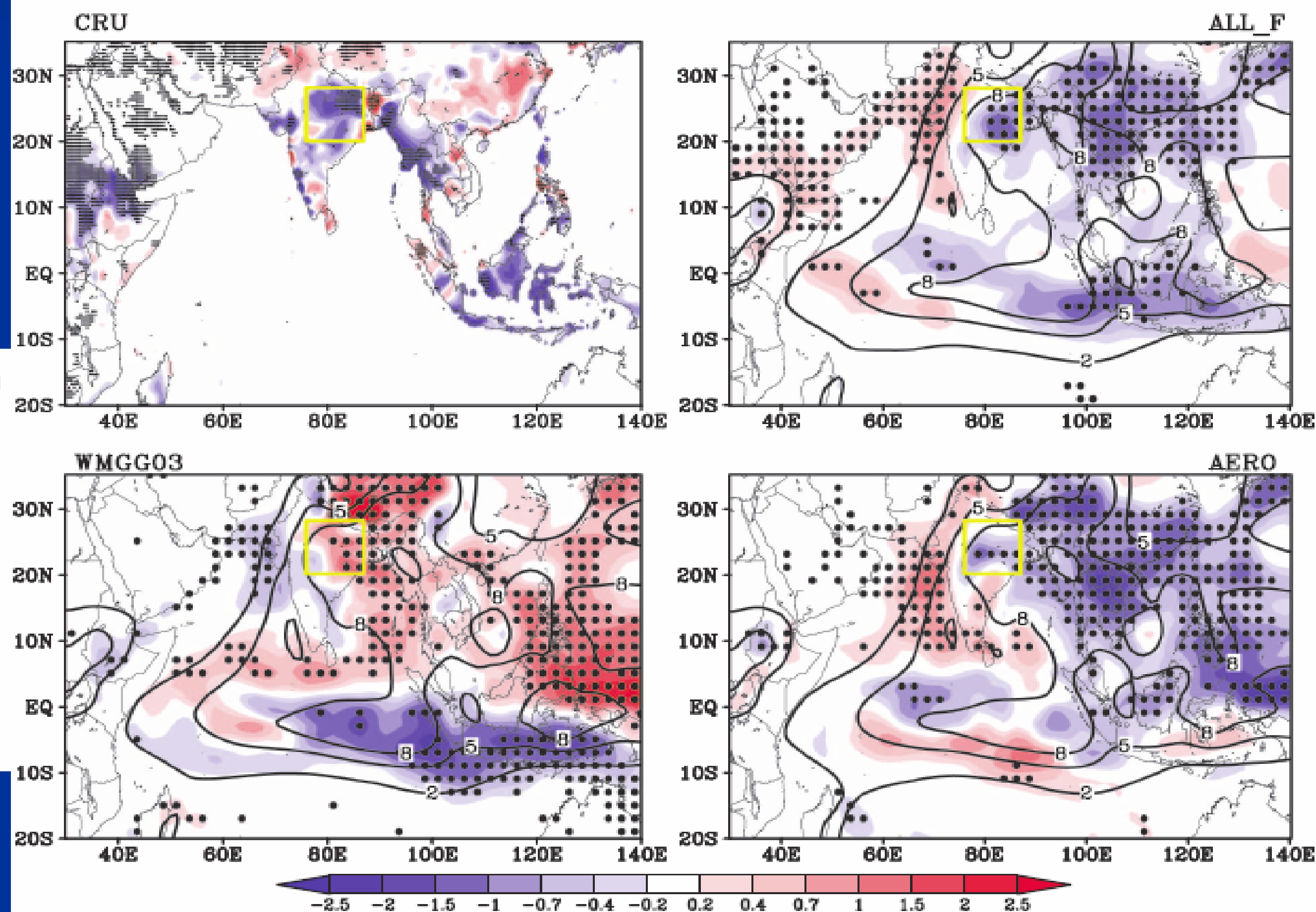
Chul Eddy Chung & V. Ramanathan
J. Climate, 2006

Observed Trends in Summer Rainfall: 1950 to 2002



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

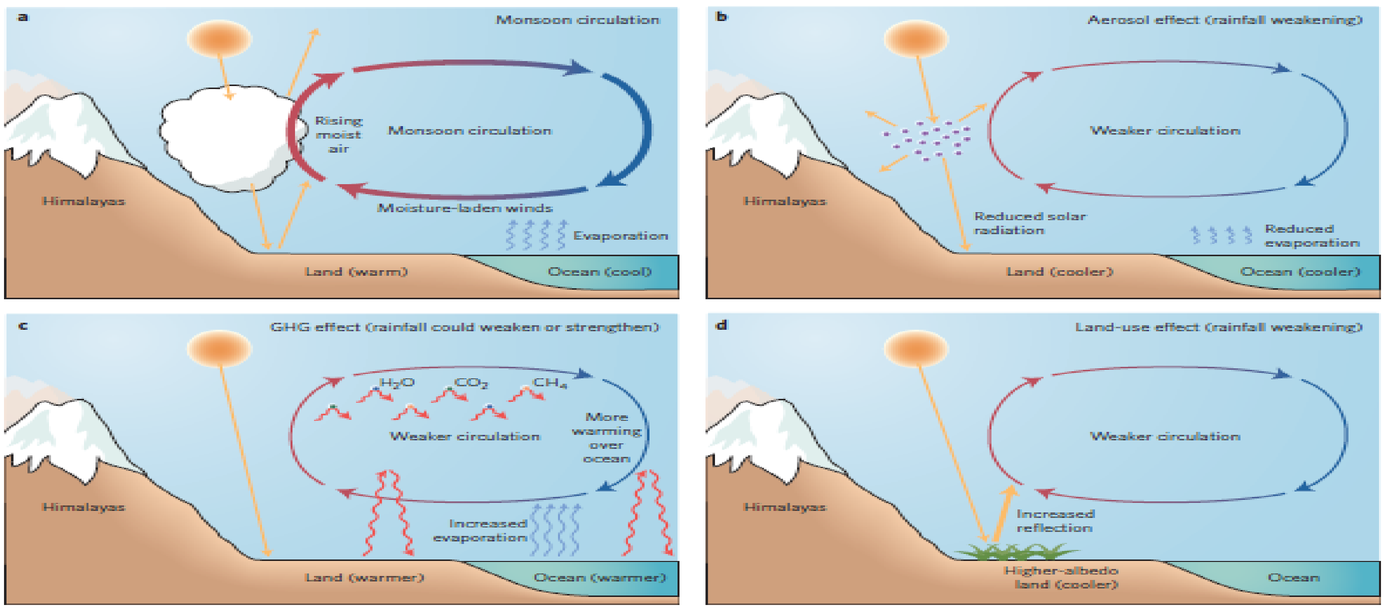




Bollasina, Ming, Ramaswamy, Science, 2011

Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world

R. Krishnan[1] · T. P. Sabin[1] · R. Vellore[1] · M. Mujumdar[1] · J. Sanjay[1] · B. N. Goswami[1,2] · F. Hourdin[3] · J.-L. Dufresne[3] · P. Terray[4,5]



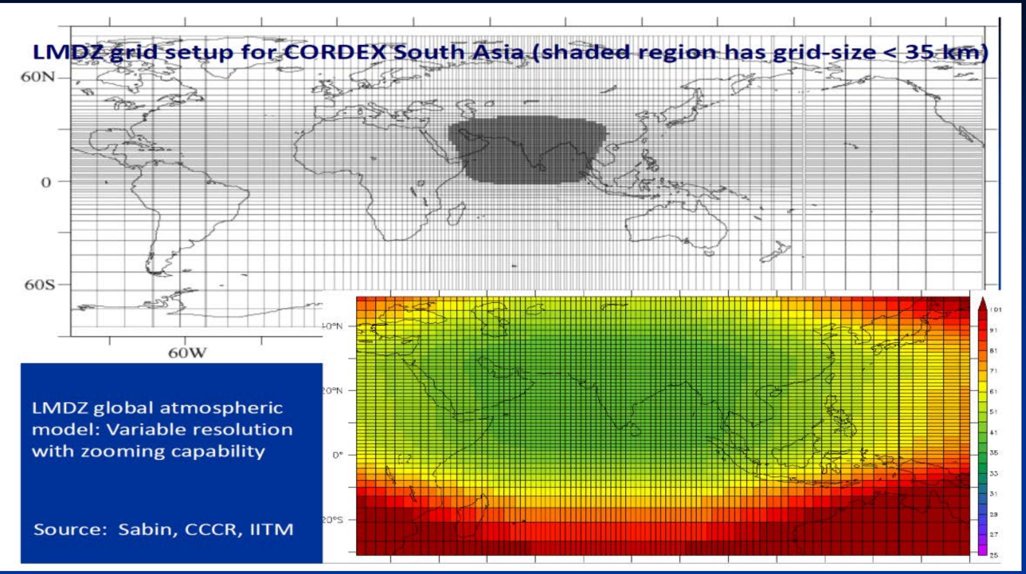
The onset of the monsoon in early June brings with it a burst of life across the region — children playing on the streets, blossoming flora, flowing rivers, and sowing of agricultural lands. The monsoon supplies ~80% of South Asia's annual rainfall, supporting the region's primarily rain-fed agriculture and recharging rivers, aquifers and reservoirs that provide water to over one-fifth of the global population. Since the 1950s, the monsoon has weakened[1] and become more erratic, with increased occurrence of extreme rainfall events[2]. This has led to crop failures and water shortages with severe socio-economic and humanitarian impacts across South Asia. Writing in *Climate Dynamics*, R. Krishnan and colleagues[3] suggest that anthropogenic greenhouse gas (GHG) emissions, aerosol emissions and agricultural land-cover changes are responsible for the observed changes in rainfall patterns. They predict that the monsoon weakening will continue through the twenty-first century, threatening the livelihoods and resources of over 1.6 billion people in the region.

SOUTH ASIAN MONSOON

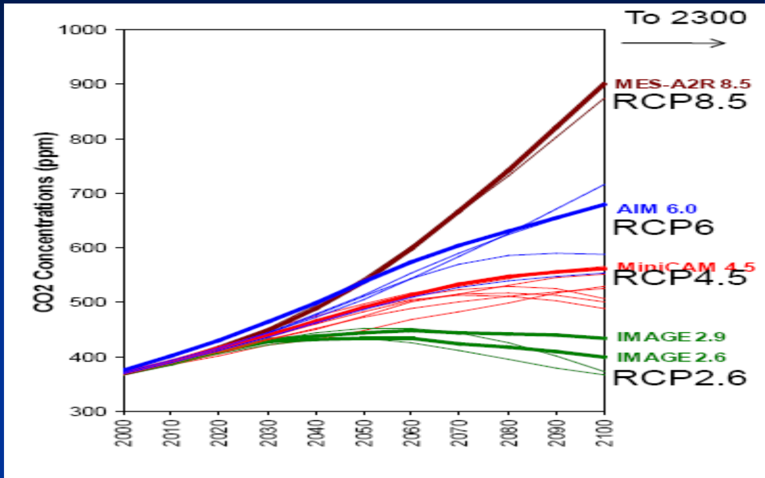
Tug of war on rainfall changes

Rainfall associated with the South Asian summer monsoon has decreased by approximately 7% since 1950, but the reasons for this are unclear. Now research suggests that changes in land-cover patterns and increased emissions from human activities have contributed to this weakening, which is expected to continue in the coming decades.

High-resolution (~ 35 km) modeling of **climate change over S.Asia**



CO2 concentration in future IPCC AR5 scenarios



Historical (1886-2005):

Includes natural and anthropogenic (GHG, aerosols, land cover etc) climate forcing for the historical period (1886 – 2005) ~ 120 yrs

Historical Natural (1886 – 2005):

Includes only natural climate forcing for historical period (1886– 2005) ~ 120 yrs

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

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

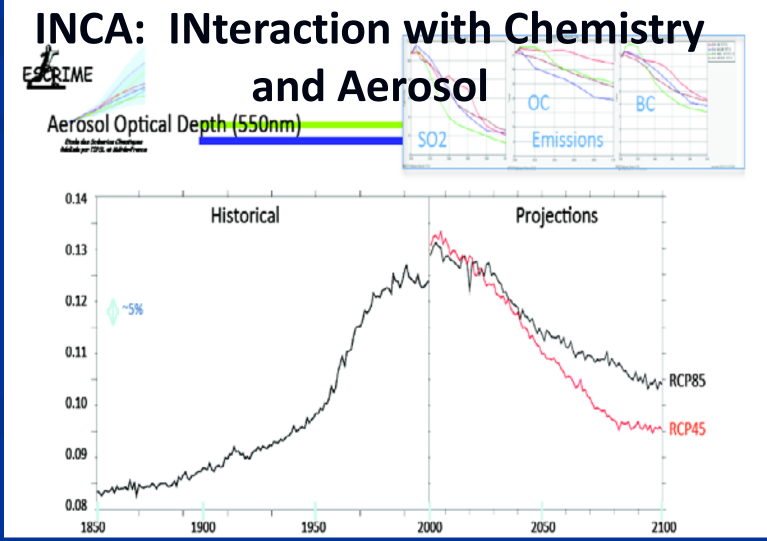
GHG-Only (1951-2005):

Includes GHG only forcing. Other forcing set to pre-industrial values

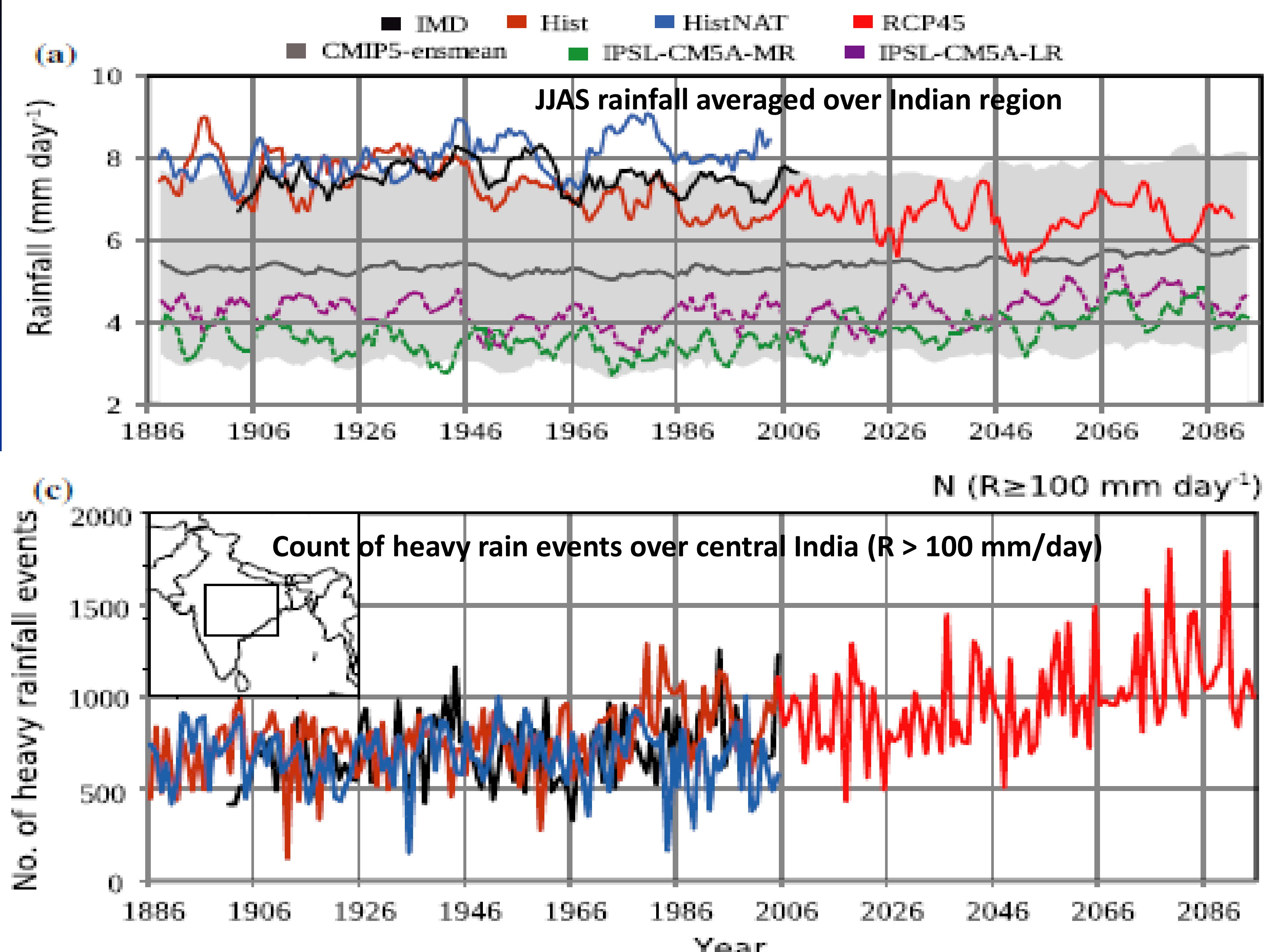
Aerosol-Only (1951– 2005):

Includes Aerosol only forcing. Other forcing set to pre-industrial values

Aerosol distribution from IPSL ESM



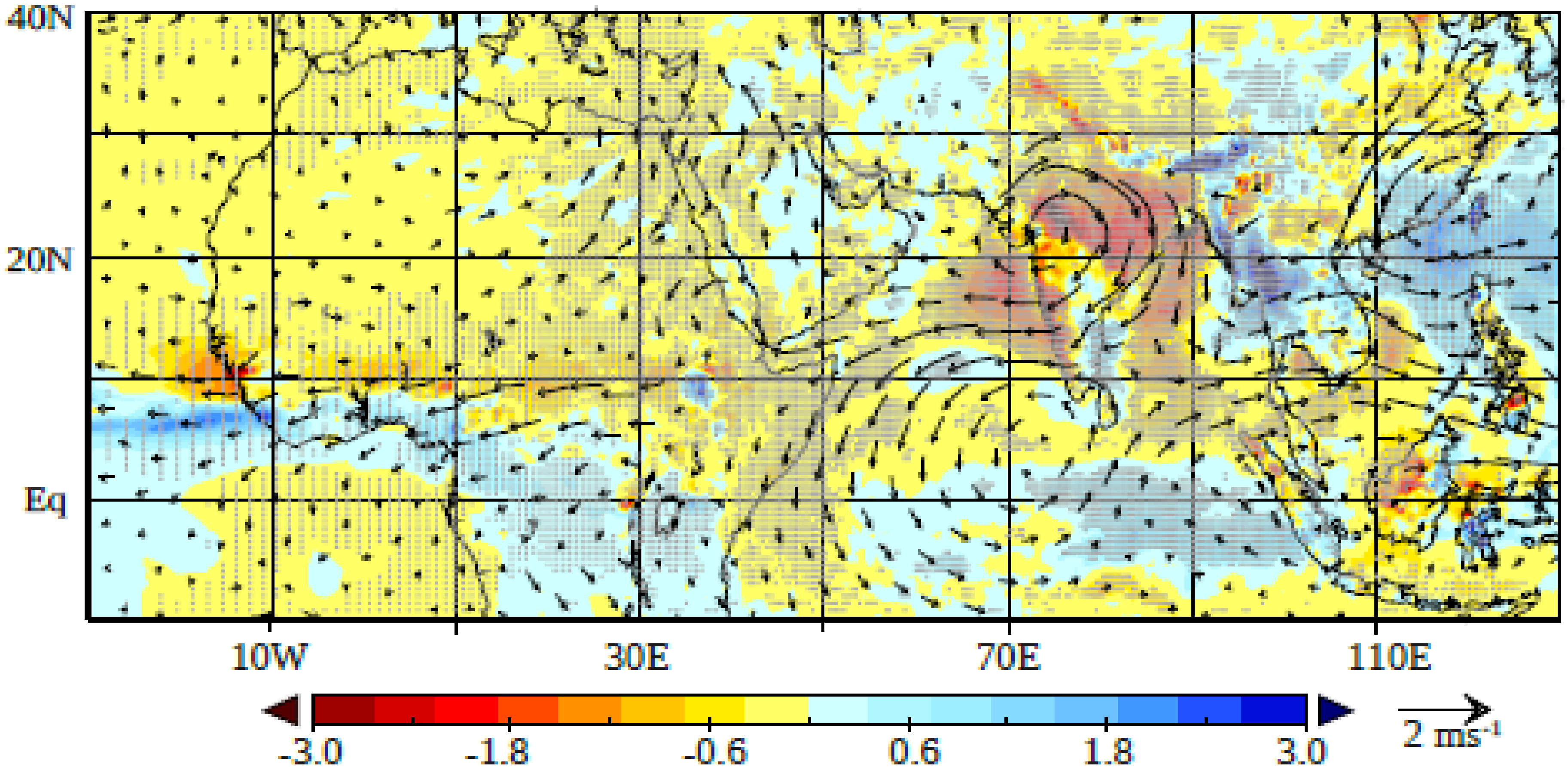
Runs performed on PRITHVI, CCCR-IITM



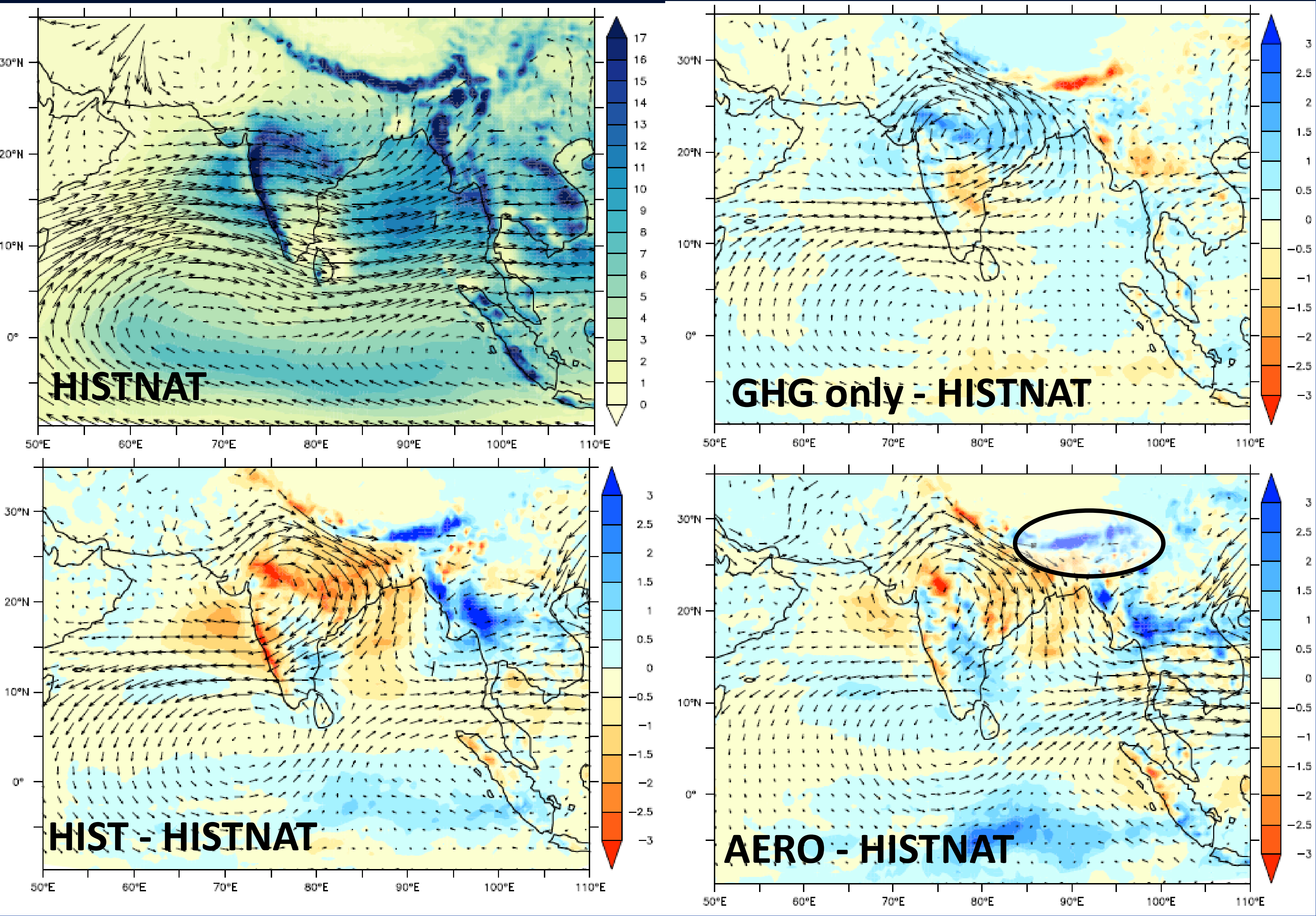
IMD
Hist
HistNAT
RCP45
CMIP5-ensmean
IPSL-CM5A-MR
IPSL-CM5A-LR
(a)
JJAS rainfall averaged over Indian region
Rainfall (mm day-1)
10
8
6
4
2
1886
1906
1926
1946
1966
1986
2006
2026
2046
2066
2086
(c)
N (R≥100 mm day-1)
Count of heavy rain events over central India (R > 100 mm/day)
No. of heavy rainfall events
2000
1500
1000
500
0
1886
1906
1926
1946
1966
1986
2006
2026
2046
2066
2086
Year

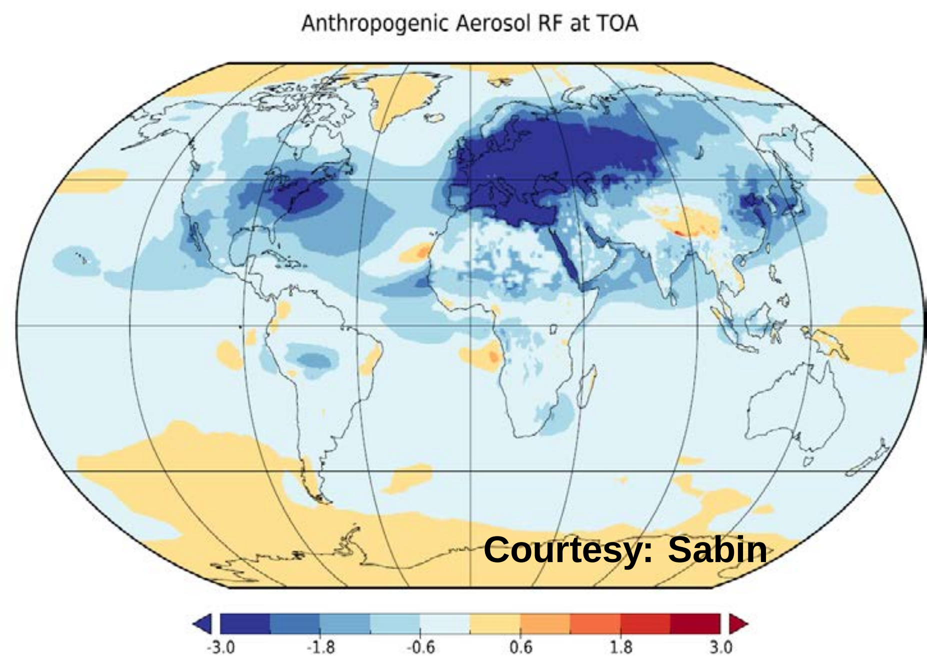
Mean difference maps (HIST minus HISTNAT) during 1951-2005

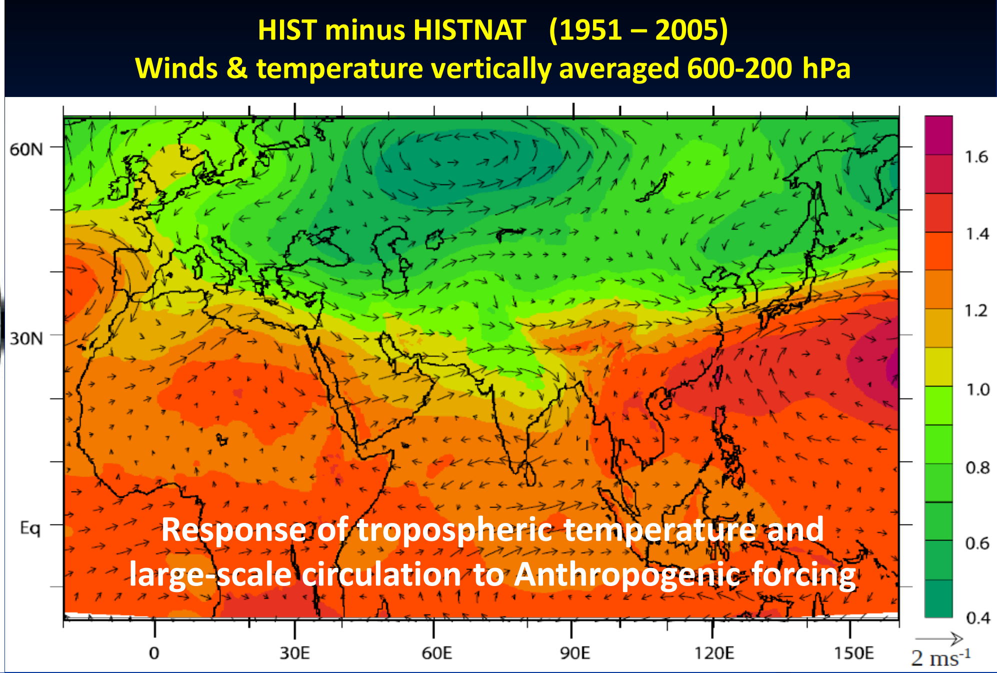
JJAS rainfall and 850 hPa winds



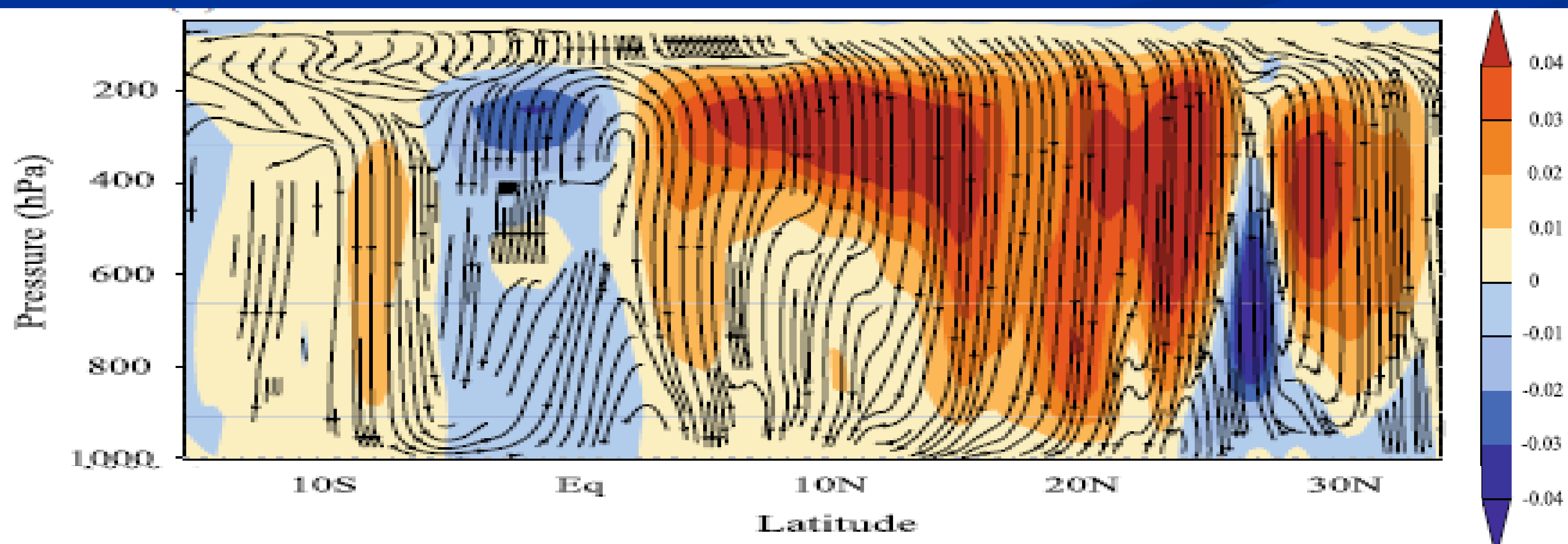
Simulation of summer monsoon precipitation & 850 hPa circulation



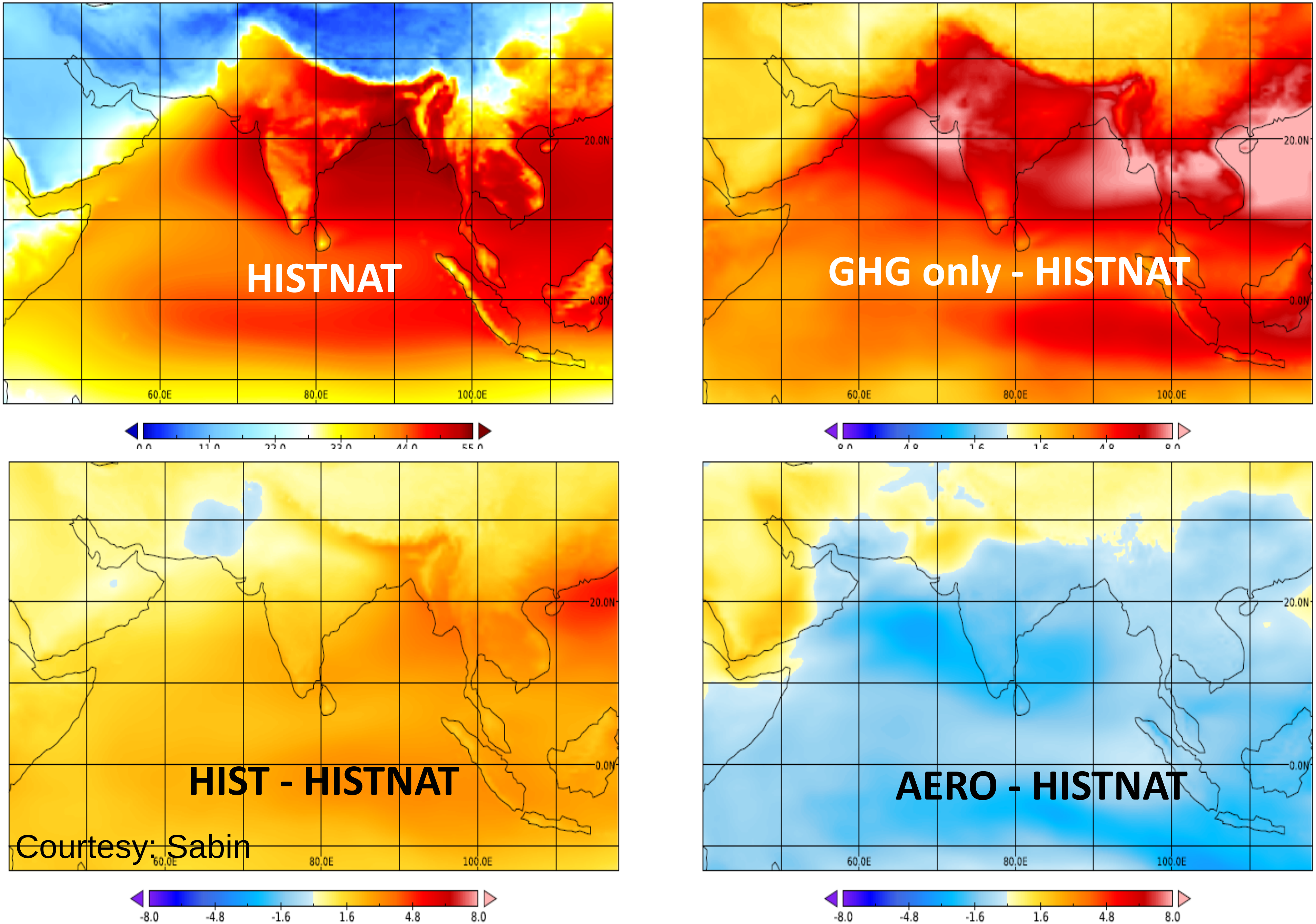




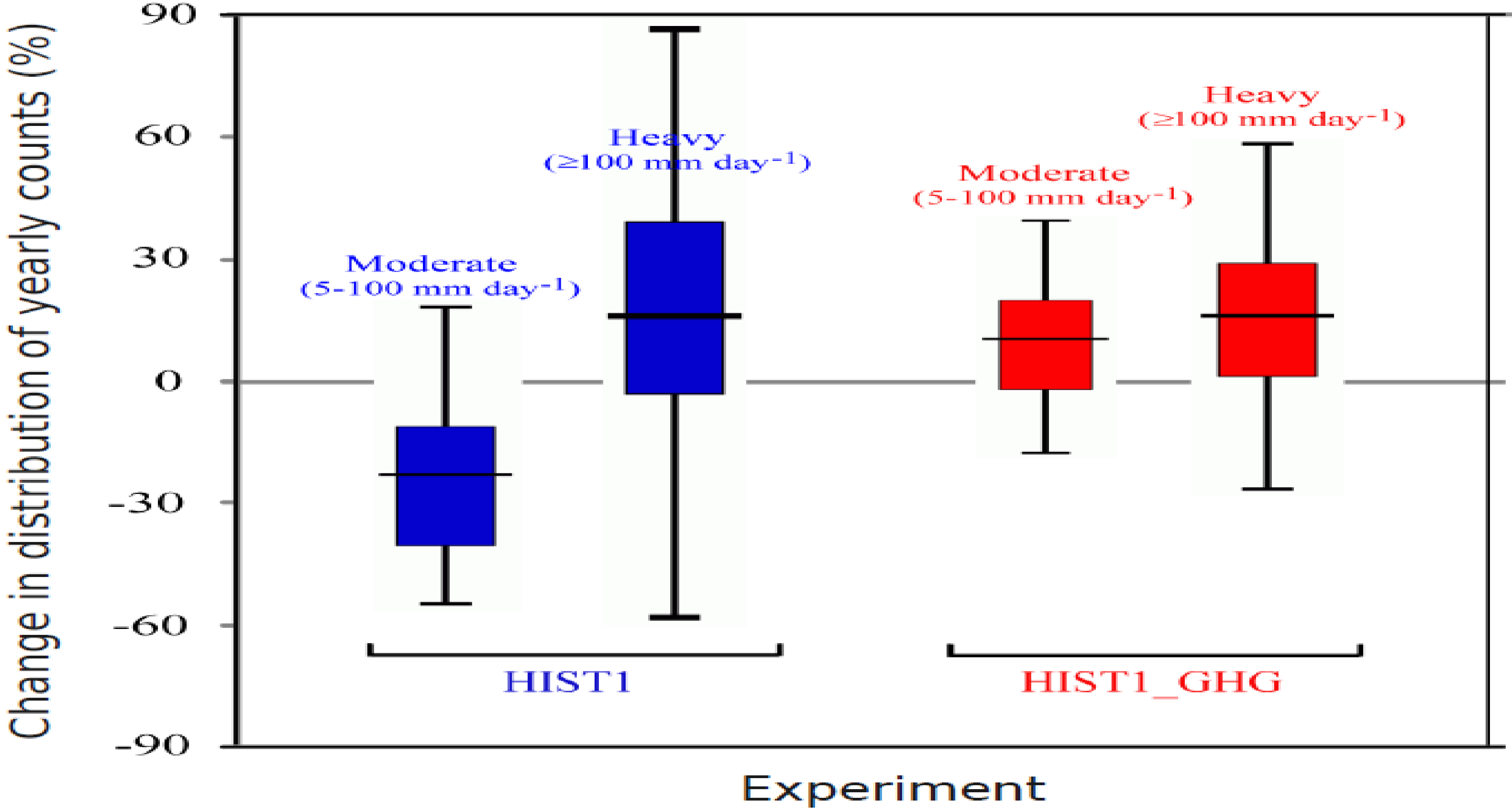
Weakening of monsoon Hadley-type overturning circulation



Simulation of summer monsoon precipitable water response



Changes in Heavy & Moderate precipitation types (HIST & GHG-only runs)



Central India: 74.5ºE – 86.5ºE, 16.5ºN - 26.5ºN

Period:1951-2000

Frequency counts for both categories are relative to HISNAT

Heavy precipitation events during South Asian summer monsoon

- Flood producing heavy rainfall over the southern slopes of **Northeast Himalayas** during breaks in the Indian monsoon
- 2010 Pakistan floods
- Heavy rainfall over Northwest Himalayas (eg. June 2013 Uttarakhand floods)

Monsoon 2017

Indian Express: 13 July 2017

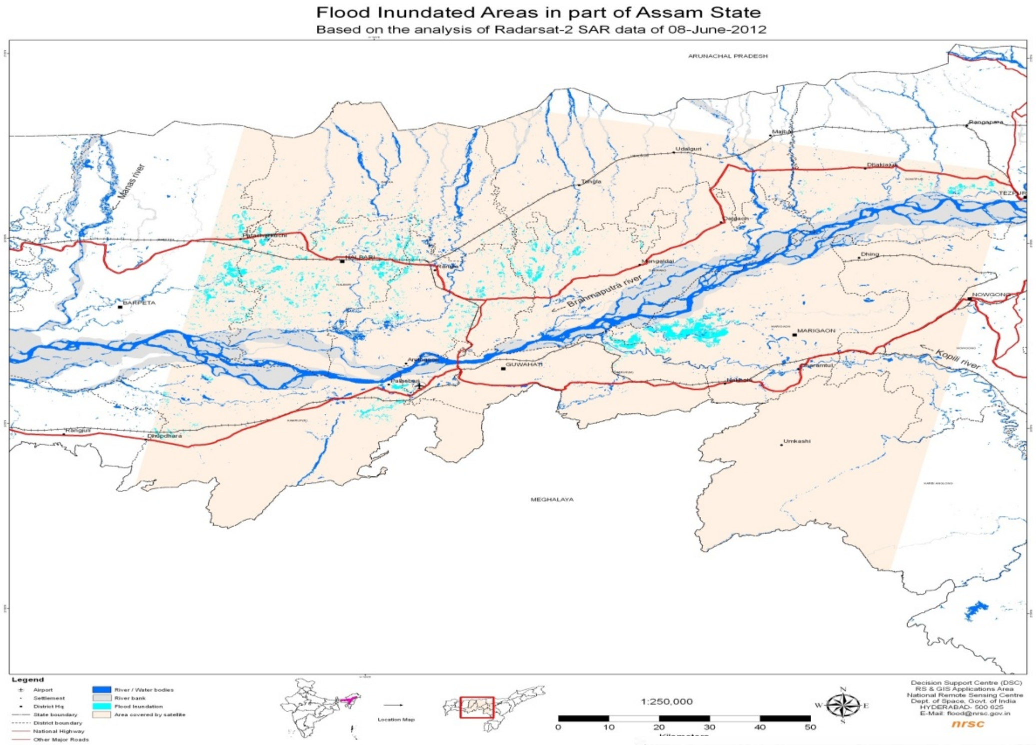
Monsoon update: Normal rainfall in most parts of India, Northeast reels under floods

In the Northeast, Assam, Arunachal Pradesh and Manipur have been witnessing floods and landslides. The mighty Brahmaputra and its tributaries in Assam has so far submerged 2,500 villages, destroyed 1.06 lakh hectares of farmland, damaged infrastructure by breaching embankments and overrunning roads and bridges.

India Today: 14 July 2017

Northeast floods cause unprecedented damage, 80 dead, 17 lakh marooned

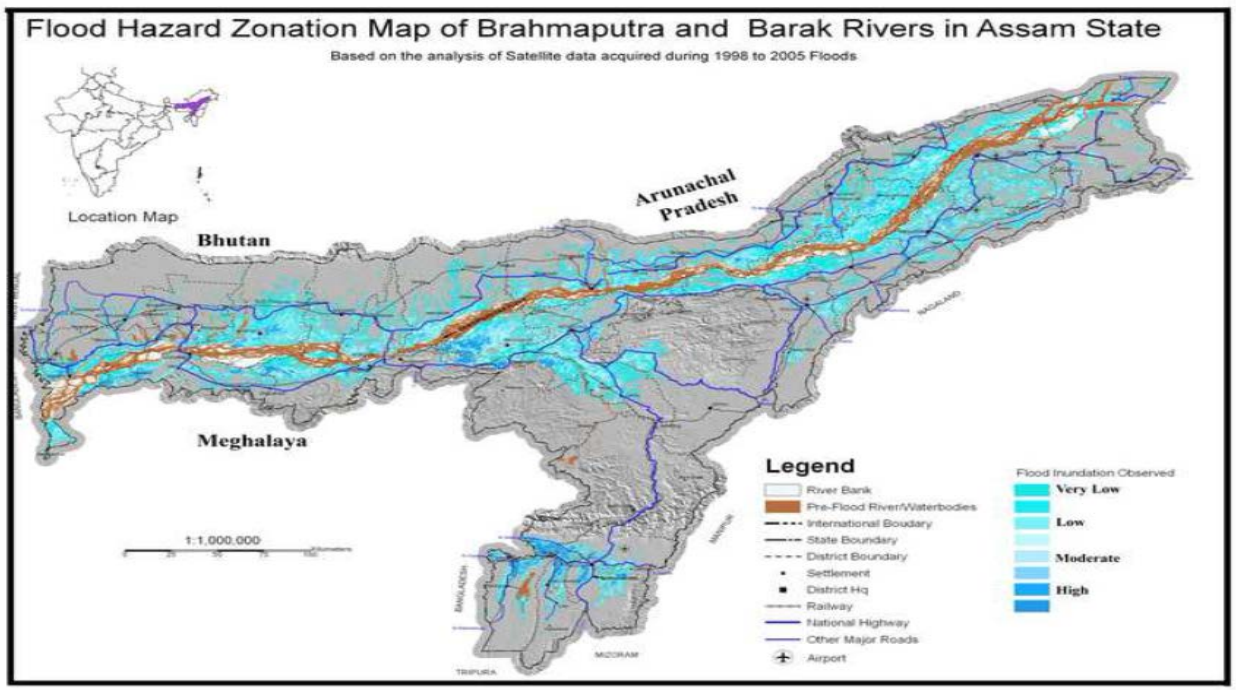
Around 80 people died so far due flooding and landslides in the Northeast, the Centre said on Thursday. The damage due to the flooding has been "unprecedented" and ISRO will be roped in to assess the extent of destruction, the Centre also said.



Flood Inundated Areas in part of Assam State: 8 June 2012 - Analysis of Radarsat SAR data

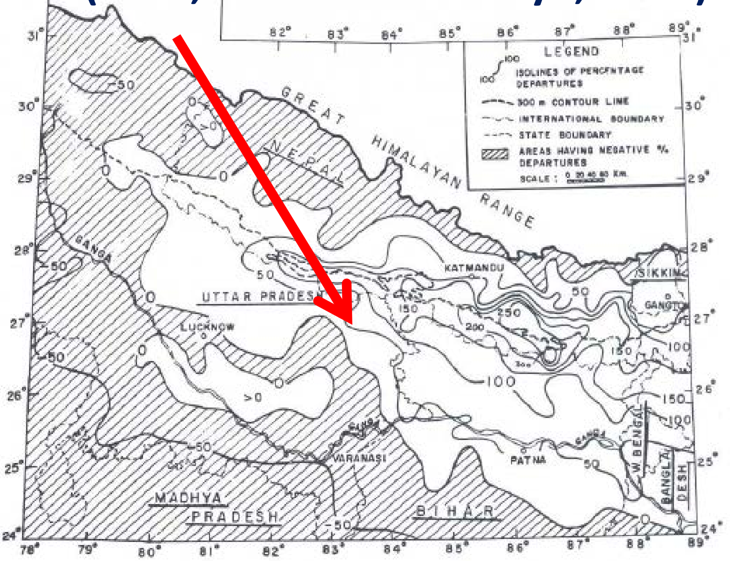
Flood Hazard Zonation Map of Brahmaputra and Barak Rivers in Assam State – Based on analysis of satellite data during 1998 – 2005 floods

Courtesy: National Remote Sensing Centre, India

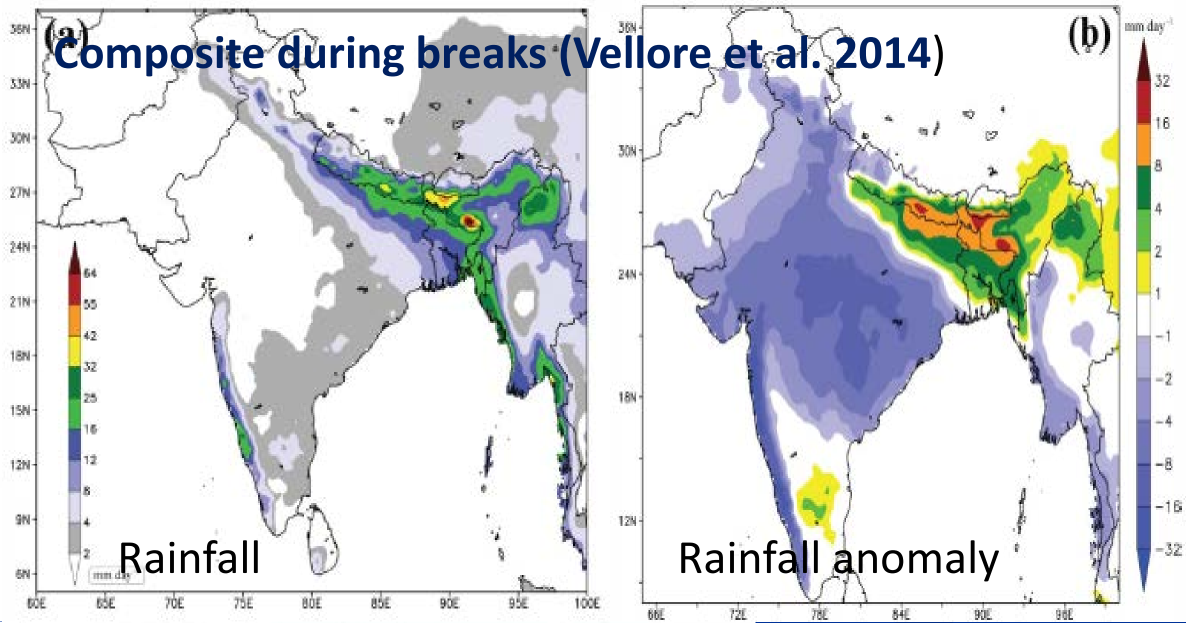


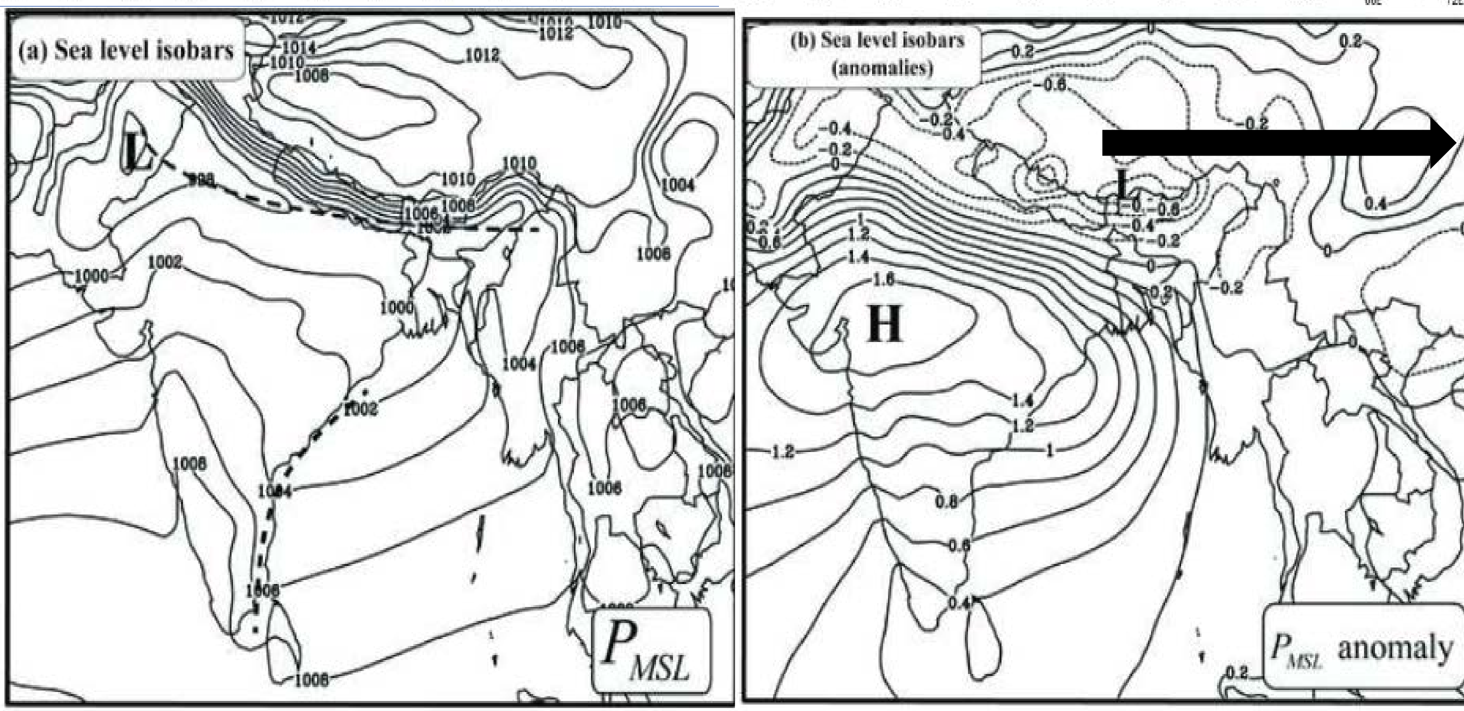
Rainfall over the southern slopes of the Himalayas & adjoining plains during monsoon breaks

(Dhar, Soman and Mulye, 1984)



Composite during breaks (Vellore et al. 2014)

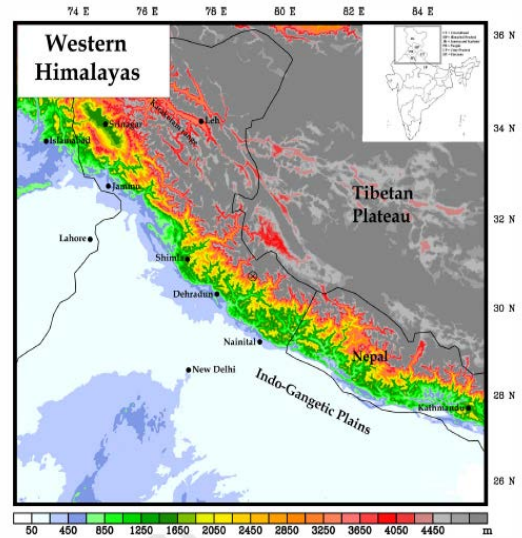


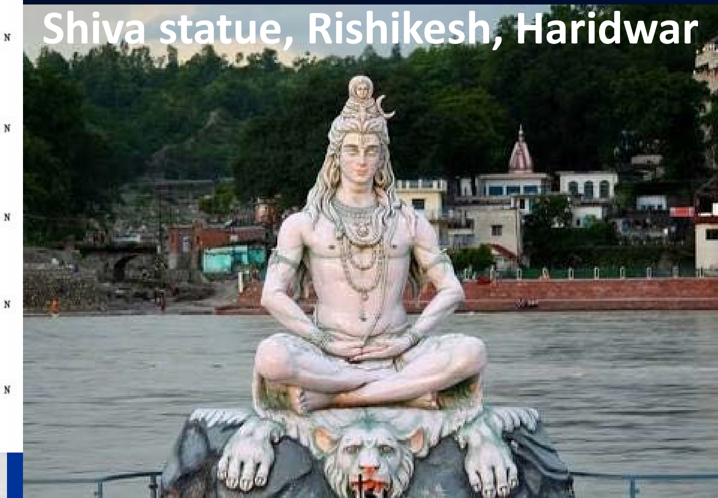


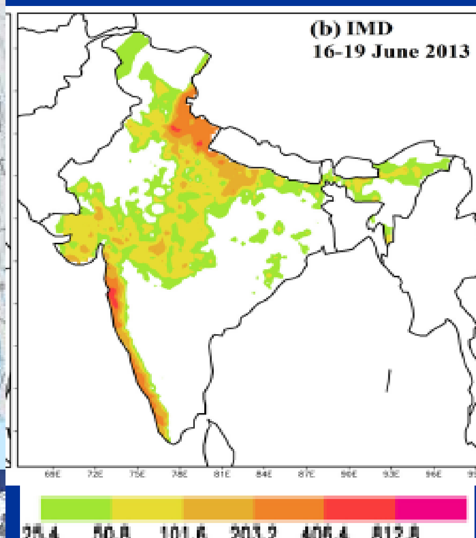
Anomalous northward shift of monsoon trough

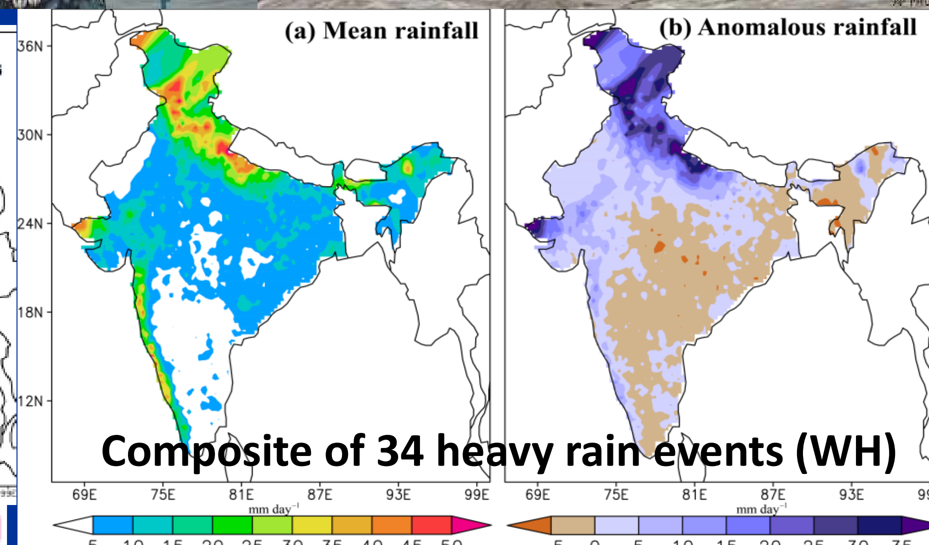
Vellore et al. 2014

17 June 2013, Uttarakhand heavy precipitation and floods







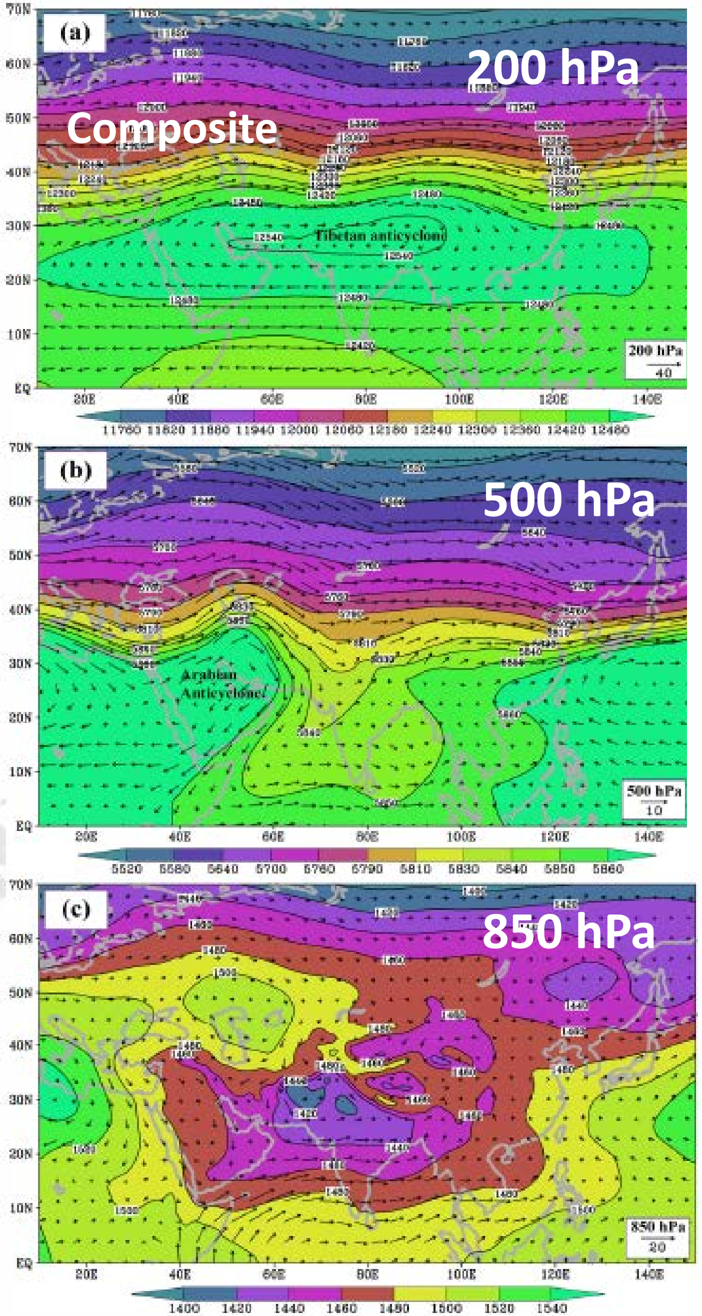


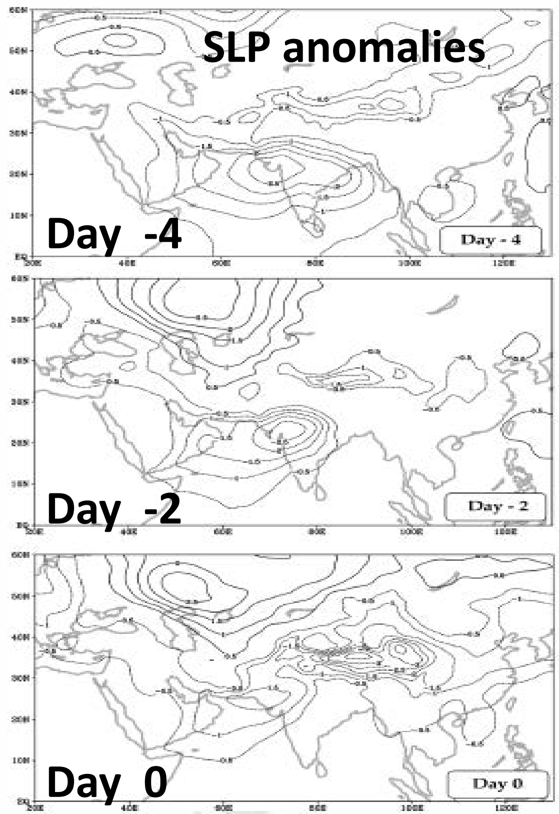
Clim Dyn
DOI 10.1007/s00382-015-2784-x
2015

Monsoon-extratropical circulation interactions in Himalayan extreme rainfall

Ramesh K. Vellore [1] · Michael L. Kaplan [2] · R. Krishnan [1] · John M. Lewis [2,3] · Sudhir Sabade[1] · Nayana Deshpande[1] · Bhupendra B. Singh[1] · R. K. Madhura [1] · M. V. S. Rama Rao [1]

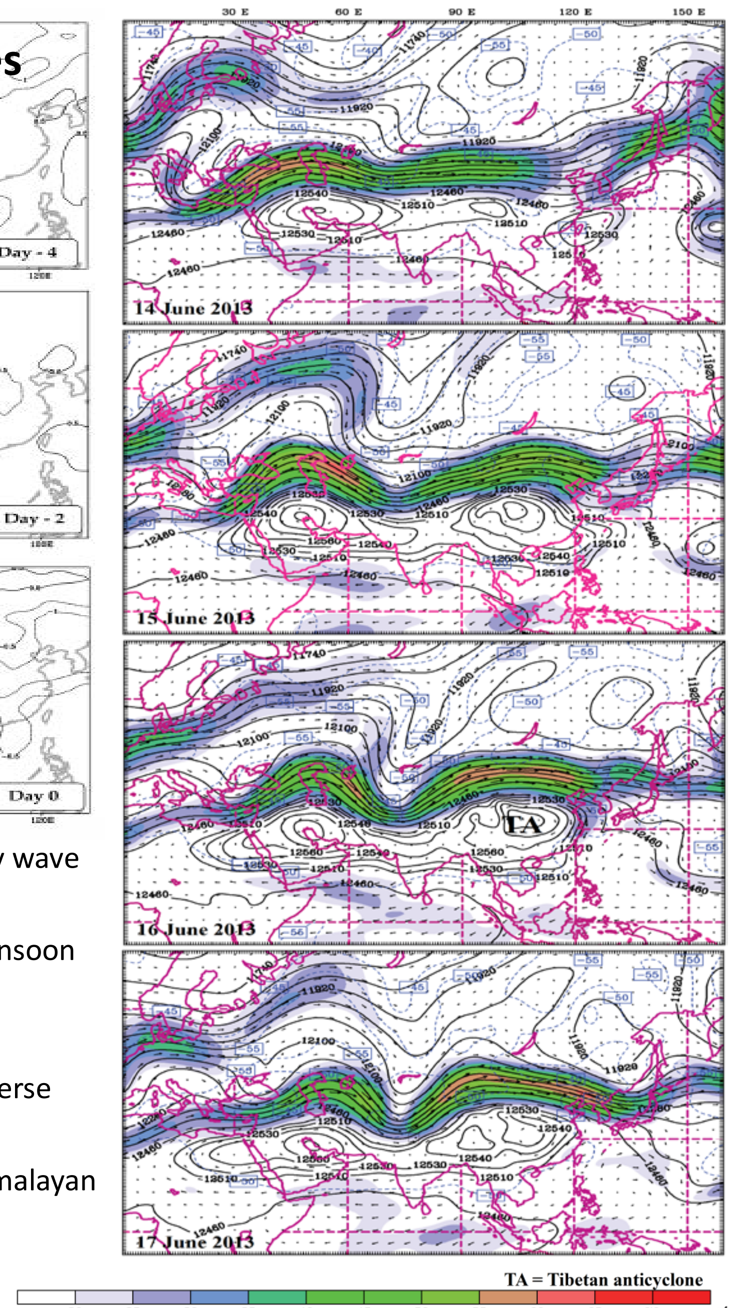
Western Himalayan Extreme precipitation events: Vigorous interactions of moisture-laden monsoon circulation and southward penetrating midlatitude westerly troughs – ERA



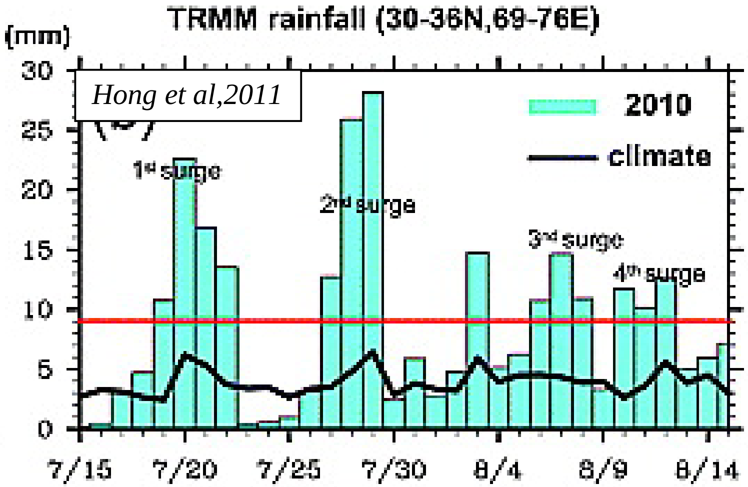


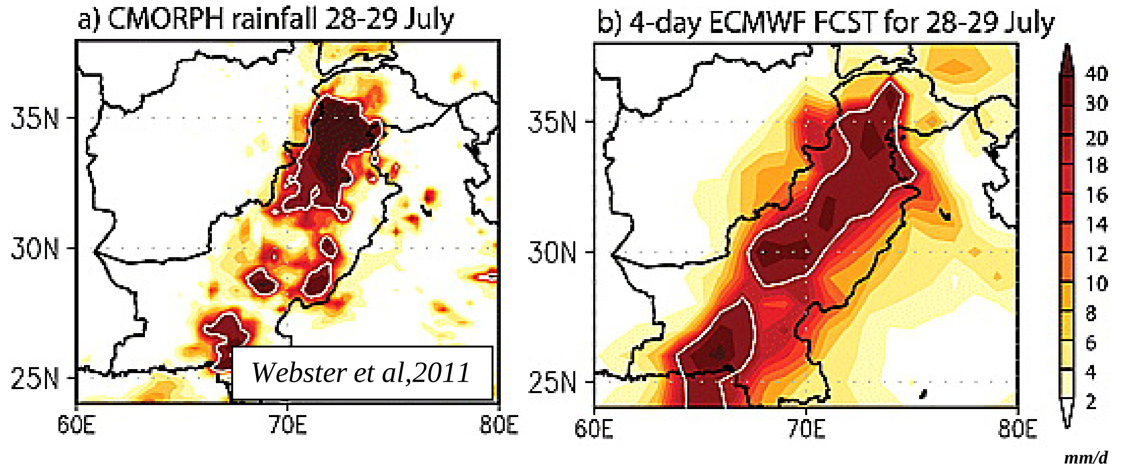
- Mid-latitude blocking and Rossby wave breaking
- West-northwest propagating monsoon low pressure system
- Eddy shedding of Tibetan High
- Ageostrophic circulations, transverse circulations across Himalayas
- Strong moist convection over Himalayan foothills

Vellore et al. 2015

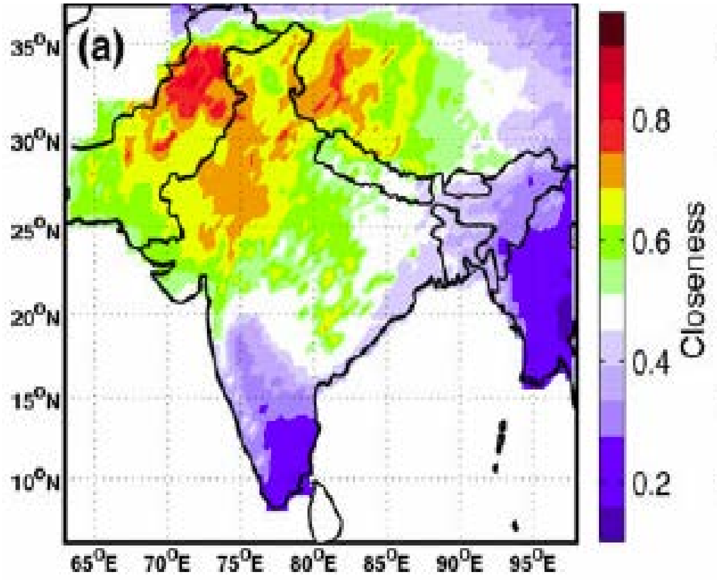


2010 Pakistan Floods





- Interaction between mid-latitude disturbance and monsoon surges *Hong et al (GRL,2011)*
- Convection of a more ocean character in a high humid environment Houze et.al. (BAMS, 2011), Rasmussen et al. 2015
- Persistent increase in conditional instabilities *Wang et al (JGR,2011)*
- Russian heat wave–wildfires and Pakistan flood were physically connected *Lau and Kim (J. Hydrometeor., 2012)*
- Westward shift of West Pacific Subtropical High *Mujumdar et. al. (Meteo. Appli., 2012)*
- Event could have been predicted two weeks in advance *Webster et. al. (GRL, 2011)*



Nishant Malik, Bookhagen, Marwan and Kurths, 2011

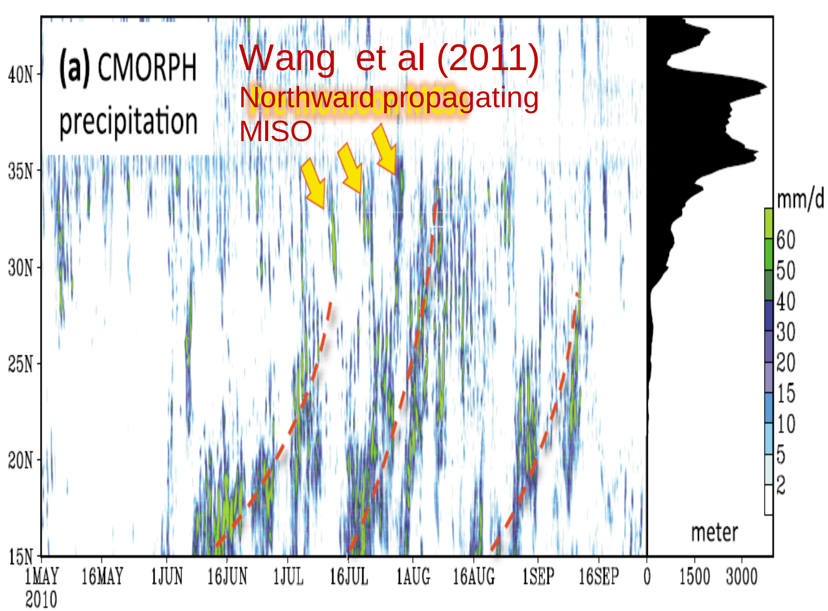
Analysis of spatial and temporal extreme monsoon rainfall over South Asia using complex networks

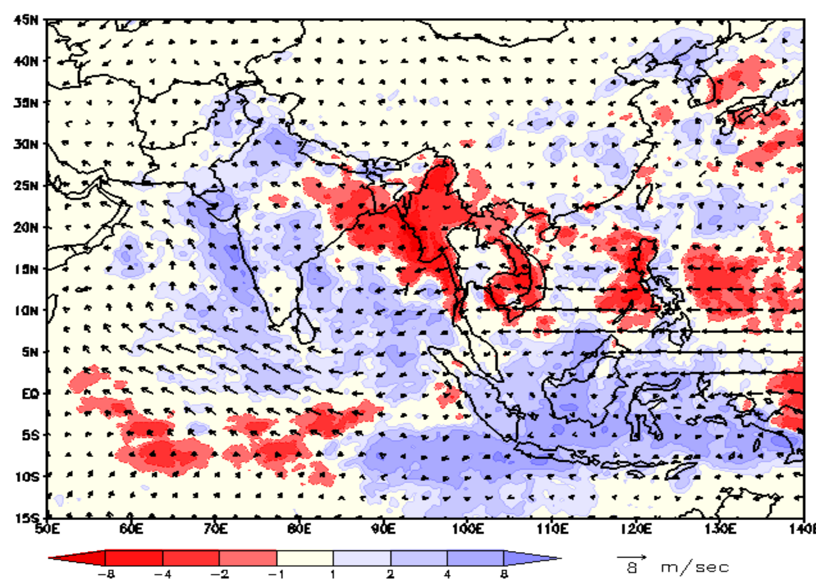
Closeness centrality: High closeness centrality lies in the northwest subcontinent.

This indicates that the information travels fastest to and from these points. Any perturbation occurring in this region can affect the monsoonal rainfall patterns at rapid temporal scales.

Convective instabilities in this region occur due to interactions between the cold /dry subtropical winds with the warm /moisture laden monsoonal winds over a dry and hot region during the peak of the summer with low pressure fields

Role of large scale atmospheric/oceanic conditions in favoring heavy precipitation <u>over Pakistan & Northern India during 2010</u> (eg., Wang et al 2011, Saeed et al 2011, Webster et al 2011, Houze et al 2011, Mujumdar et al. 2012, Rasmussen et al. 2015, Priya et al. 2015).

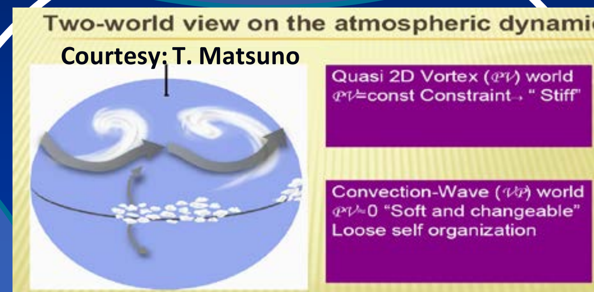


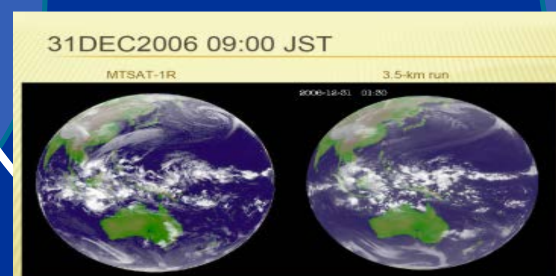


Observed rainfall anomaly (TRMM) wind anomaly at 850 hPa – JJAS 2010 (Mujumdar et al. 2012)

Summary

Indian Monsoon
Multi-scale Interactive Phenomenon





Internal Dynamics

- Land-sea thermal contrast / Convective coupling / Atmospheric internal variability
- Atmosphere-Ocean-Land-Cryosphere-Biosphere coupling, Carbon and Biogeochemical cycles
- Teleconnections - ENSO, PDO, IOD, MJO, NAO, AMOC, Extra-tropics / Polar, Arctic Amplification, Climate Drivers
- Spatial-scales: Turbulence, CCN Microphysics Aerosols, Clouds, MCS, Meso-scale, Organized Convection, Circulation (Synoptic [lows, depressions, monsoon trough, active/break,], large-scale, planetary-scale..)
- Diurnal, Synoptic (lows, depressions, MTCs), Extremes, Intra-seasonal (10-20 day, 30-60 day modes), Interannual, Decadal & long-term

External forcing

- Greenhouse gases (CO2, CH4, CFCs, …), Human Induced Climate Change
  Aerosols (Natural - Dust, Sea-Salt, Volcanoes, …; Anthropogenic: Sulphates, Nitrate, Ash, Black Carbon, Organic Carbon, …)
- Land-use / Land cover changes (Deforestation, Agriculture, Rivers / Lakes, …
- Atmosphere and Ocean Chemistry

Impacts

Water, Agriculture, Energy, Health, Ecosystems, Environment
Adaptation Strategies, Policy making, Economy, Mitigation, Sustainable Development, Capacity Building

Methodologies: Computer simulations, Earth System Models / Climate models of varying complexities, Application models (eg. Hydrology, crops , energy, ecosystems …), Observations and Satellite Data Analysis, Data Assimilation, Ensemble Prediction Tools, Advanced techniques to study behavior of Complex Systems, Networks, etc.