Sub-seasonal aspects of Indian monsoon variability

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Workshop on subseasonal predictability
European Centre for Medium Range Weather Forecasts
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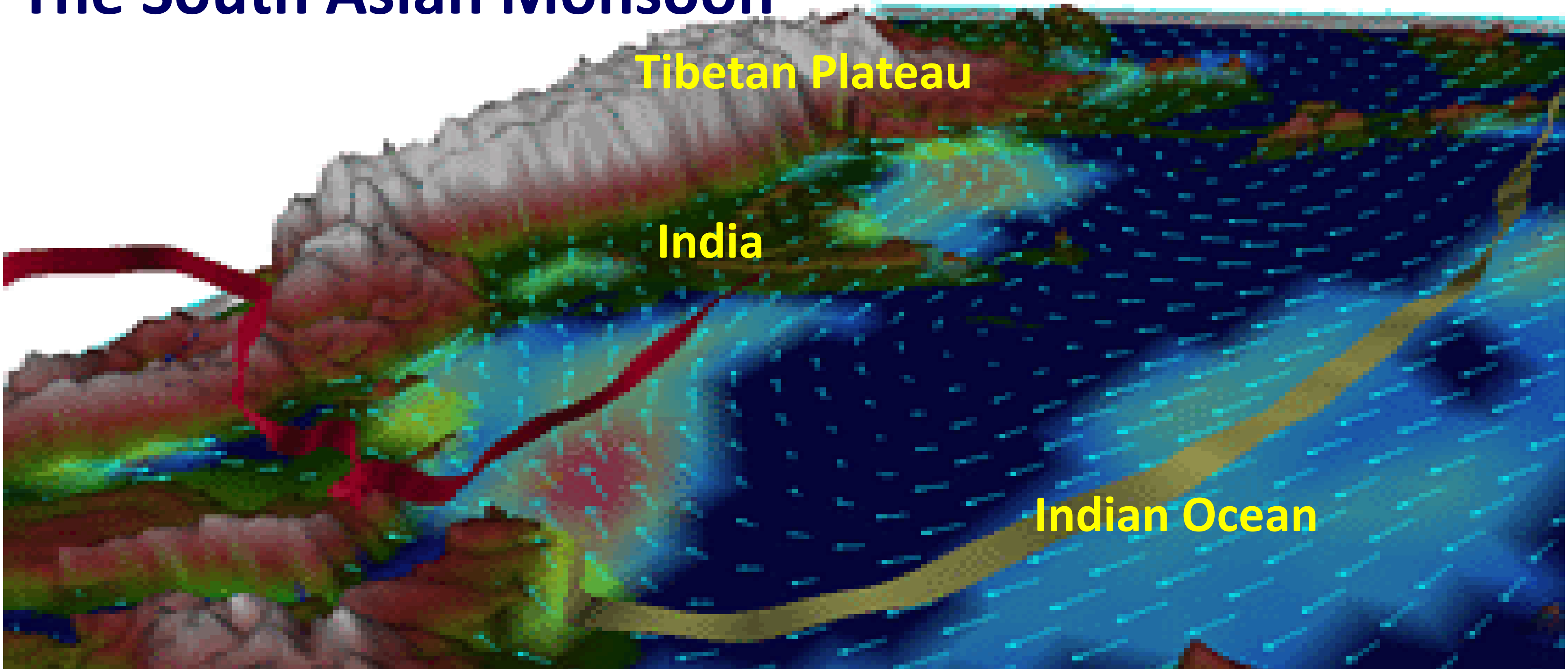
The South Asian Monsoon



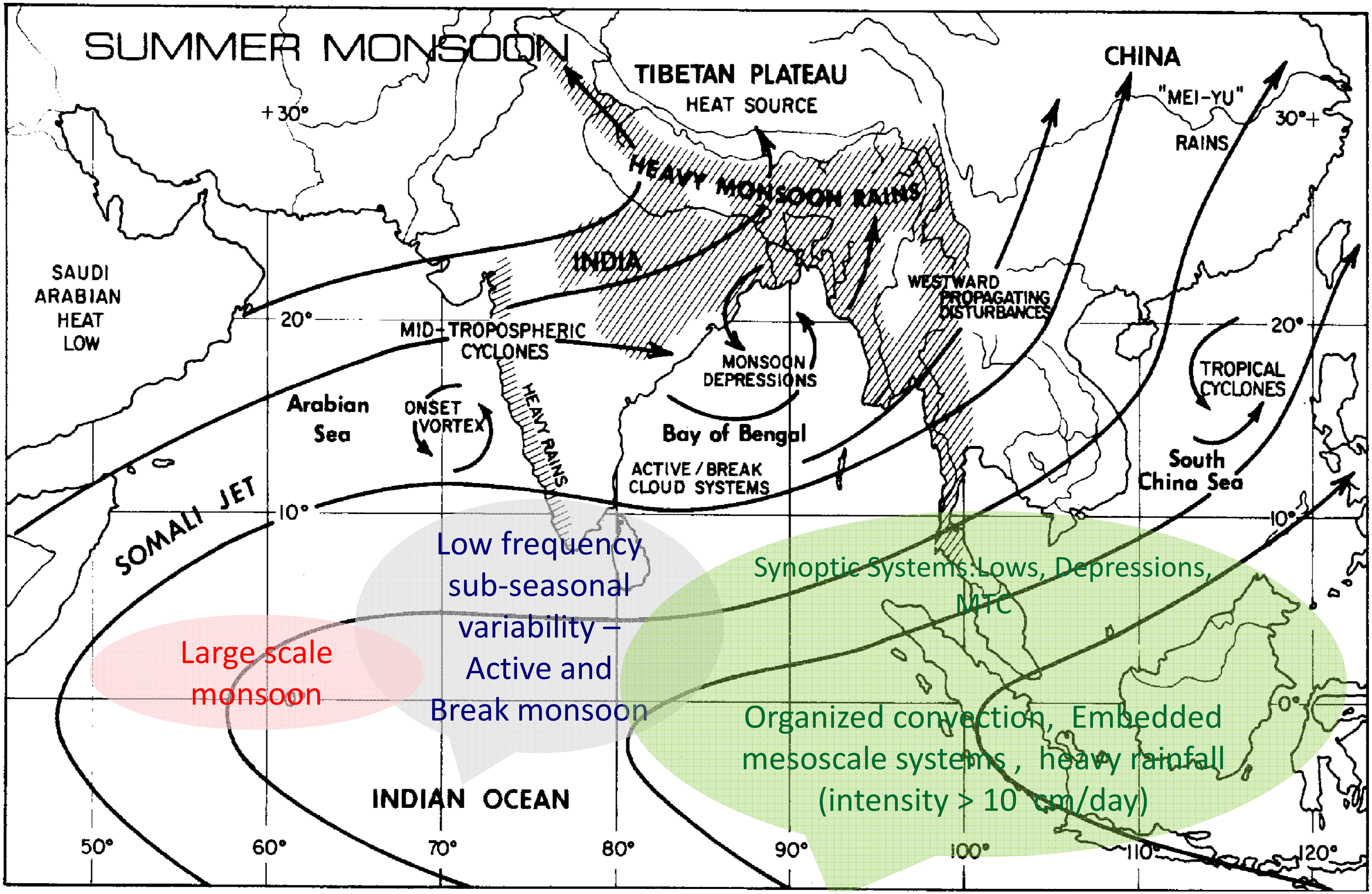
Monsoon circulation and rainfall: A convectively coupled phenomenon

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

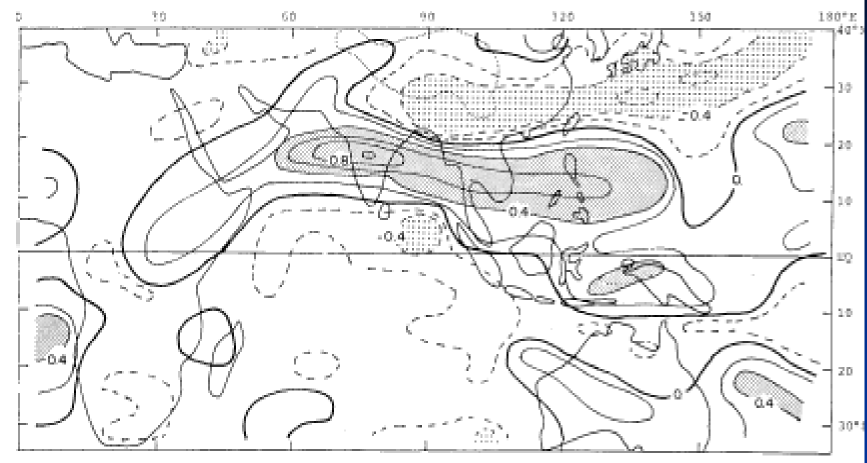
Once established, a positive feedback between circulation and latent heat release maintains the monsoon

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

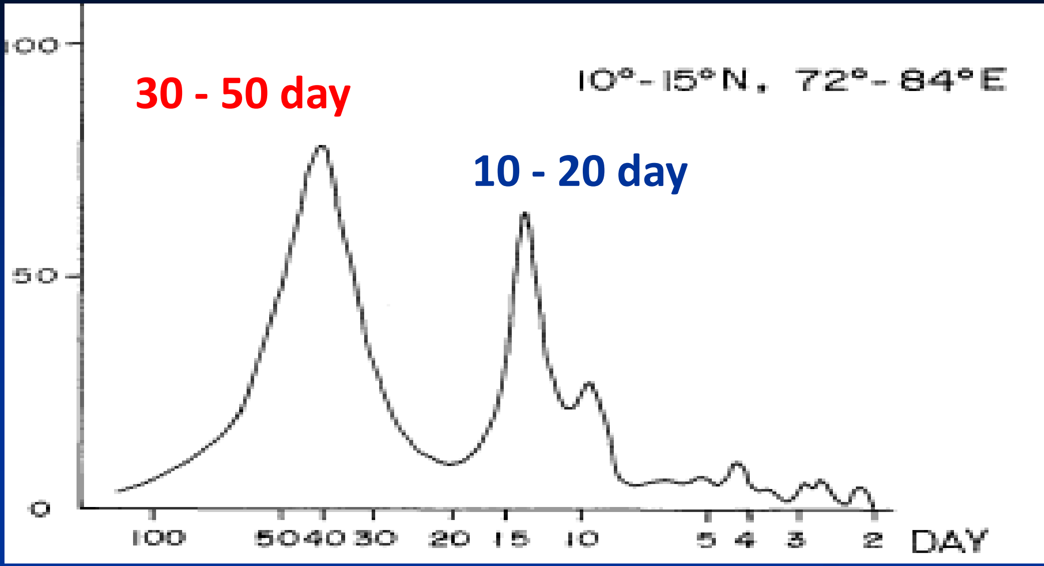
Primary synoptic & smaller scale circulation features that affect cloudiness & precipitation. Locations of June to September rainfall exceeding 100 cm over the land west of 100°E associated with the southwest monsoon are indicated (**Source: Rao, 1981**).



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

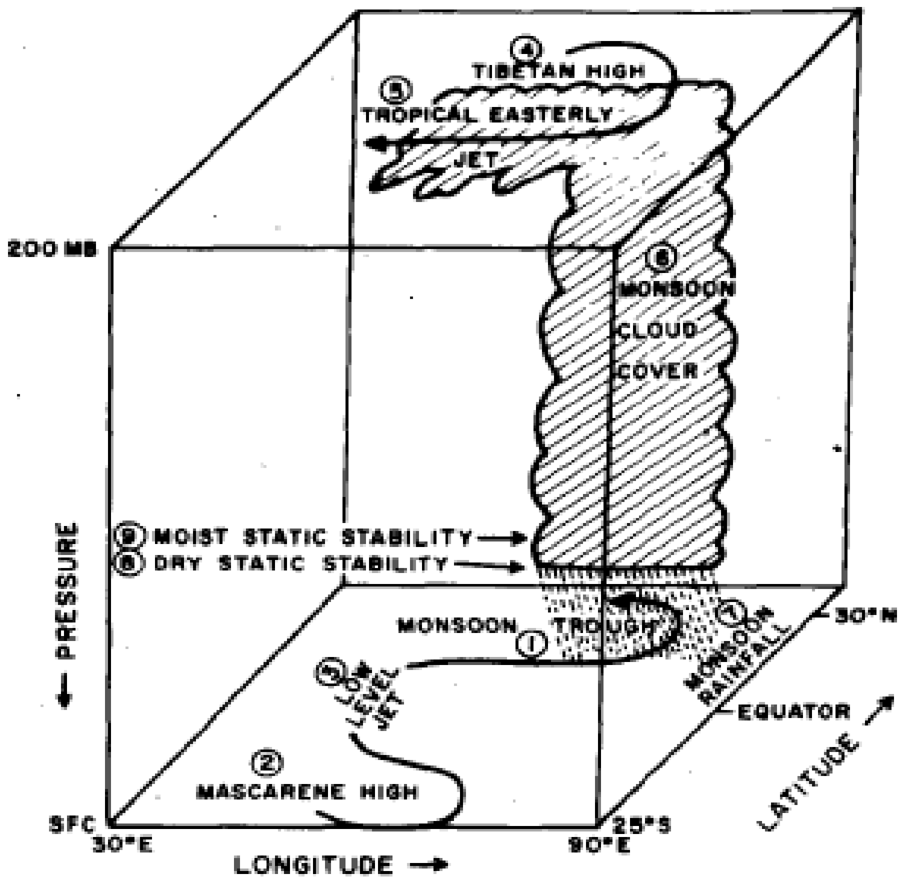
10-20 day oscillation: Westward propagation in the Asian summer monsoon

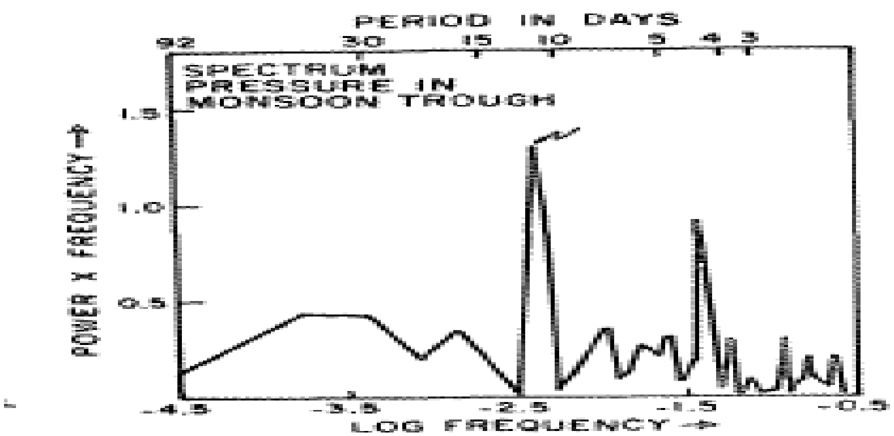
Keshavamurty 1973, Murakami, 1977 – Meridional winds, Krishnamurti et al. 1973: Spectrum of Tibetan High; Krishnamurti and Bhalme (1976); Murakami & Frydrych (1974), Murakami (1975), Krishnamurti et al. (1977), Krishnamurti & Ardanuy (1980), Yasunari (1978, 1980) and others

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

Schematic diagram of the salient elements of the monsoon system





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

Krishnamurti and Bhalme (1976): A model of radiative-convective feedback for monsoon quasi-biweekly oscillation

Destabilizing phase:

•Net radiative effects warm the earth's surface. Sensible and evaporative fluxes build dry & moist instabilities in the lower layers

•Heat is transported up by moist convective adjustment. Heating is augmented by large-scale condensation

•As convection and condensation increase, cloudiness increases

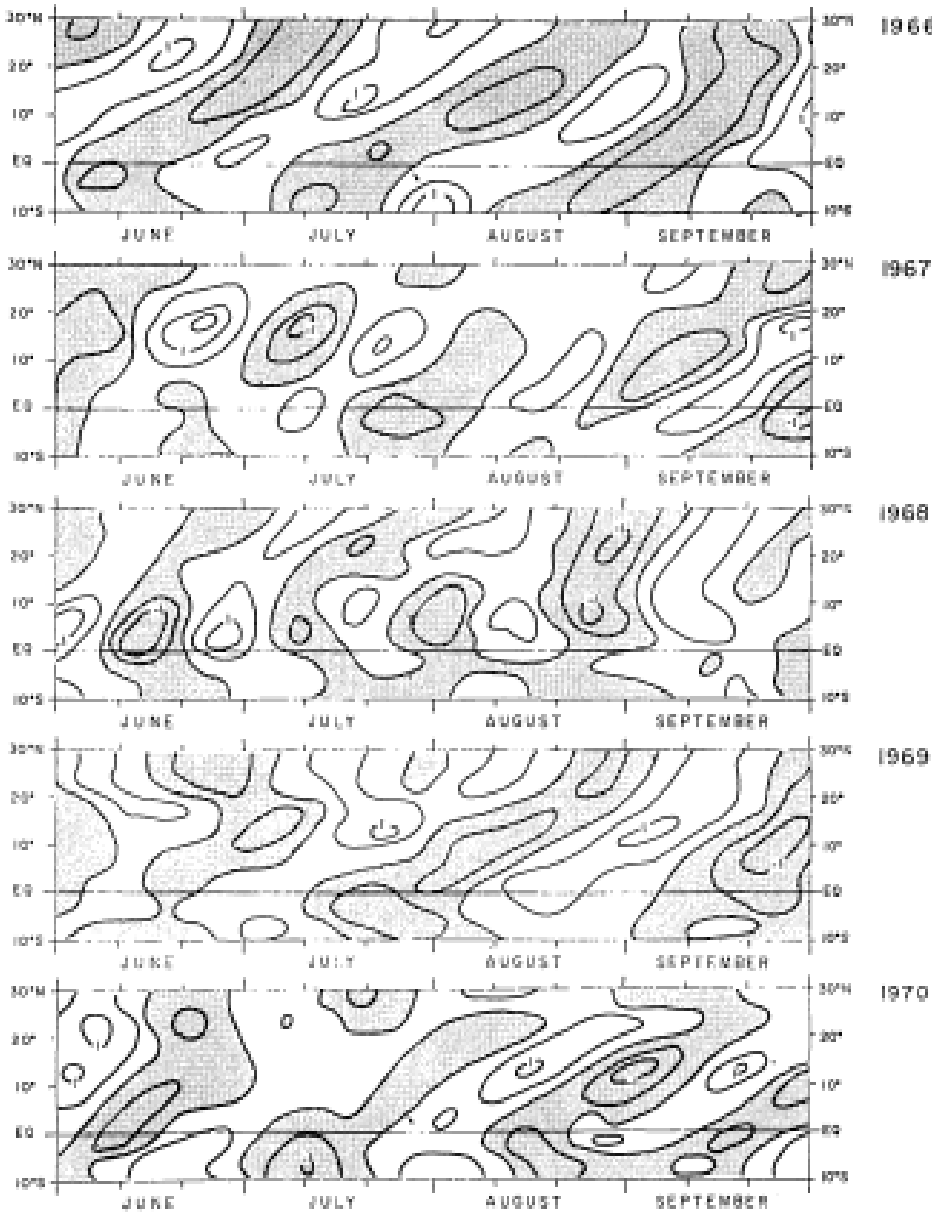
Stabilization phase:

•Increase of cloudiness results in decrease of incoming shortwave radiation at the earth's surface

•Stabilization of lower layer and decrease of moist convective processes and cloud cover

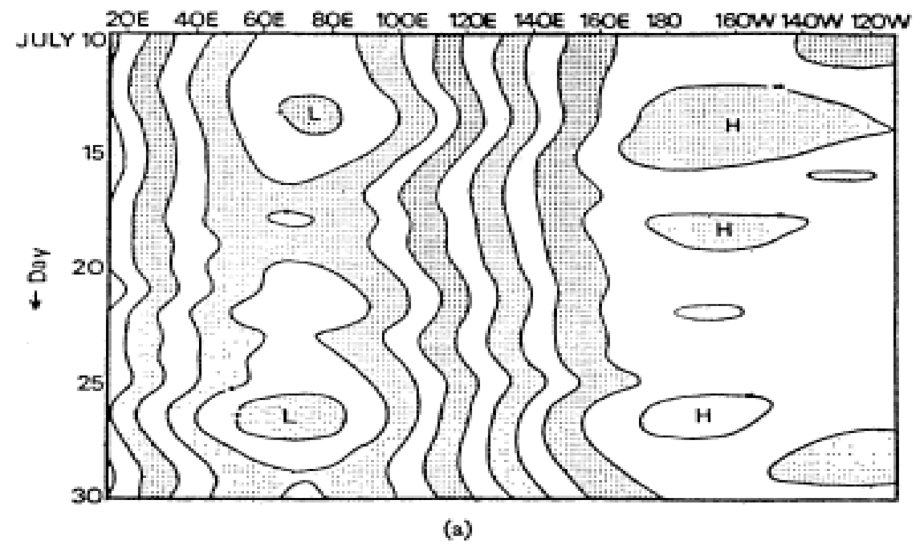
•Again shortwave radiation starts becoming effective. The cycle starts all over again.

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



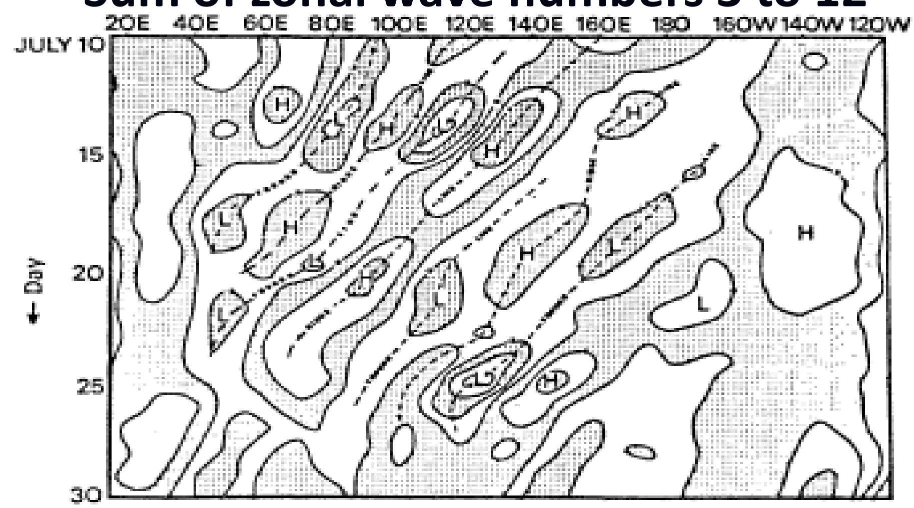
Westward propagation of sea level pressure at 20N latitude during July 1965 : Krishnamurti et al. 1977

Sum of zonal wave numbers 1 & 2



(a)

Sum of zonal wave numbers 3 to 12

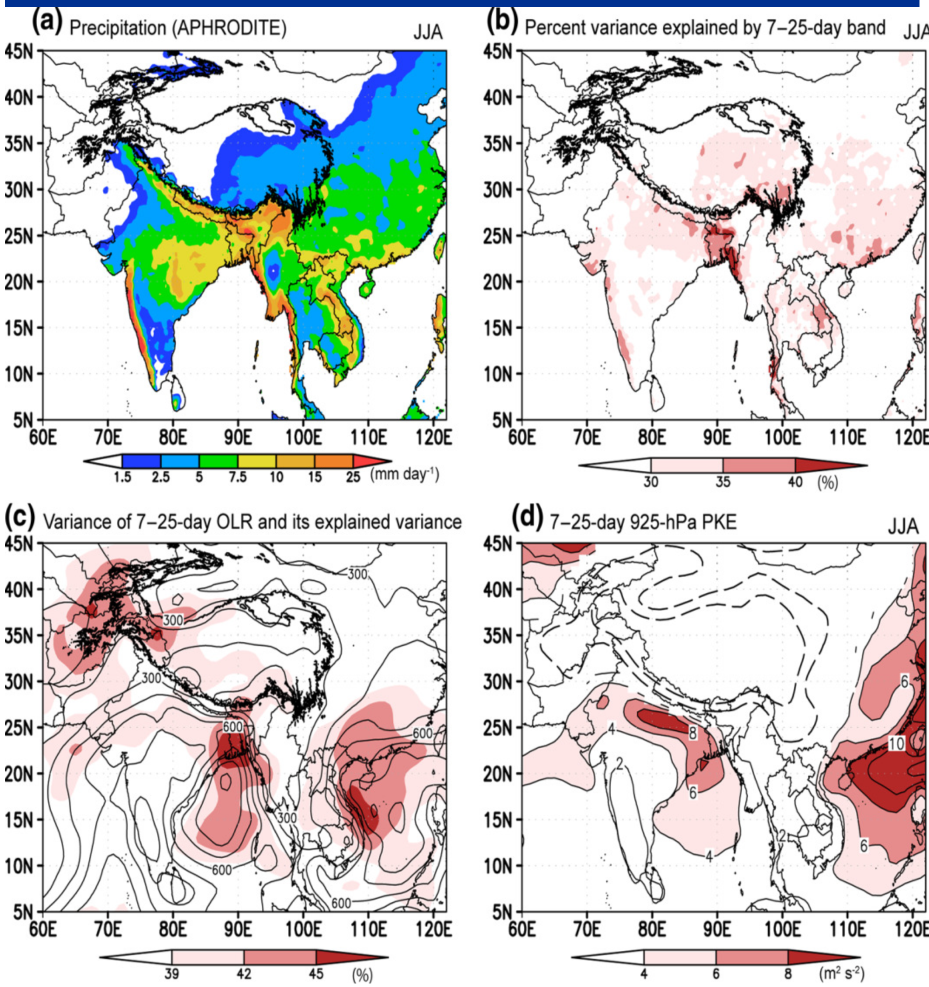


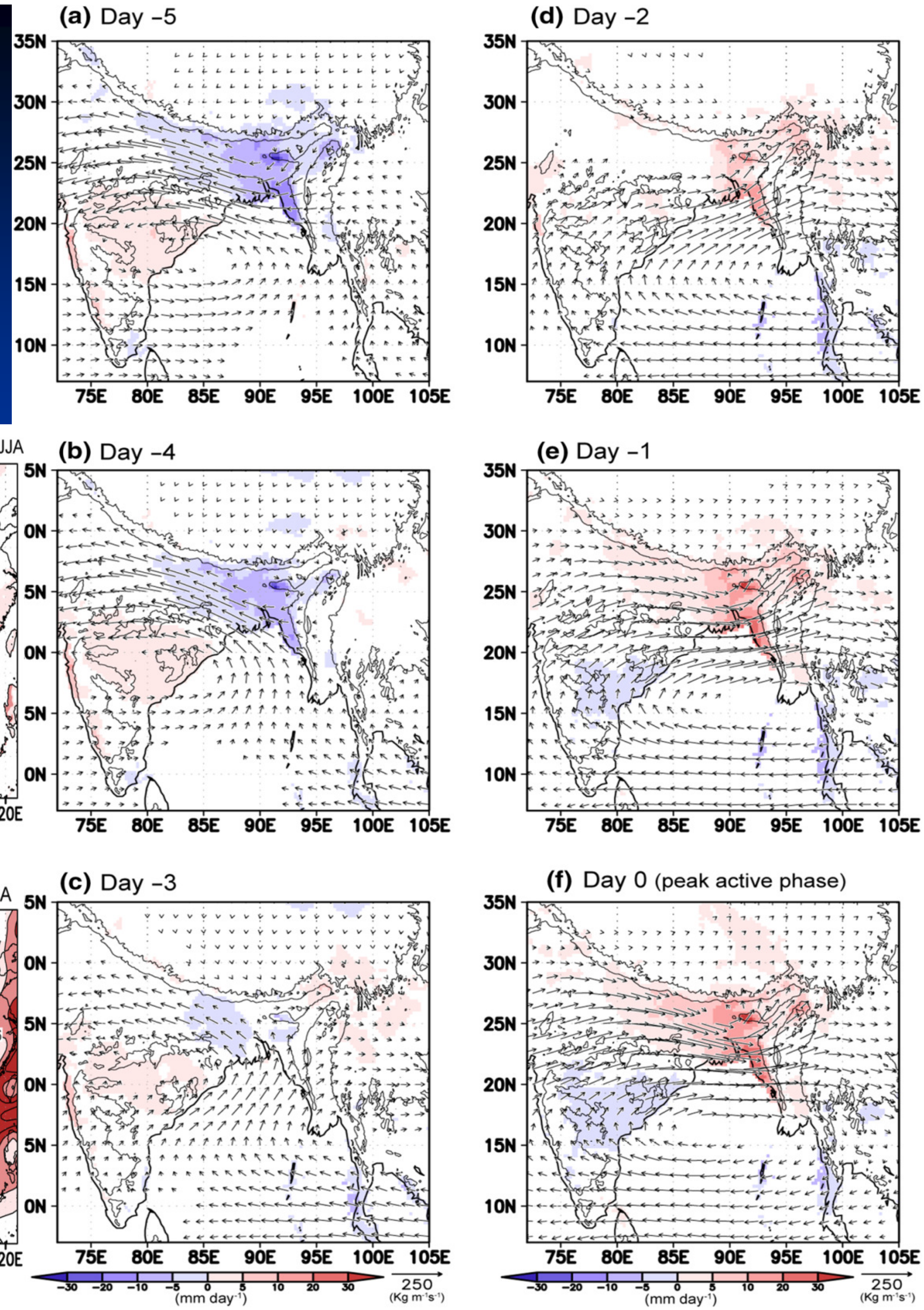
(b)

Sub-monthly scale or quasi-biweekly (7- 25 day) oscillations of rainfall over Meghalaya Bangladesh, Myanmar

-Fujinami, Yasunari, Morimoto (2014)

Covariability between the tropics and midlatitudes





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}

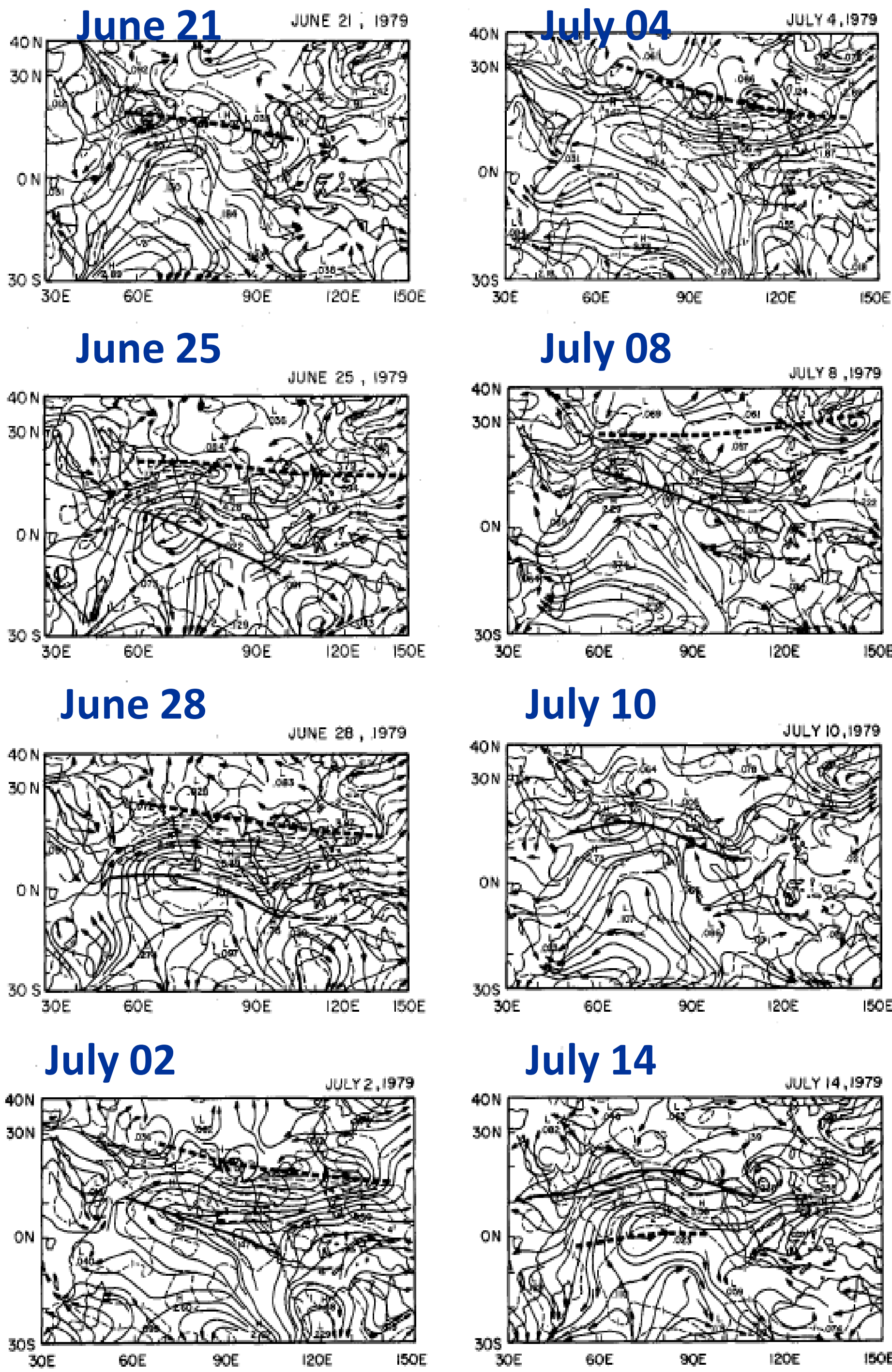
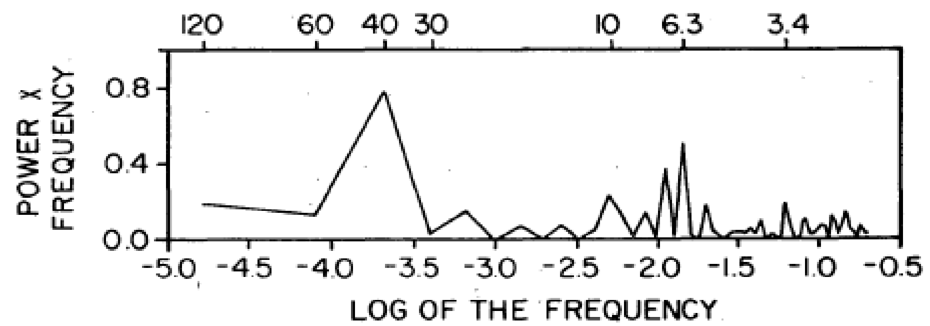
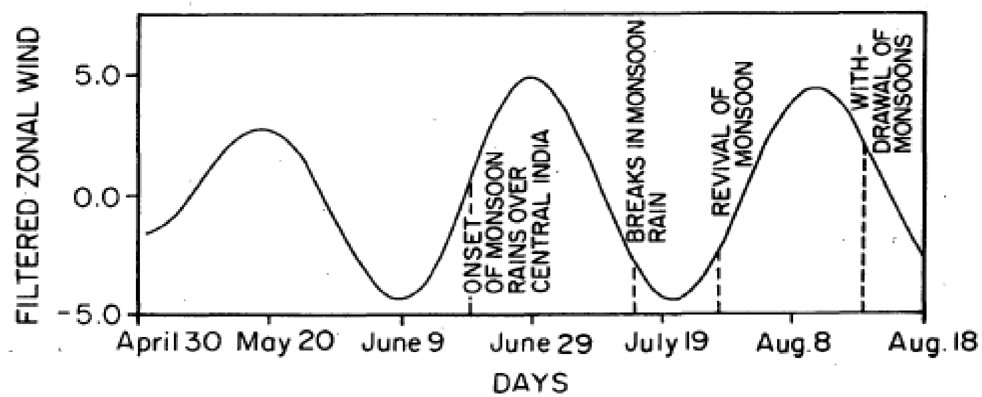
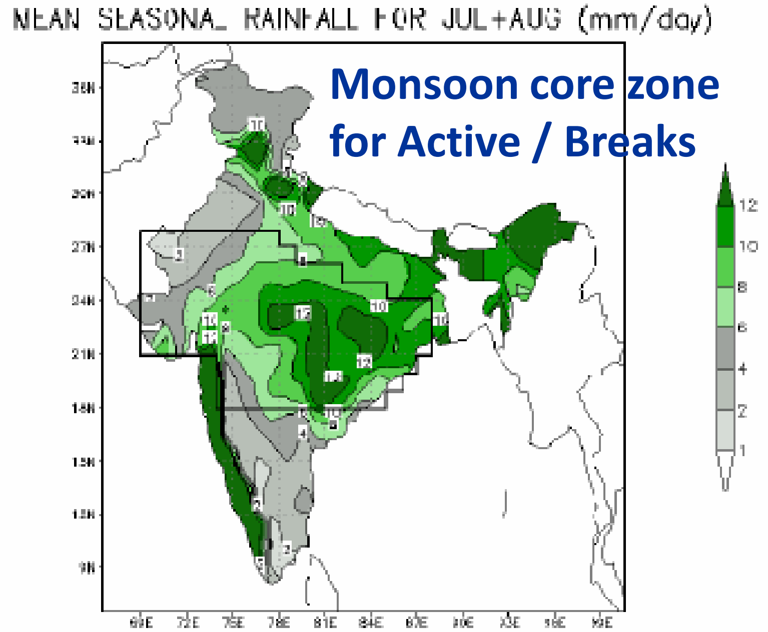


FIG. 3. (*Continued*)

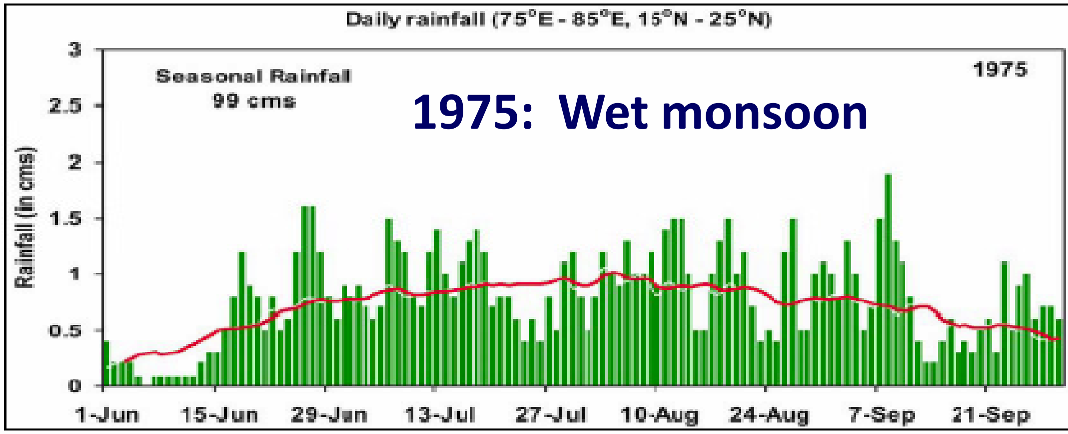


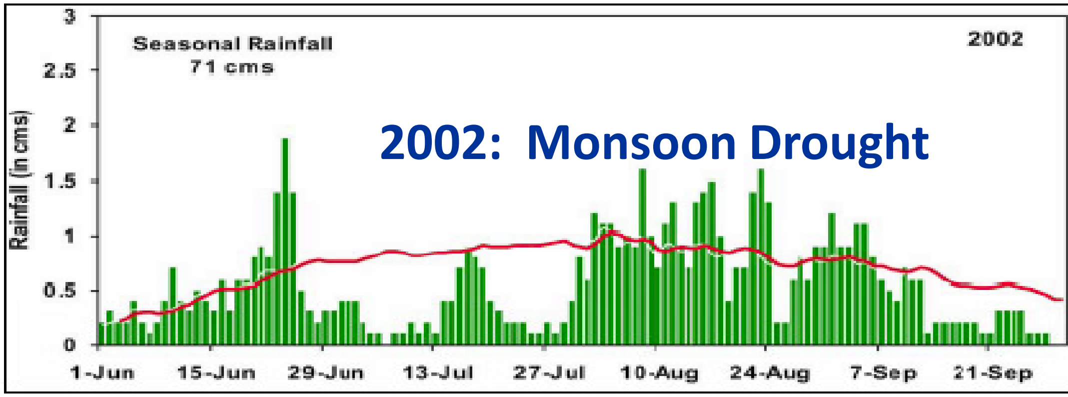


Mean rainfall during July & August

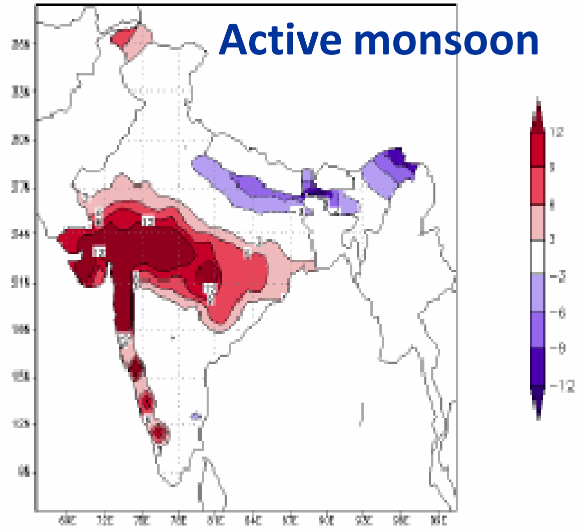


Variation of daily rainfall over central India

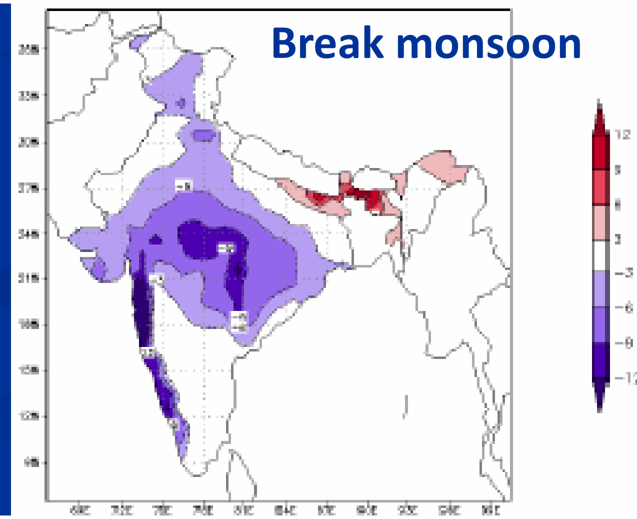




Rajeevan, Gadgil , Bhate (2008): NCC Res Rep No.3. IMD, Pune



Composite of rainfall anomaly (mm / day) during active and break monsoons. Daily rainfall data (1951 – 2004)



Monsoon sub-seasonal variability

Multi-scale interactive phenomena

Active Monsoon:

- Vertical deepening of the South Asian monsoon trough
- Continental scale mid-level cyclonic circulation
- Large-scale organization of convection
- Wide-spread rainfall over Central India - Westward and northward propagating systems
- Monsoon synoptic systems: Lows, depressions, mid-tropospheric cyclones (MTC)
- Clustering of monsoon lows and depressions
- Heavy precipitation over Western Himalayas: Eddy-shedding of Tibetan High, Interaction with mid-latitude circulation

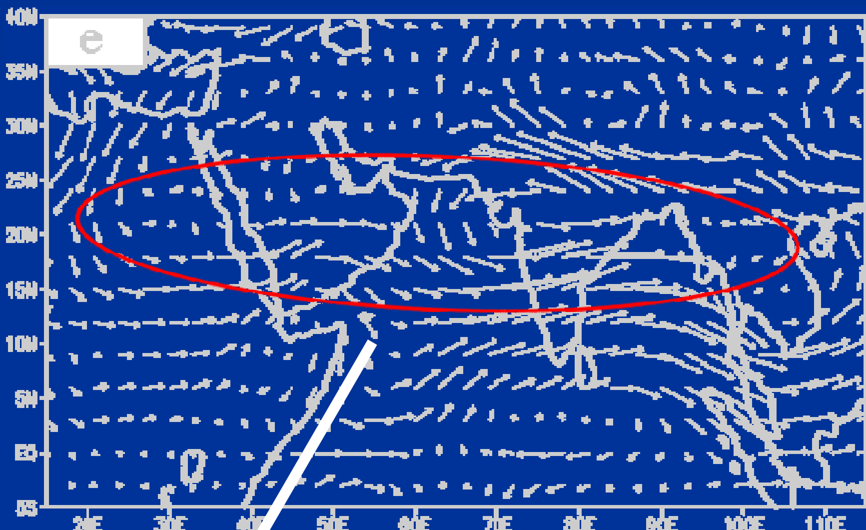
Break Monsoon:

- Northward shift of monsoon trough to the Himalayan foothills
- Suppression of monsoon convection over central-north India. Evolution of circulation anomalies linked to low-latitude Rossby wave dynamics
- Anomalous mid-latitude and monsoon circulation interaction
- Role of Indian Ocean and Monsoon coupling during long breaks
- Anomalous precipitation enhancement over Northeast India and Indo-China

Dynamical response of monsoon trough during active monsoons

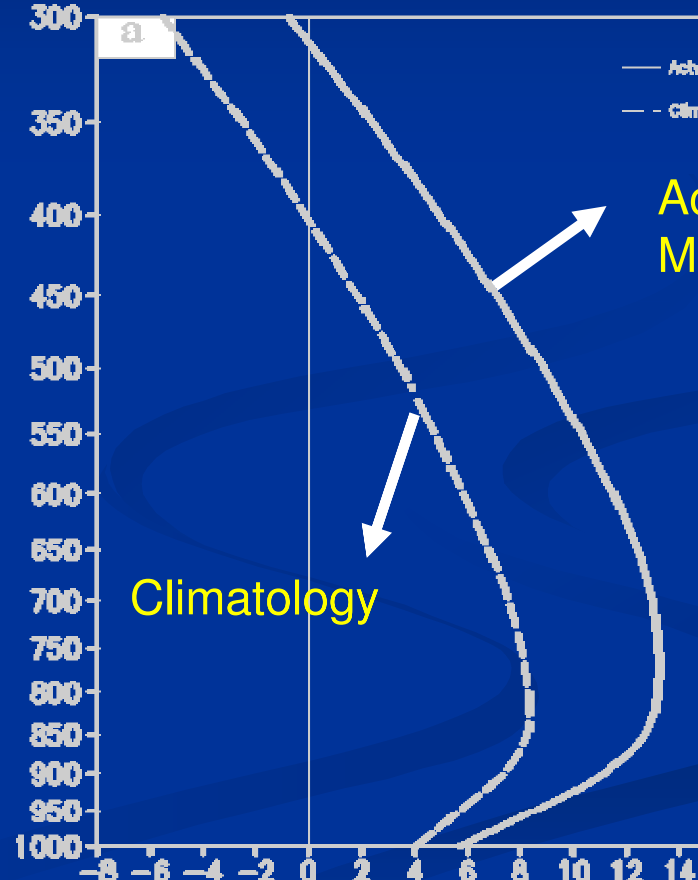
Vertical development of cyclonic circulation well above the mid-troposphere !

Wind anomaly at 500 hPa during active monsoons

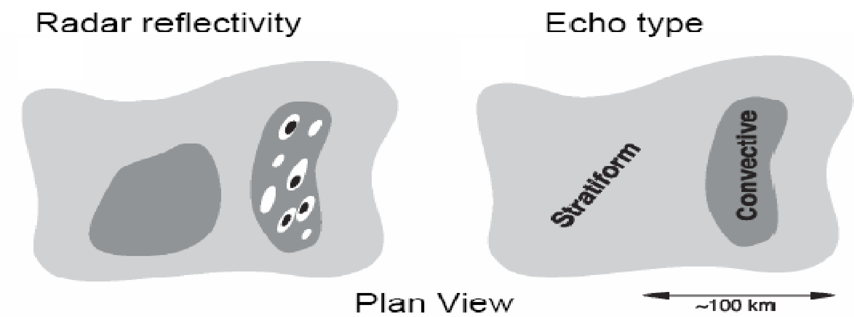


Large-scale mid–level circulation anomalies extending into the African ITCZ region

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 :

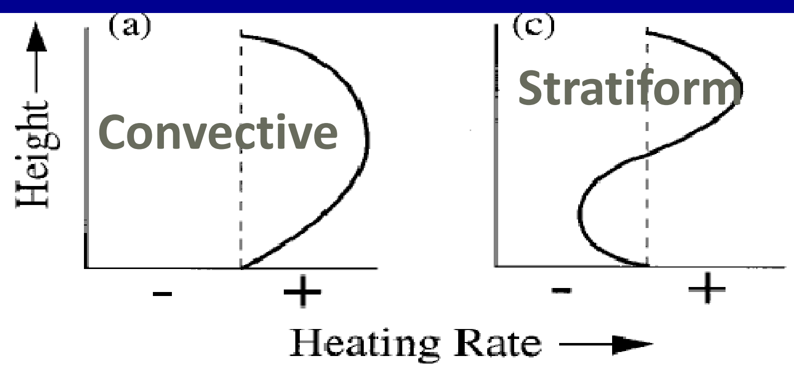
Convective-

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

Stratiform–

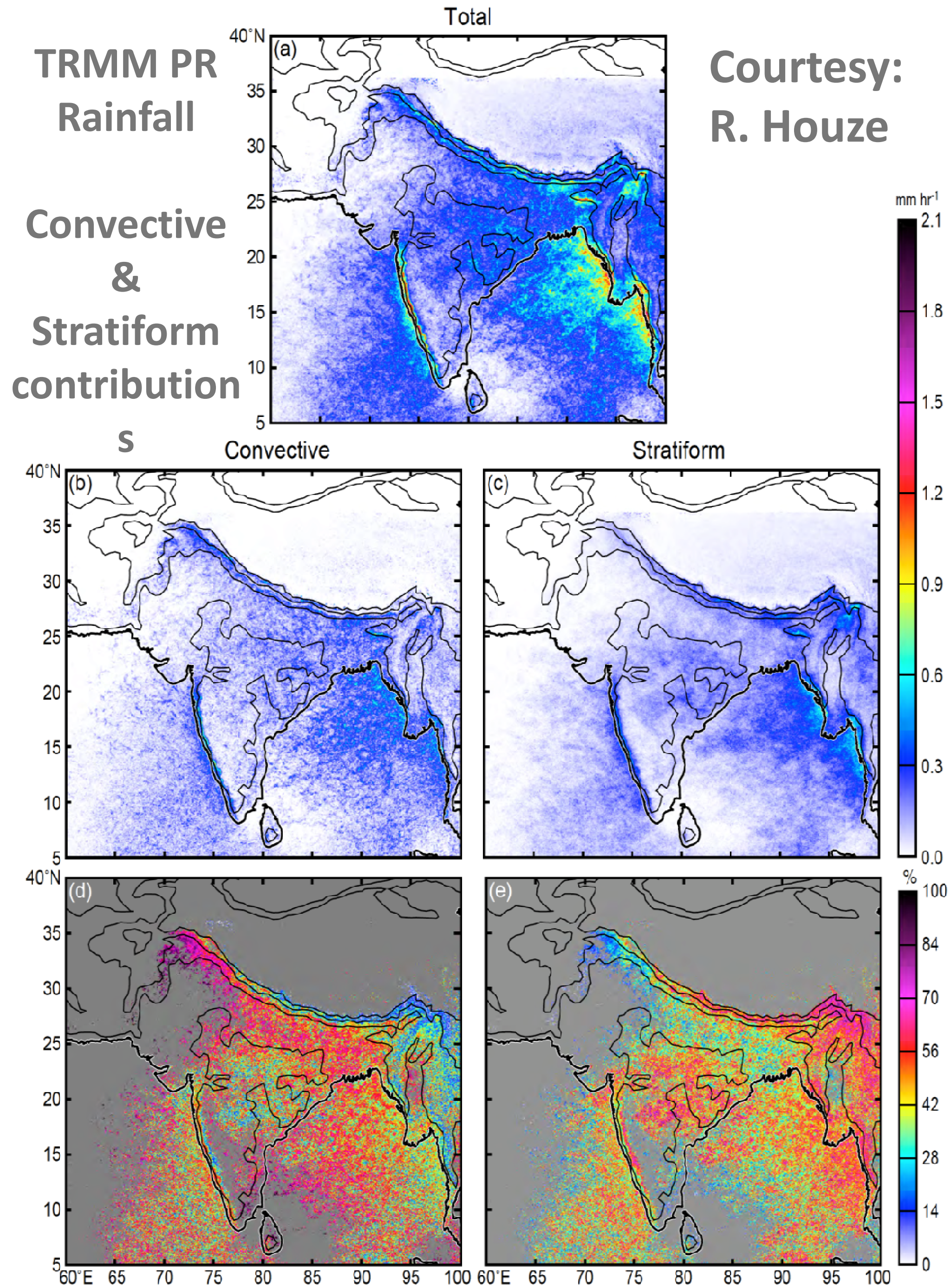
- ✓Older and less active convetion
- ✓w~ <1-2m/s
- ✓Heating upper levels and cooling lower levels

Vertical profiles of latent heating



TRMM PR Rainfall

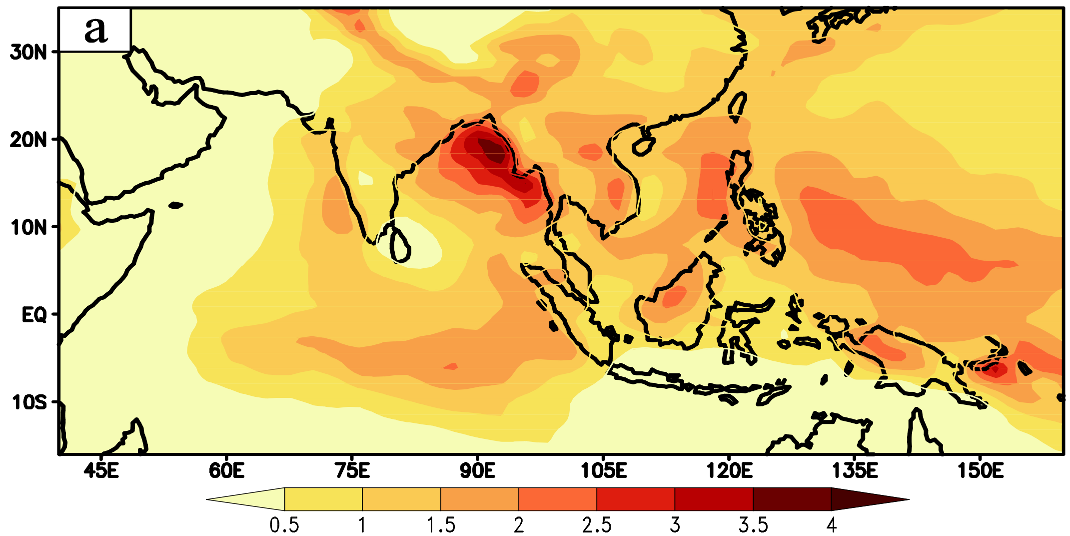
Convective & Stratiform contributions



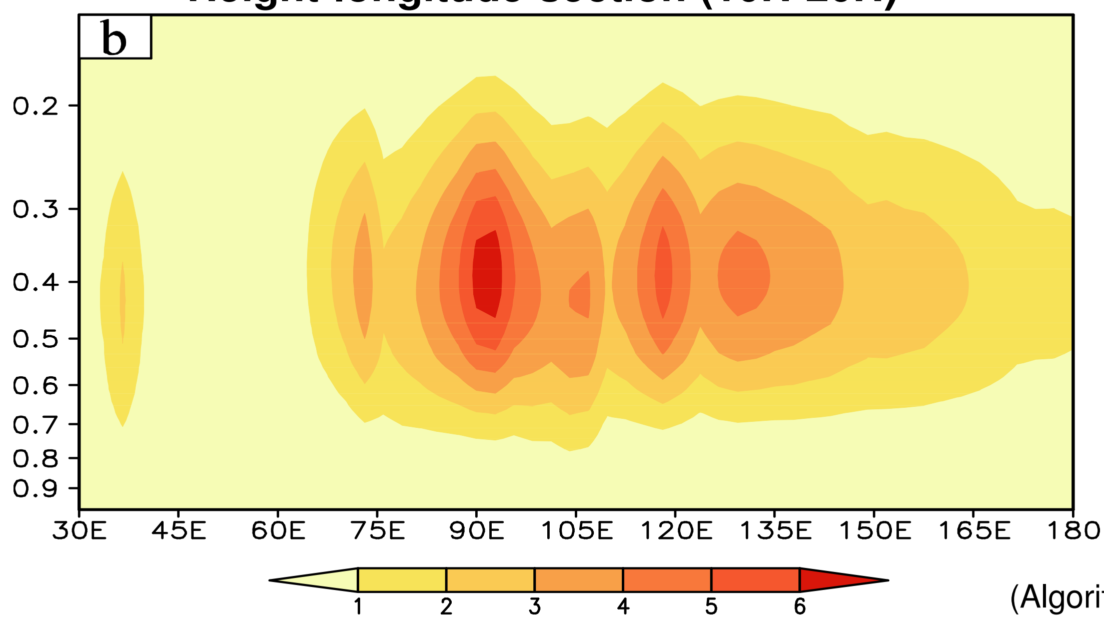
Courtesy: R. Houze

Climatological JJAS latent heating derived from TRMM rainfall

Vertically averaged heating



Height-longitude section (10N-20N)

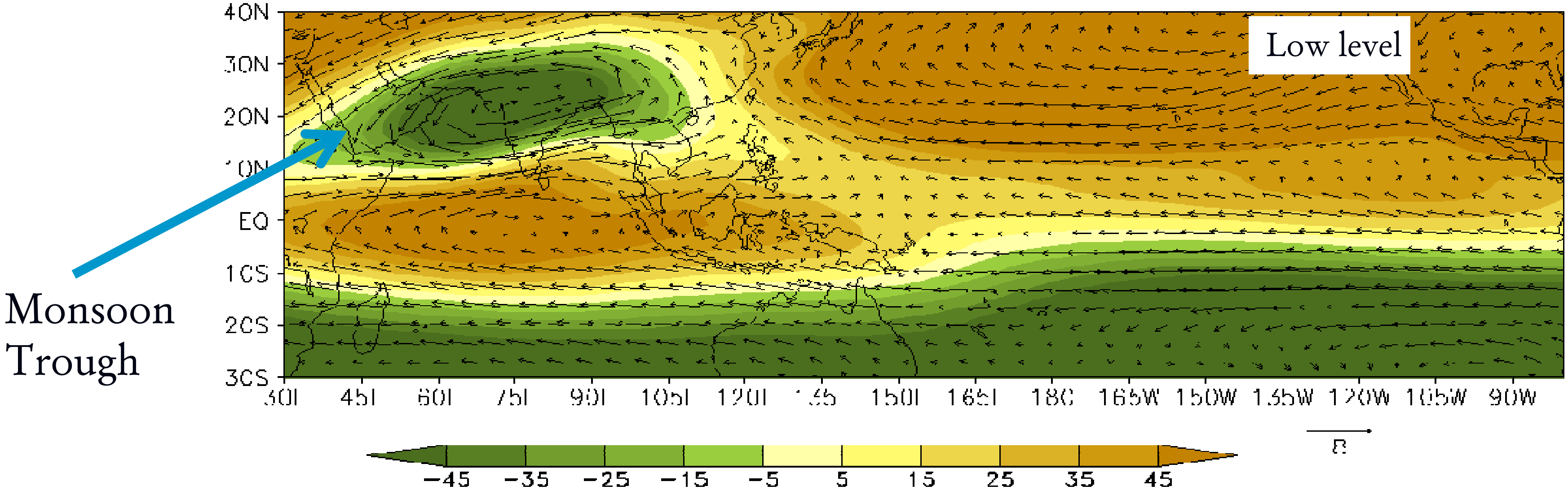


Choudhury and Krishnan (2011)

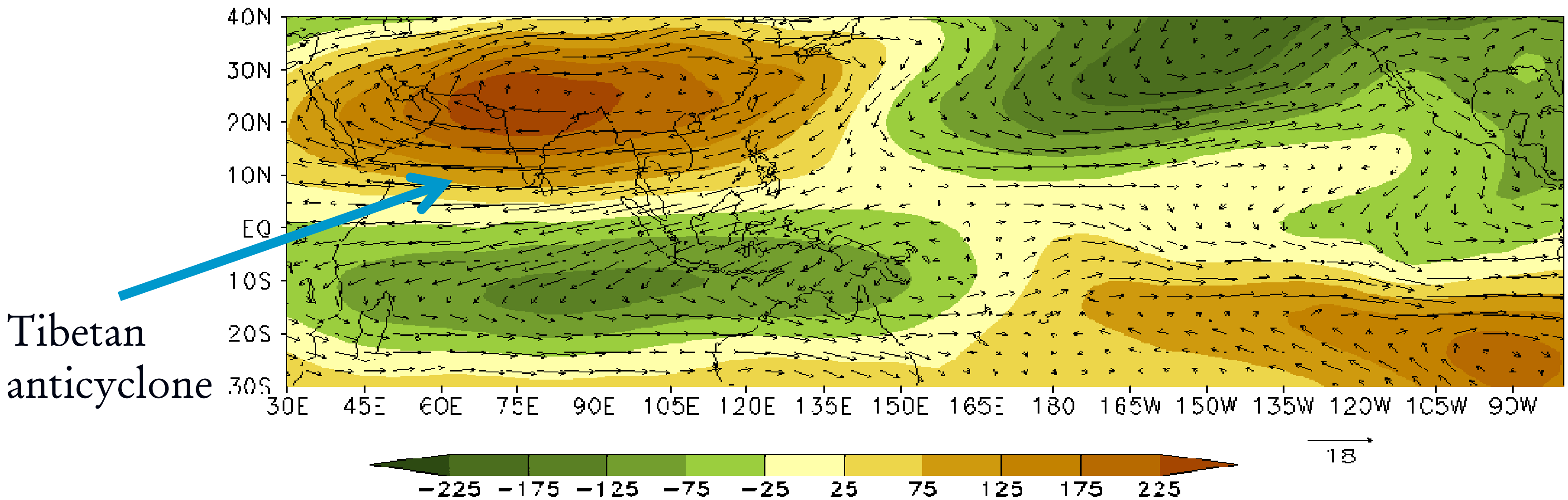
(Algorithm from Schumacher 2004)

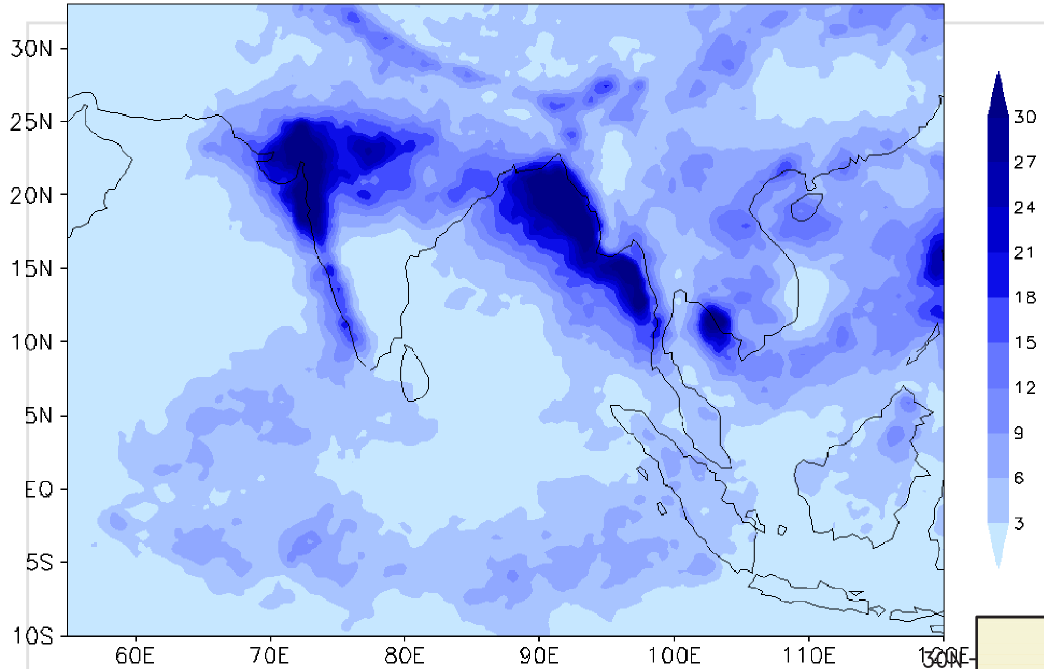
Dry model response to prescribed heating: Control (CTL)

Lower tropospheric circulation



Upper tropospheric circulation

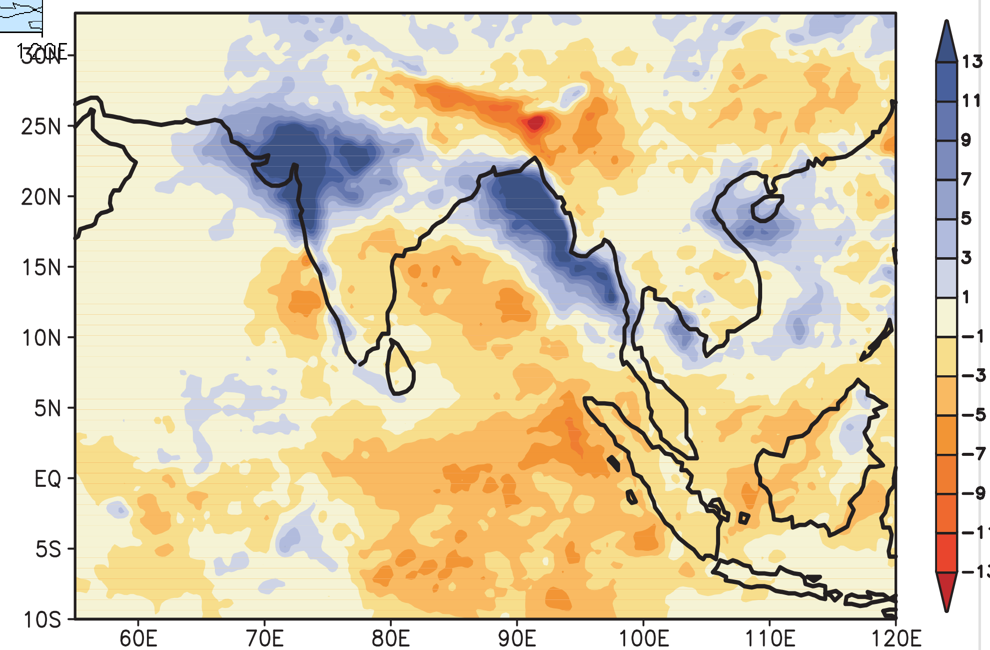




Composite map of rainfall (mm day $^{-1}$) based on active monsoon days. The data is from TRMM 3B42 daily rainfall dataset. The active monsoon dates are from Rajeevan et al. (2008)

Active Monsoon

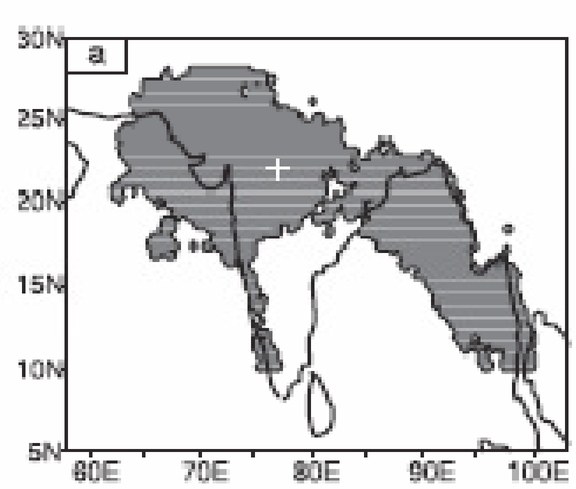
Large-scale organization of meso-scale convective systems MCS (3000-4000 km)



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.

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



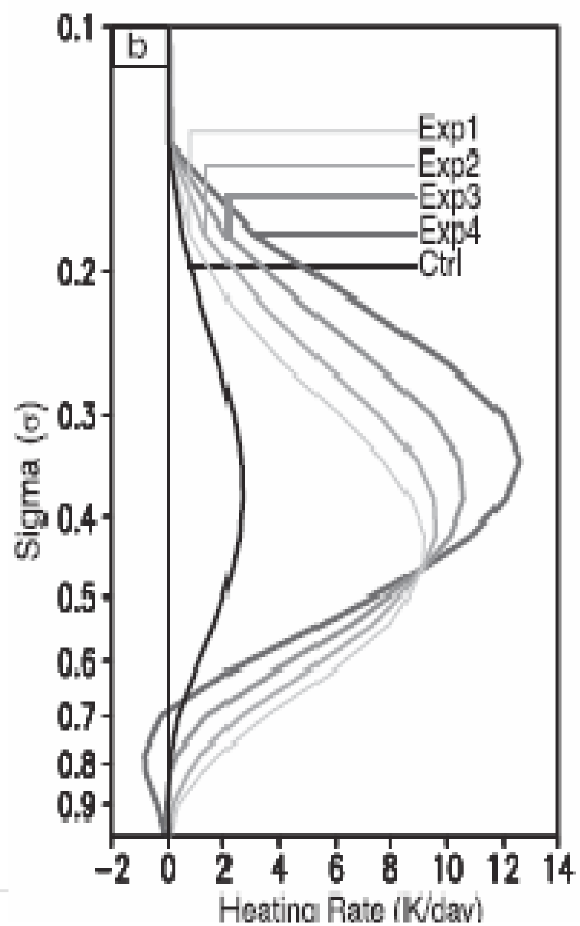
Shaded area: Monsoon trough (MT) zone

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



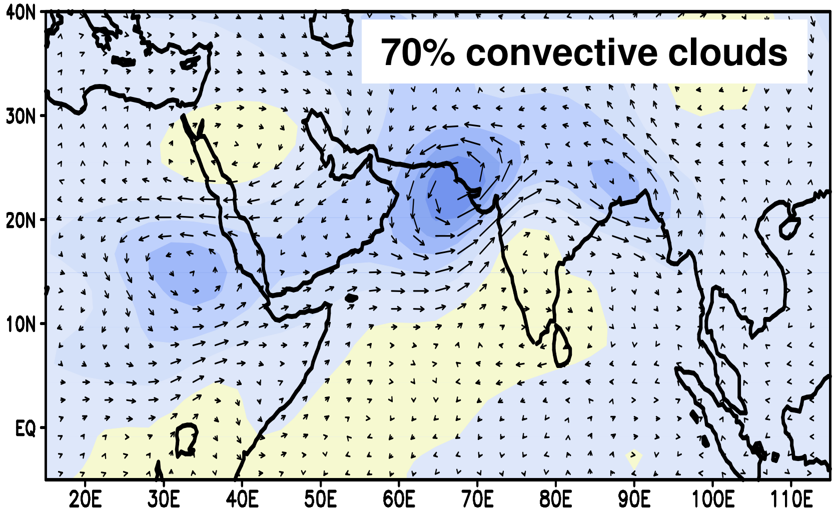
Model sensitivity experiments

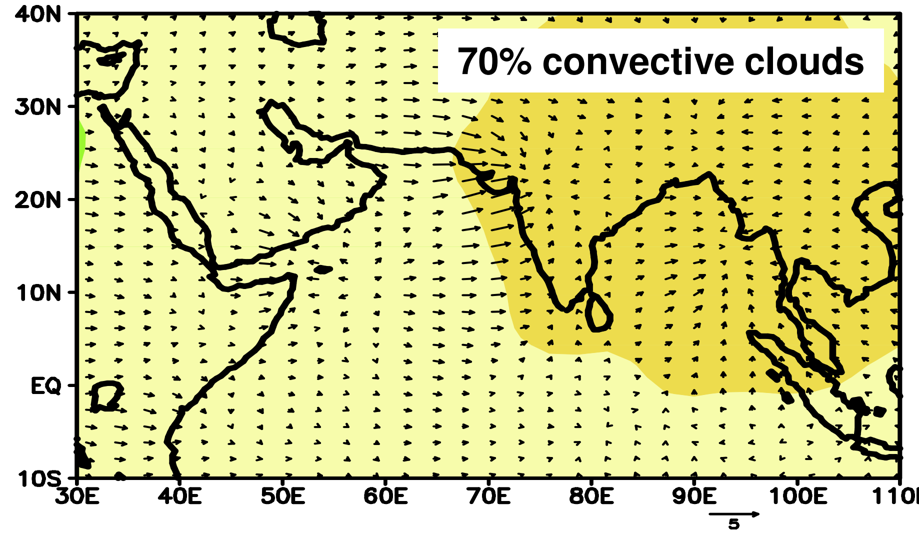
Experiment	Stratiform and convective fractions of rain anomaly during active monsoon period		Active period rain anomaly	
	Stratiform Fraction (SF)	Convective Fraction (CF)	Stratiform anomaly	Convective anomaly
Exp 1	0%	100%	0.0 % of Rain anomaly	100 % of Rain anomaly
Exp 2	30%	70%	30 % of Rain anomaly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

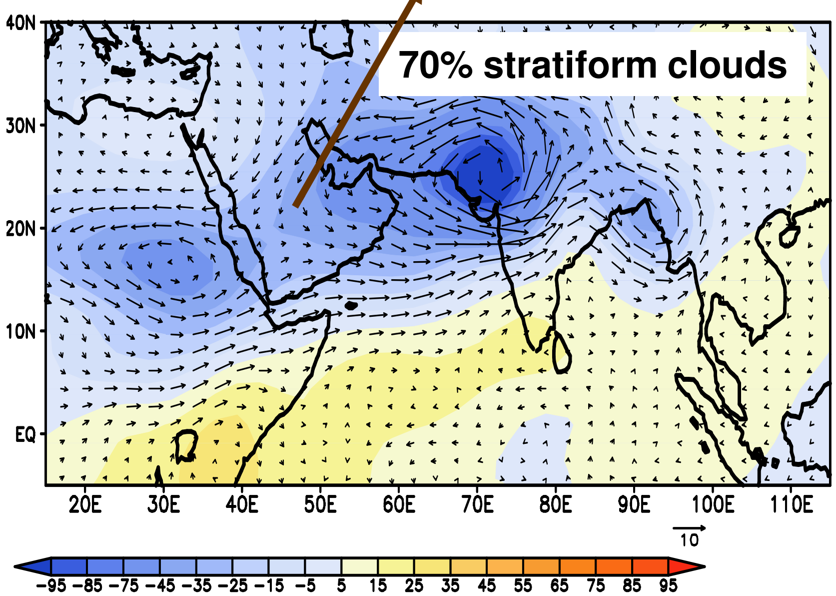
Streamfunction

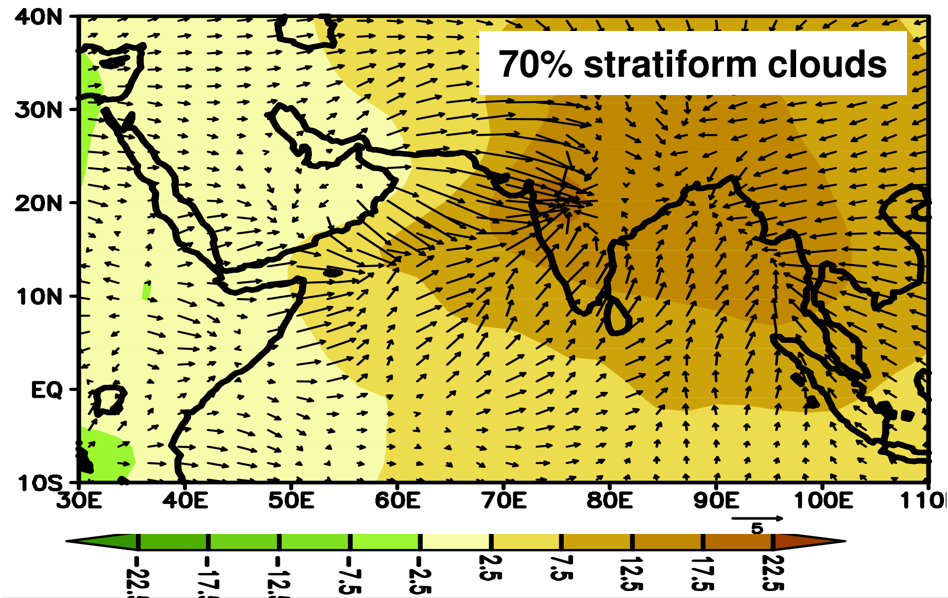
Velocity potential



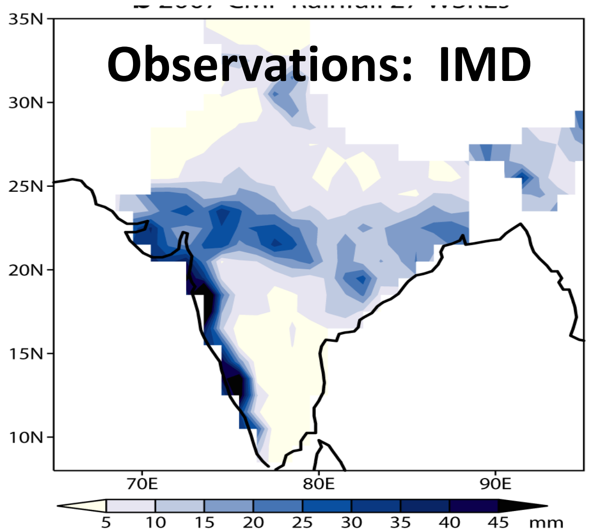


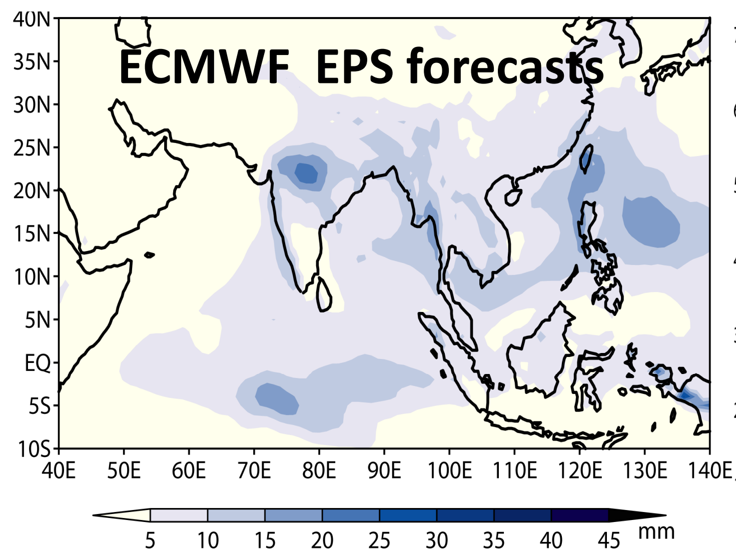
Large scale structure of mid-level cyclonic response extending into African ITCZ region



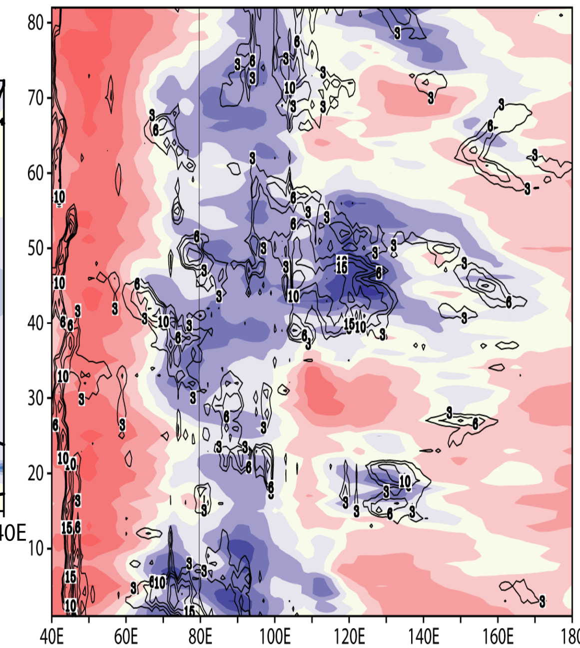


Rainfall composite: 11 widespread rain events during 2007



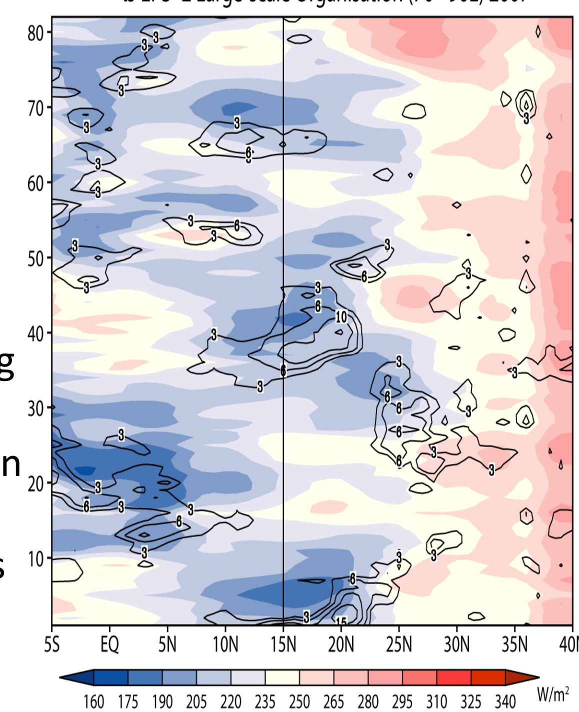


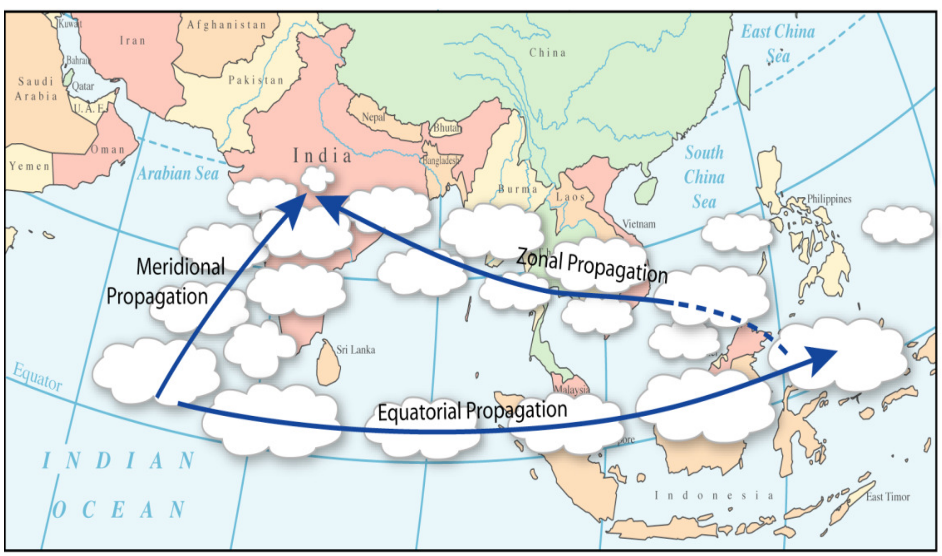
a EPS–2 Large-scale Organisation (10 –25N) 2007



Assessment of ECMWF forecasts: Widespread rainfall events during the Indian summer monsoon: M. Mujumdar, F. Molteni, Ghelli, F. Virart, P. Dando, J.M. Slingo (2009). ECMWF Tech. Mem. No. 580

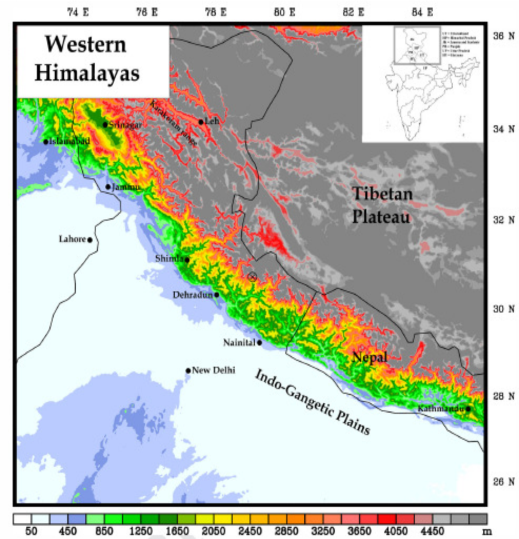
b EPS–2 Large-scale Organisation (70 –90E) 2007

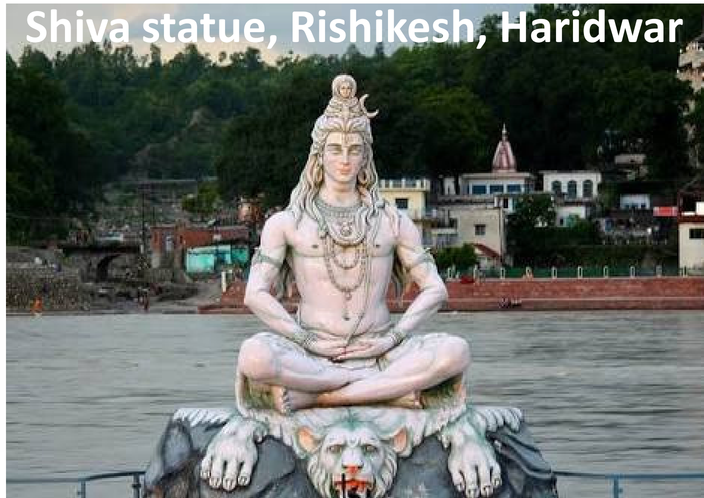


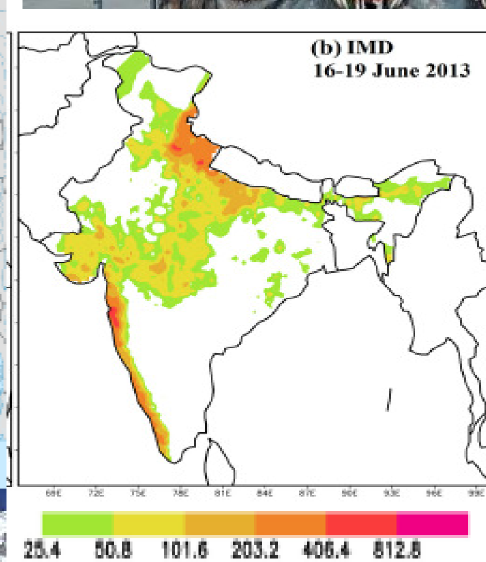


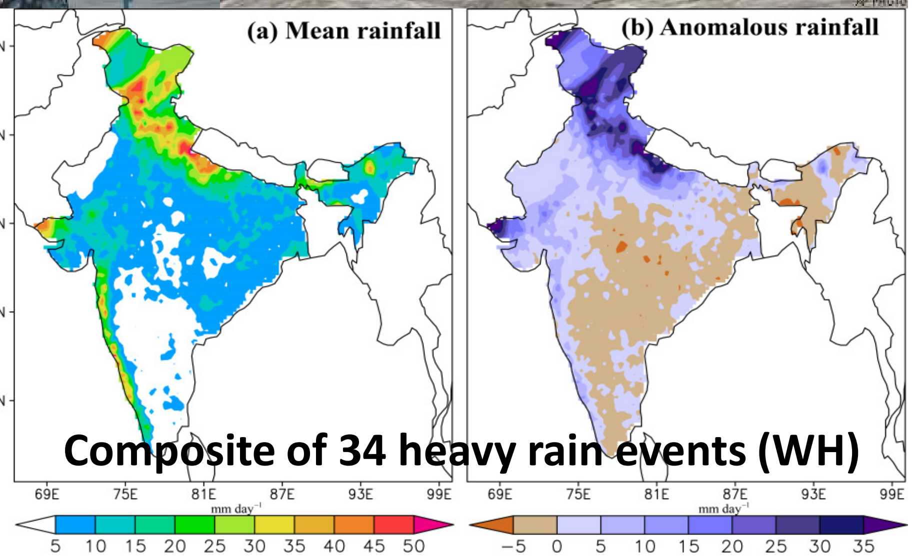
ECMWF EPS skillful in capturing westward & northward propagating organized convection during wide spread rain events over Central India – with lead times up to 10 days

17 June 2013, Uttarakhand heavy precipitation and floods









Clim Dyn
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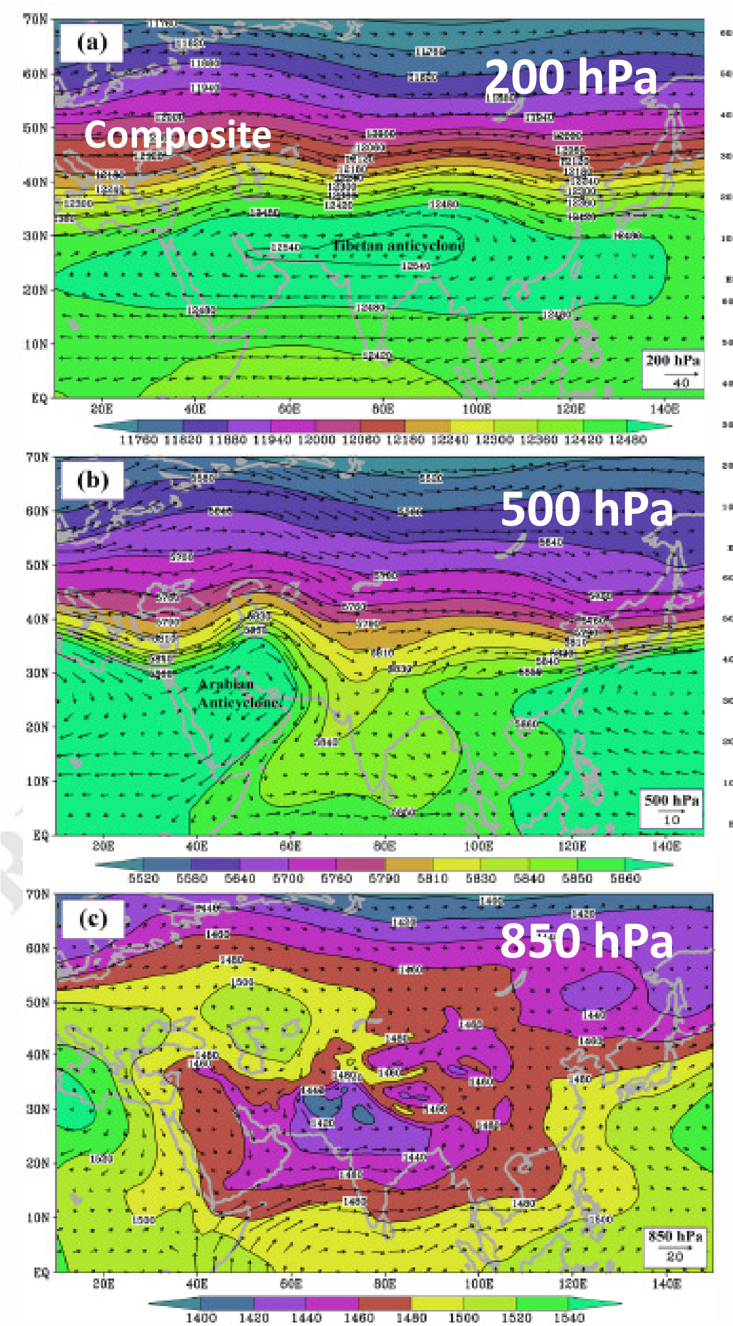
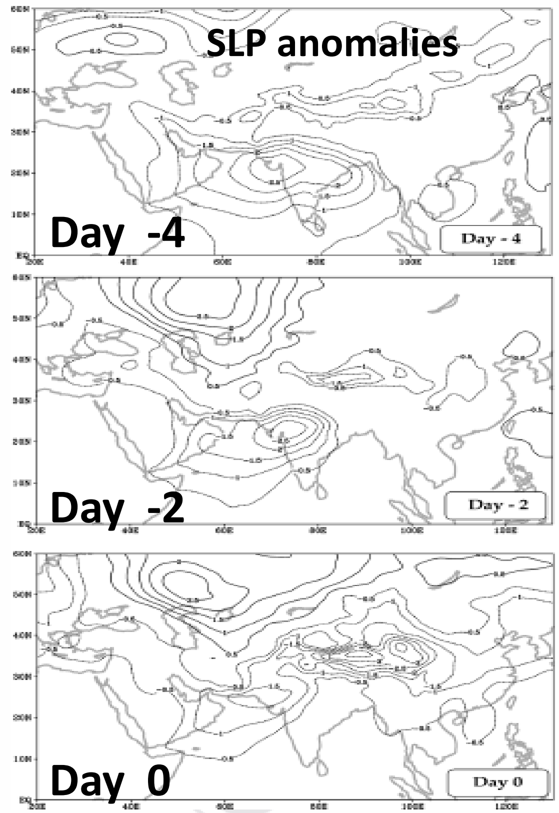
2015

Monsoon-extratropical circulation interactions in Himalayan extreme rainfall

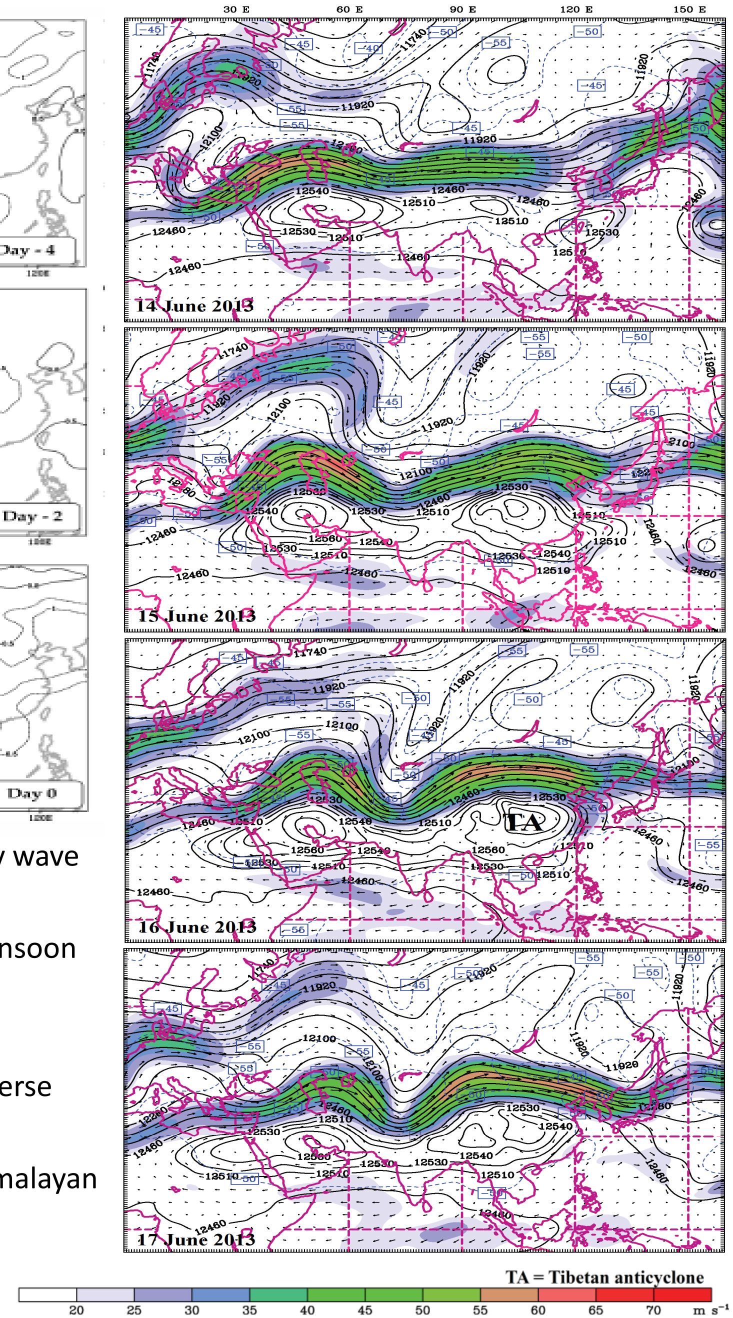
Ramesh K. Vellore[1] · Michael L. Kaplan[2] · R. Krishnan[1] · John M. Lewis[2,3] · Sudhir Sabade[1] · Nayana Deshpande[1] · Bhupendra B. Singh[1] · R. K. Madhura[1] · M. V. S. Rama Rao[1]

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



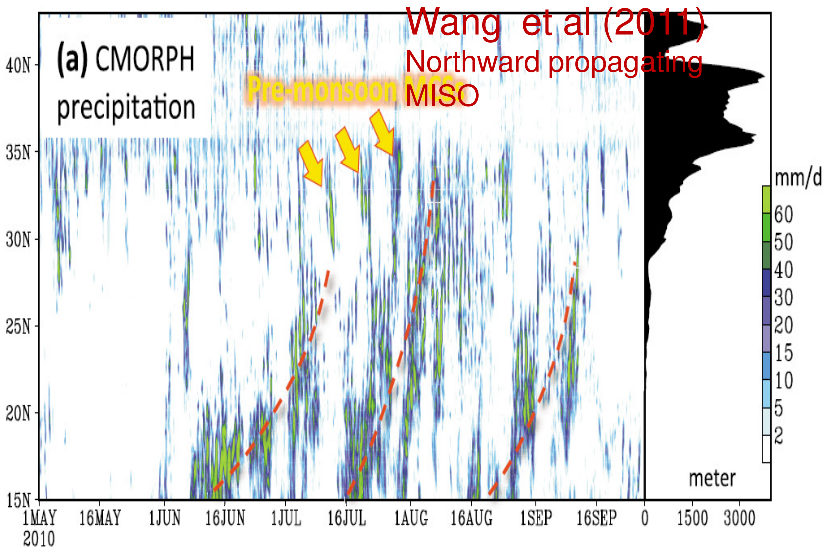


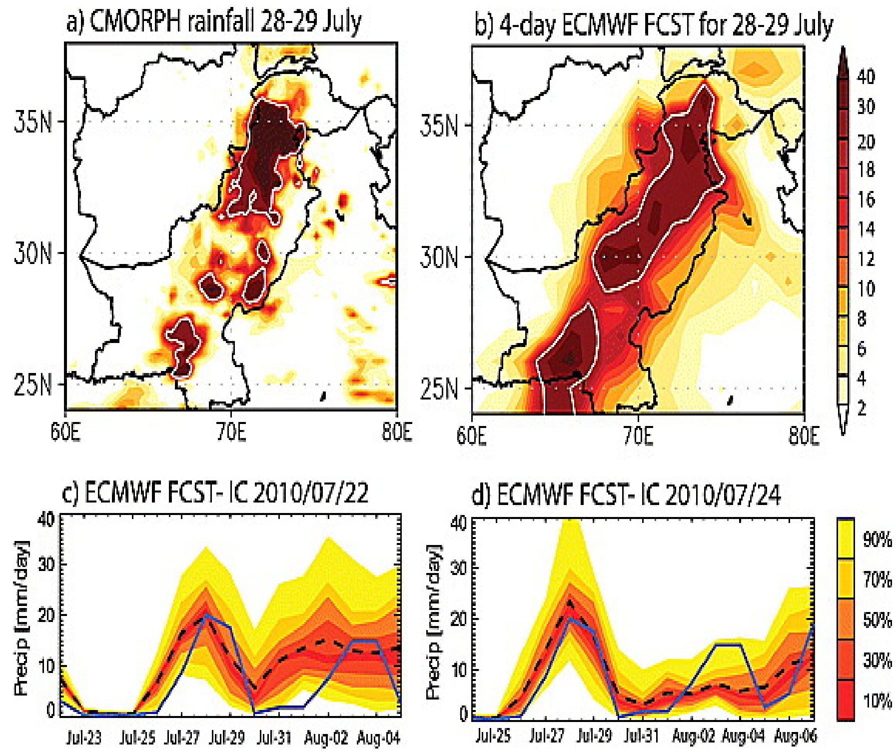
- •Mid-latitude blocking and Rossby wave breaking
- •West-northwest propagating monsoon low pressure system
- •Eddy shedding of Tibetan High
- •Ageostrophic circulations, transverse circulations across Himalayas
- •Strong moist convection over Himalayan foothills



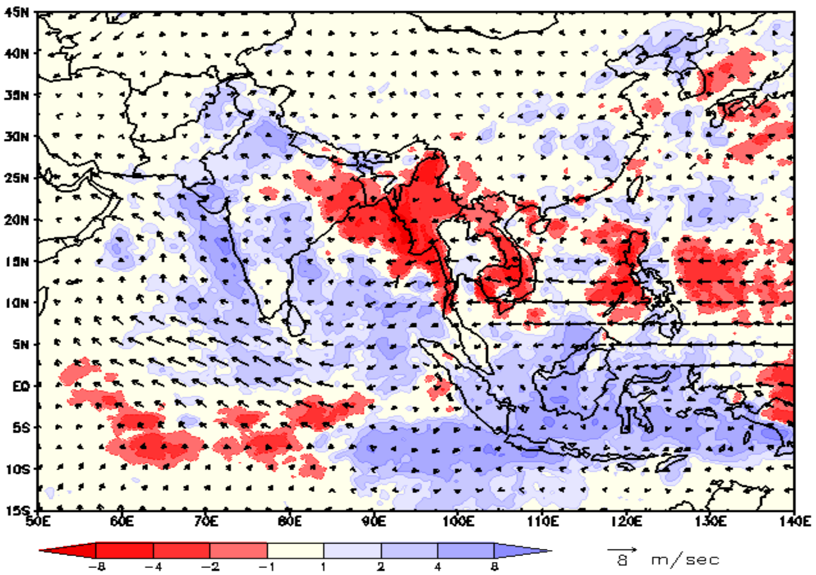
Vellore et al. 2015

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





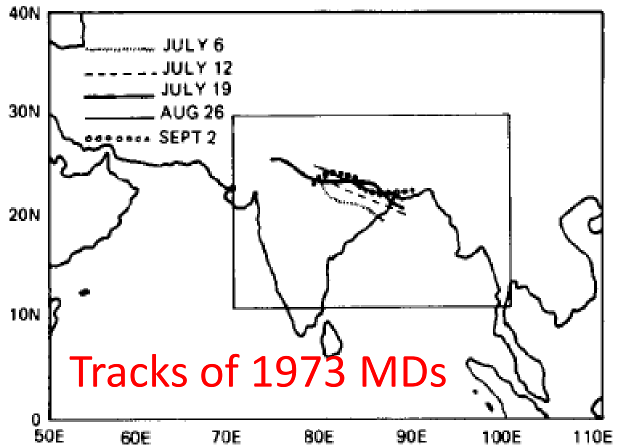
Total precipitation [mm/day] for (a) CMORPH over 28–29 July 2010 and (b) ECMWF ensemble mean of the forecast initialized four days previously (July 24, 2010) for the same time period. White contour shows 20 mm/day. ECMWF 15-day forecast of the precipitation [mm/day] in the area (70E-74E,30N-36N) initialized on July (c) 22nd, and (d) 24th, 2010. Black dashed line shows the ensemble mean. Colored shading depicts the probability of precipitation rate based on the 51 ensemble members. Dark blue line represents the observed CMORPH precipitation averaged for the same region.



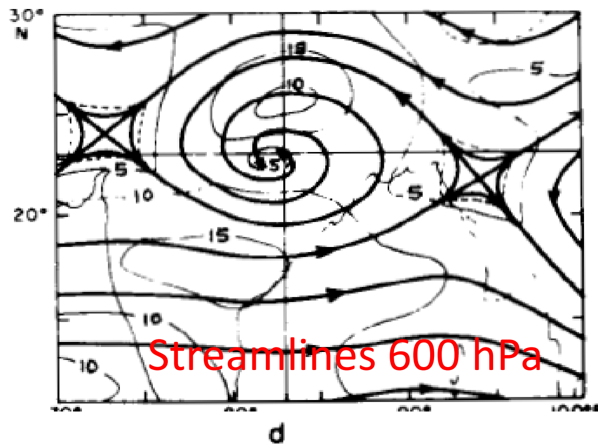
Observed rainfall anomaly (TRMM) wind anomaly at 850 hPa – JJAS 2010 (Mujumdar et al. 2012)

The 2010 Pakistan floods could have been predicted about two weeks in advance if forecasts were available (Webster et al 2011)

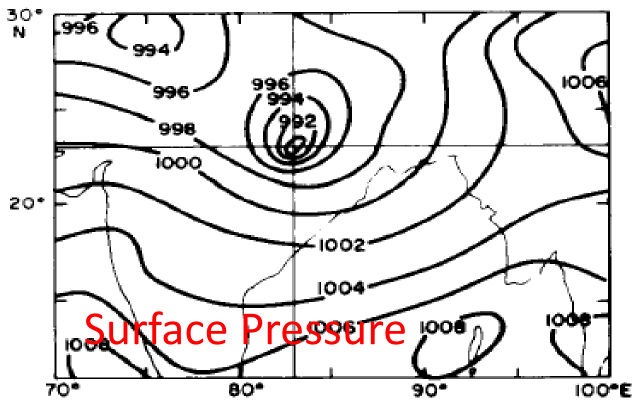
Composite structure of monsoon depressions - Godbole, 1977, Tellus

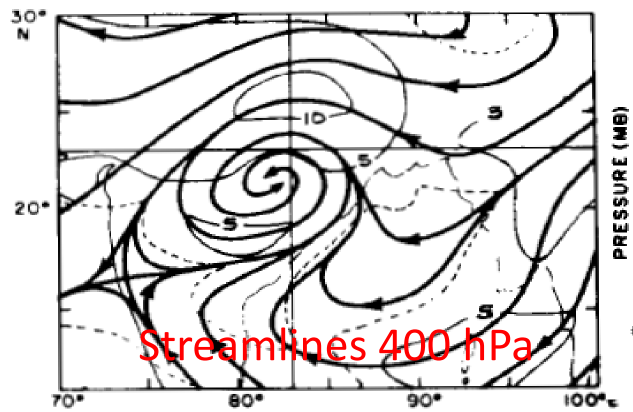


Tracks of 1973 MDs

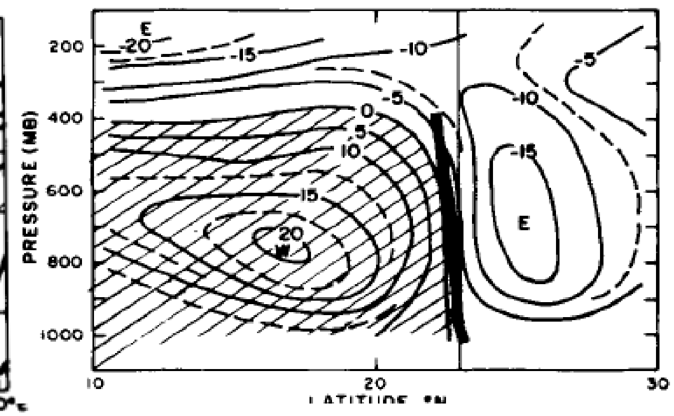

Streamlines 600 hPa

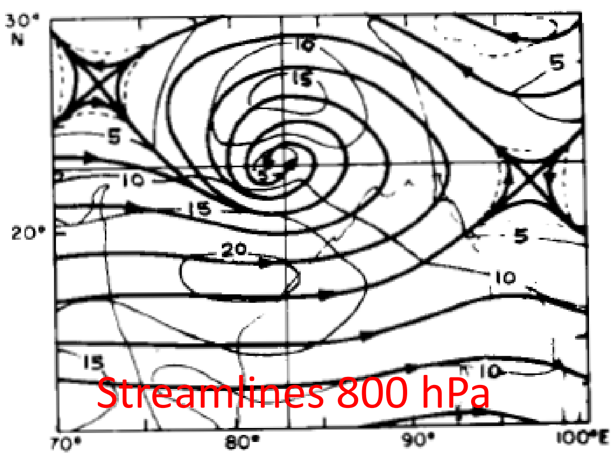
Horizontal dimension ~ 1500 km
Vertical dimension ~ 8 km
Central pressure: 990 hPa
Horizontal winds > 20 ms^{-1}
Strongest winds: Southwest
Cold core systems

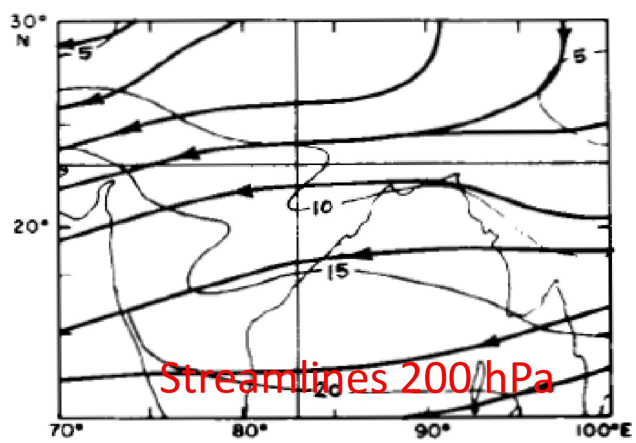

Surface Pressure


Streamlines 400 hPa

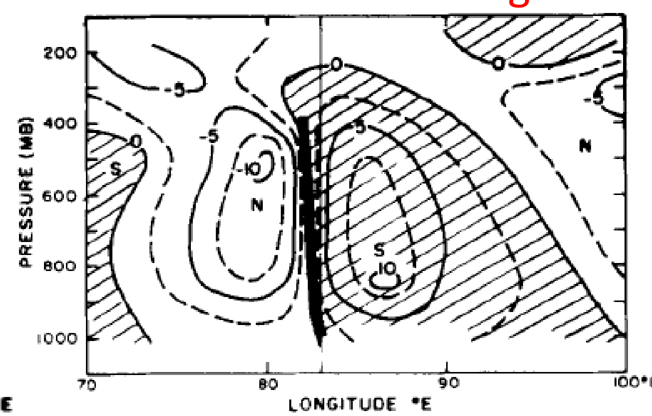
Zonal wind along 83E

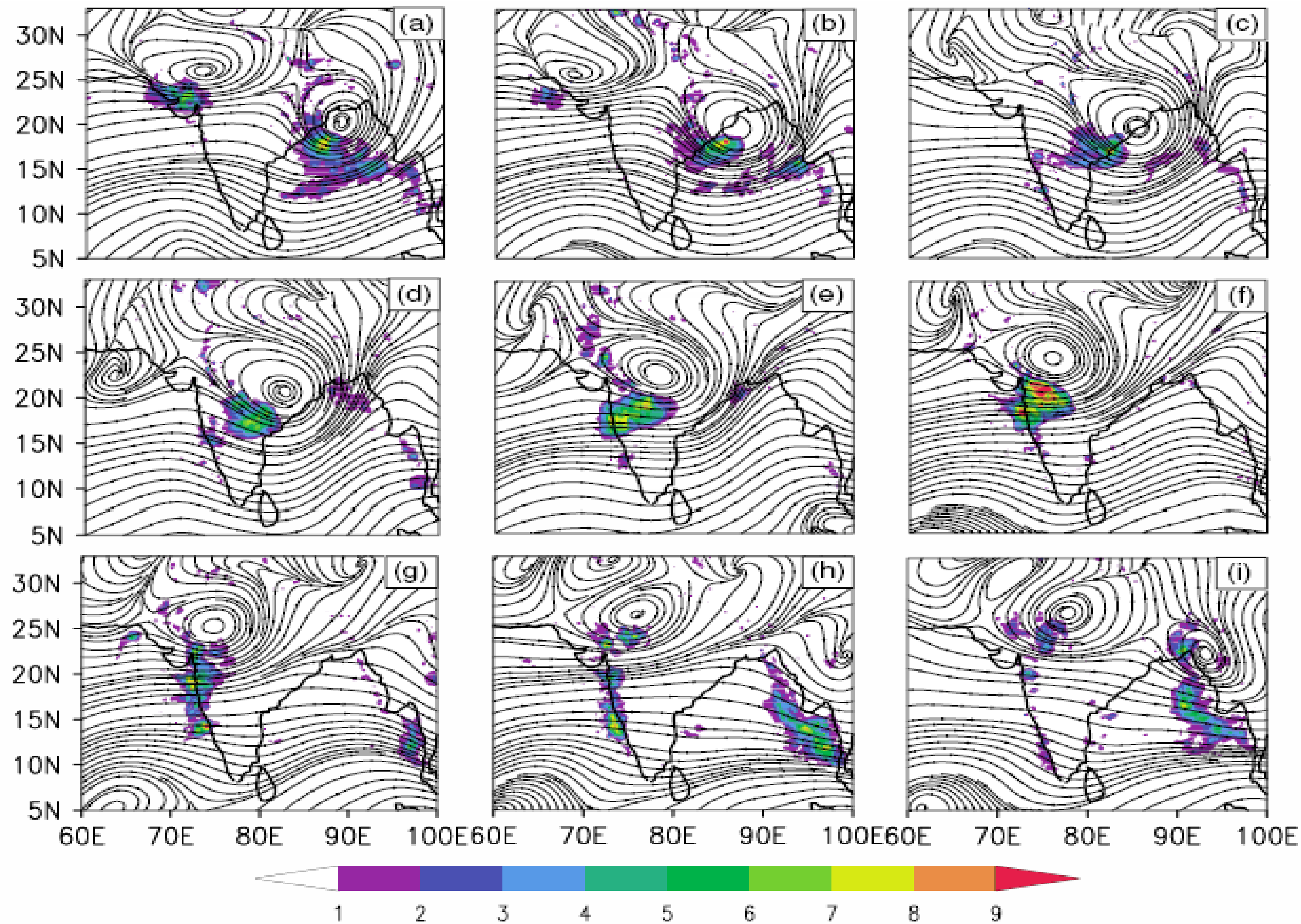



Streamlines 800 hPa


Streamlines 200 hPa

Meridional wind along 23N





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

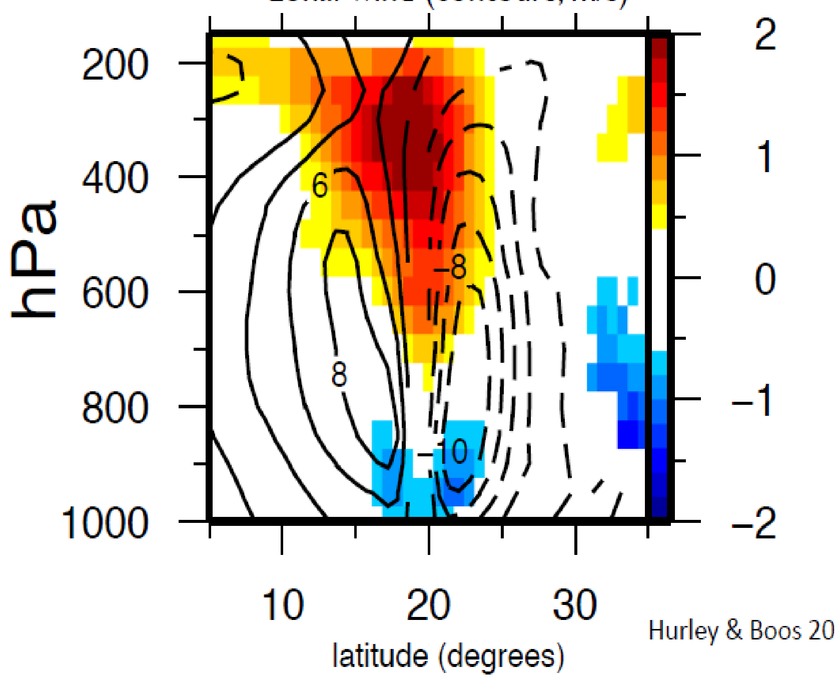
Genesis and Growth : Sheared instability of monsoon flow is necessary (barotropic, baroclinic, combined Barotropic-baroclinic) – e.g., Keshavamurty et al. 1978, Keshavamurty and Shankar Rao, 1992, Shukla, 1978, Satyan et al. 1980, Goswami et al. 1980, Mishra and Salvekar, 1980, Mak, 1983, Moorthi and Arakawa, 1985

Propagation: Westward propagation thought to be determined by low-level dynamics and heating – Rao and Rajamani, 1970, Sanders, 1984, Goswami, 1985, Chen et al. 2005

Hurley and Boos, 2014, QJRMS

Cold-core cyclonic vortices

Indian monsoon depression composite mean anomalies of potential temperature (colors, K) and zonal wind (contours, m/s)

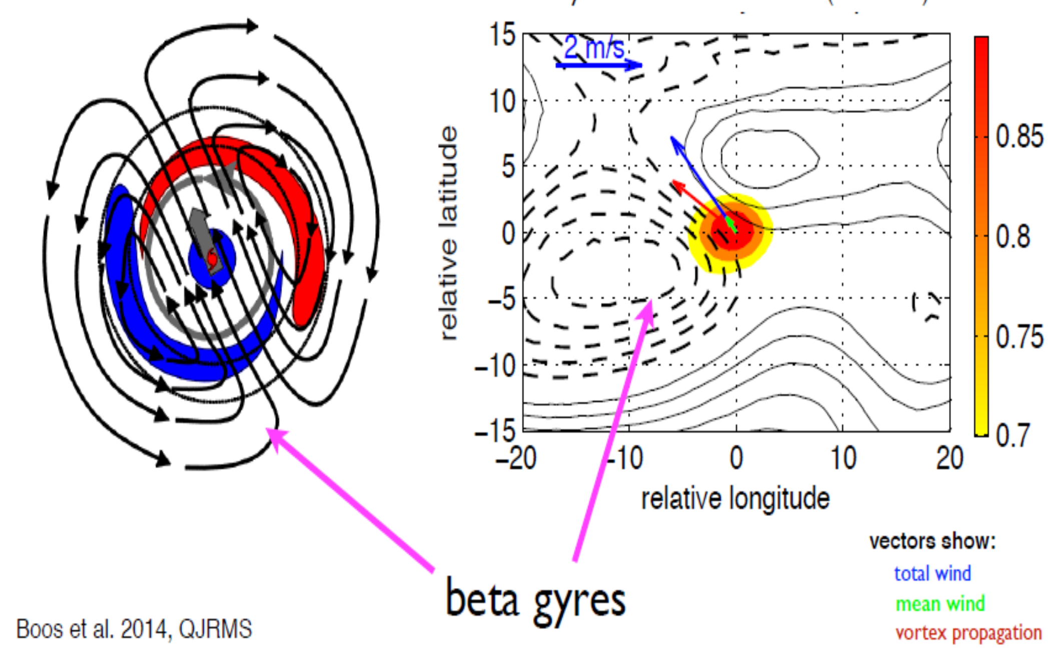


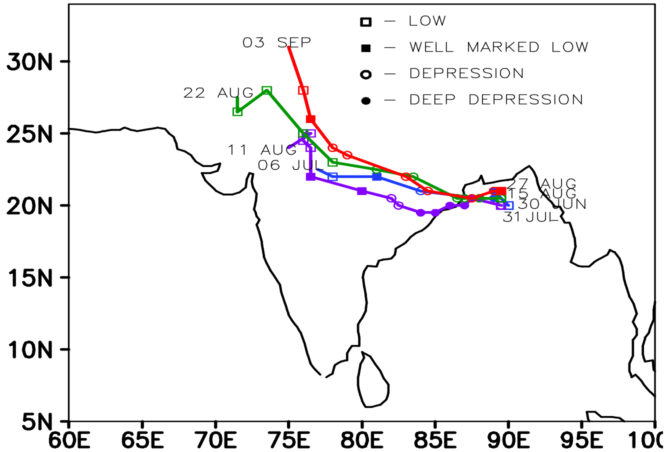
Boos et al. 2014, QJRMS

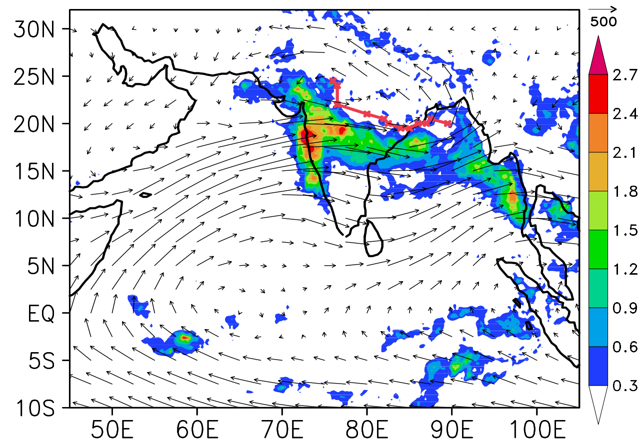
Propagation by self-advection ("beta drift")

schematic of beta gyres in a tropical cyclone

composite Indian monsoon depression: 500 hPa PV (colors) and azimuthally asymmetric streamfunction (contours)



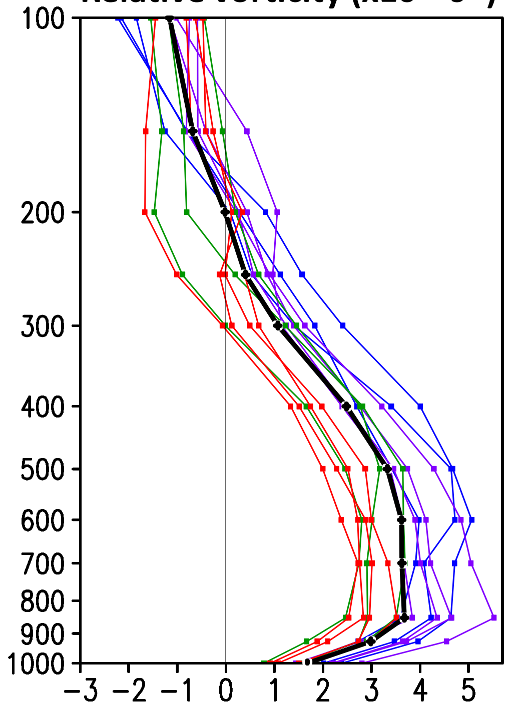




Long-lived monsoon depressions during 2006

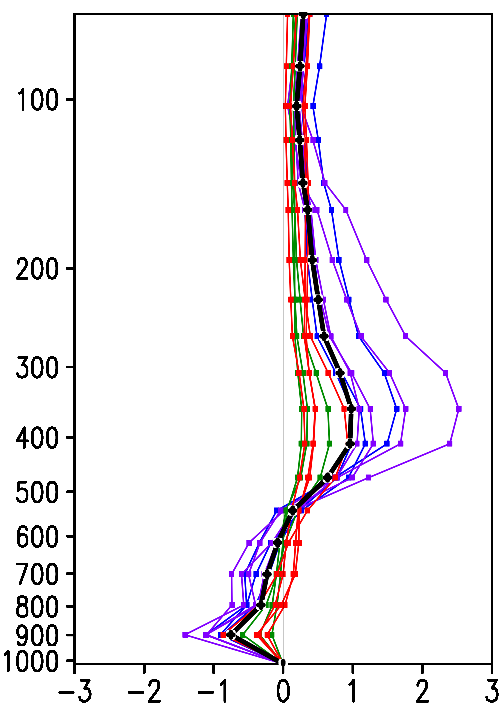
Krishnan et al. 2011
Int. J. Climatol.

Relative vorticity (x10^{+5} s^{-1})



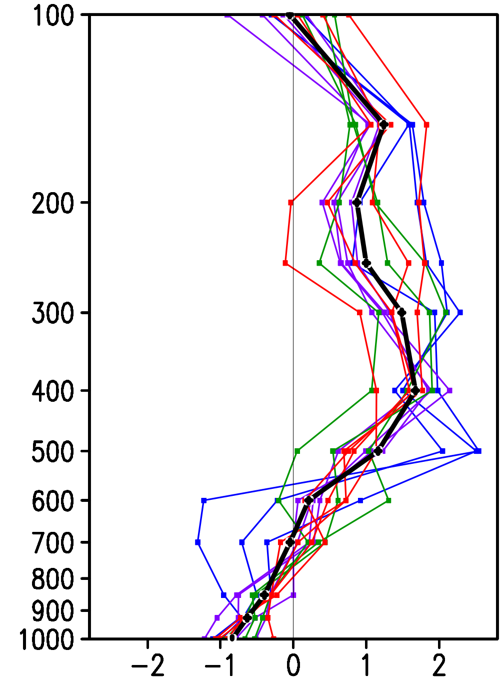
Intensification and vertical stretching of relative vorticity

TMI latent-heating (Khr $^{-1}$)



Latent heating above 600 hPa : Maximum near 400hPa & cooling in lower levels

Temperature difference (K) between the depression region and environment

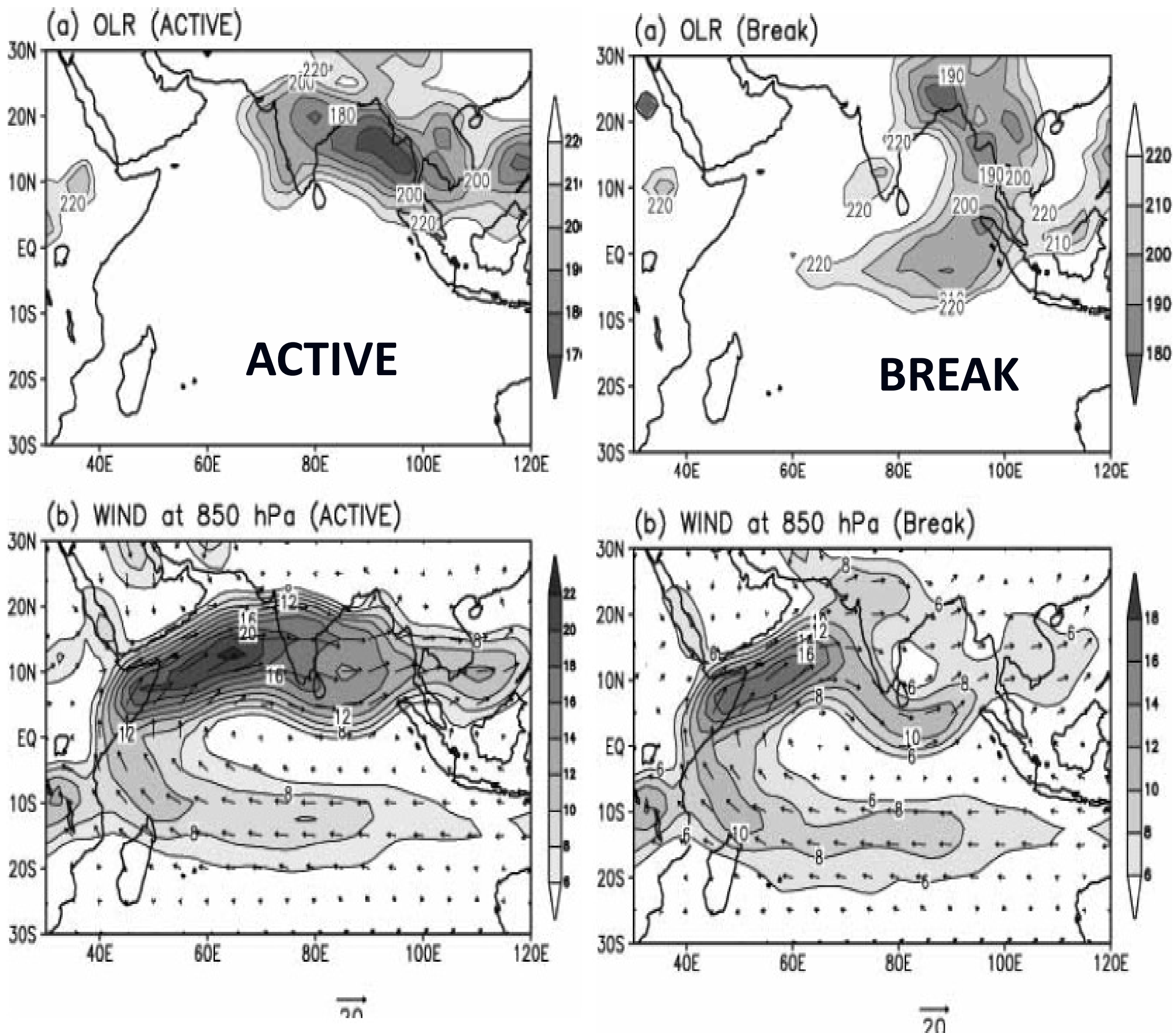


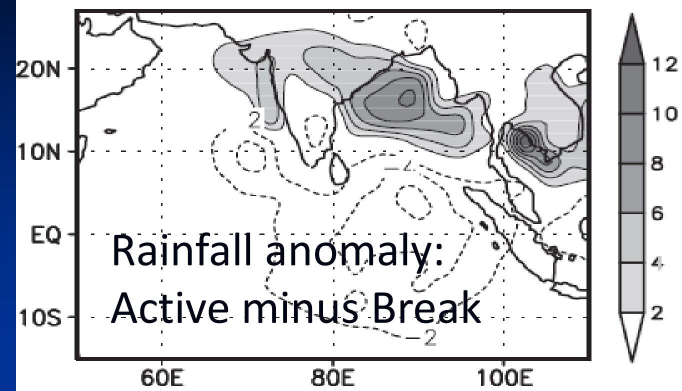
Cold core system: The depression is cooler than environment below 600 hPa

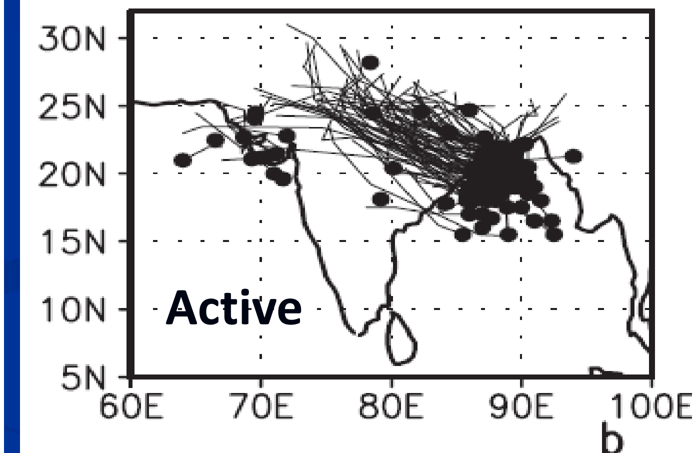
Active / Break composites of OLR & 850 hPa winds

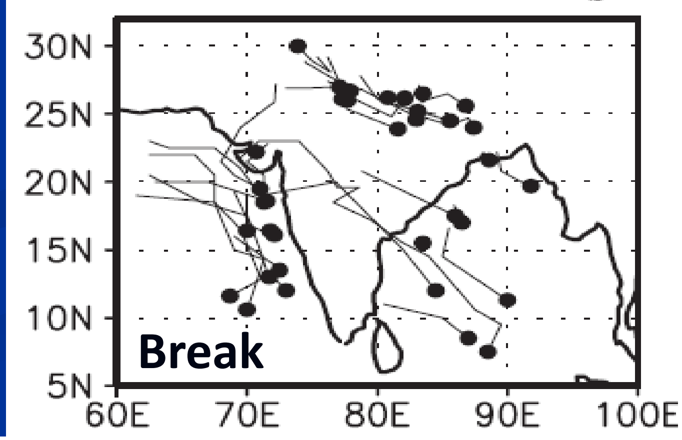
Goswami et al. 2003

Joseph and Sijikumar (2004): J. Climate





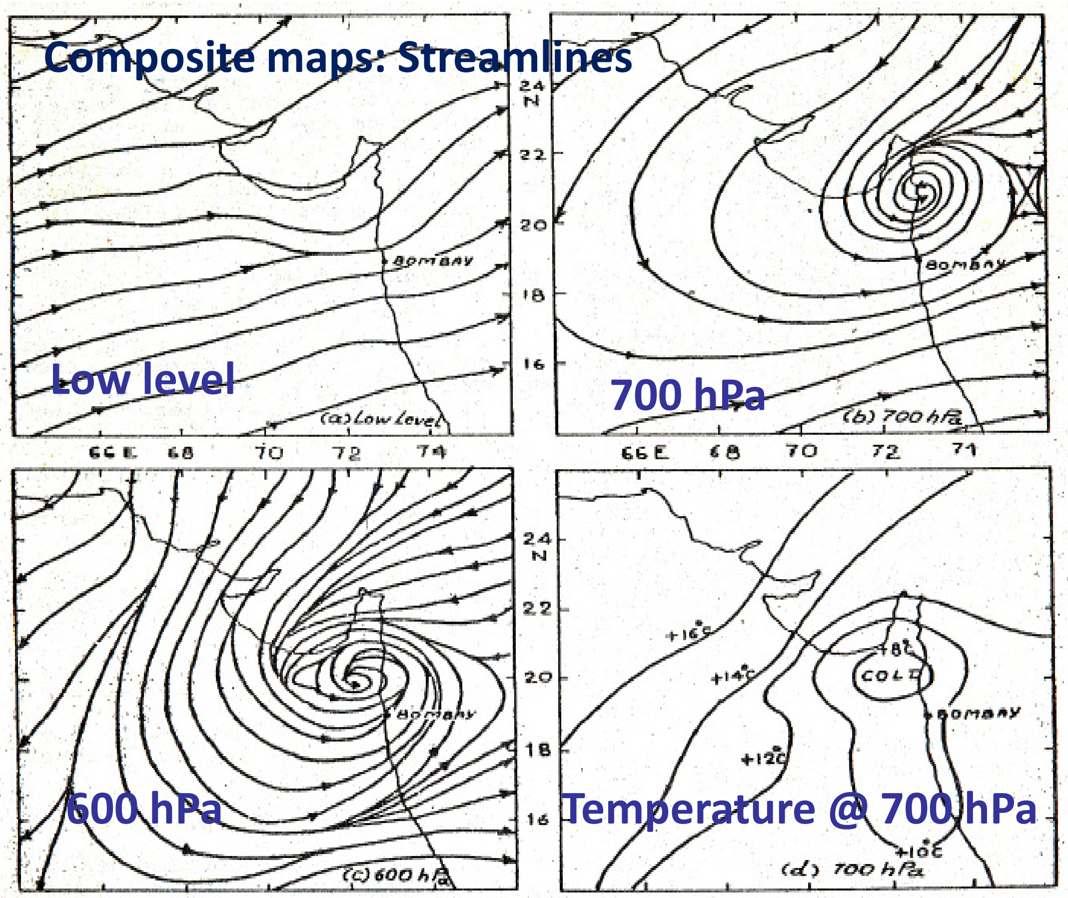




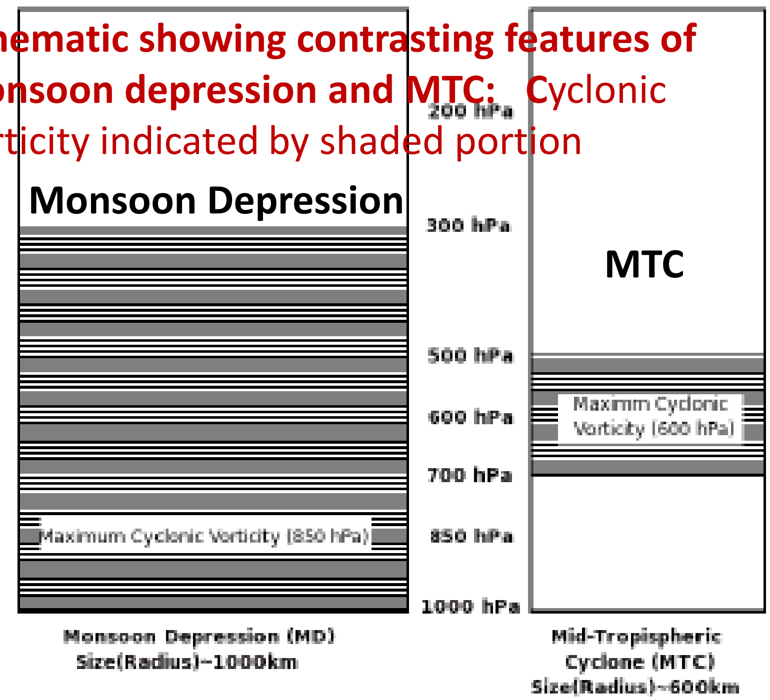
Clustering of synoptic activity by monsoon intraseasonal oscillations: Goswami et al. 2003, GRL

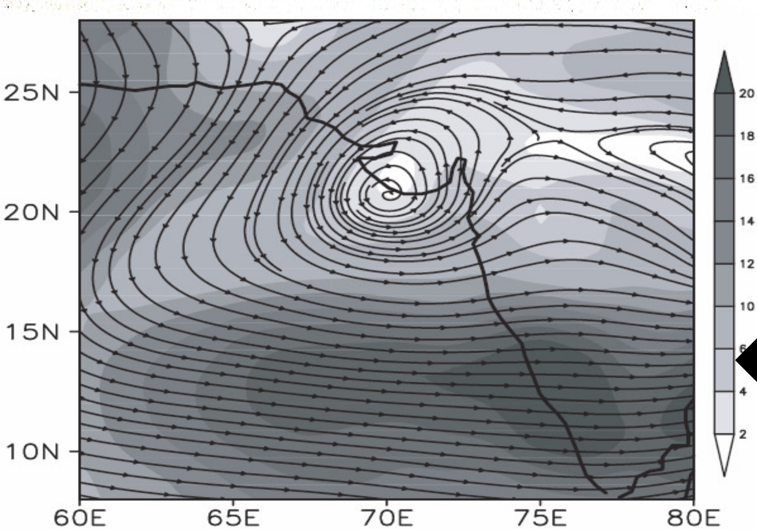
Mid-tropospheric cyclones (MTC):

- Miller and Keshavamurti (1968)



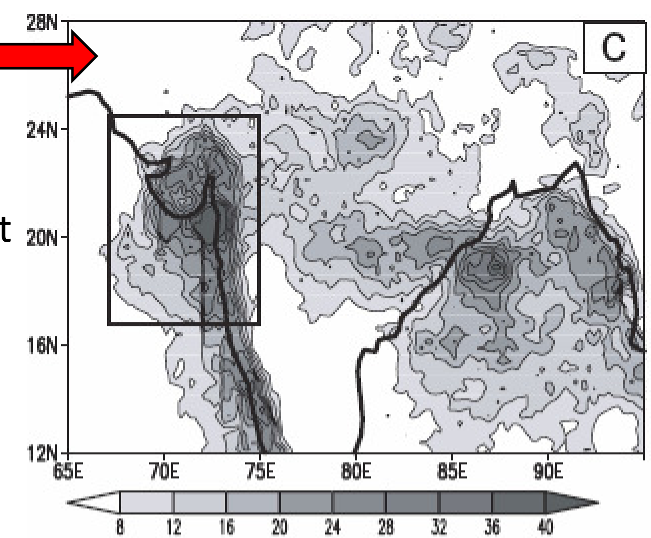
Schematic showing contrasting features of monsoon depression and MTC: Cyclonic vorticity indicated by shaded portion





Rainfall composite during MTC: TRMM 3B42 dataset

Streamlines, wind-speed at 600 hPa during 2007 MTC.
ERA Interim

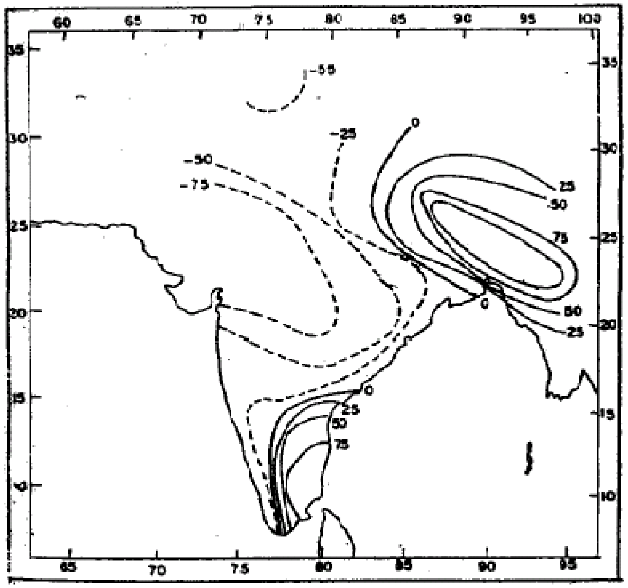


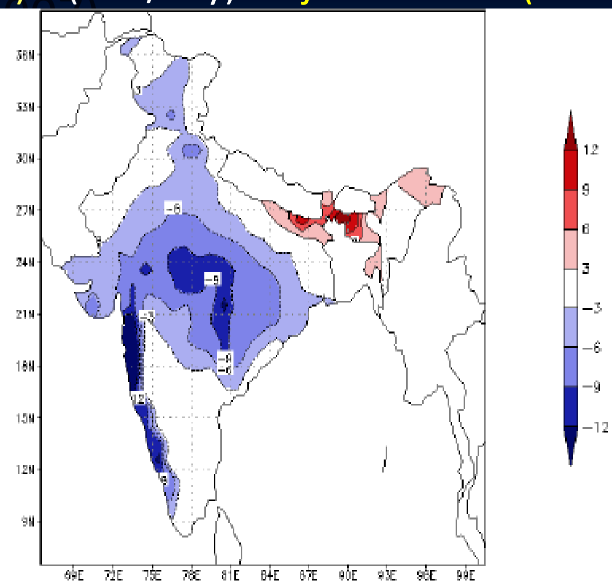
Ayantika Dey Choudhury, R. Krishnan, R. Vellore

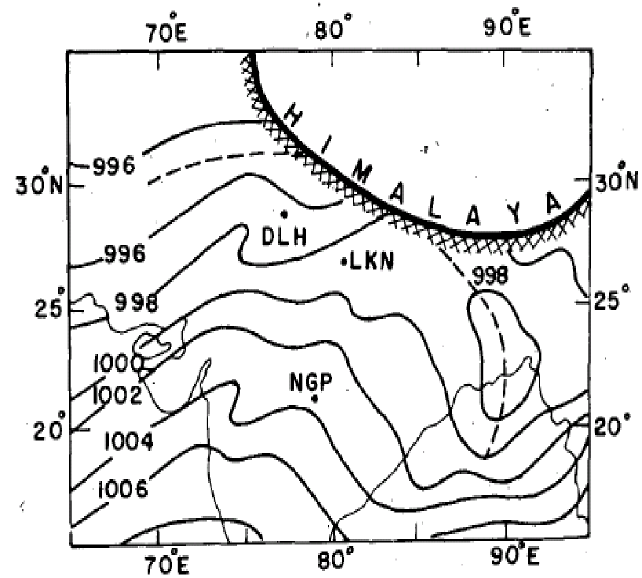
Mean departure (%) of rainfall during Monsoon breaks : Ramamurthy (1969)

Break monsoon rain anomaly (mm/day): Rajeevan et al. (2008)

Sea-level isobars (mb) on 02 Aug 1965 Raghavan (1973)

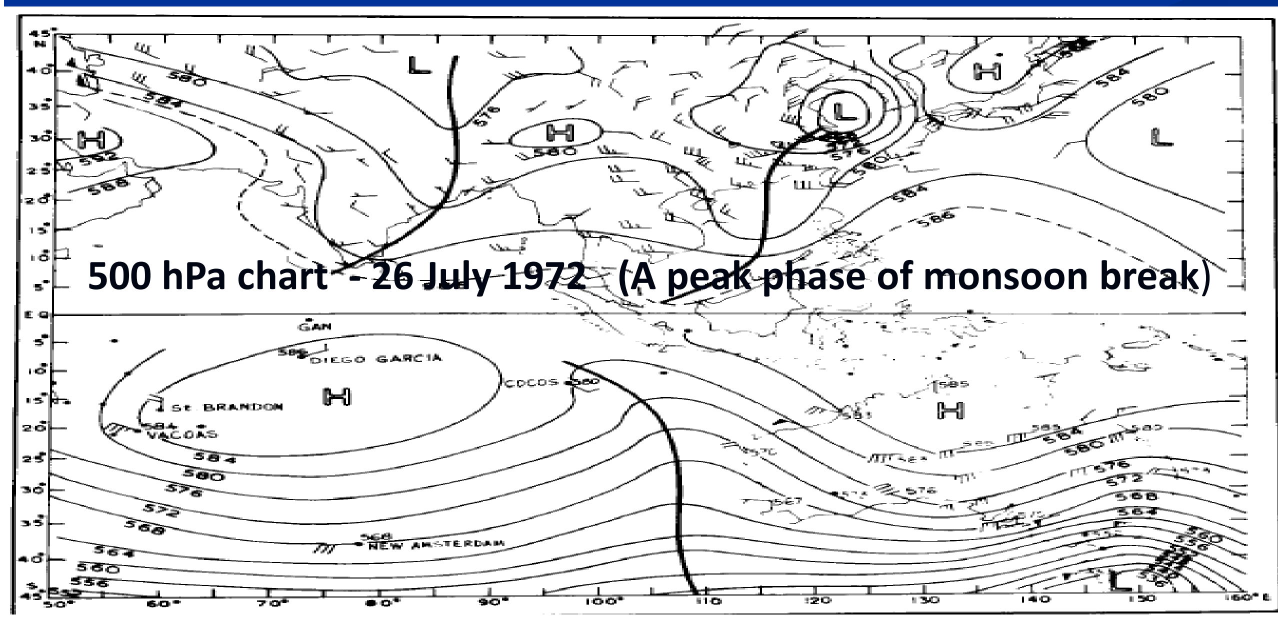




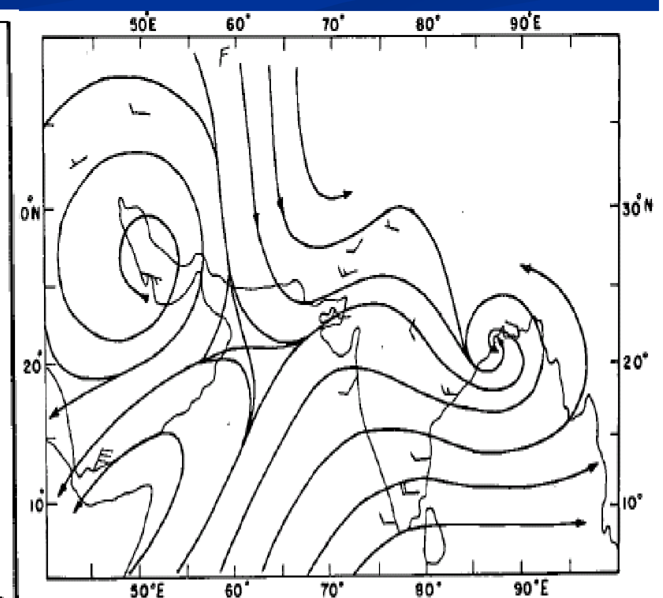


Ramaswamy and Pareekh (1978): Development of westerly circulation in both Hemispheres during monsoon breaks

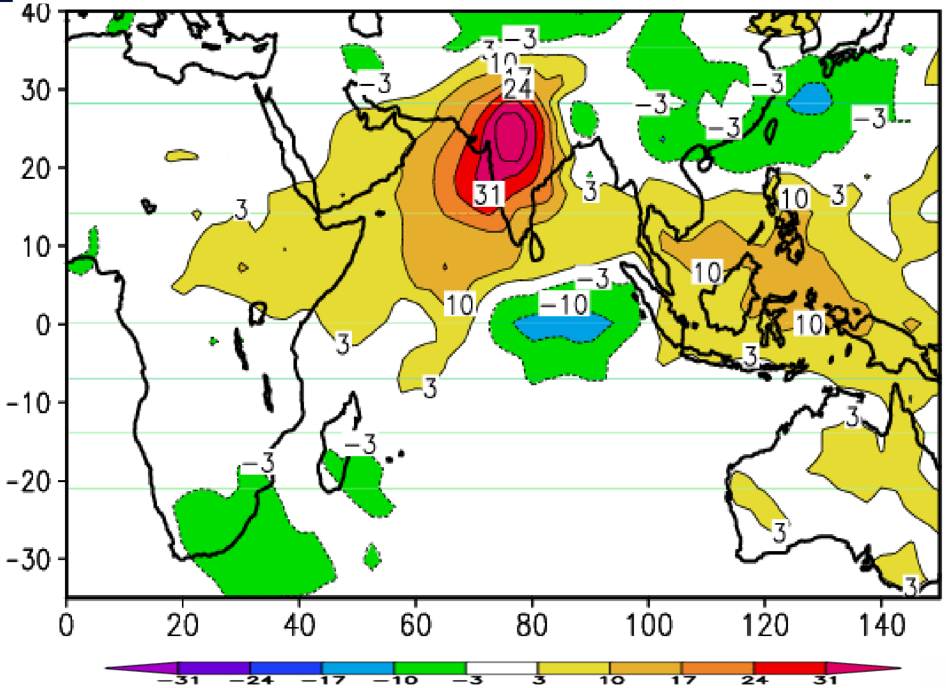
Winds & Streamlines @ 500 hPa on 02 Aug 1965 Raghavan (1973)



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



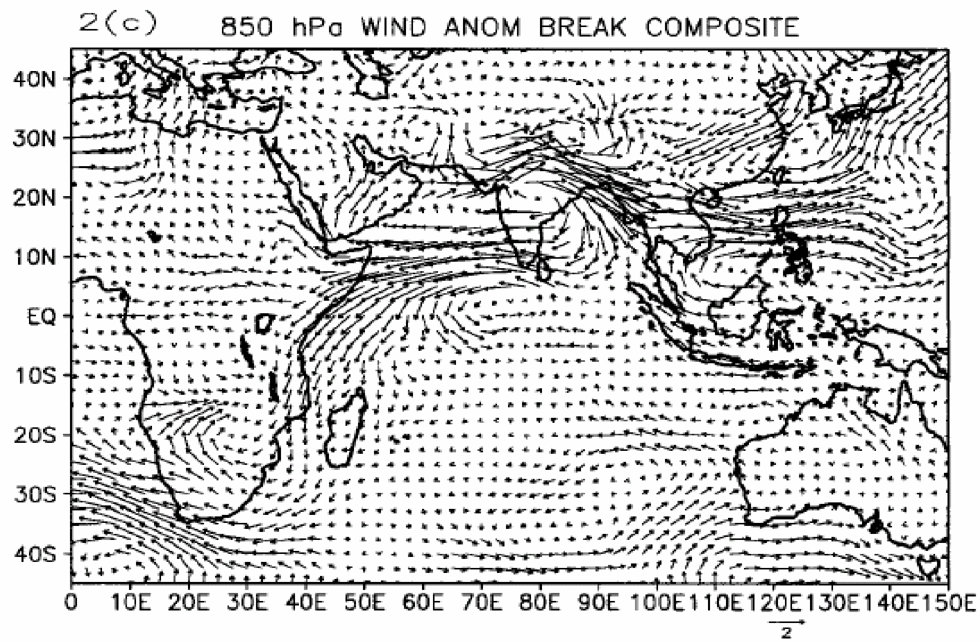
Large-scale structure of break monsoon anomalies



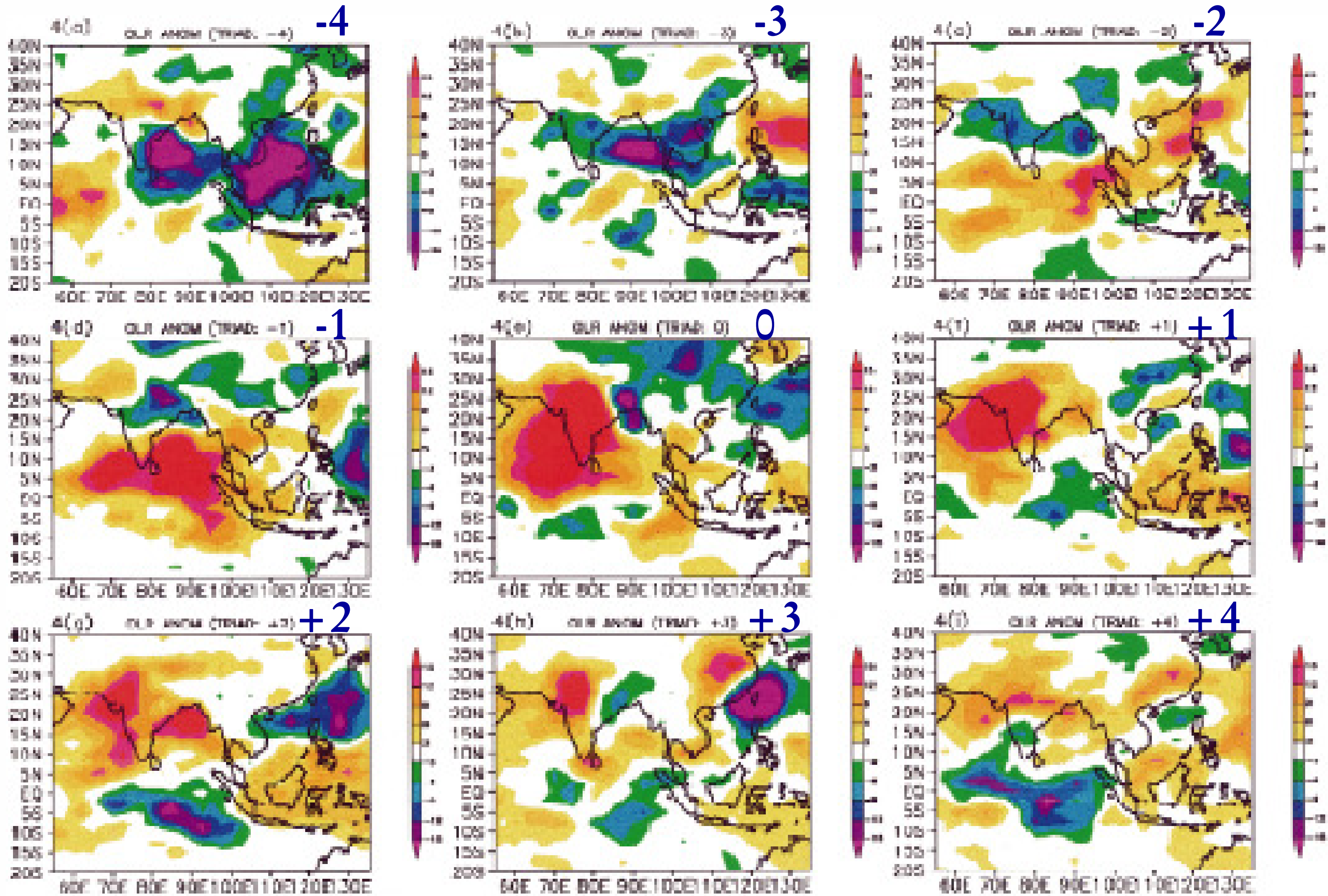
Composite map of OLR anomaly

High OLR over tropics indicates scarcity of cloud cover

Composite map of 850 hPa wind anomaly

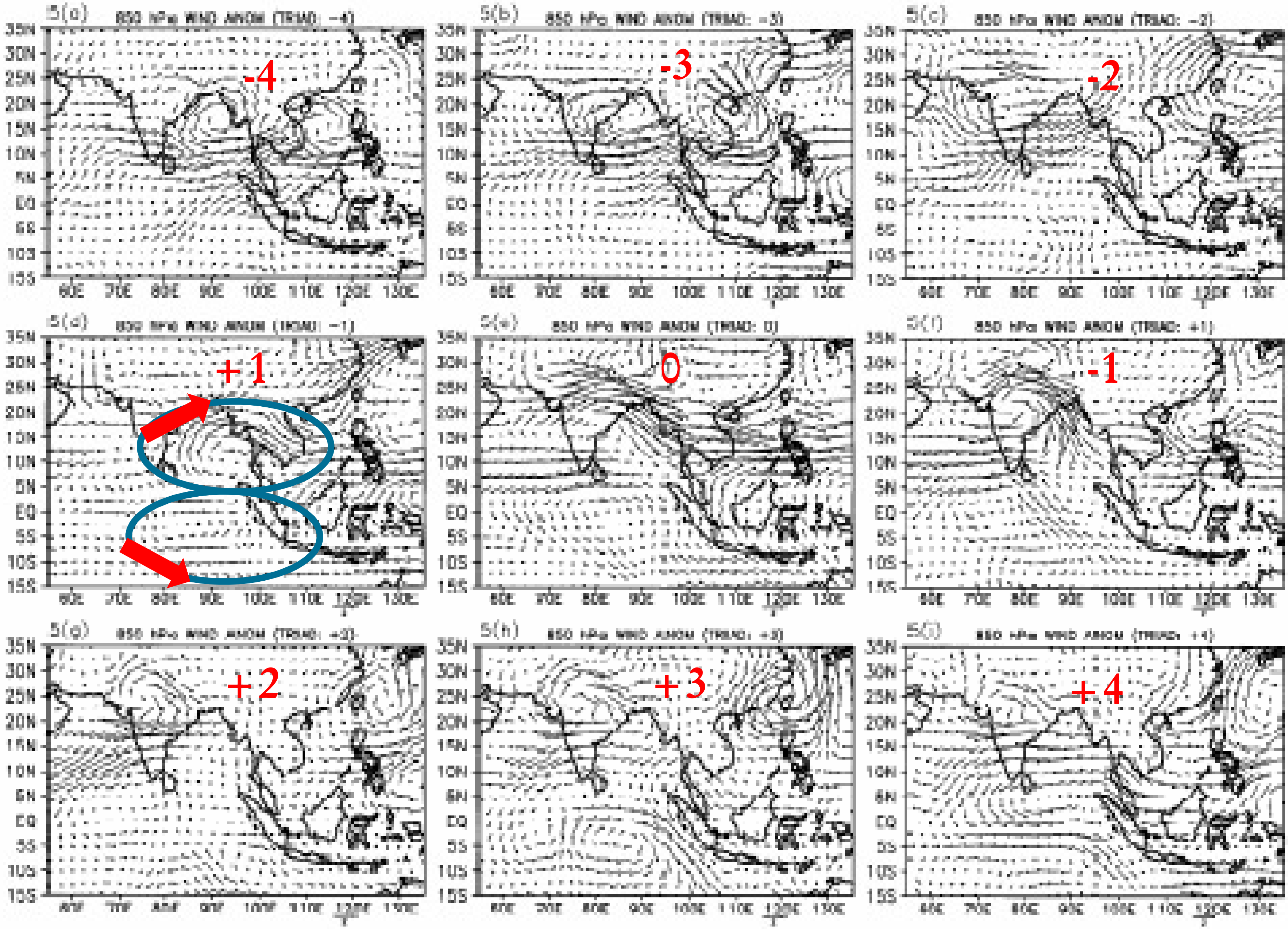


Krishnan, Zhang and Sugi (2000) J.Atmos.Sci., 57, 1354 - 1372



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

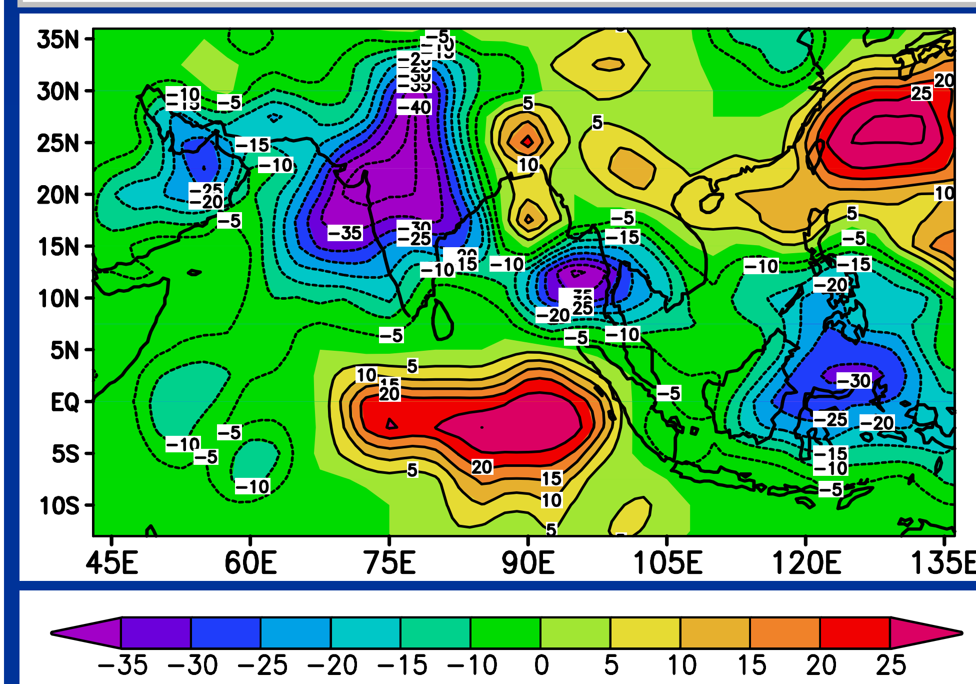
Sequence of composited 850 hPa wind anomalies during evolution of breaks (Triads)

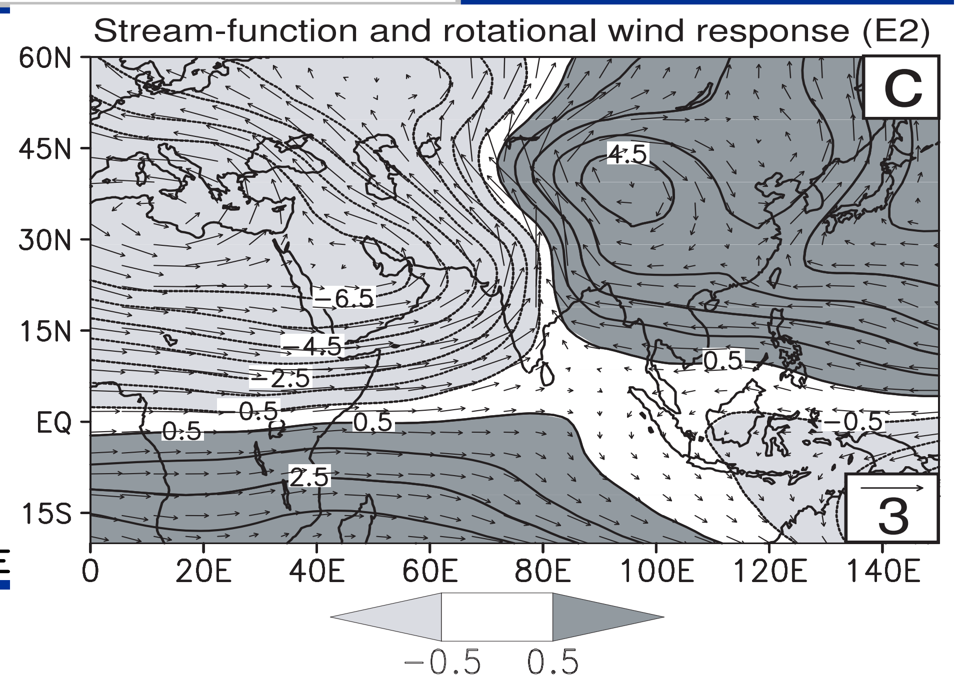


Anomalous southward intrusion of mid-latitude westerly troughs in middle and upper levels during breaks

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

Forced divergent barotropic vorticity equation



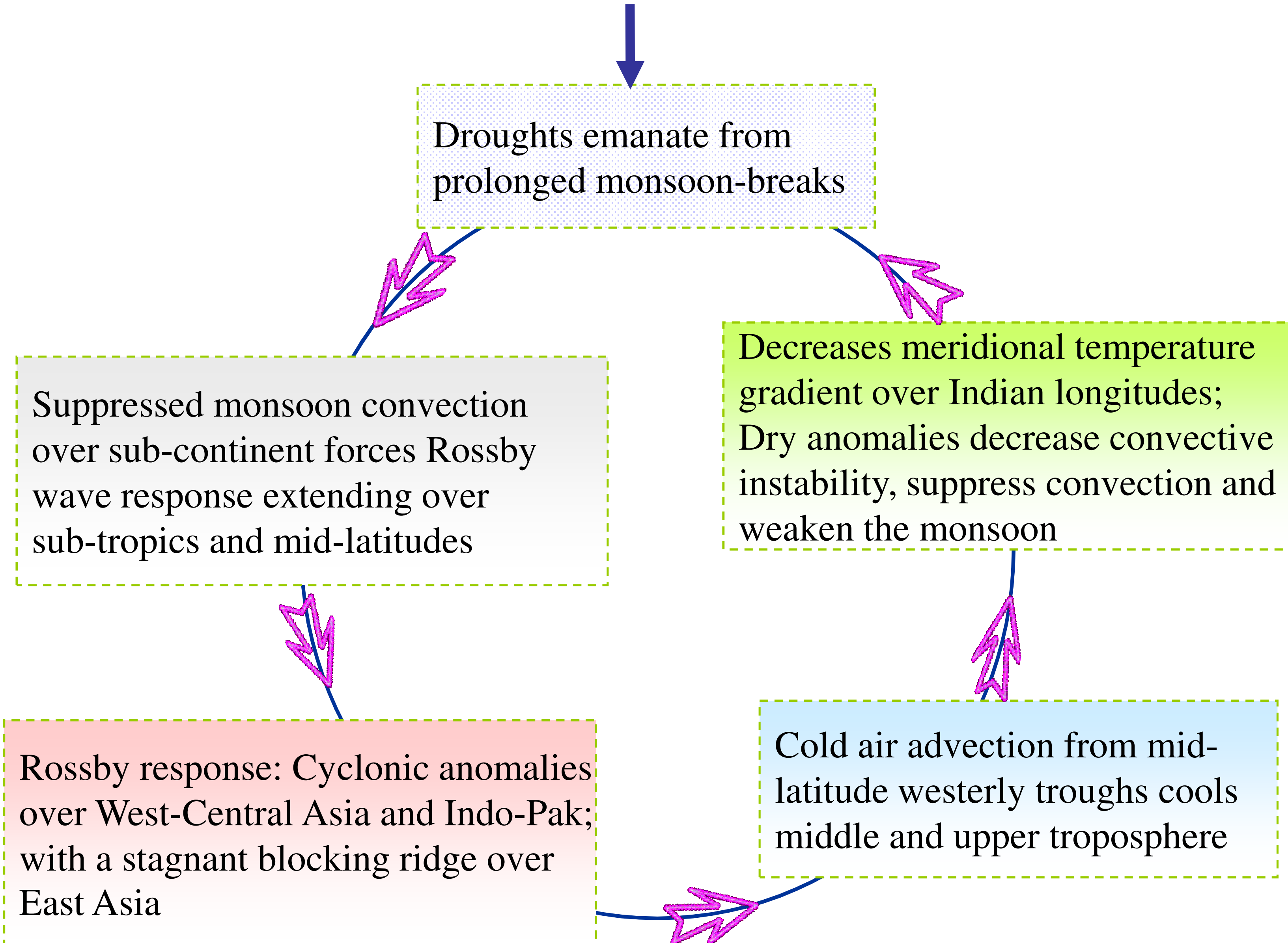


Divergence anomalies at 200 hPa during monsoon breaks - estimated using OLR : Krishnan et al. 2009

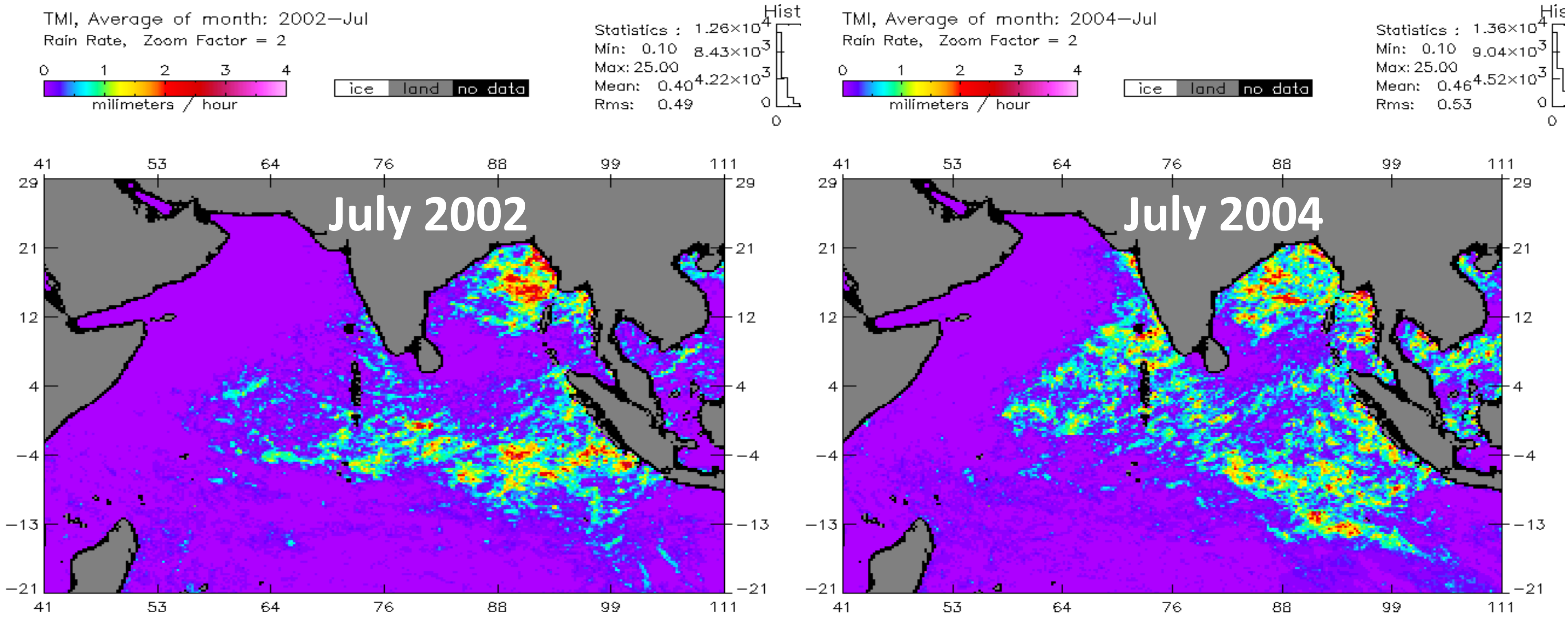
Simulated Rossby wave response to forcing from upper-tropospheric (200 hPa) divergence anomalies

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

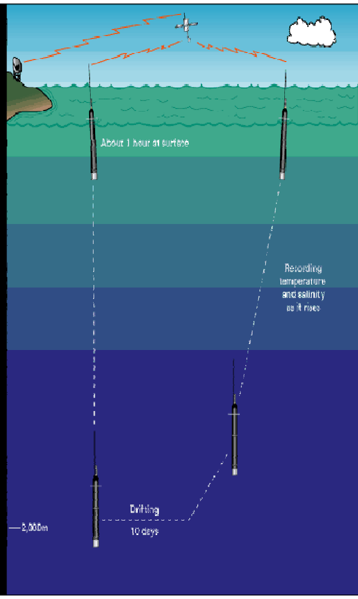


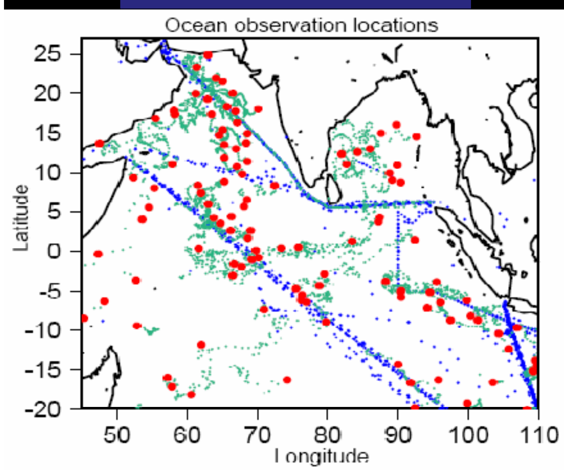
TMI rain rate (mm/hr)

- Enhancement of rainfall over near equatorial eastern Indian Ocean during weak monsoons !!
- What forces the near-equatorial rainfall anomaly ?
- Role of atmosphere – ocean interaction ?

Krishnan R., KV Ramesh, BK Samala, G Meyers, JM Slingo, MJ Fennessy (2006): Geophy. Res. Lett, **3**3, L08711, doi:10.1029/ 2006GL025811.

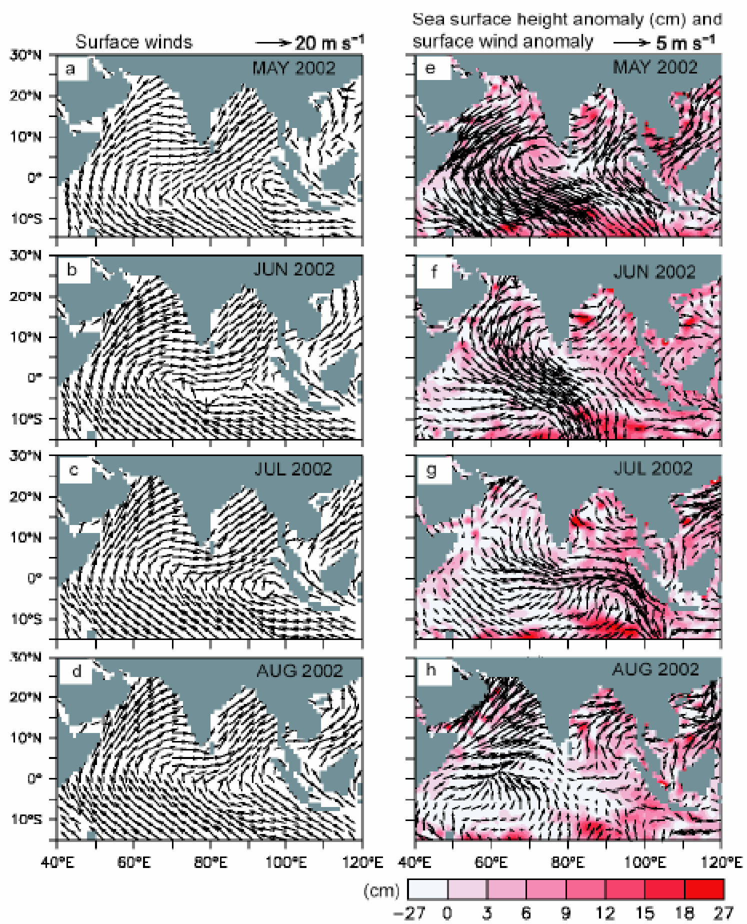
The operating sequence of an ARGO float (Source: Southampton Oceanography Centre, UK)

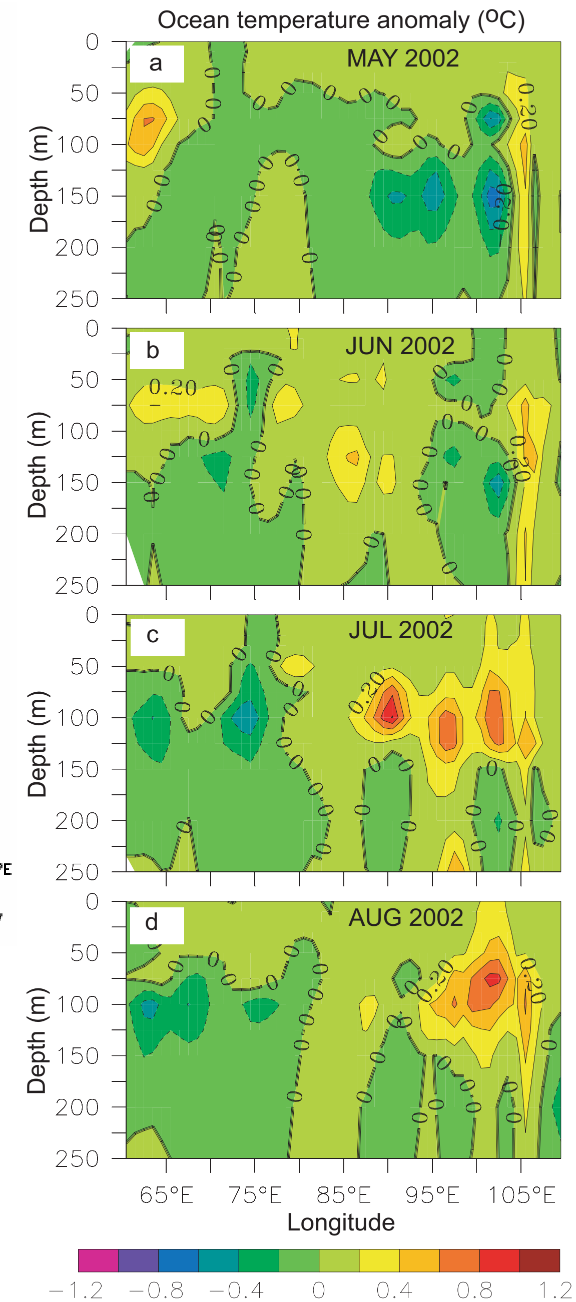




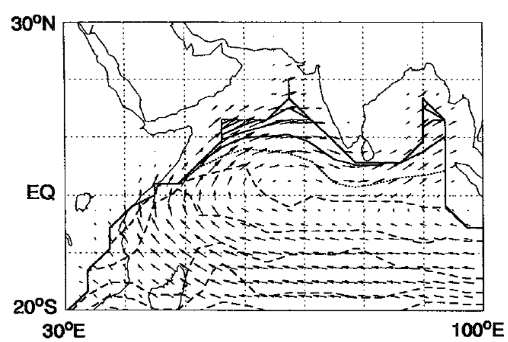
Krishnan, R., K.V. Ramesh, B.K. Samala, G. Meyers, J.M. Slingo & M.J. Fennessy (2006)

Indian Ocean – Monsoon Coupling during monsoon breaks





PV & wind on 302K surface



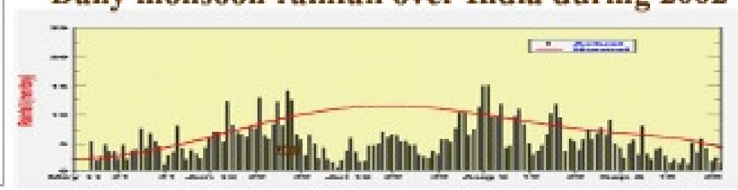
Rodwell and Hoskins 1995

Indian Ocean - Monsoon Coupled interactions & Droughts over India

Long-standing scientific question

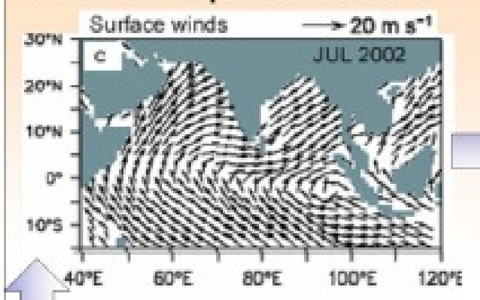
Can the Indian Ocean dynamics influence the occurrence of long-lasting "breaks" in the monsoon rainfall over the Indian subcontinent ?

Daily monsoon rainfall over India during 2002

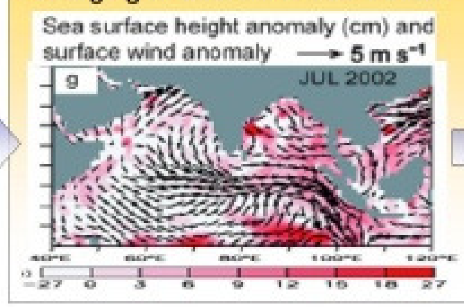


Reference: Krishnan, R. et al., (2006): ***Geophysical Research Letters***, 33, L08711, doi:10.1029/ 2006GL025811

Intensified Equatorial Westerlies

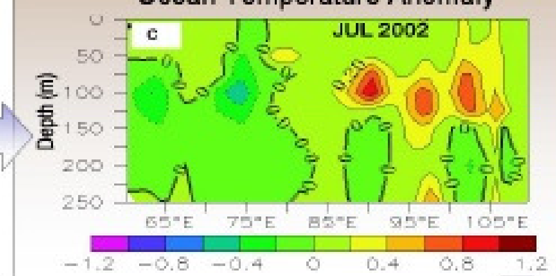


Charging of Eastern Indian Ocean



Bjerknes feedback

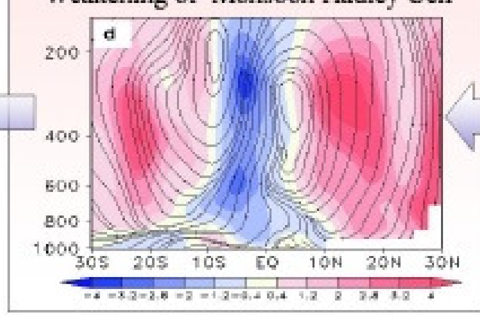
Ocean Temperature Anomaly



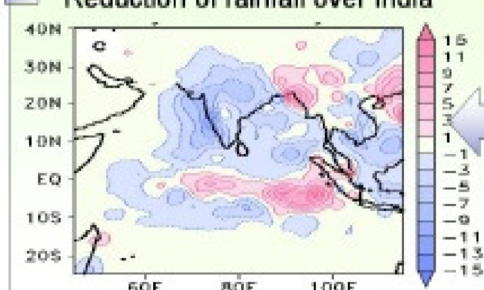
Atmospheric convection intensifies over EEIO

- SST gradient along the equator
- Moisture convergence over EEIO

Weakening of Monsoon Hadley Cell

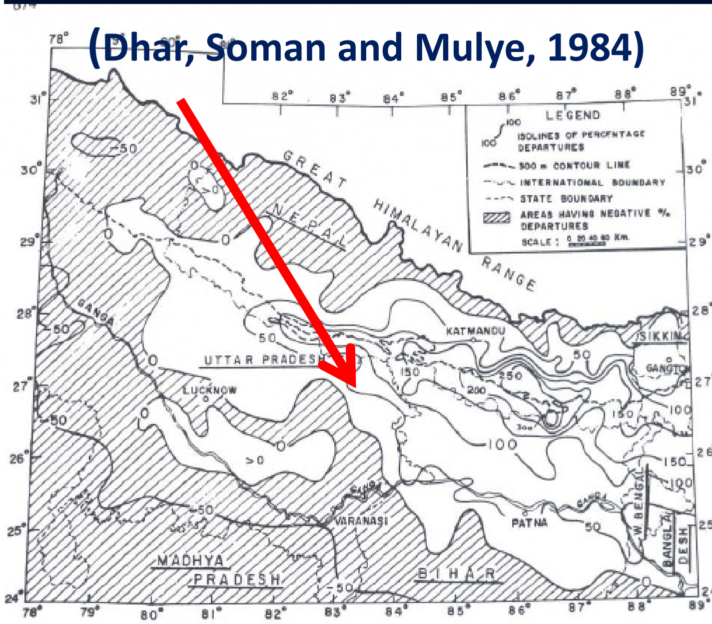


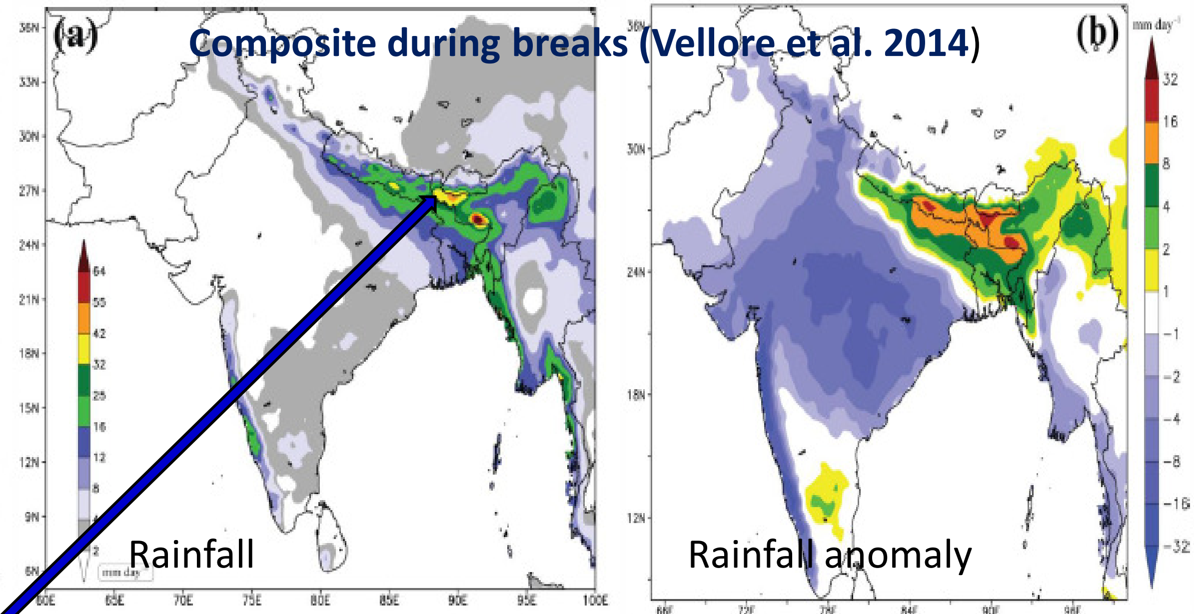
Reduction of rainfall over India

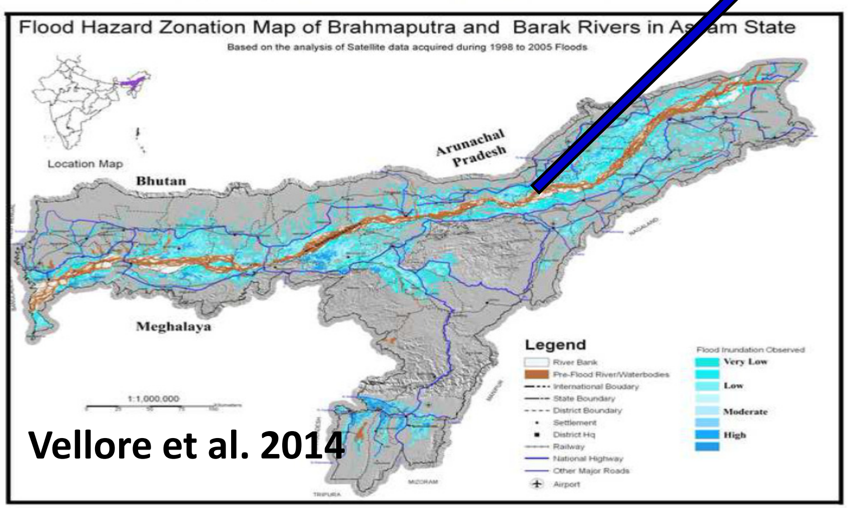


Krishnan et al. (2006): Geophy. Res. Lett, **3**3, doi:10.1029/ 2006GL025811

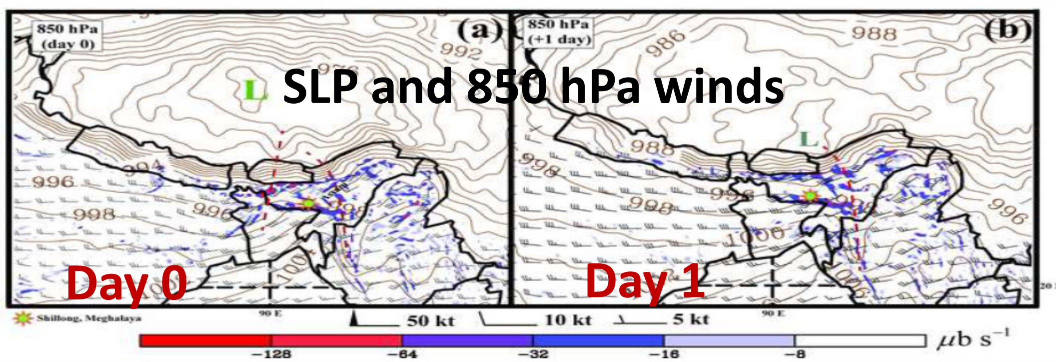
Rainfall over the southern slopes of the Himalayas & adjoining plains during monsoon breaks

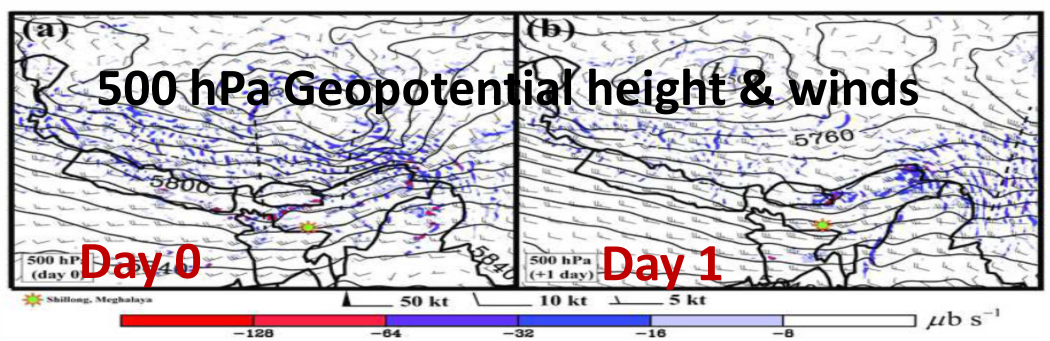






Flood Hazard Zonation Map of Brahmaputra , Barak Rivers in Assam State – Based on analysis of satellite data during 1998 – 2005 floods. Source: National Remote Sensing Centre, India





Summary

•Monsoon sub-seasonal variability: Multi-scale interactive phenomena (Dominated by large-scale organized convection and feedbacks between monsoon circulation and latent heating from convective and stratiform precipitation systems. Vertical deepening of monsoon trough, continental-scale mid-level circulation, 10-20 day and 30-50 day modes, westward and northward propagation of rain / cloud bands and circulation systems, widespread rainfall over north-central and west coast of India, Monsoon synoptic systems (lows, depressions, mid-tropospheric cyclones), Heavy precipitation over Western Himalayas: Eddy-shedding of Tibetan High, Interaction with mid-latitude circulation).

•Potential for predicting active monsoons: Evolution of organized convection (westward and northward propagating systems) and widespread rains over Central India about 10 days in advance noted in ECMWF EPS (Mujumdar et al. 2011). Potential for predicting heavy precipitation events over Western Himalayas and northwest Pakistan 1-2 weeks in advance (Webster et al. 2011, Joseph et al. 2014).

•Pathways for prolonged monsoon breaks and droughts (Basic physical mechanism: Rossby wave dynamics; Internal feedbacks involving anomalies of monsoon convection and mid-latitude circulation; Indian Ocean and Monsoon coupled interaction

•Antecedent signals of initiation of monsoon break first emerge over the equatorial Indian Ocean (Satellite remote sensing & insitu ocean observations provide vital information to understand and track the evolution of monsoon breaks ; Improvements in coupled modeling and data-assimilation should foster major improvements in predicting monsoon breaks 2-3 weeks in advance)

Thank you !