A Mechanistic Model of the Indian Monsoon

Lecture-8

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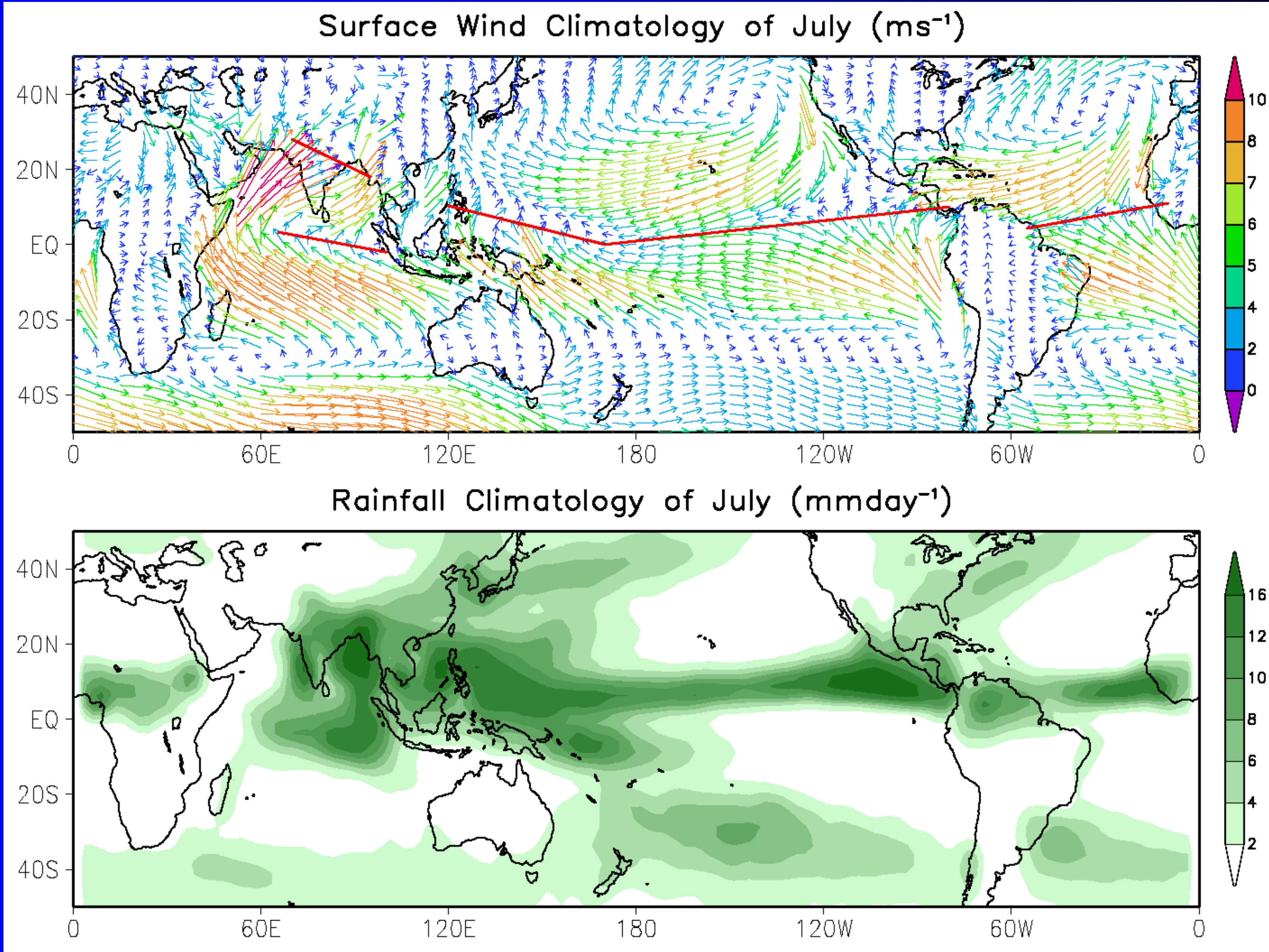
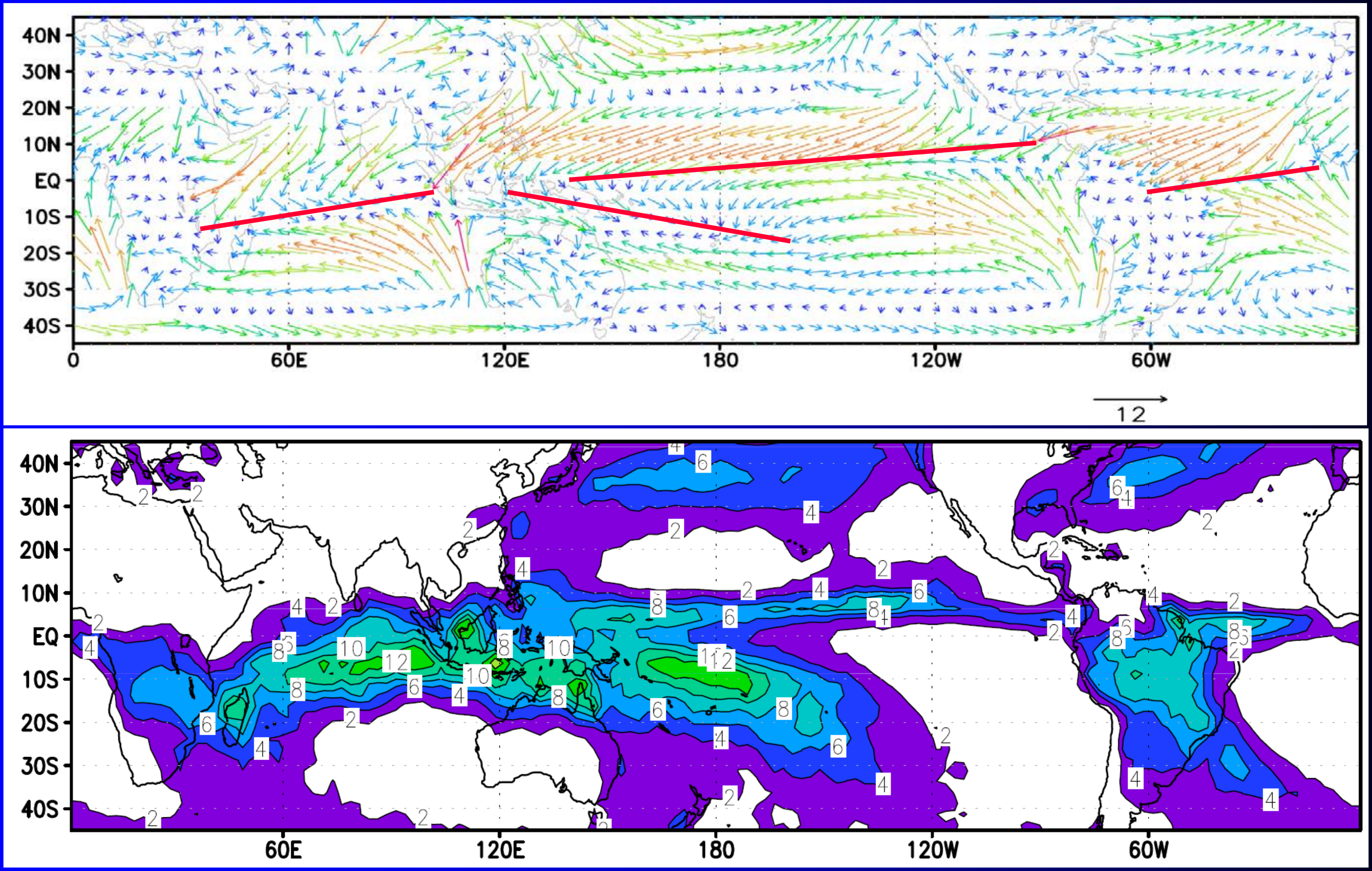
Recap of Major Features of Indian Monsoon

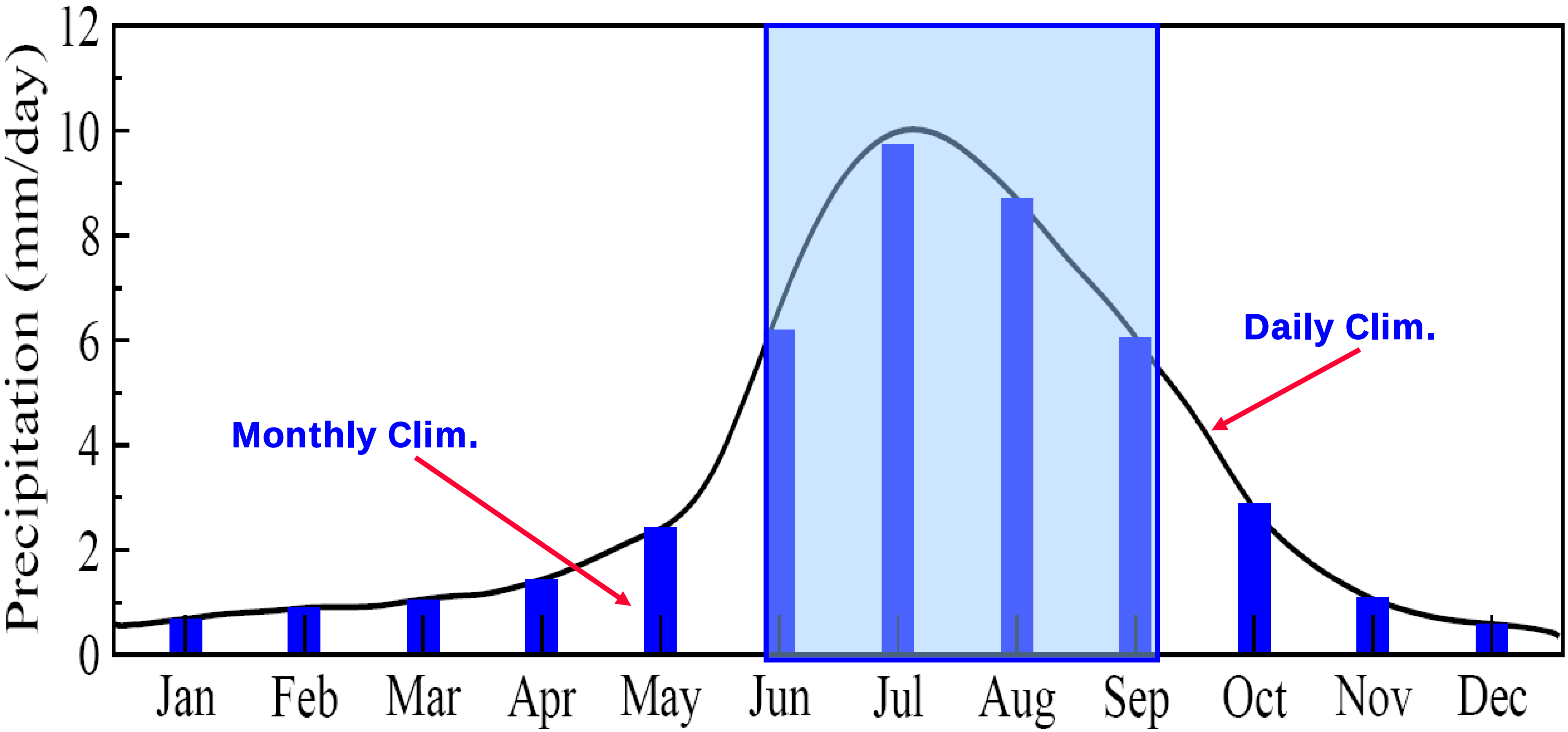
Mean July rainfall and surface wind convergence



Mean January rainfall and surface wind convergence



Annual cycle of Rainfall over India



Long term mean

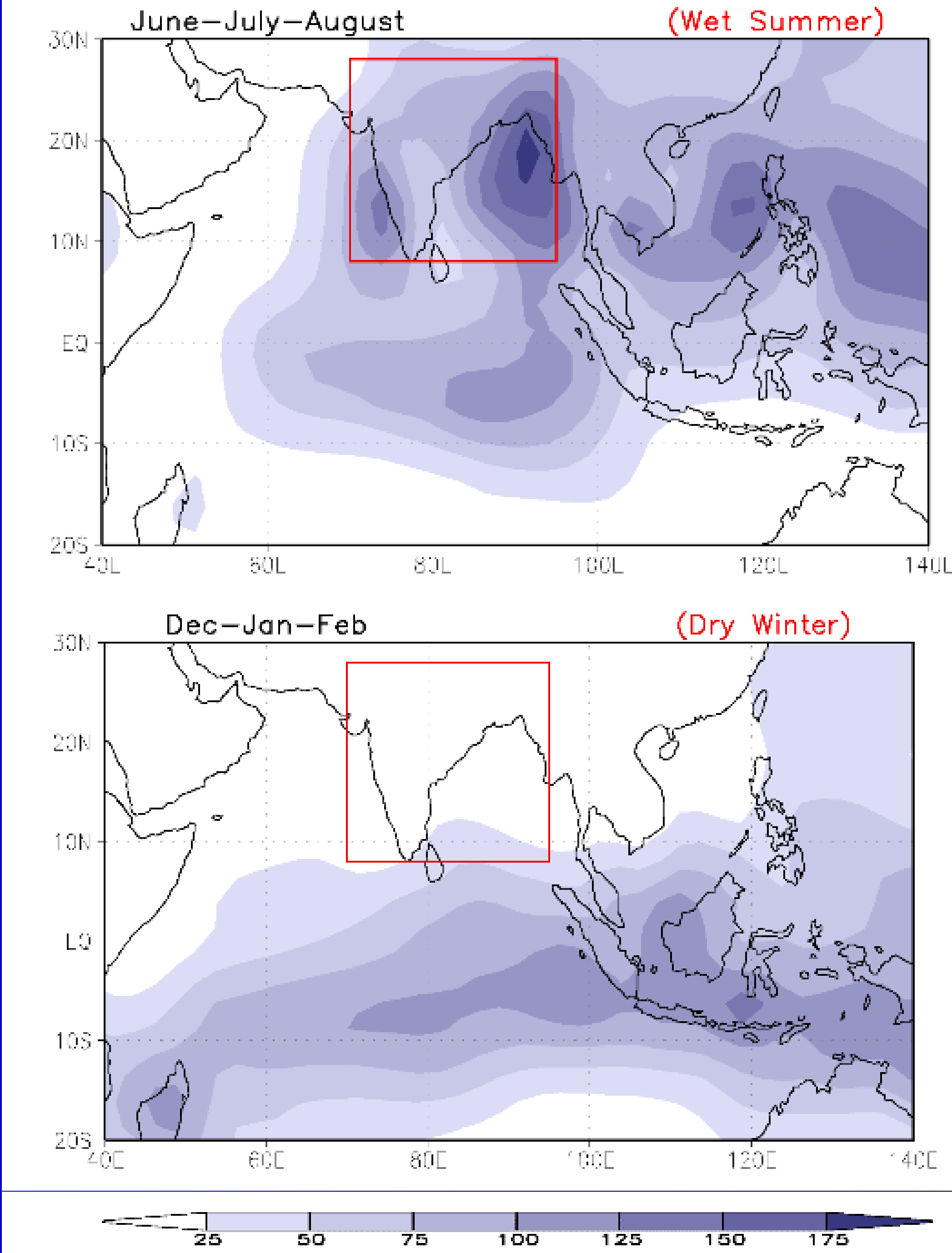
JJA precipitation and

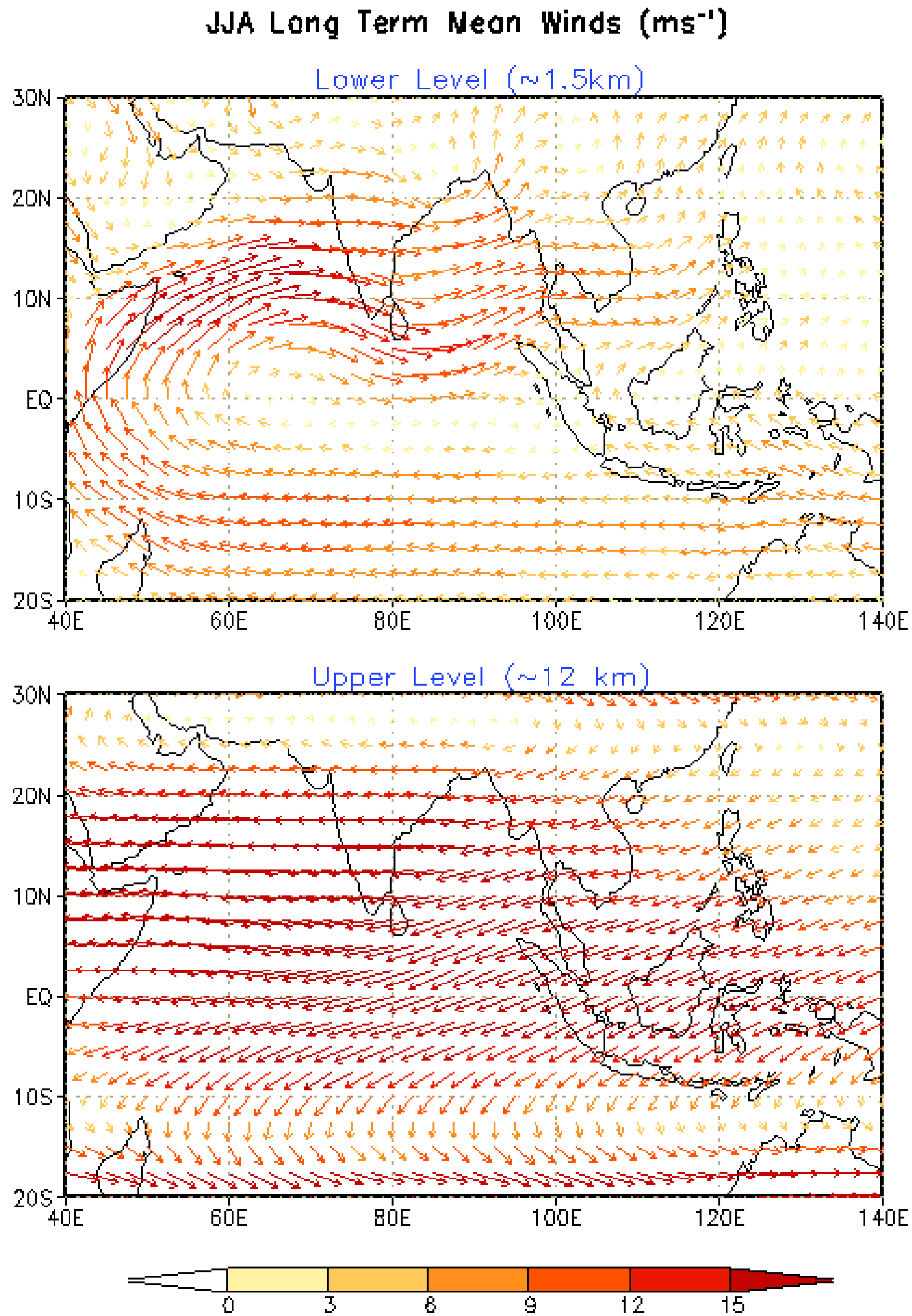
DJF precipitation

Monsoon ?

Wet- summer

Dry - winter





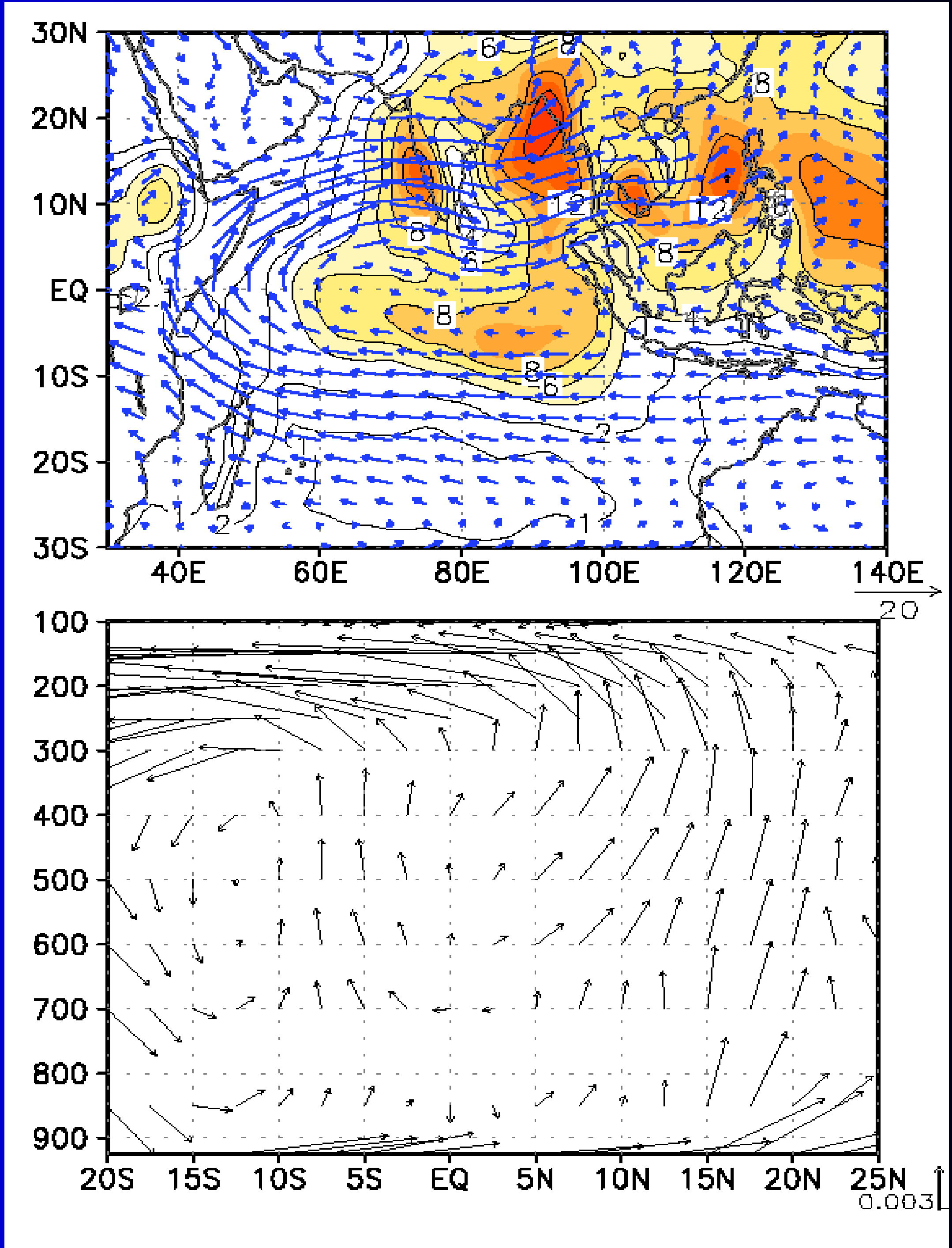
Characteristic features of summer monsoon circulation

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

Upper level easterlies, Monsoon Easterly Jet

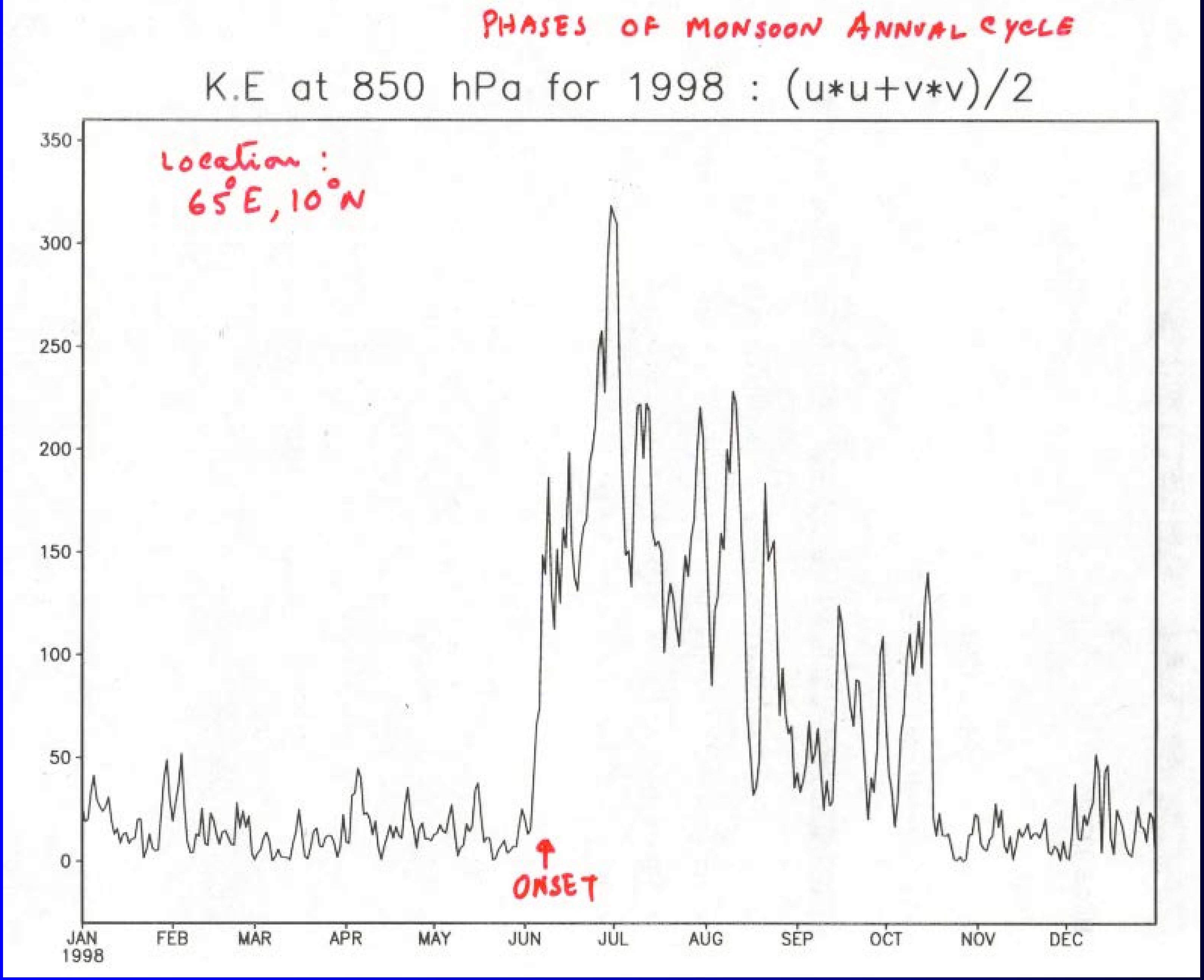
Climatological mean JJAS P and 850 hPa winds

- Indian monsoon circulation is convectively coupled and
- Has first baroclinic deep vertical structure



Mean monsoon Hadley circul.

70E-90E



Onset of the monsoon

A Model of Indian Monsoon must explain:

- **Convective Coupling: Association with ITCZ**
- **Seasonal reversal of winds**
- **Wet summer and dry winter: Strong Seasonal Cycle of rainfall**
- **Deep baroclinic vertical structure**
- **Abrupt onset**

Indices of the Indian monsoon:

1. Rainfall Index, 2: Large-Scale Circulation Indices of Indian monsoon

1. Primary Rainfall Index: All India Rainfall (AIR) or Indian Summer Monsoon Rainfall (ISMR) Index;

   ➔JJAS rainfall over land points excluding mountainous regions in north and east.

2a. Webster and Yang Index (WYI) (Webster and Yang, 1992, QJRMS.

- JJAS (U850-U200) averaged <0-20N,40E-110E>
- A vertical wind shear index

2b. Monsoon Hadley Circulation Index (MHI) , Goswami et al., 1999, QJRMS

- JJAS (V850-V200) averaged over <10N-30N, 70E-100E>
- A meridional wind shear index

Convective Coupling and Large-Scale Circulation Indices of Indian monsoon

In addition to the WYI and MHI, a couple of other indices are also introduced (HWSI: Prasad and Hayashi, 2007, SMI, Wilson and Mohankumar, 2020)

In a recent study,

- Zahan, Rajesh, Choudhury and Goswami. 2020: Why Indian summer monsoon circulation indices? QJRMS, DOI: 10.1002/qj.3972

Using longer (1851 and 2014) Circulation and rainfall data, we reexamined the veracity of indices

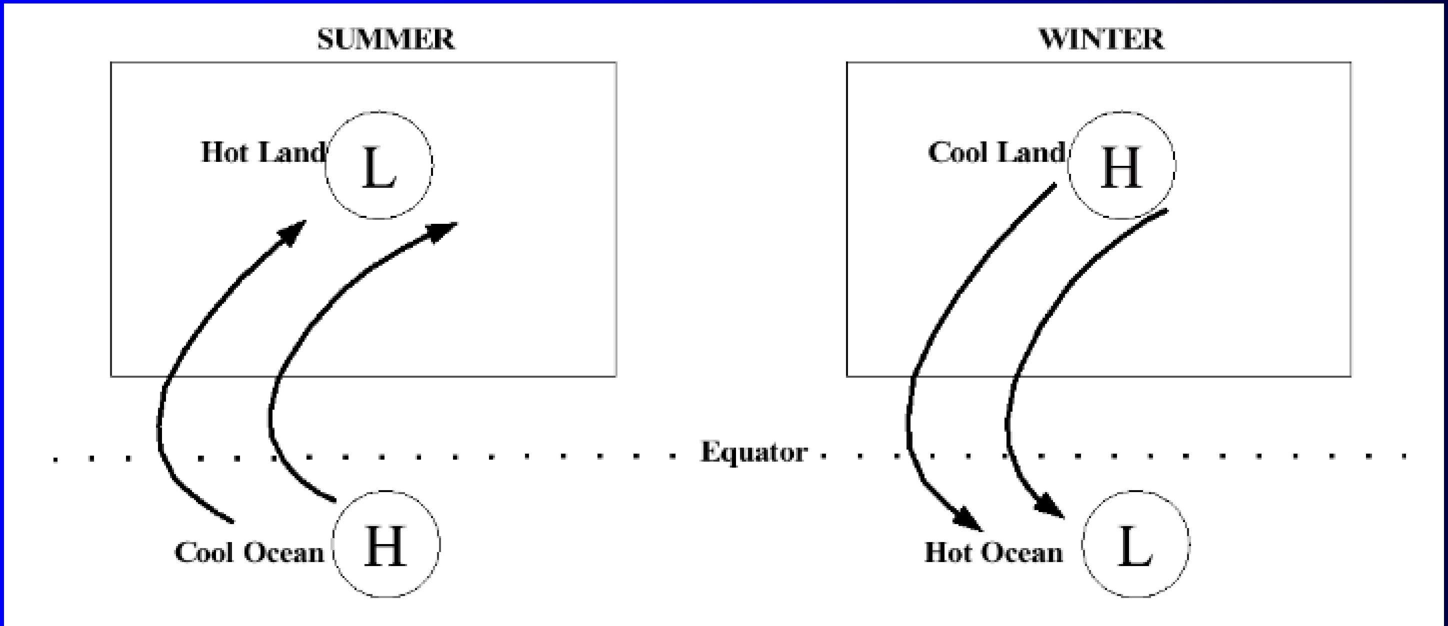
The dominant coupled mode of Variability explains ~25% of IAV
→Circulation indices could explain At most 25% of ISMR variability
→Limitation of circulation indices

TABLE 1 Correlations between (a) the normalized ISMR and the normalized circulation indices, and (b) detrended ISMR series and detrended circulation indices, for the period 1851–2014

Data	Temporal co-relation (normalized series)	Temporal co-relation (detrended -normalized series)
ISMR–MHI	0.4403*	0.5003*
ISMR–SMI	0.3504*	0.3658*
ISMR–HWSI	0.2649*	0.2681*
ISMR–WYI	0.1913†	0.1860†

Note: "*" and "†" represents the values are significant at 99.9 and 99.0% confidence levels respectively.

Classical model of monsoon: Large-scale Land-sea Breeze



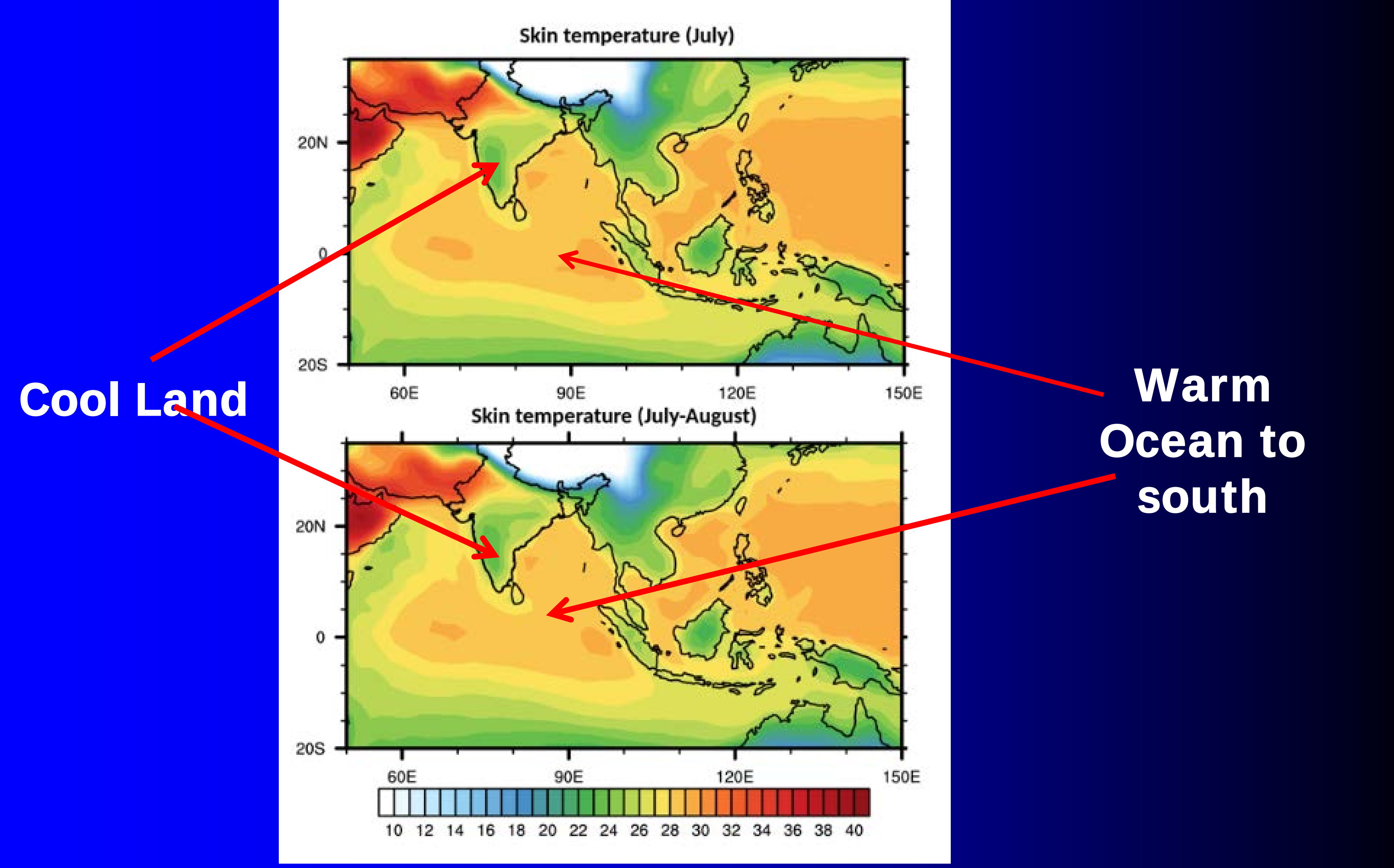
Can Explain:

- Seasonal reversal of low level winds

- **Cannot Explain:**

- **Vertical structure of circulation : Low level conv. , upper level div.**

- **→More importantly, after the initial rainfall, the land temperature is actually cooler than that of the ocean**



It may be noted that during peak of monsoon months of July and August, the continent is cooler than the Ocean to the south indicating that the north-south surface temperature gradient has reversed and became negative!

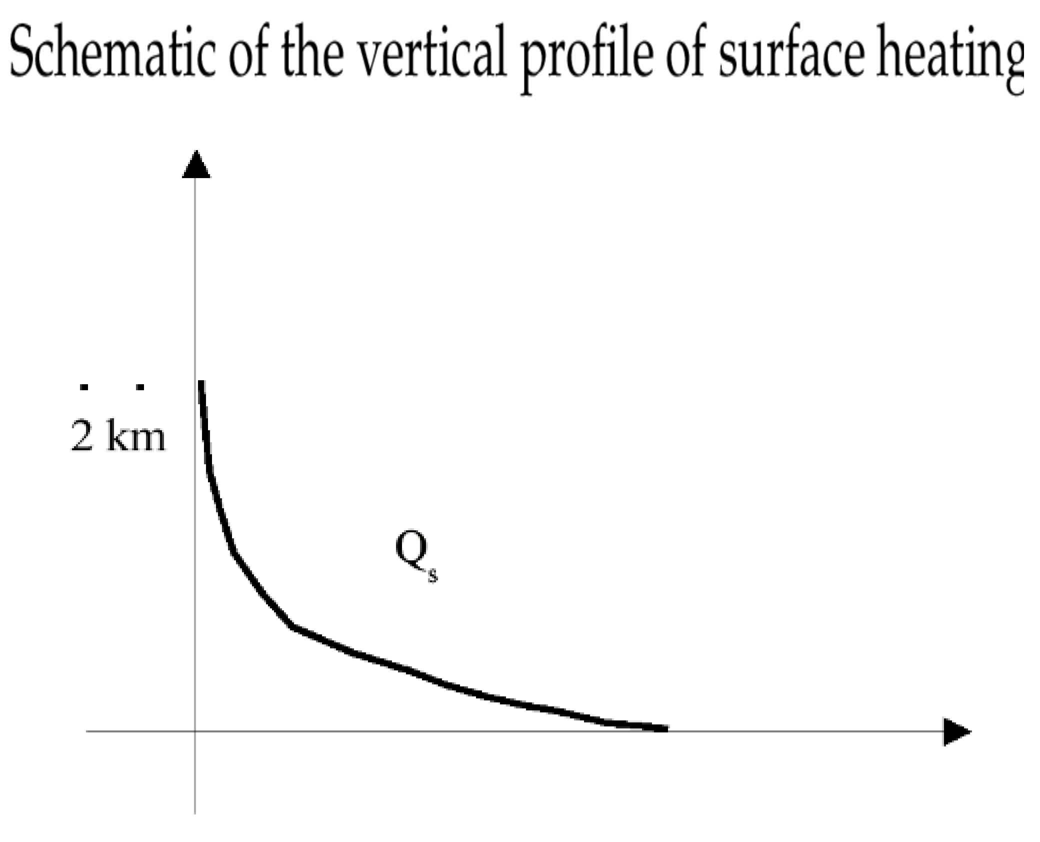
Why does the land is cooler after ‘Onset’ and remains cooler during the season?

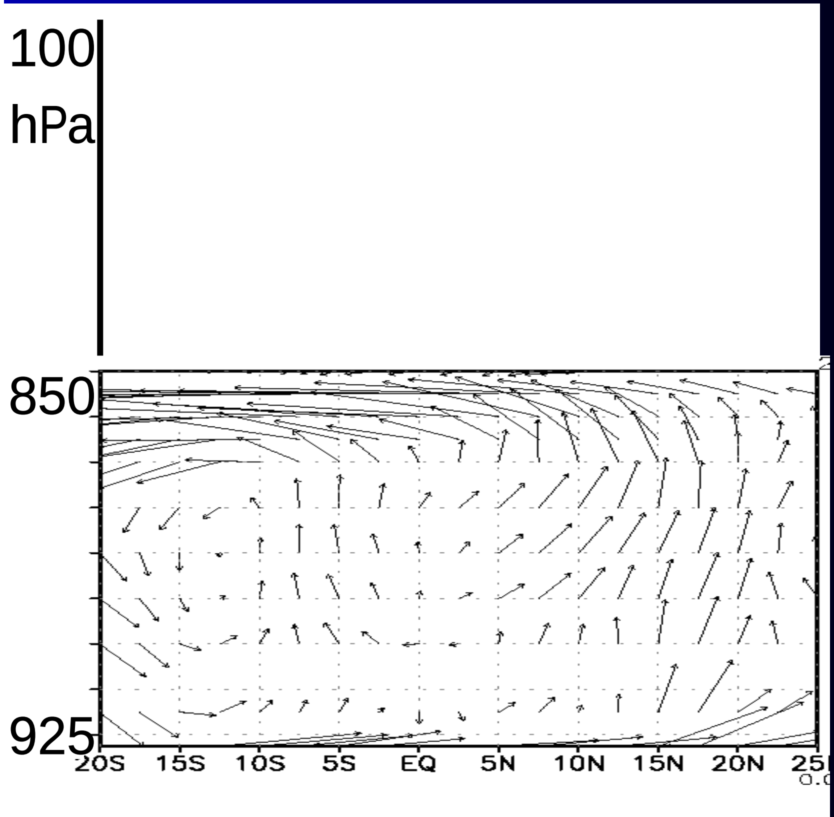
- **Effect of large scale rain over land**
- **Land is very hot before ‘onset’. After ‘onset’ while the land soaks up rainfall, it also evaporates and cools.**
- **As the rain comes in ‘spells’, it continues to soak up rain and evaporate and cool.**
- **Input of Solar radiation reduces due to cloudiness but whatever solar raidiation reaches suraface, it goes in evaporation and not in raising the surface temperaure.**

Note: Steady state Thermodynamic Equation:

$$\frac{\partial[\bar{T}]}{\partial t} = 0 = -(\Gamma_d - \Gamma)[\bar{w}] + P + Q$$

W → Q (net heating)





Another problem with the surface heating theory is that such a heating profile is confined to the lower boundary layer as shown above and can not force deep vertical circulation as observed

Convective Coupling

- With emerging recognition that winds and rainfall in the region cannot be separated, a more appropriate description of the Indian monsoon is the seasonal reversal of winds coupled to a seasonal reversal of rainfall (wet summer/dry winter season) over the region. Hence, without invoking the monsoon rainfall, monsoon circulation cannot be explained! Monsoon rainfall must be an integral part of a 'monsoon model'.

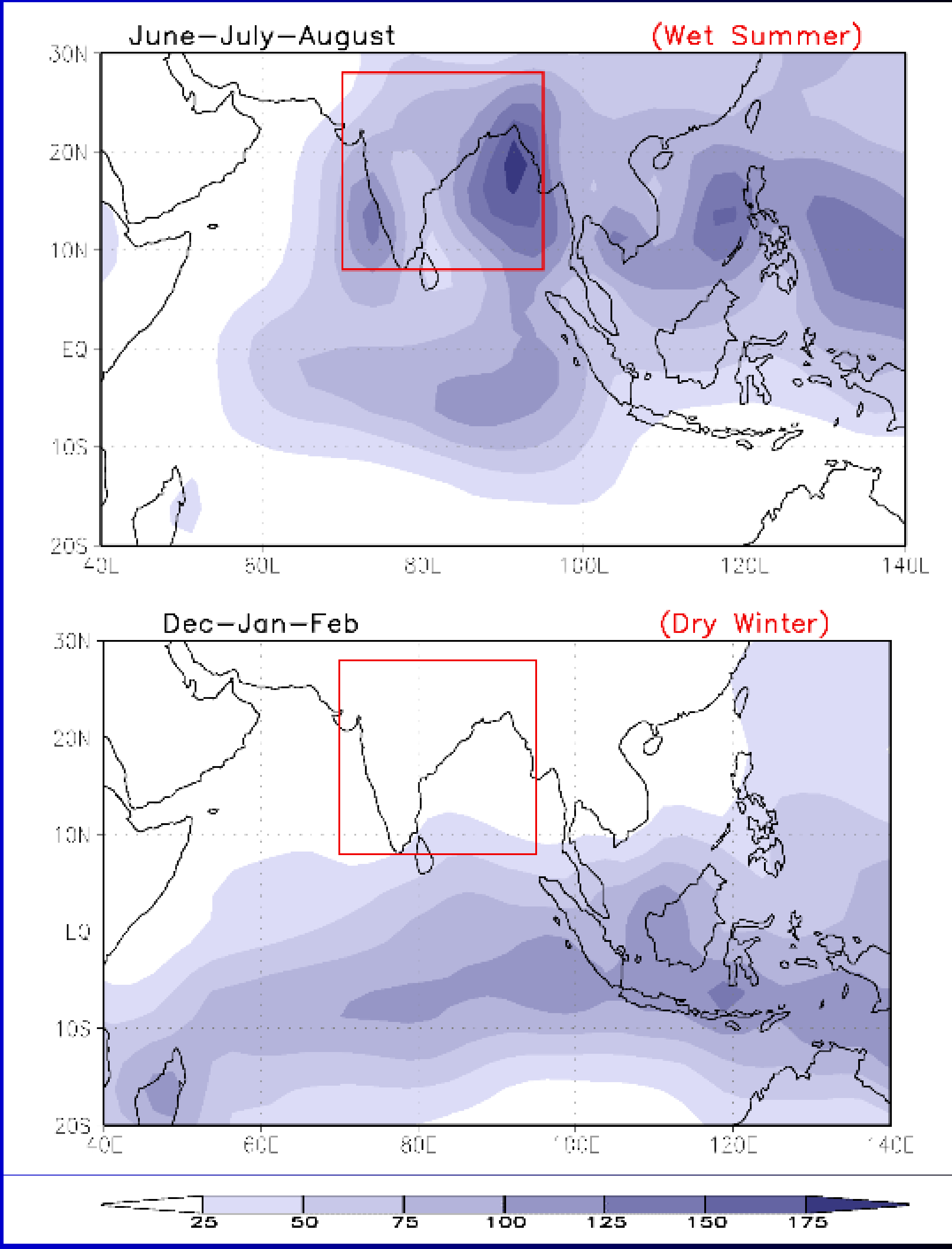
- Where the circulation is essential to bring in and converge moisture to sustain the deep clouds and produce rain while the clouds and rain are essential for intensifying the circulation and sustain the moisture convergence.

Long term mean

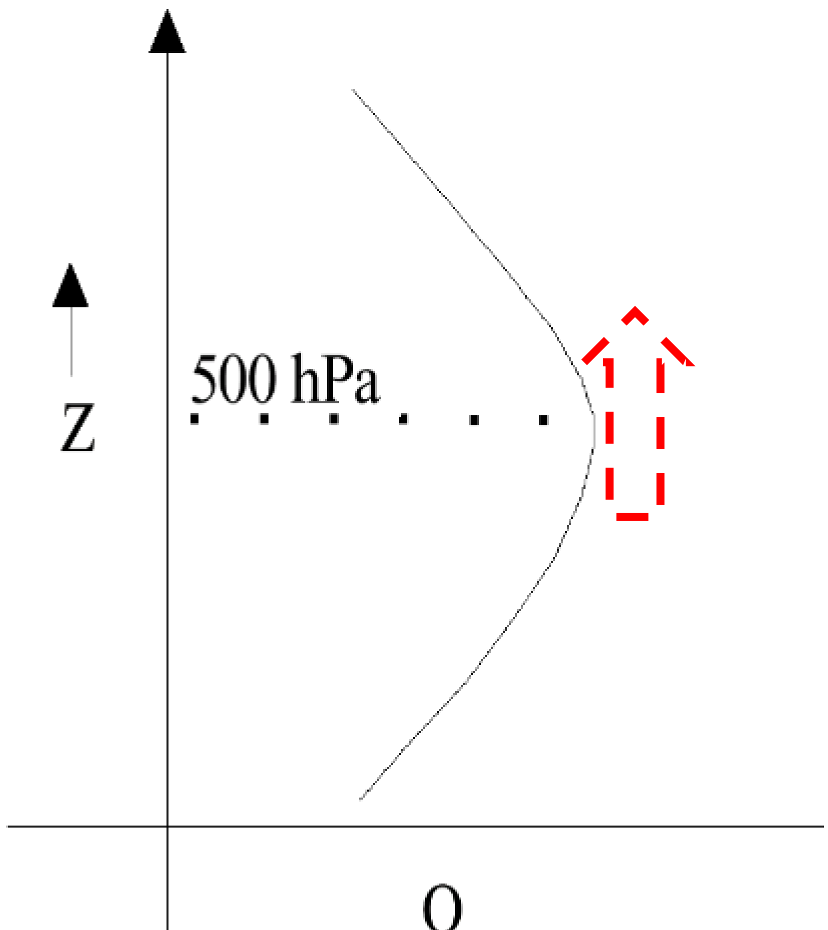
JJA precipitation and

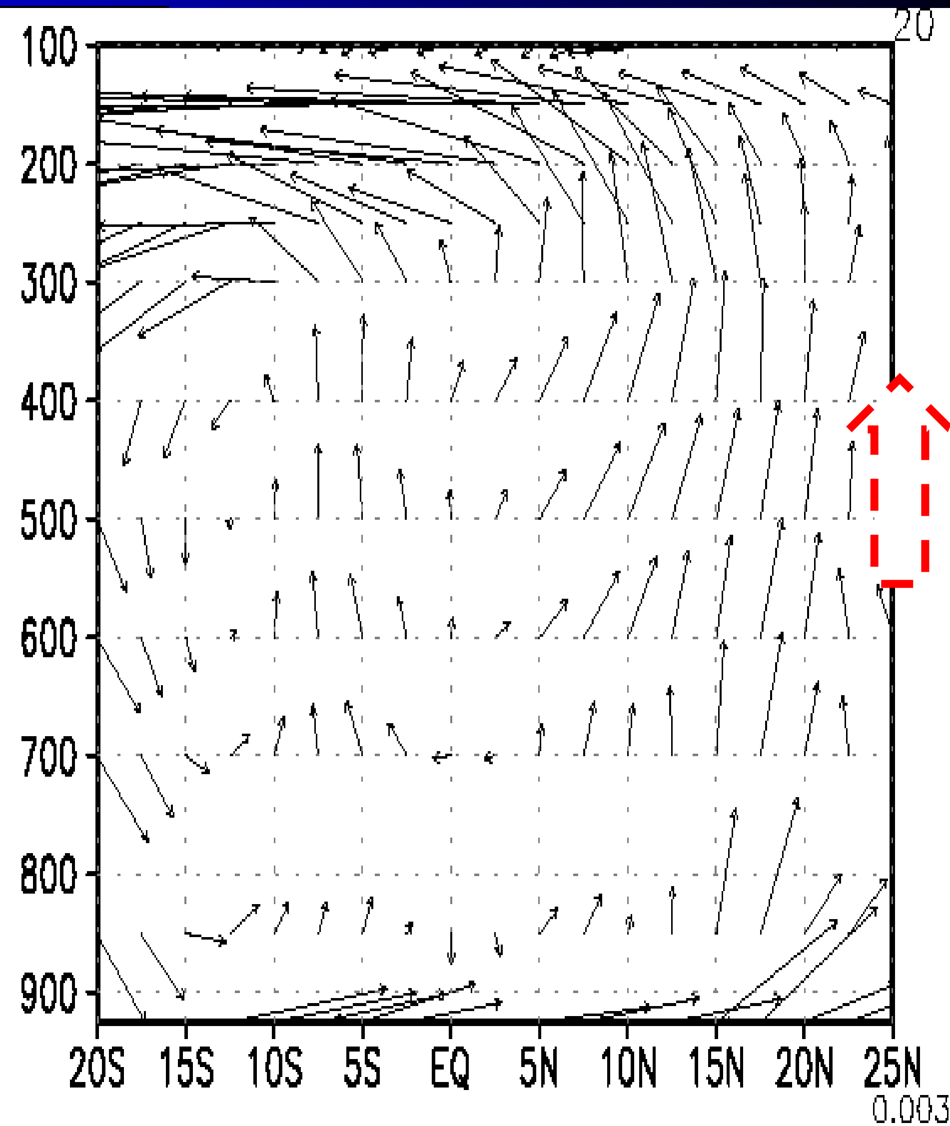
DJF precipitation

After ‘onset’, once we invoke the monsoon rainfall itself as part of the drivers of the circulation, a consistent picture emerges

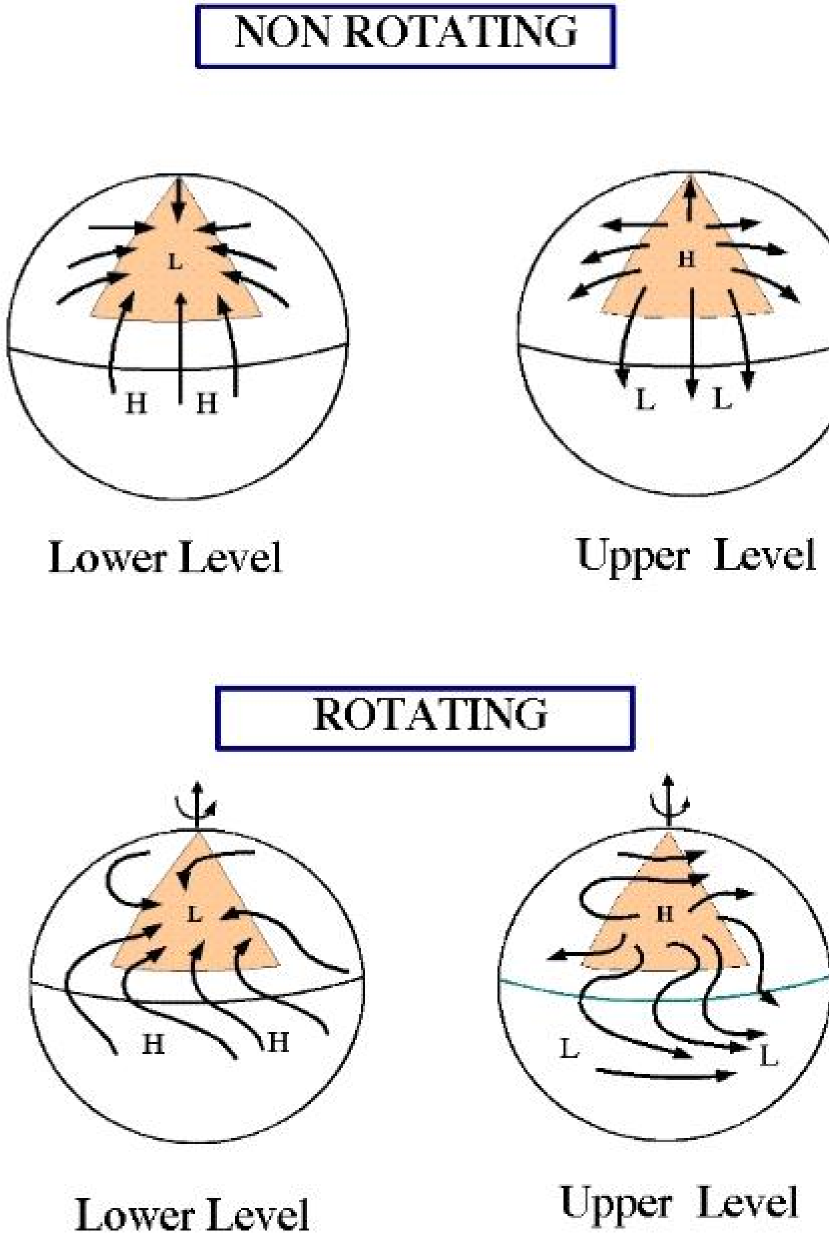


During summer monsoon about 60% of rainfall comes from convective clouds and the vertical structure of heating associated with them is schematically shown below:



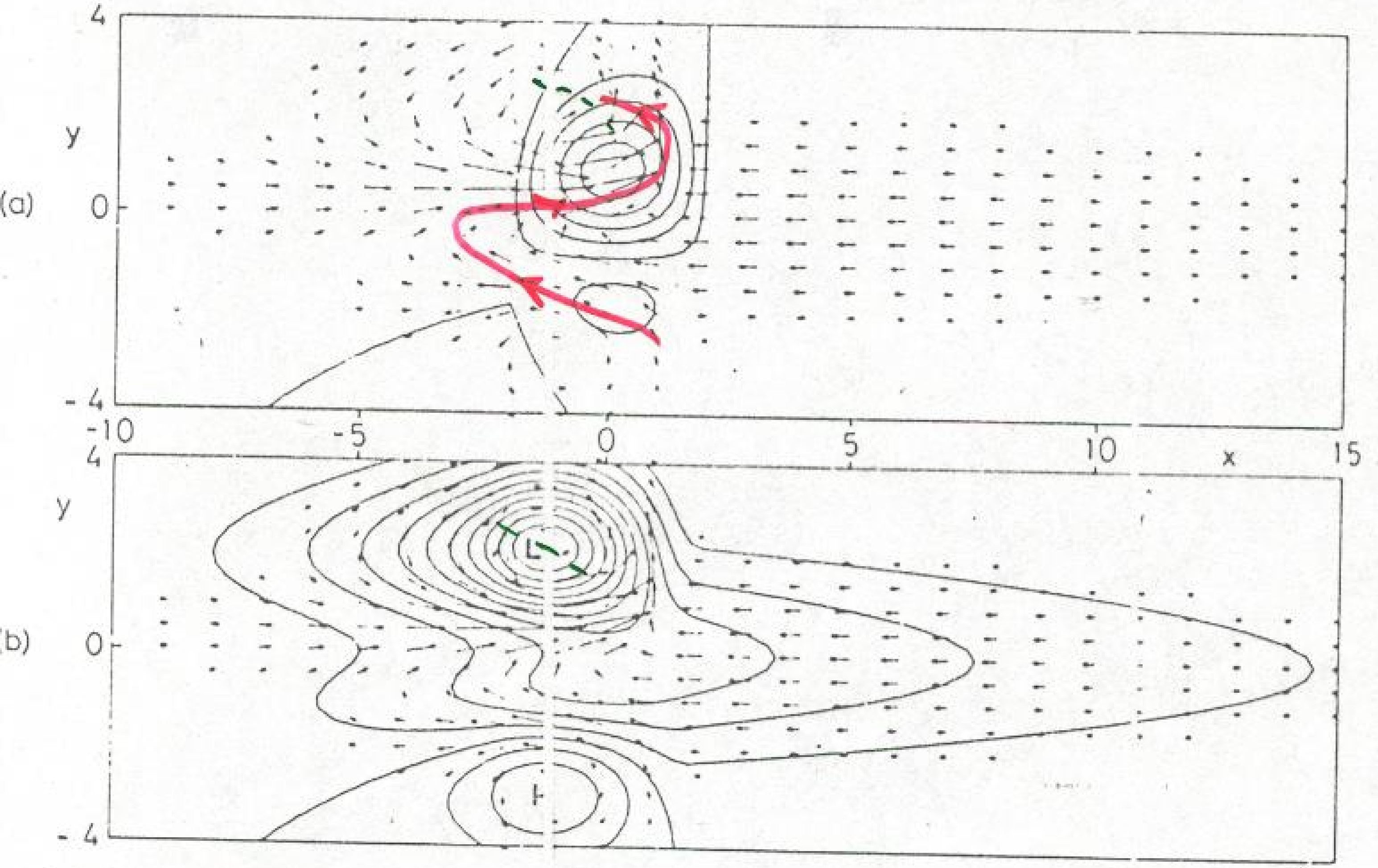


Vertical structure of deep moist convective heating



After the onset, the monsoon is maintained by latent heat released from convection. Such heating has maximum at the middle troposphere and leads to baroclinic structure of the circulation.

Response of an off-equatorial heat source (like Indian monsoon rainfall) analytically obtained from a simple Gill Model.



g. 9.16. Distribution of the flow obtained by the addition of the response to heating nfined about the equator and heating which is concentrated to the north of the uator. Upper diagram shows the distribution of vertical velocity and the lower agram the perturbation pressure pattern. Vectors indicate the horizontal flow field. (From Gill, 1980.)

An Off-equatorial heat source like the monsoon rainfall would cause convergence of air to it and Coriolis force would generate south-westerly and a cyclonic vorticity

- **The Off equatorial heating due to precipitation is therefore important in explaining the monsoon circulation.**

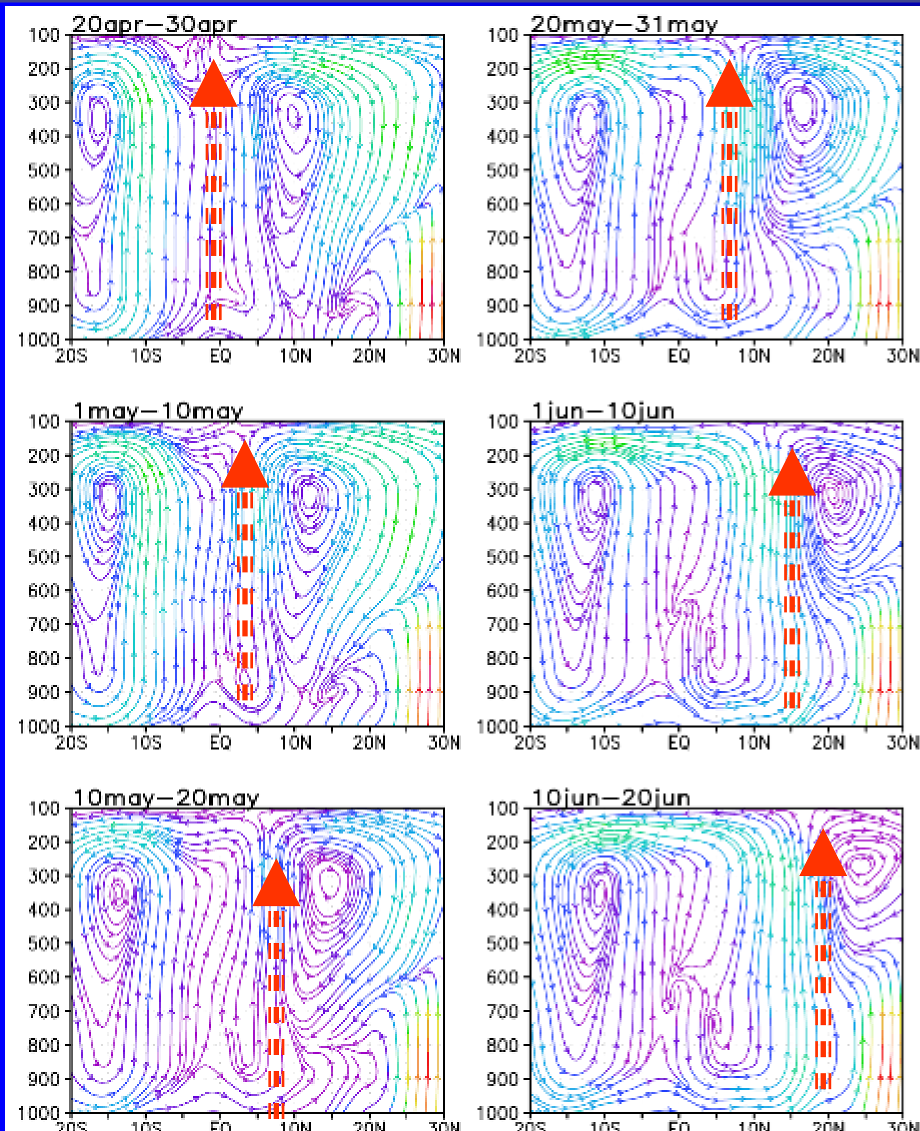
However, we still need to explain:

- **How is it linked with ‘Onset’ ?**
- **And what causes the northward migration of the ITCZ to about 25 N in the Indian monsoon region and establishment of the land ITCZ after ‘Onset’ that then becomes sustaining force for the monsoon?**

A Model of Indian Monsoon must explain:

- **Convective Coupling: Association with ITCZ**
- **Seasonal reversal of winds**
- **Wet summer and dry winter: Strong Seasonal Cycle of rainfall**
- **Deep baroclinic vertical structure**
- **Abrupt 'Onset', 'Withdrawal' and 'Length of Rainy season (LRS) as they are integral part of the ITCZ movement.**

The ‘Onset’ and northward migration ITCZ is associated with the First pulse of northward propagating MISO.(shall discuss more details in the ISV lecture)



mean (omega,V) averaged between 60E-95E, over 10-day periods from mid-April to mid-June.

To note:

1.Northward movement of deep upward motion (TCZ), rapid between last week of May and first week of June.

2.The barrier of massive descending motion is overcome at the time ‘Onset’.

3.The shallow meridional circulation during pre-onset takes north warm moist air near the surface and brings south dry air above PBL

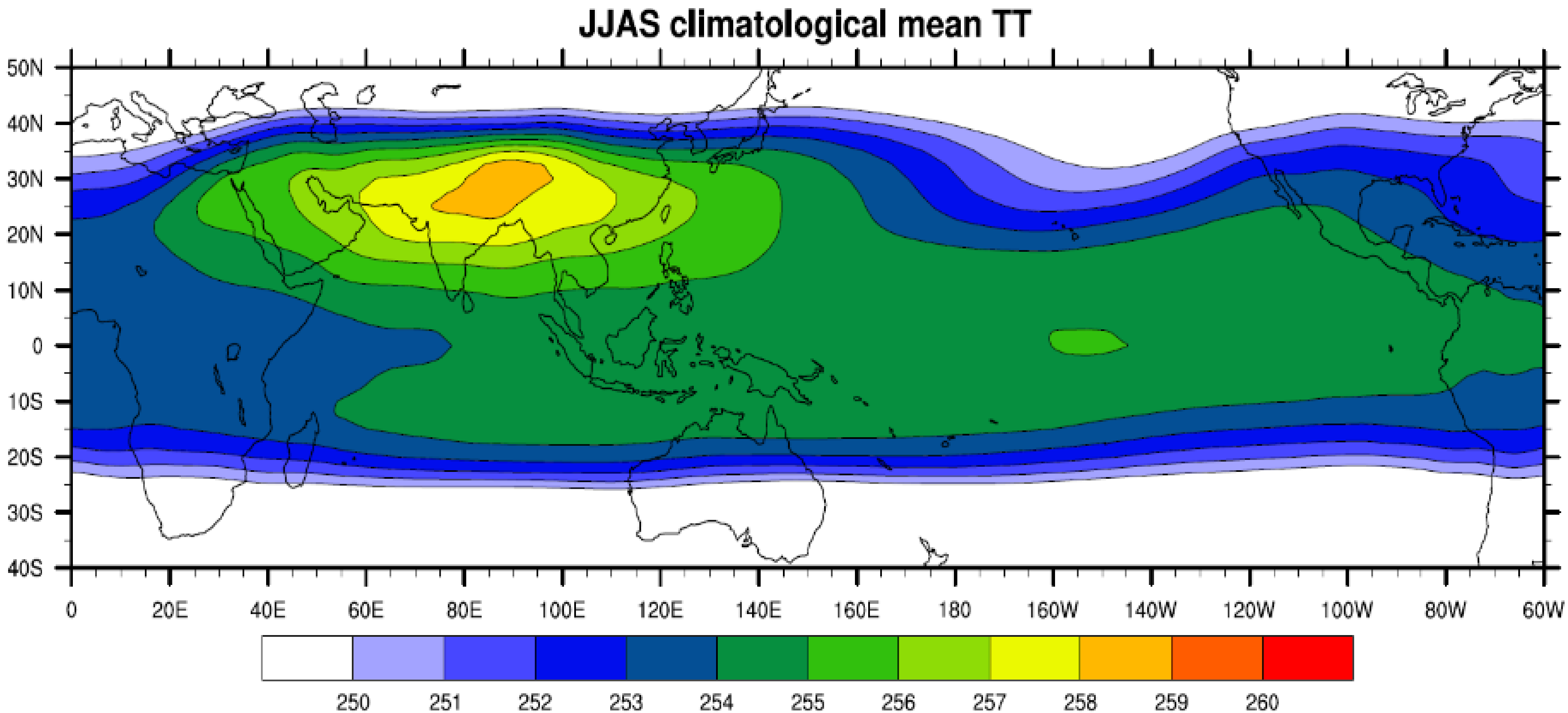
A Model of Indian Monsoon explaining All aspects

Here, I present a model of monsoon that requires only a small but significant change in the 'classical model'

Instead of N-S surface temperature gradient forcing the monsoon, it is forced by

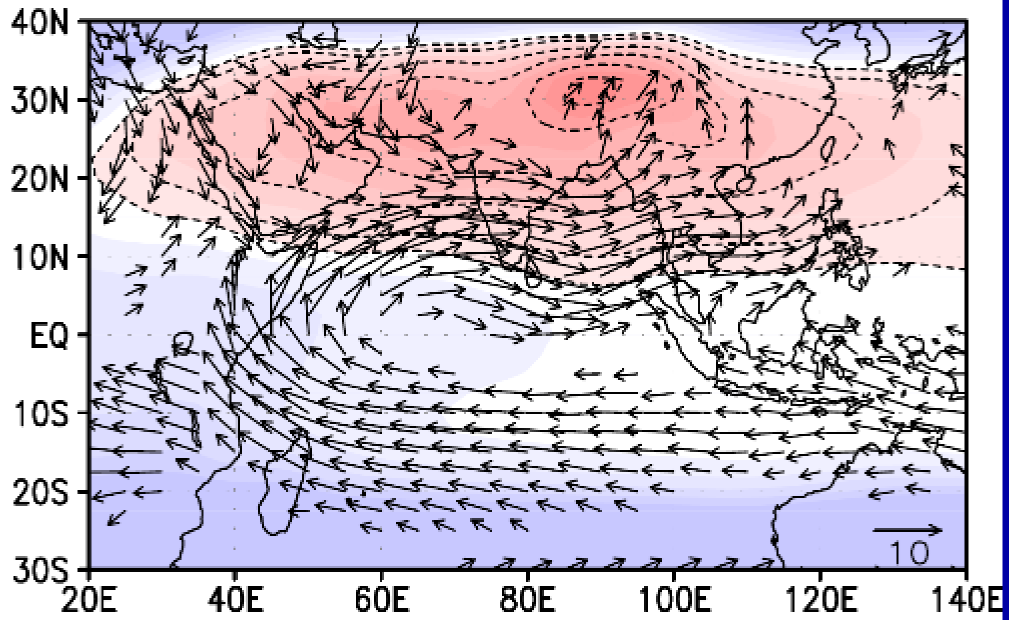
➔Meridional gradient of Tropospheric heating drives the monsoon circulation!

Meridional gradient of Tropospheric Heating → **Meridional gradient of Tropospheric Temperature (TT)**

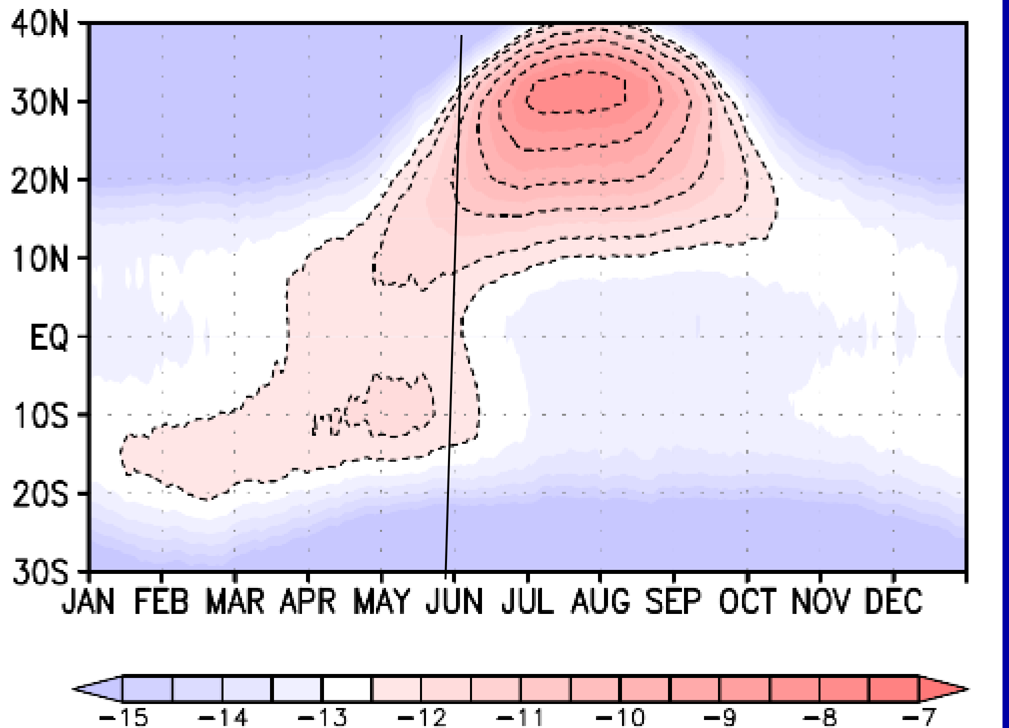


Indeed, largest TT during northern summer is over Indian monsoon region!

Low level winds are coupled to the TT



Tropospheric temperature (TT, in °C) averaged over 200 hPa-700 hPa (shaded) and 850 hPa winds. JJAS average.



TT (in °C) averaged over 200 hPa- 700 hPa (shaded) averaged between 70E-100E as a function of time and latitude.

Once we accept that monsoon winds are driven by 'monsoon heating' associated with monsoon rainfall, an objective definition of monsoon 'Onset' and 'withdrawal' is possible.

- While in May, the surface heating of land produces surface cross equatorial flow and south westerlies, a large scale divergence above makes winds at 850 hPa from north and northwest.
- The winds above the boundary layer (free atmosphere) can be southwesterly ONLY when the N-S Atmospheric heating gradient (not surface heating gradient) becomes positive.
- Therefore, monsoon 'Onset' takes place when the N-S TT gradient becomes +ve.
- And monsoon 'withdrawal' takes place when N-S TT gradient becomes –ve.

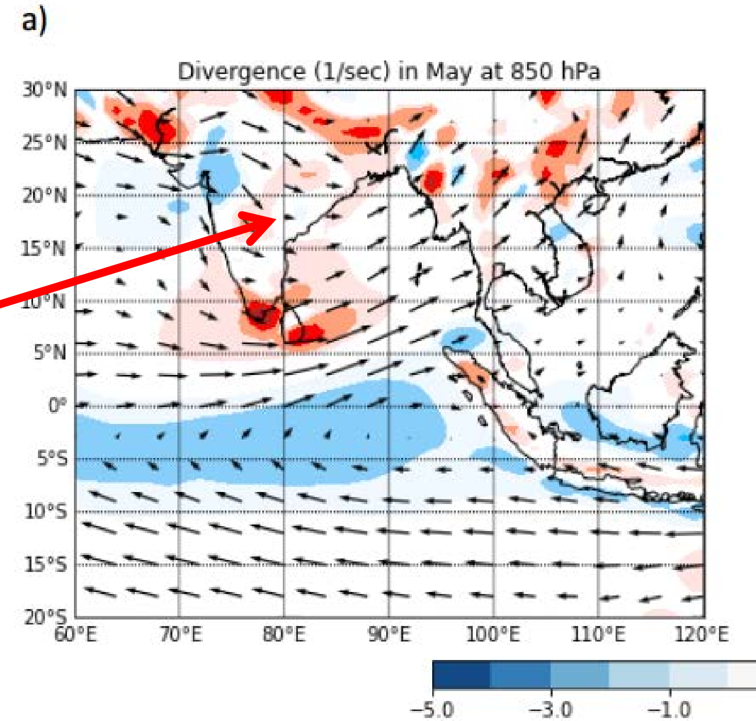
Wind vectors and divergence in May at 850 hPa

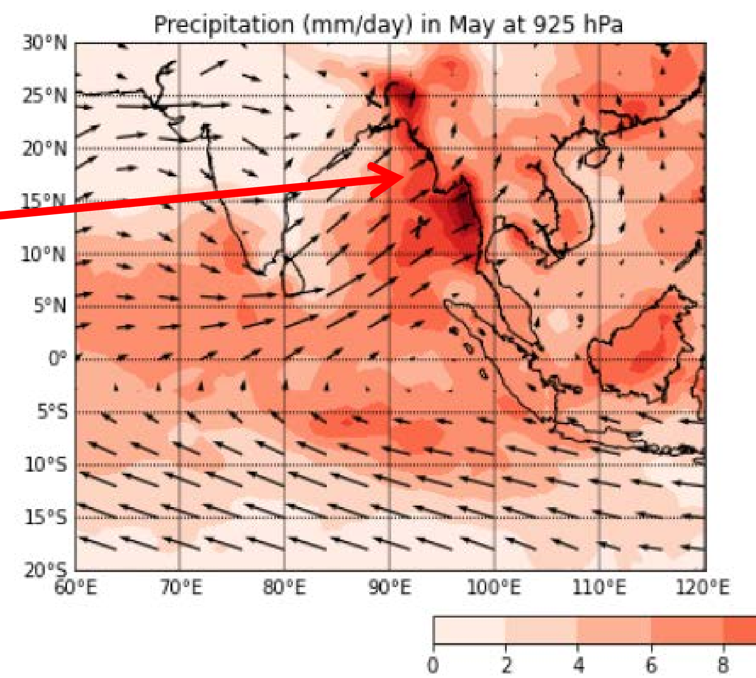
Note the large scale divergence at 850 hPa

Note also the orographic rain in May over NEI and Miyanmar coast.

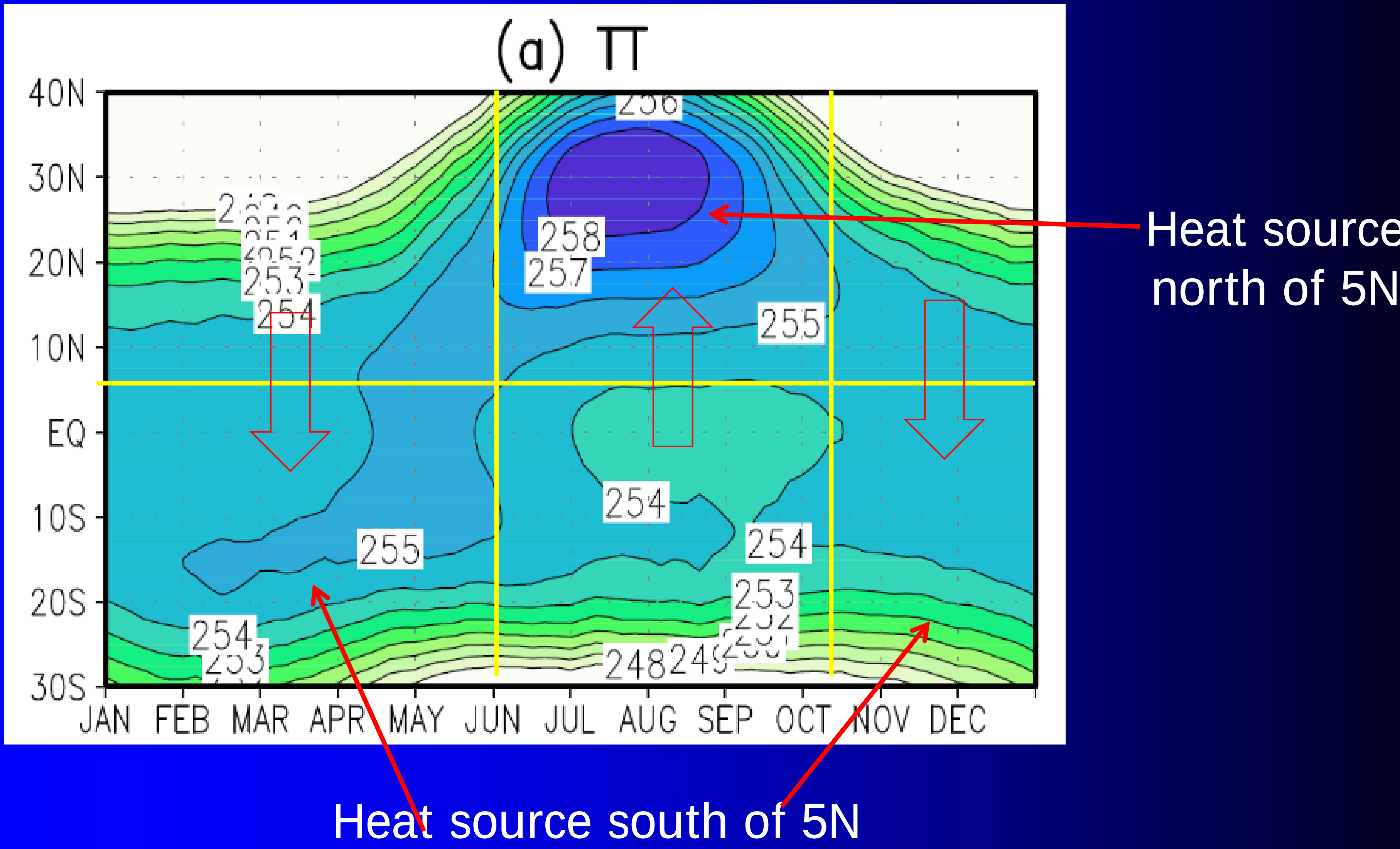
Wind vectors at 925 hPa and precipitation in May.

Courtesy: Devabrat Sharma





Tropospheric temperature averaged between 200 and 600 hPa (TT) averaged between 40E and 100E



Goswami and Xavier 2005, GRL, doi:10.1029/2005GL023216

Xavier, Marzin and Goswami, 2007: QJRMS, https://doi.org/10.1002/qj.45

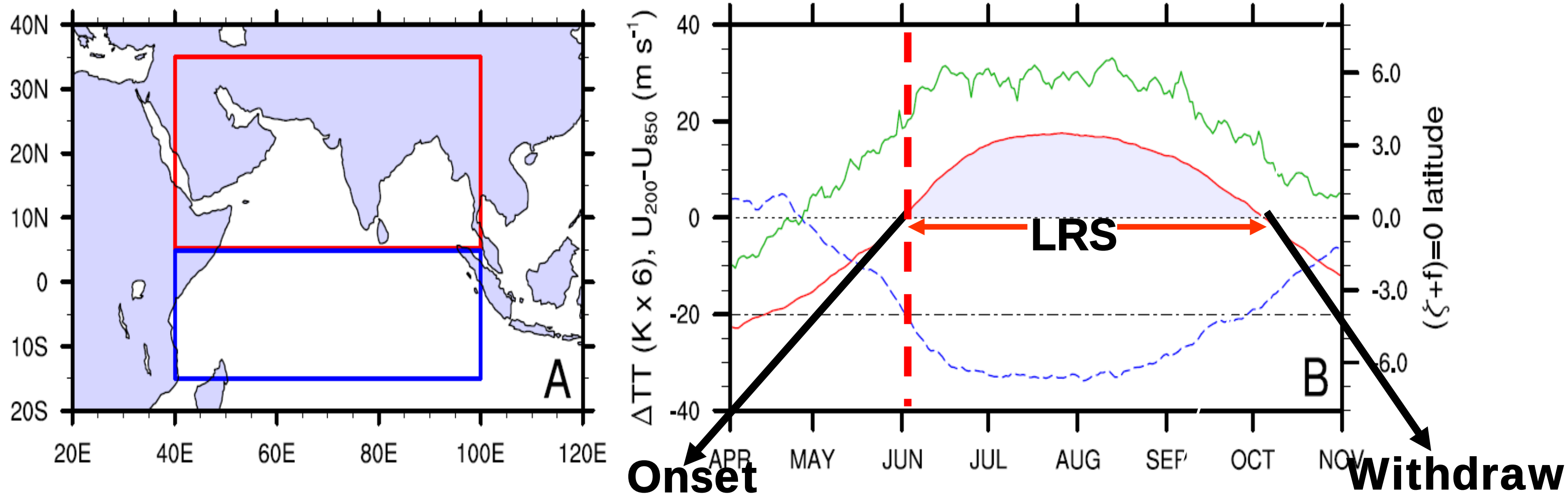


FIGURE 3.3: (A) The area used to define ΔTT. (B) Shows the evolution of climatological values of ΔTT (K×6, solid red line, scale to the left) and the climatological mean vertical shear of zonal winds (U_{200} - U_{850}) averaged over 50°-95°E, 0°-15°N (m s^{-1}, dashed blue line, scale to the left). The latitude of zero absolute vorticity averaged between 50°E and 100°E (solid green line, scale to the right). Shaded area under the ΔTT curve represents the climatological value of TISM (Section 3.1.1).

Green → absolute vorticity (ζ + f) averaged between 50E -100E

Red → Meridional gradient of TT (ΔTT = TT_n –TT_s)

Blue → Vertical shear of zonal wind (U_{200} –U_{850}) ave (50E-95E, 0-15N)

- **Thus, the mew model defines ‘Onset’ and ‘Withdrawal’ objectively and hence also defines the ‘Length of the Rainy Season (LRS)’ objectively.**

- **How is it Objective? Because, ‘Onset’ is related to establishment of the monsoon heat source north of 5N and establishment of monsoon westerly jet while ‘withdrawal’ happens when the heat source moves south of 5N and reversal of winds at 850 hPa to north-easterlies’ takes place.**

- **It also opens up a new degree of freedom for Indian monsoon that the monsoon season need not be fixed June-September, which physically makes more sense.**

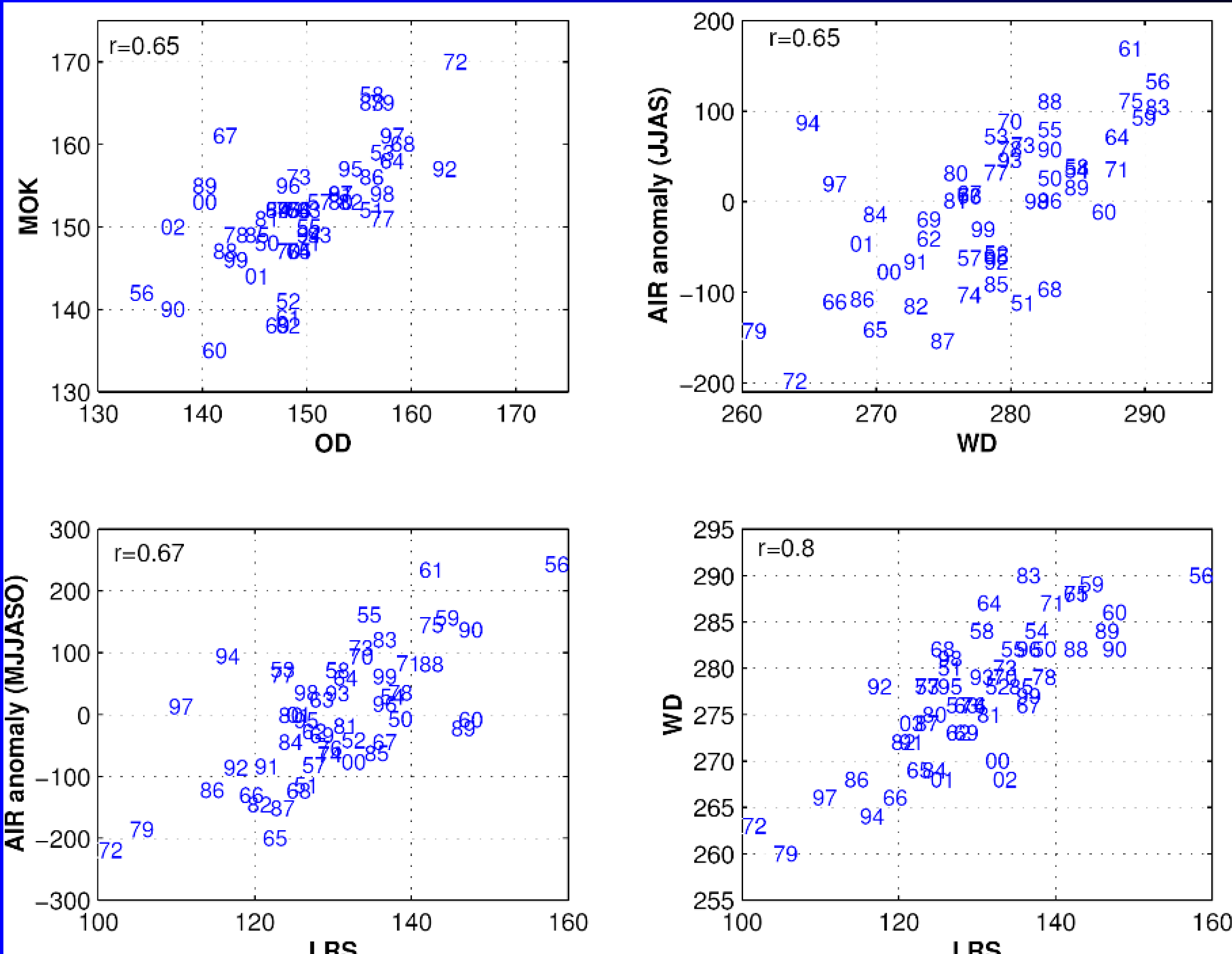
Table 3.1: Statistics of OD, WD, and LRS from NCEP and ERA

	NCEP			ERA		
	OD	WD	LRS (days)	OD	WD	LRS (days)
Earliest/minimum	14 May	16 Sep	98	10 May	20 Sep	105
Latest/maximum	13 Jun	20 Oct	159	10 Jun	18 Oct	159
Mean	30 May	10 Oct	129	26 May	6 Oct	131
S.D. (days)	7	9	12	7	8	11

Statistics of Onset dates (OD), withdrawal dates (WD) and length of the rainy season (LRS) in Julian days from NCEP/NCAR reanalysis between 1950-2002.

Climatological mean OD → 30th May

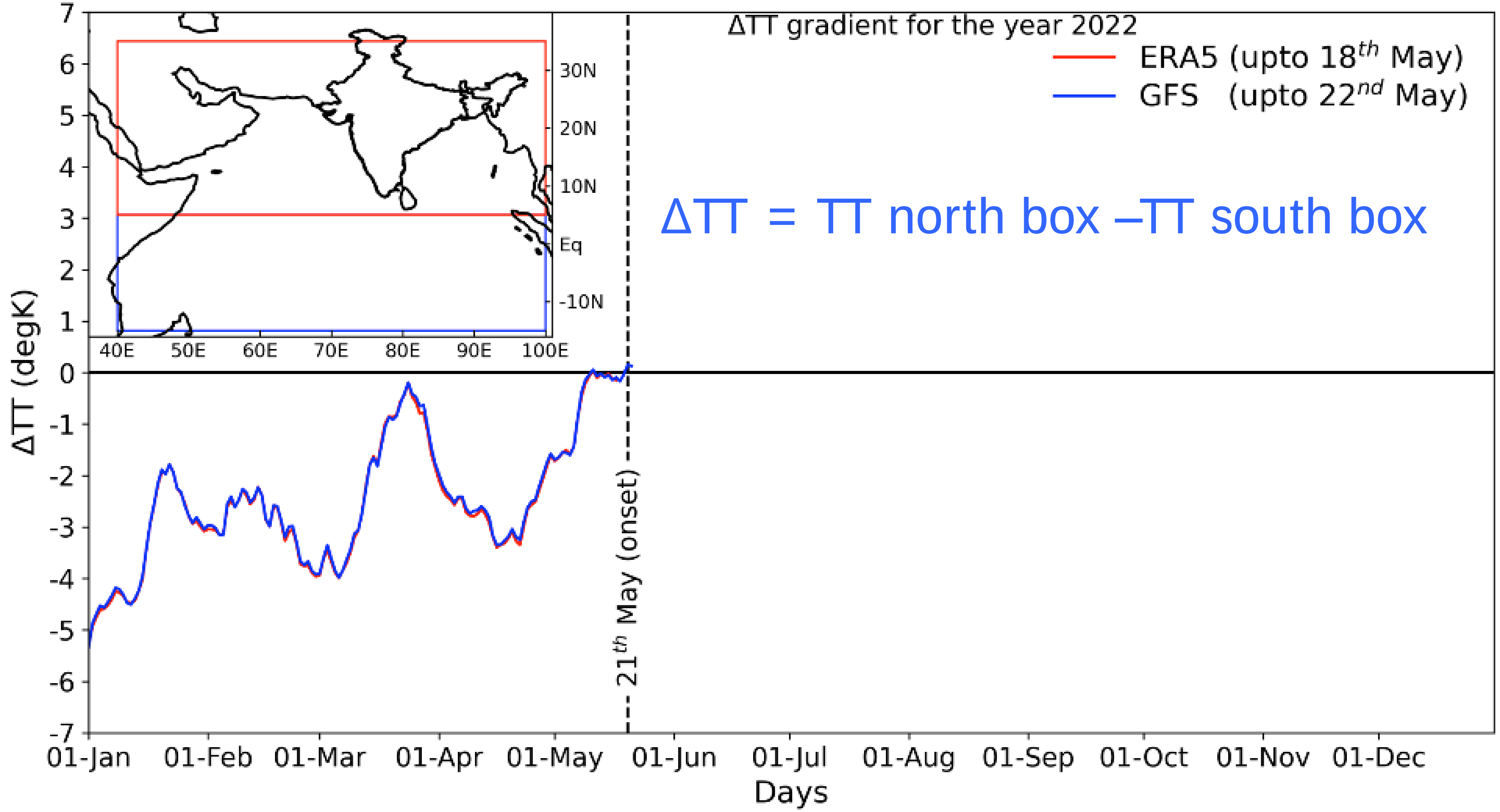
Climatological mean WD→ 10th October



r=0.65
MOK
OD
130
140
150
160
170
r=0.65
AIR anomaly (JJAS)
WD
200
100
0
−100
−200
260
270
280
290
r=0.67
AIR anomaly (MJJASO)
LRS
300
200
100
0
−100
−200
−300
100
120
140
160
r=0.8
WD
LRS
295
290
285
280
275
270
265
260
255
100
120
140
160

With Operational Analysis available from many prediction Centers, the TT gradient can be monitored on real time with possibility of nowcasting the 'Onset' .

Lets us see what is happening to ΔTT this year!



Indian 'monsoon season' (LRS) as defined from ΔTT helps us to identify a teleconnection pathway with the ENSO

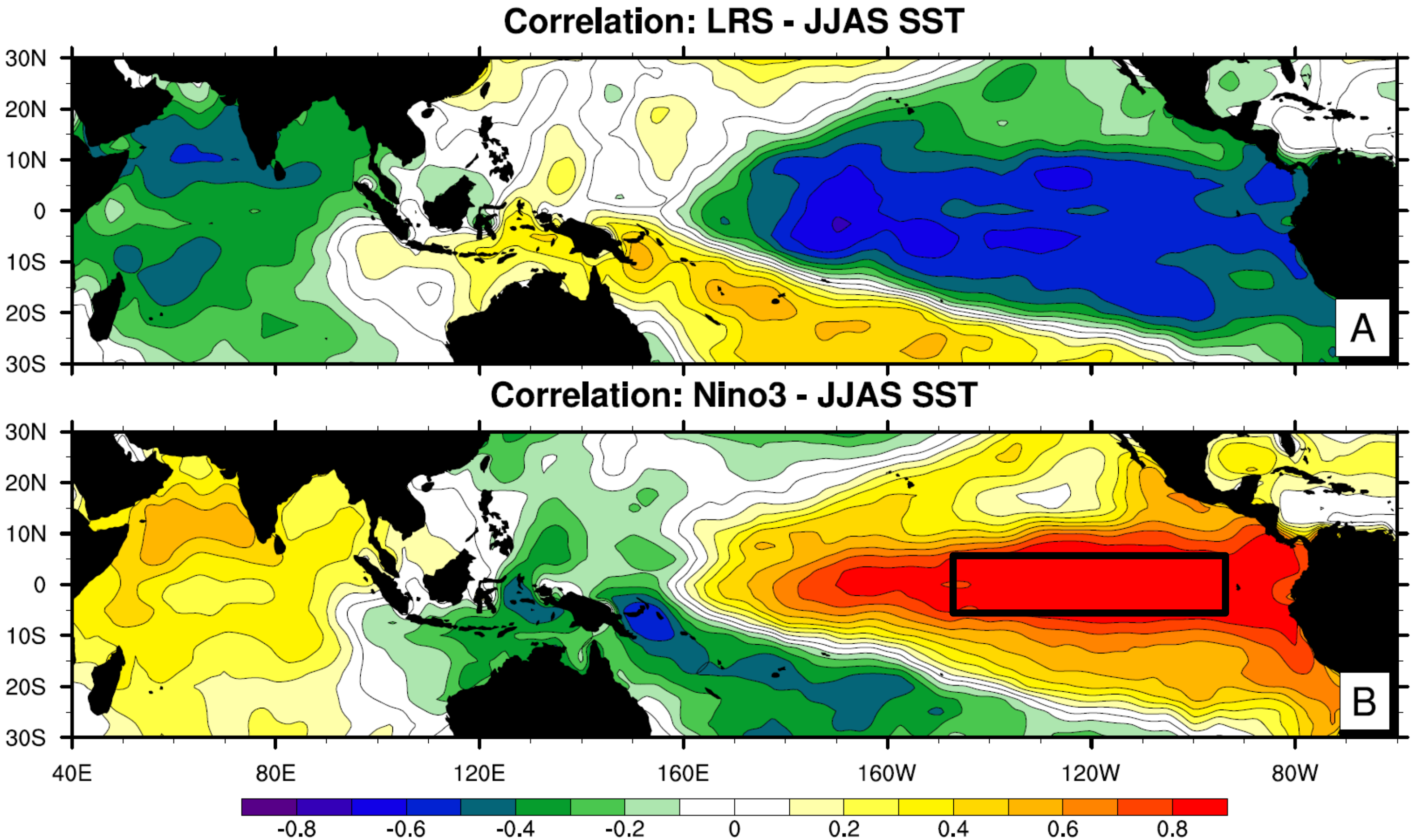


FIGURE 3.8: Correlation coefficient of June-September SST anomalies at every grid box with (A) LRS and (B) with Niño 3 SST anomalies, based on data between 1950 and 2003.

The model also facilitates linking with global climate modes like the ENSO and AMO through large scale TT stationary wave.

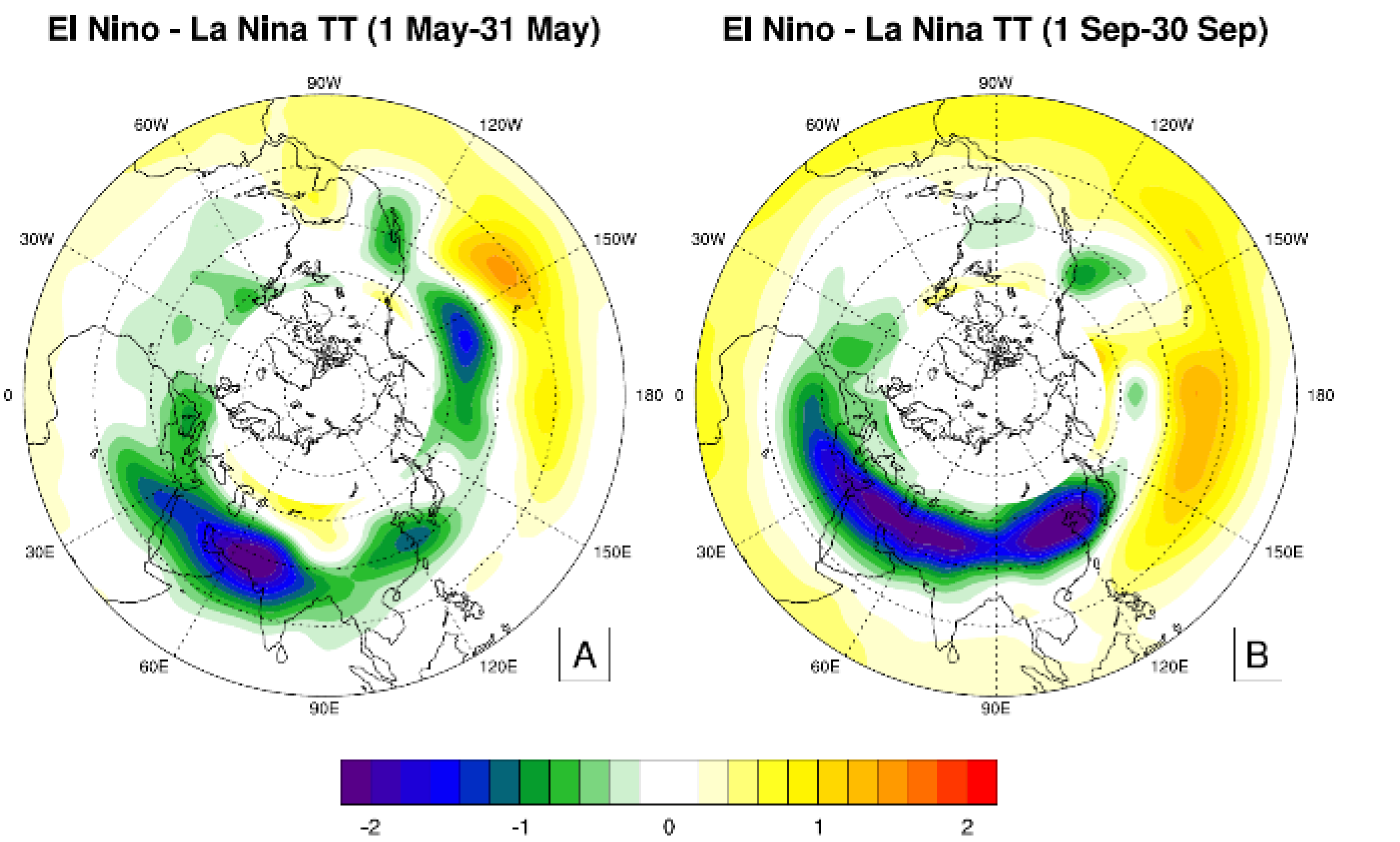


FIGURE 3.9: El Niño minus La Niña composites of TT (K) averaged between (A) 1 May and 31 May and (B) 1 September and 30 September. These are based on 11 El Niño (10 La Niña) years defined using normalized Niño3 SST anomalies being > 1 (< -1).

Note the large scale wave number one type TT anomaly associated with El Ninos influencing the north box.

The model also explains why the ‘Onset’ is abrupt...

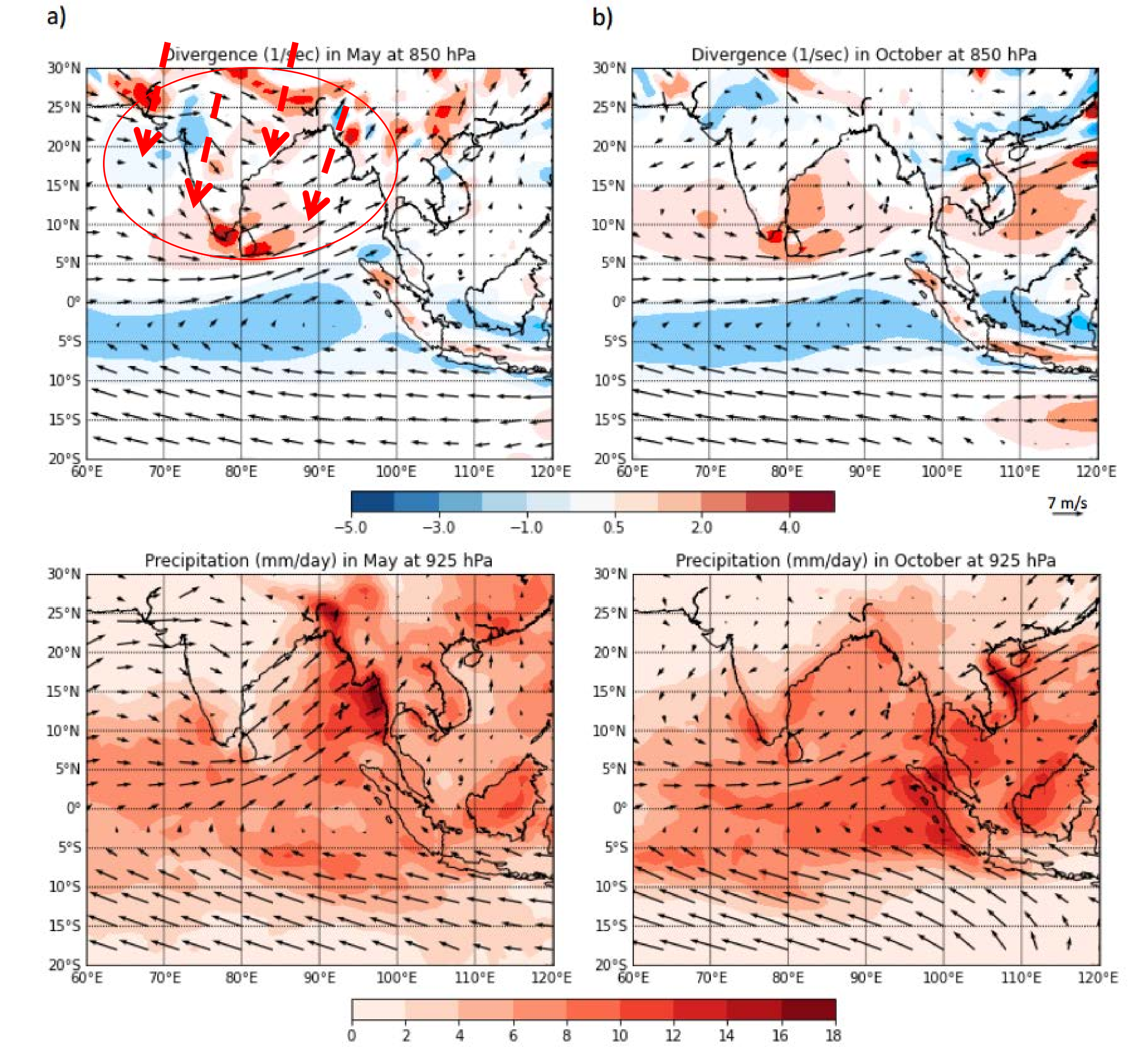
- It is abrupt because, a ‘moist intertial symmetric instability’ (Krishnakumar V, Lau KM. 1997, tellus, 49: 228–245. Tomas and Webster, 1997, QJRMS, 123, 1445–1482) is required to overcome the inhibition of subsidence (divergence) for the ITCZ to become vigorous north of 5N.

- Necessary condition for the instability is, Zero of Absolute vorticity of mean flow (ζ +f) must be north of Equator.

- This condition is satisfied when the monsoon heat source moves north of 5N and the mean flow has a large-scale cyclonic vorticity north of equator.

Sequence of events➔

Wind vector and divergence at 850 hPa and 925 hPa During May



Events that lead to the Indian summer monsoon ‘Onset’ (MOK)

Surface heating (land-ocean contrast) during pre-monsoon season produces cross-equatorial flow near the surface but is capped by subsidence and divergence and a southward flow above the PBL. Builds up potential convective instability, but can not be realized.

↓

When tropospheric heating gradient changes sign, primarily due to the influence of the Tibetan Plateau heating, cross equatorial flow and a large scale cyclonic vorticity above the PBL is set up.

↓

Zero absolute vorticity line at 850 hPa moves north to about 5N and conditions for conditional moist inertial instability is established.

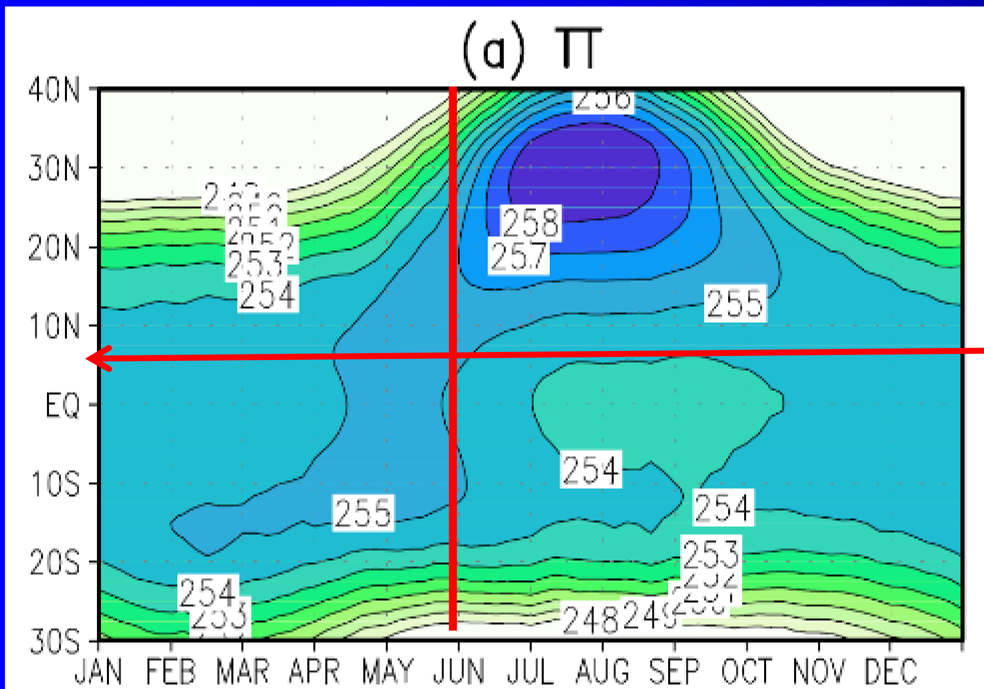
↓

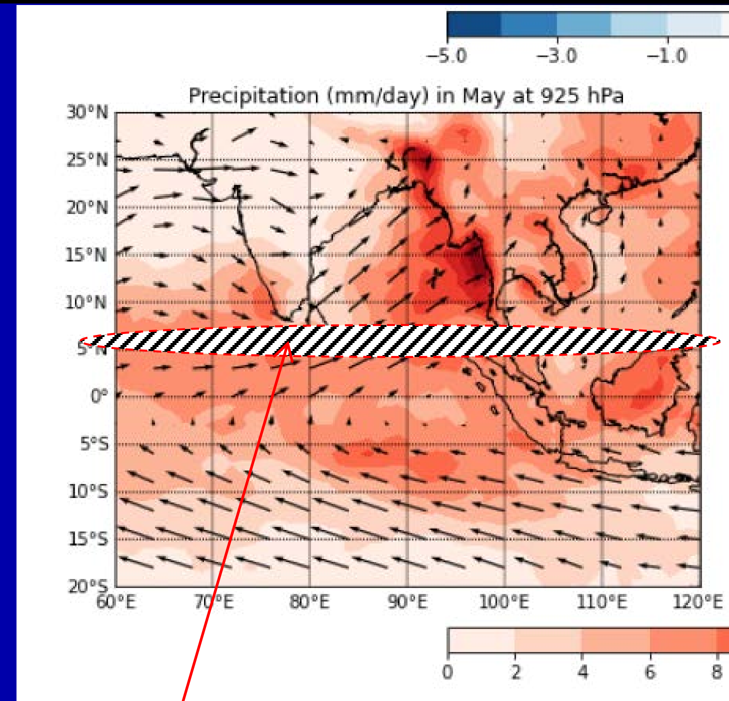
Dry inertial instability overcomes the inhibition of subsidence, moist inertial instability takes over and explosive organized convection takes place.

↓

Onset over Kerala takes place

Northward propagation and establishment of monsoon over continent after ‘Onset’





- At the time on ‘Onset’, no rain over land. The TT becomes positive to the north due to dry processes of Tibetan plateau heating and TT anomaly from planetary scale stationary waves.
- At ‘Onset’ the symmetric instability breaks the inhibition and deep convection on ITCZ scale takes place.
- **A convective-feedback makes it move northward=➔**

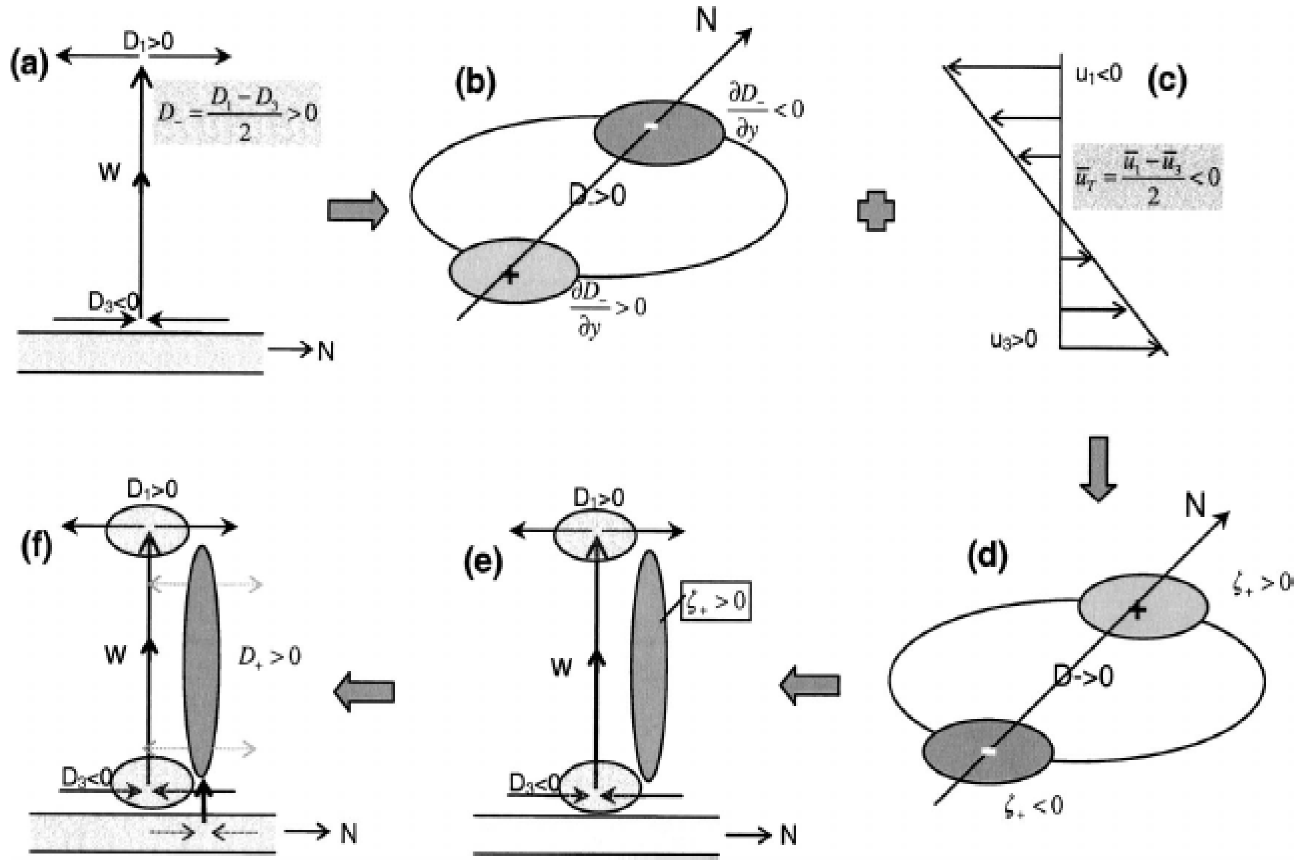


FIG. 10. Schematic diagram for the vertical shear mechanism. (a) Consider initially an ISO convection with a baroclinic structure. (b) This leads $\partial D_-/\partial y < 0$ ($\partial D_-/\partial y > 0$) north (south) of the convection center. (c) In the presence of the easterly shear of the mean flow, (d), (e) a positive barotropic vorticity is induced north of the convection, leading to (f) a barotropic divergence in situ. The latter further leads to a PBL convergence and thus a northward shift of convective heating.

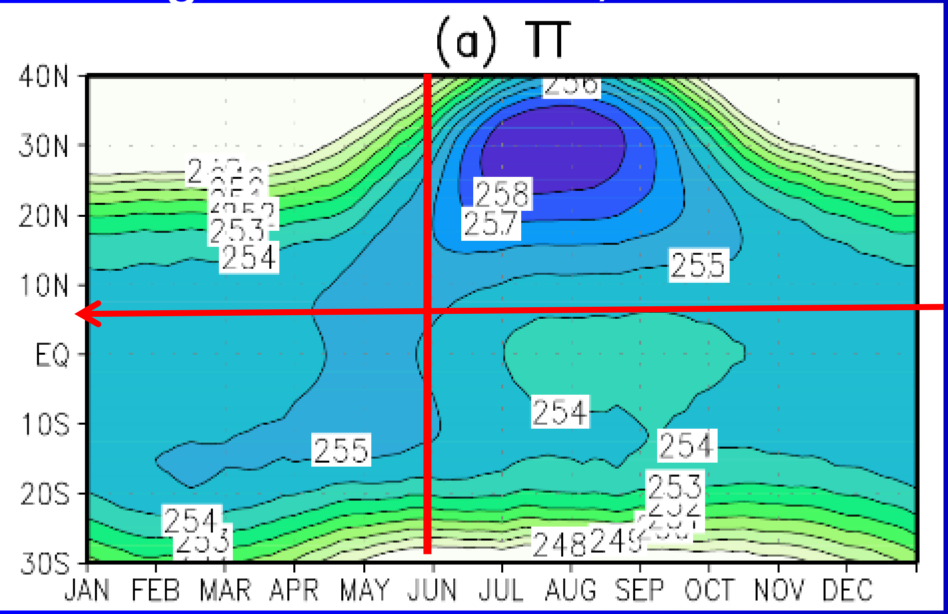
Jiang X et al., 2004, Structures and Mechanisms of the Northward Propagating Boreal Summer Intraseasonal Oscillation

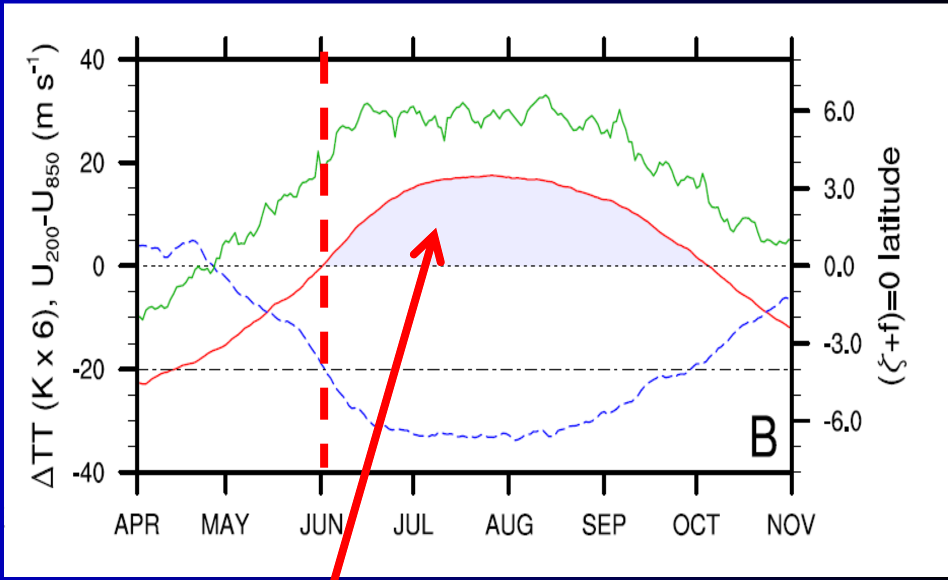
J. Climate, 17, 1022–1039

Deep convective heating of the ITCZ in the presence of background easterly shear of background winds leads to anomalous barotropic vorticity response to the north of the original heat source→ anomalous moisture convergence to the north→ heat source moves north

Critique of the model

The TT in the north box is contributed by the monsoon rainfall during JJAS. Can we, then use the TT gradient to define 'Onset'





- At the time on 'Onset', no rain over land. The TT becomes positive to the north due to dry processes of Tibetan plateau heating and TT anomaly from planetary scale waves. Therefore, there is no issue in defining 'onset' with the TT gradient.
- After 'Onset' indeed the monsoon rainfall influence the TT and ΔTT and adds to the TT from external forcing. Hence we can define a Thermodynamic Index of Summer monsoon (TISM) as area under positive ΔTT. (Xavier et al. 2007, QJRMS)

Critique of the Model (contd.)

- The physics of the ΔTT based 'Onset' refers to the First 'Onset' over the southern tip or 'Onset over Kerala' (MoK). It refers to the first invigoration of the ITCZ and commencement of its northward midration on intraseasonal time scale.

- It compares quite well with other definitions of MoK (IMD, Pai etal., 2020, Joseph et al. 1994, Wang et al.2009).

- Because, it is based on large scale temperature field, our definition is protected from 'Bogus Onset'

- However, this method cannot define 'Onset' on further to the north and on specific locations.

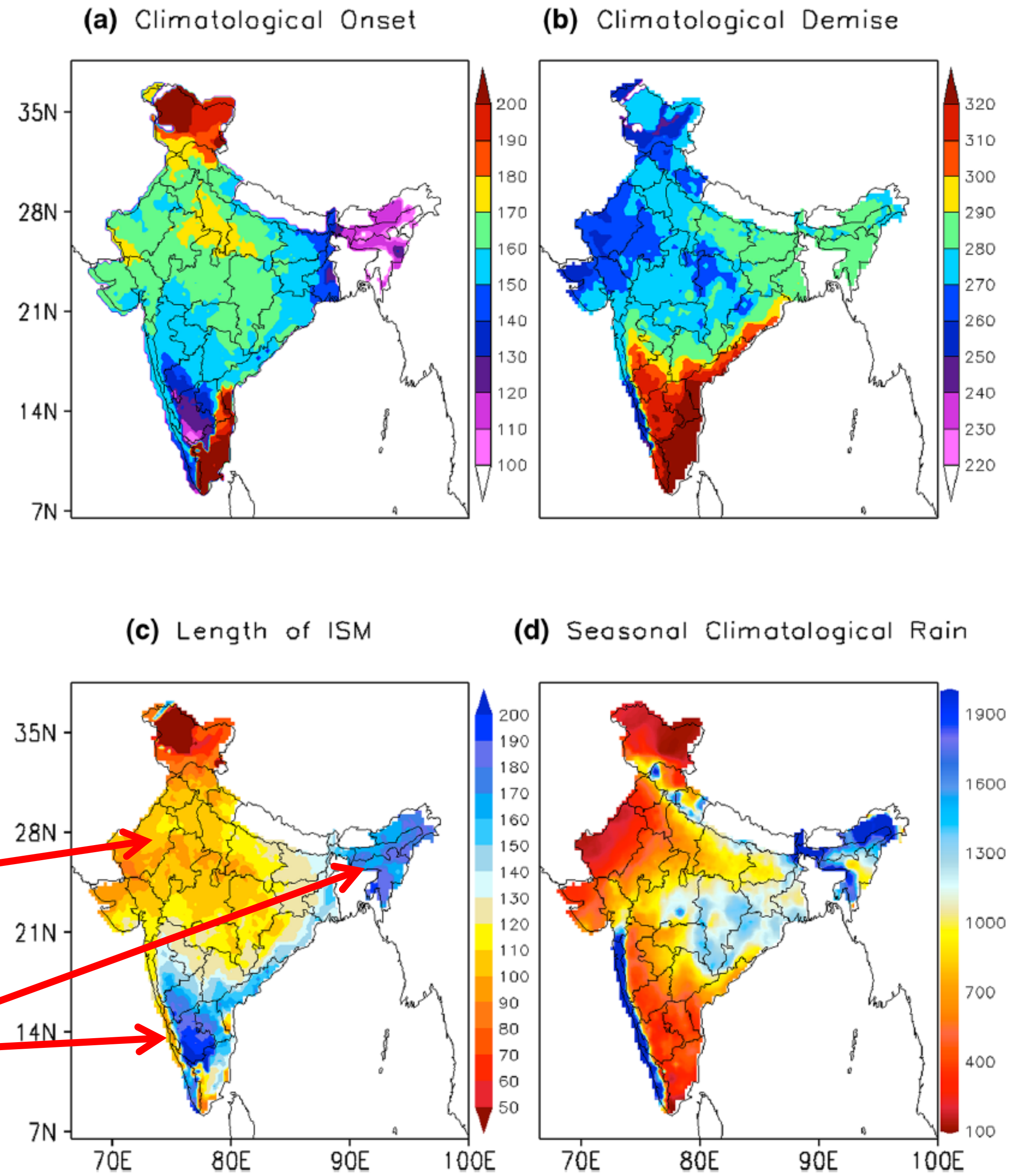
Other methods of defining 'Onset', 'withdrawal' and Length of the rainy season (LRS):

1. Wang, B and LinHo, 2002: J. Climate,15, 386–398
2. V. Mishra et al.,2018, Climate Dynamics volume 51, pages 1609–1622
3. Fasullo and Webster, 2003: J. Climate, 16, 3200–3211

- **The first two methods are based on daily rainfall and uses thresholds that relate to local amplitude of the annual cycle of rainfall. The third uses VIMT (vertically integrated moisture transport) to define 'onset' and 'withdrawal'**

- **The Mishra et al method is less susceptible to 'Bogus Onset' as it uses 'cumulative daily rainfall anomaly". However, cannot distinguish between SW and NE monsoon rainfall leading long LRS over Kerala/TN**

Fig. 1 The climatological **a** onset and **b** demise date (in Julian days), and **c** length (in days) of the Indian Summer Monsoon (ISM) defined at every grid point of the Indian Meteorological Department (IMD) gridded rainfall dataset at 0.25° grid interval. **d** The climatological seasonal mean rainfall (mm), accumulated between the climatological local onset and demise date of the ISM at each grid point



Mishra et al., 2018

Short LRS

Long LRS

Special attention is required in defining the ‘Rainy Season’ over North-east India (NRI)

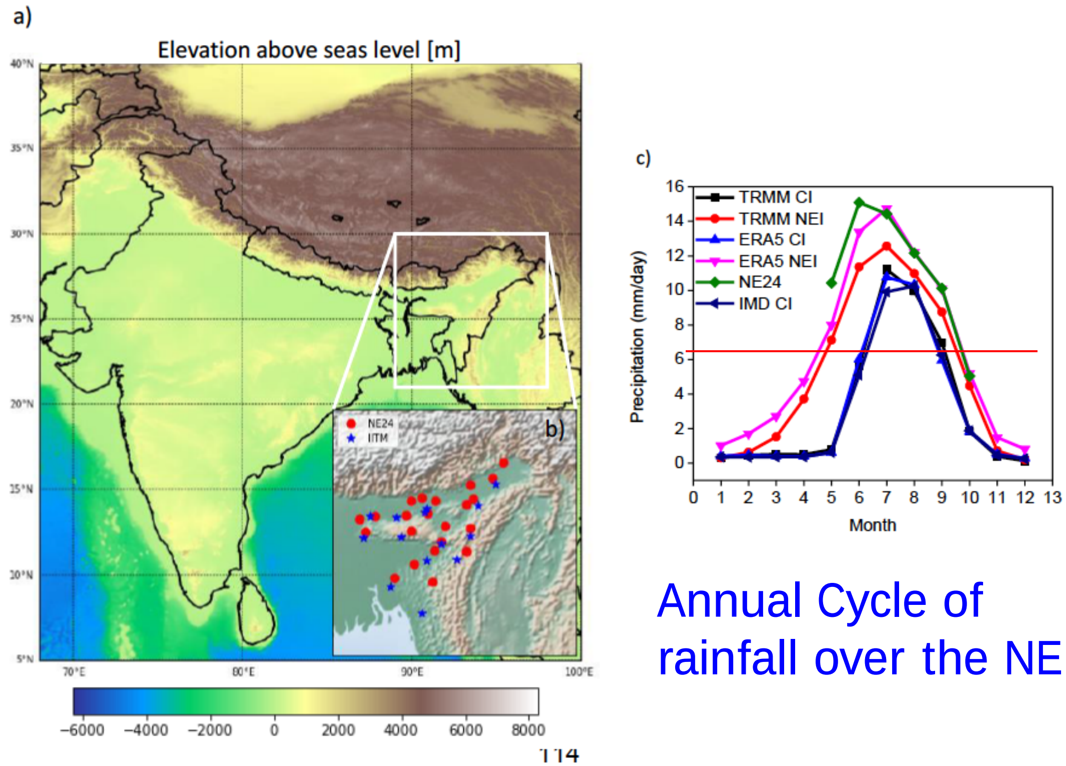
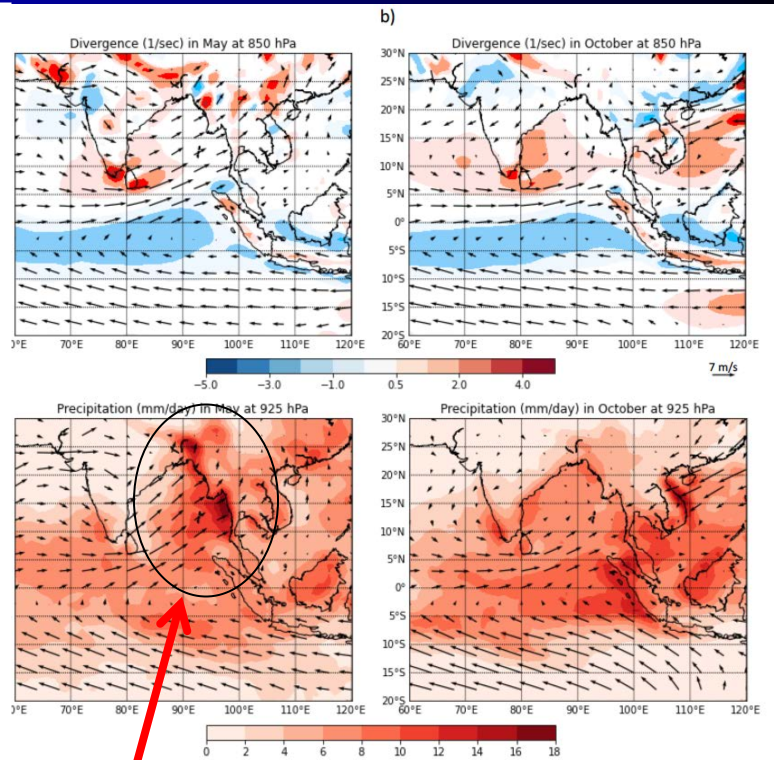


Figure 1: Introduction. **(a)** Topography of the Indian sub-continent (66E-98E,5N-38N). **(b)** Distribution of the 24 stations of the NE24 dataset (Red circles) and 14 stations of the Parthasarthy el al., 1994 dataset (Blue stars). **(c)** Climatological annual rainfall over NEI and CI estimated using both observed and reanalysis dataset.

Annual Cycle of rainfall over the NEI



May rainfall over NEI orographic rain induced by southwesterlies

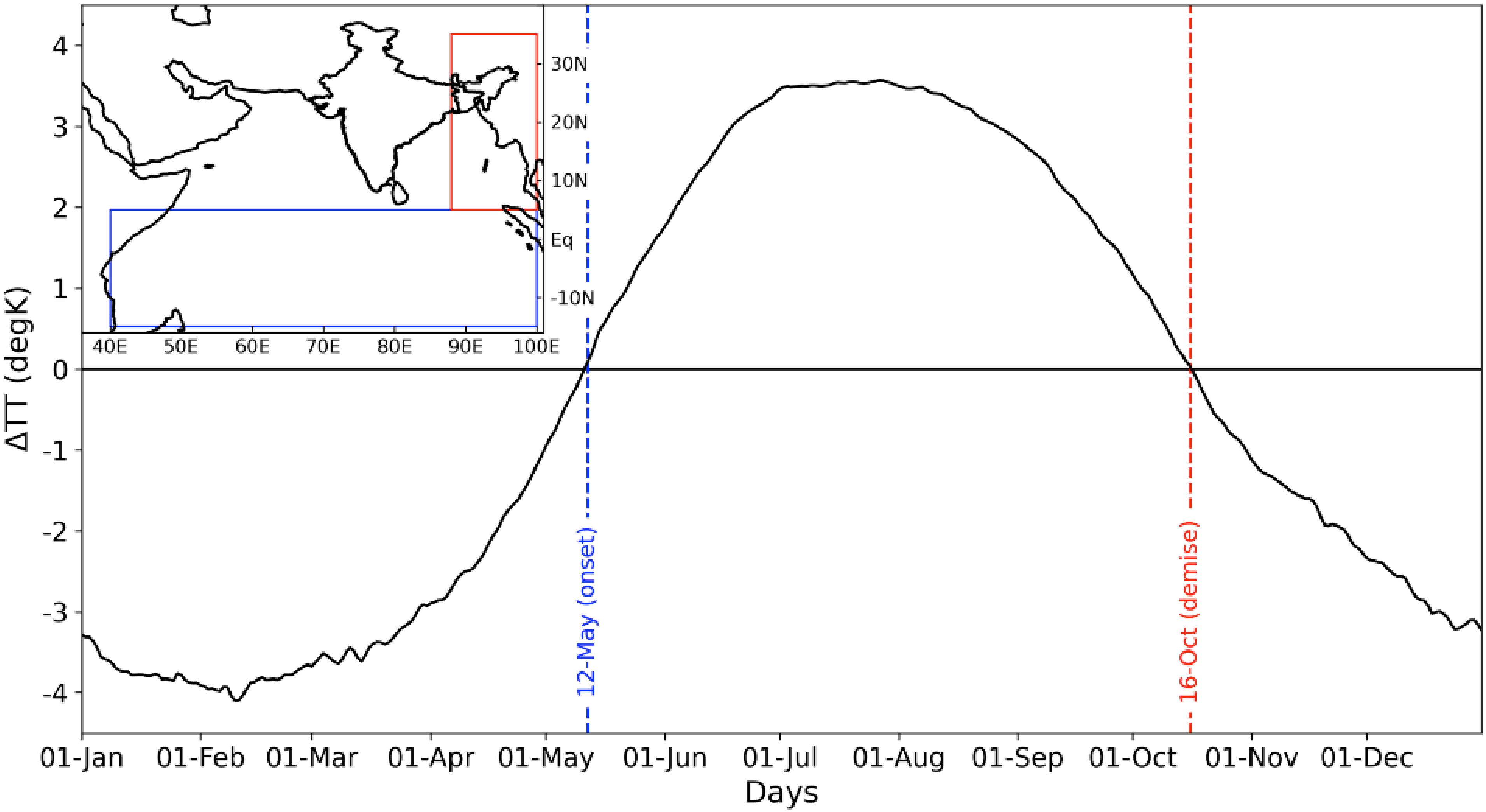
Sharma D, S. Das and B. N. Goswami, 2022: (under review)

Our model helps define 'Onset' over NEI correctly

- The MoK is due to invigoration and northward propagation of the ITCZ.
- On the other hand, 'onset' over the NEI need not be due to the tropical ITCZ but could happen if the the troposhpheric heat source (TT) gets established in the NEI by May. Then, it could maintain SW winds above the boundary layer and sustain persistent rainfall due to orographic effect. In that case, we should declare 'Onset'.
- You do not need the inertial instability to overcome the inhibition because orographic lifting can do the same.

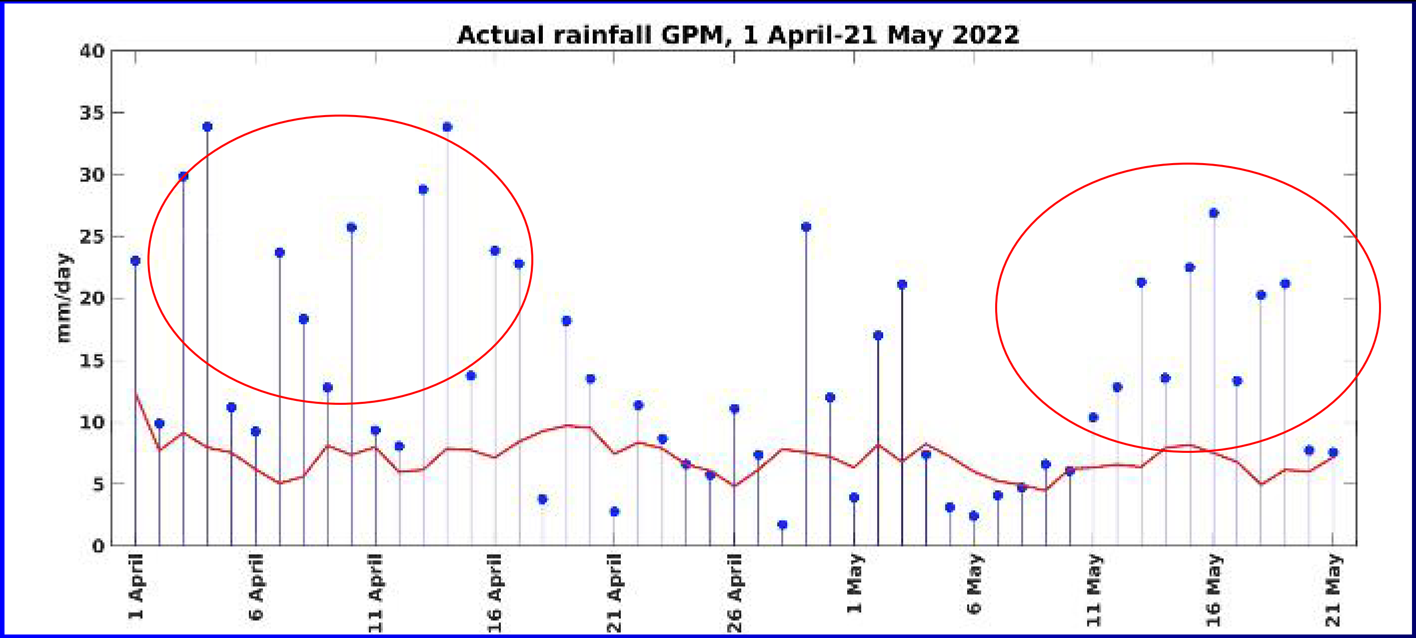
Onset of summer monsoon over north-east India (NEI)

Does the NEI monsoon heat source establish before June 1?



The 'Onset' over NEI seems to take place 12 May! (Prolay Saha et al., Cotton, under preparation)

What is happening to the Onset over NEI this year?

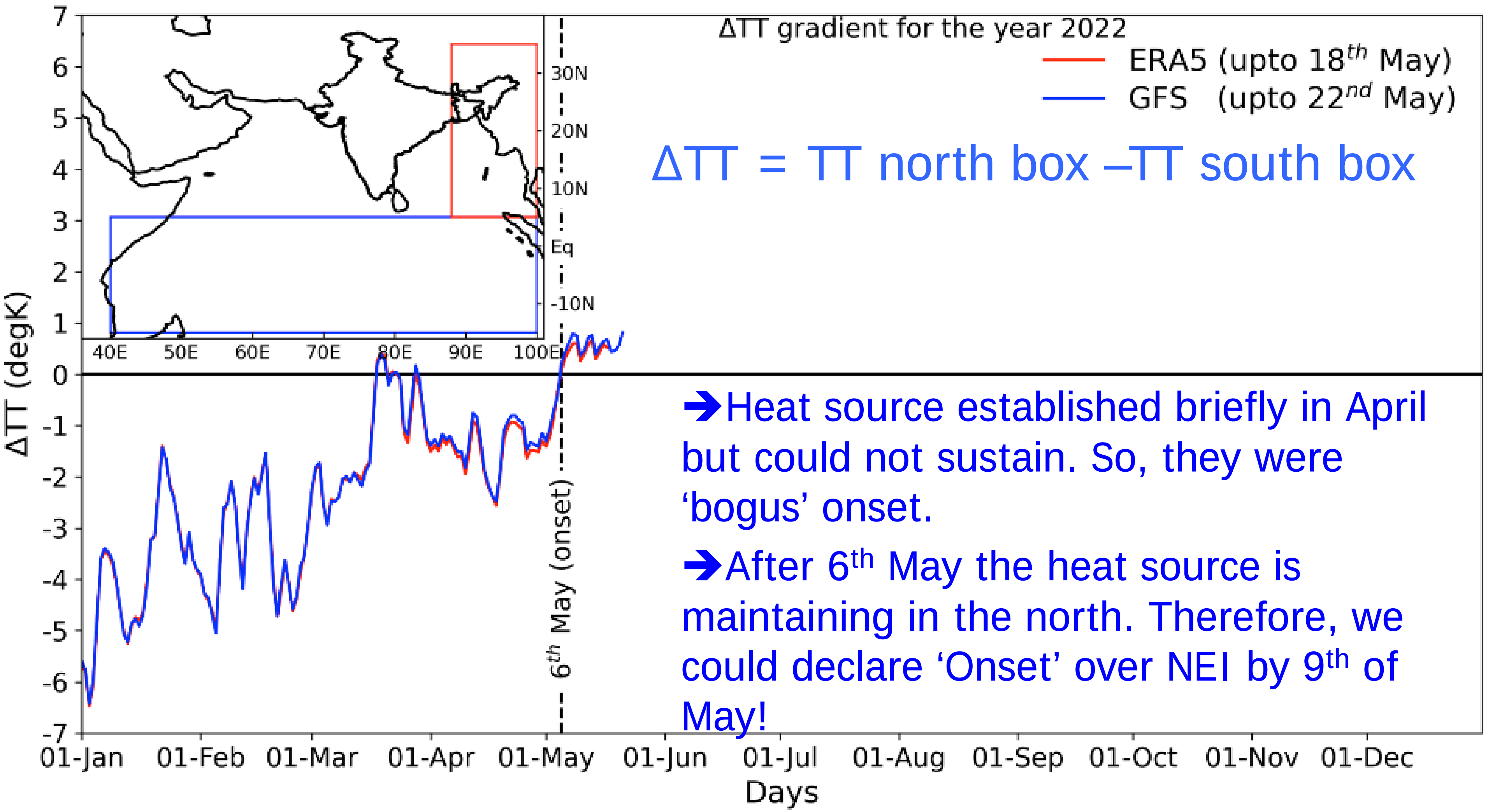


Daily rainfall from GPM averaged over NEI

Coutesy: Dhruba J. Goswami

- There was a spell rainfall for more than 2-weeks in April.
- Then again from about May 10, there is almost a 10-day spell of rain over northeast India. The spells are large-scale covering the region with large stratiform component due to organized large scale uplift!
- **Do we call them 'pre-monsoon rainfall'??**

What does the ΔTT indicates about 'Onset' of summer monsoon over NEI this year?



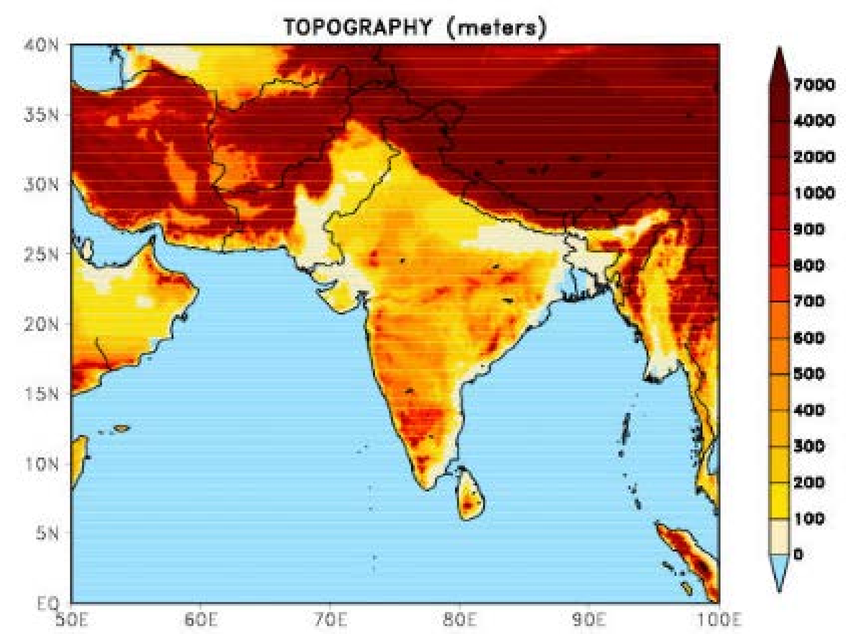
ΔTT = TT north box –TT south box

➔Heat source established briefly in April but could not sustain. So, they were 'bogus' onset.

➔After 6th May the heat source is maintaining in the north. Therefore, we could declare 'Onset' over NEI by 9th of May!

What is the role of Tibetan Plateau and Himalays in the Monsoon Model ?

The Tibetan Plateau and Himalays has



1. A Mechanical effect on monsoon by blocking cold and dry air advection from north and sustaining high MSE for convection
2. A Thermal Effect of the 'elevated heating of the Plateau'

- The 'elevated heating' helps move the TT heat source to the north 'early' thereby advancing the 'onset' by about a month compared to if the Plateau were not there.
- Climate model experiments support this.
- Thus, Tibetan Plateau and Himalayas is responsible for intensification of the modern monsoon by increasing LRS.

Therefore, lifting of Tibetal Plateau and Himalayas and strengthening of ISM has been investigated extensively.

- **Terrestrial and marine sediments archieves indiate Himalyan uplift to early Miocene (23-20 million years ago (Ma)**
- **However, Indian Ocean paleorecords place onset of strong Indian monsoon winds around late miocene (13 Ma)**
- **Reconciling this discrepancy has been a major open science question in Indian monsoon science.**

A very recent study seems to provided answer to this question:

nature geoscience

ARTICLES

https://doi.org/10.1038/s41561-022-00919-0

Check for updates

Neogene South Asian monsoon rainfall and wind histories diverged due to topographic effects

Anta-Clarisse Sarr[1] ✉, Yannick Donnadieu[1], Clara T. Bolton[1], Jean-Baptiste Ladant[2], Alexis Licht[1], Frédéric Fluteau[3], Marie Laugié[1], Delphine Tardif[1,3] and Guillaume Dupont-Nivet[4,5]

- Uses an Earth System Model (ESM) with a biogeochemical model
- Transient experiments for 2500 years for deep ocean to come to equilibrium for early Miocene (EM) and late miocene (LM) external forcing
- Paleogeography for EM and LM
- Large # of Sensitivity Experiments for influlene of orography

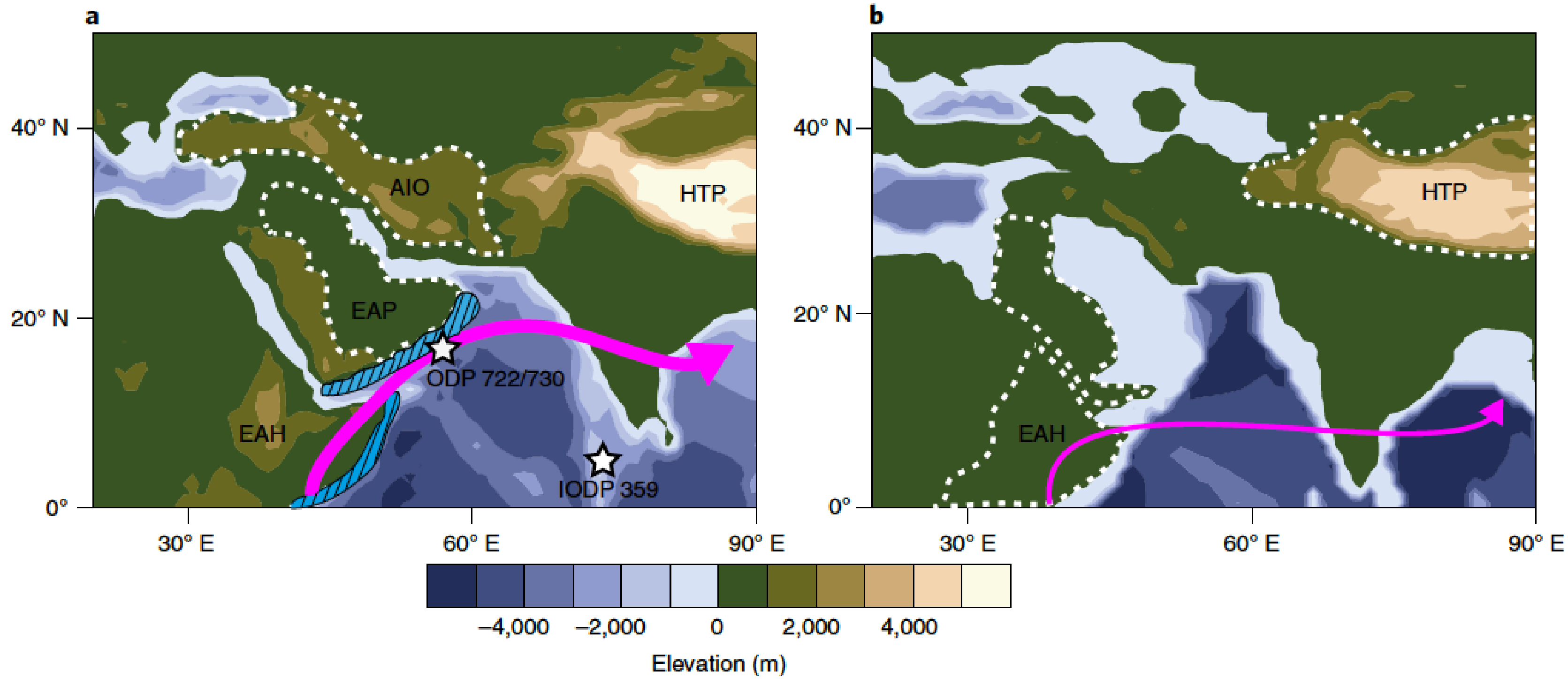
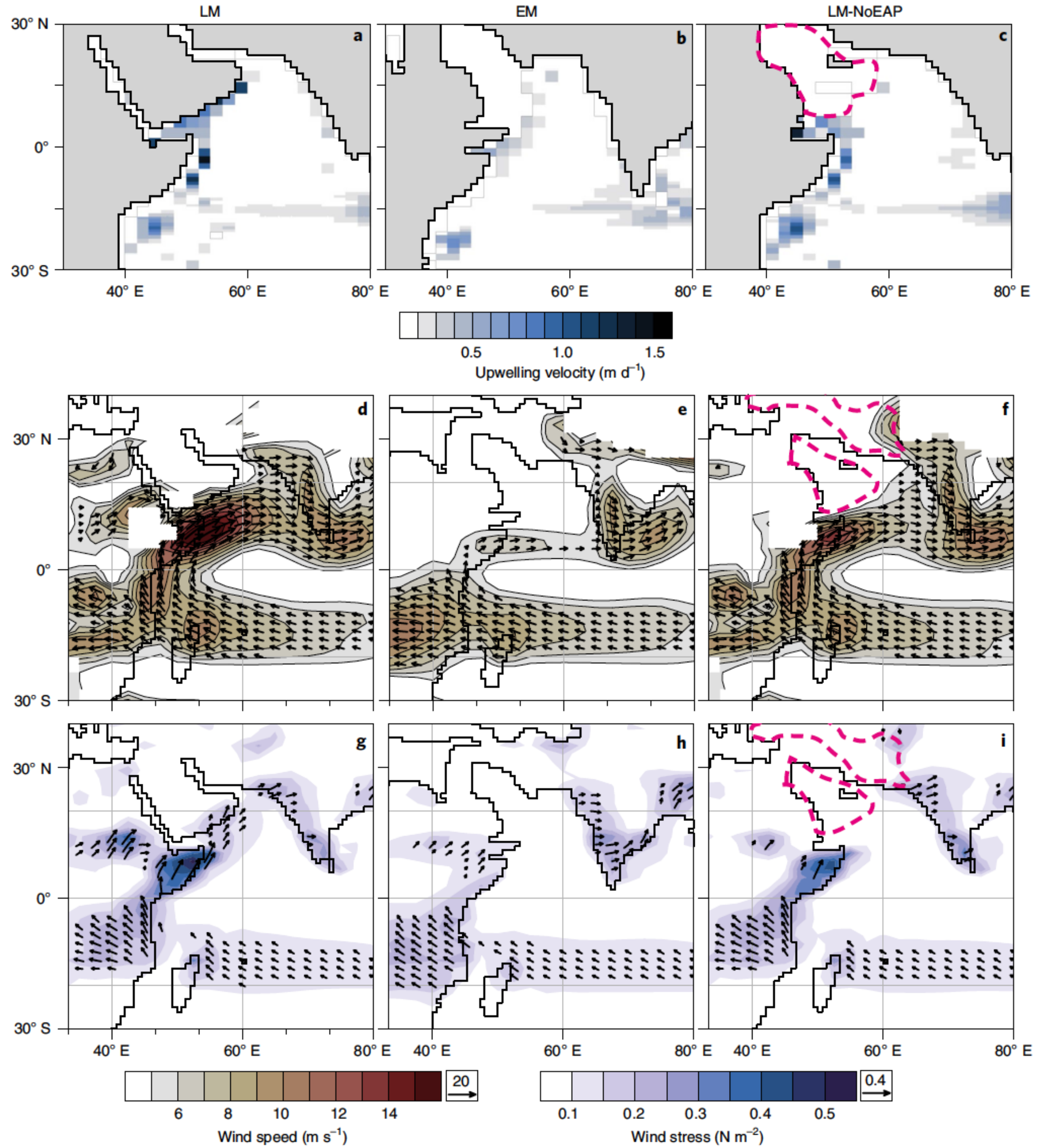


Fig. 1 | Western Indian Ocean palaeogeographic reconstructions. **a**, Late Miocene (~10 Ma) (data updated from ref.[37], see Methods); **b**, early Miocene (~20 Ma)[38]. AIO, Anatolian–Iran Orogen; EAH, East African Highlands; EAP, East Arabian Peninsula; HTP, Himalaya–Tibetan Plateau; ODP, Ocean Drilling Program; IODP, International Ocean Discovery Program. Present-day geography and ocean–atmosphere dynamics resemble the LM in this region. Dashed contours show areas where modifications were applied in sensitivity experiments (see Methods, Extended Data Table 1 and Extended Data Fig. 4 for detailed descriptions). Simulated Somali Jet patterns are represented by the magenta arrows, with the thickness indicating the strength of the jet. Blue hatched areas show the locations of upwelling from simulations. Stars show the locations of drilling sites or expeditions cited in the text.

- Factors forcing the South Asian Monsoon circulation versus rainfall are decoupled and diachronous.
- Although elevated rainfall seasonality was probably a persistent feature since the India–Asia collision in the Paleogene, modern-like monsoonal atmospheric circulation only emerged in the late Neogene

Thank you



ig. 3 | Changes in ocean–atmosphere dynamics in response to Miocene palaeogeographic evolution. a–c, Upwelling velocity (vertical velocity at 80 m epth, averaged over JJA) for the LM (**a**), EM (**b**) and LM-NoEAP (**c**) simulations. **d–f**, Corresponding low-level winds (850 hPa) during boreal summer JA). **g–i**, Wind stress during boreal summer (JJA). Arrows highlight the pattern of low-level winds (**d–f**) and wind stress (**g–i**). Dashed pink contours in **c**, and **i** indicate the location of geographic modifications compared with the LM simulation (**a**, **d** and **g**).

In Conclusion:

- The observed 3-D structure of the Indian summer monsoon circulation and rainfall are presented.
- A conceptual framework for sustaining the mean monsoon rainfall and its variability presented. An objective method of defining the length of the rainy season (LRS) discussed.
- Spatial structure of Inter-annual variability and potential drivers of inter-annual variability discussed. ESNSO-monsoon relationship and associated teleconnection discussed in some detail.
- The driver of the ISMR multidecadal variability discussed
- What can we expect for mean ISMR and raily rainfall extremes under Global Warming.