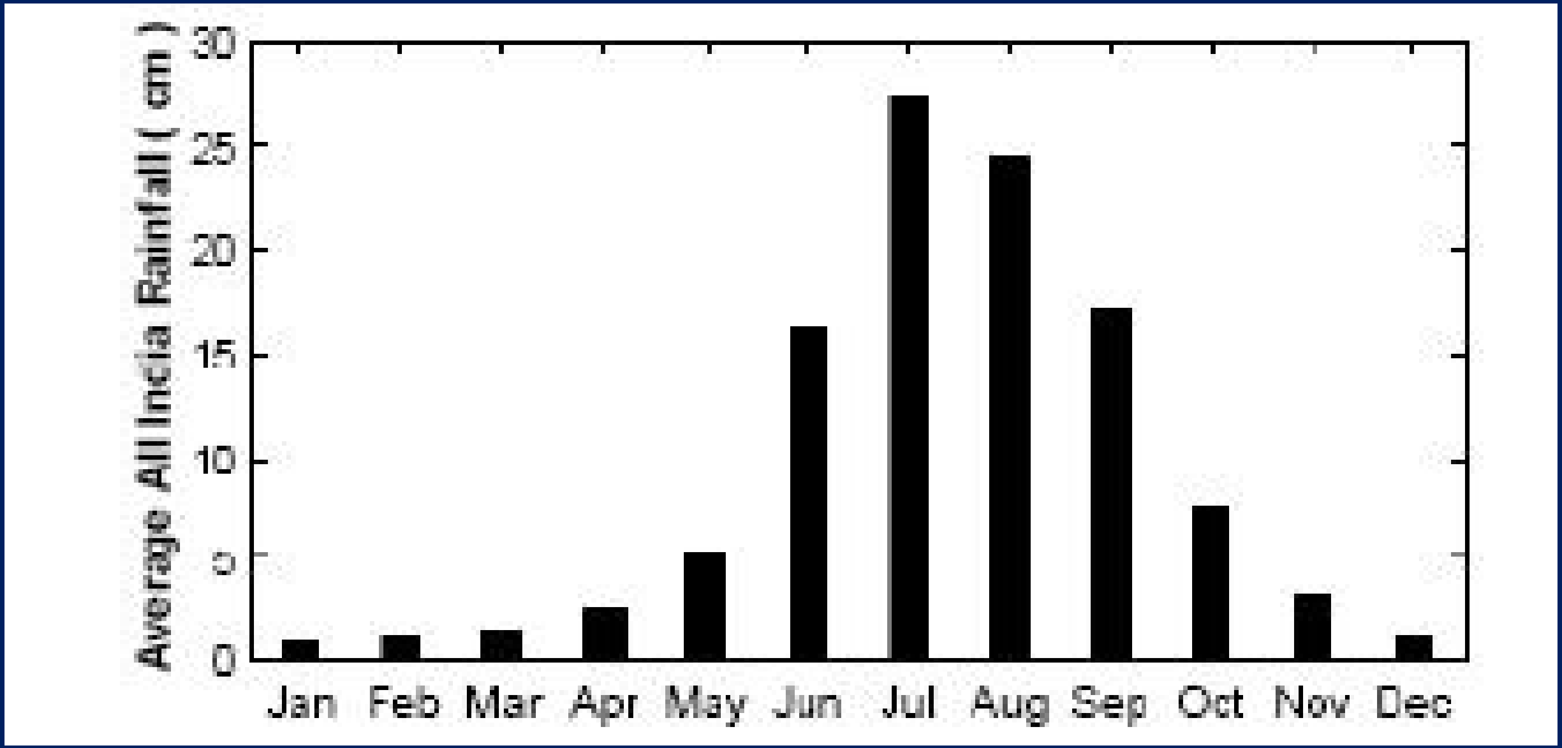
Understanding the Indian monsoon and its variability

Sulochana Gadgil
Clouds, climate and Tropical Meteorology
ICTS,CAOS
23 January 2013

- **In India, the word monsoon in common parlance refers to the system that visits the continent every year and gives us rain.**
- **The commencement of the ‘rainy season’ is associated with the onset of the monsoon and the end of the rainy season with the retreat of the monsoon.**

Rainy season

For the country as a whole, most of the rainfall occurs during the summer monsoon season June-September and the focus of most of the studies has been the Indian summer monsoon.

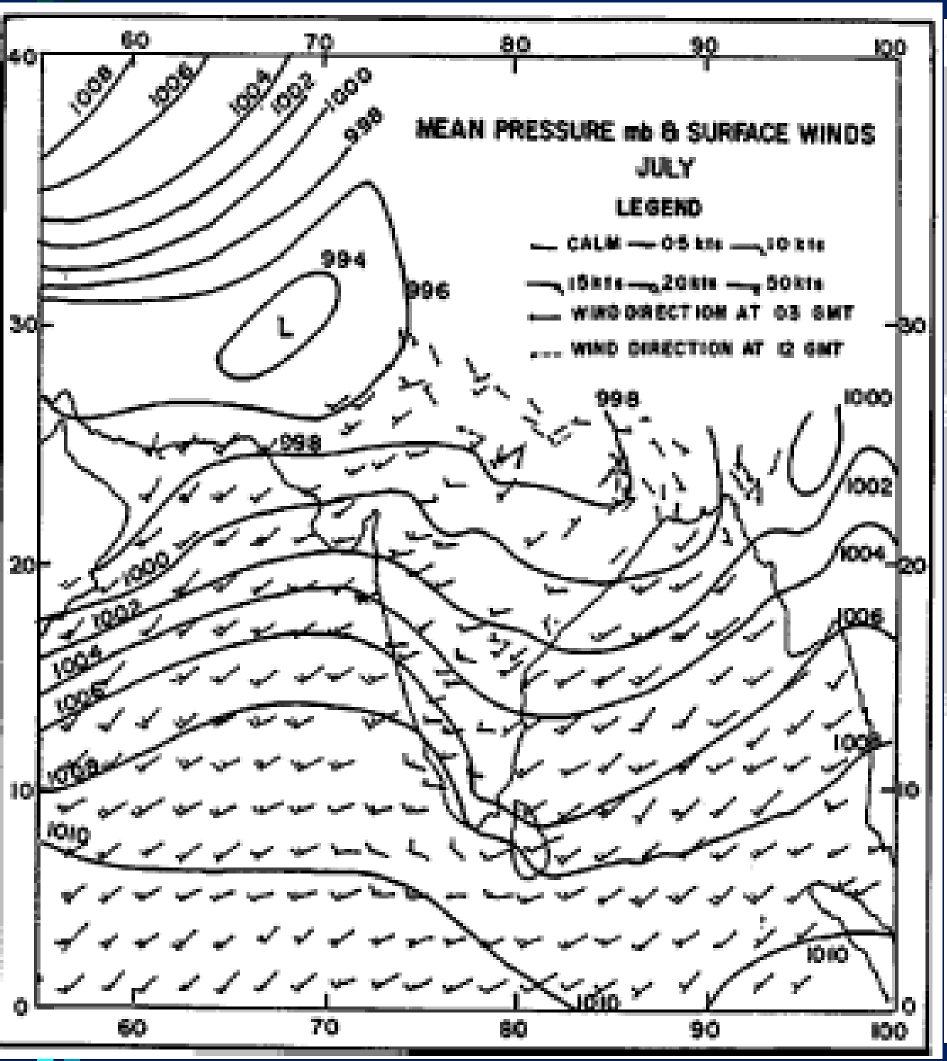


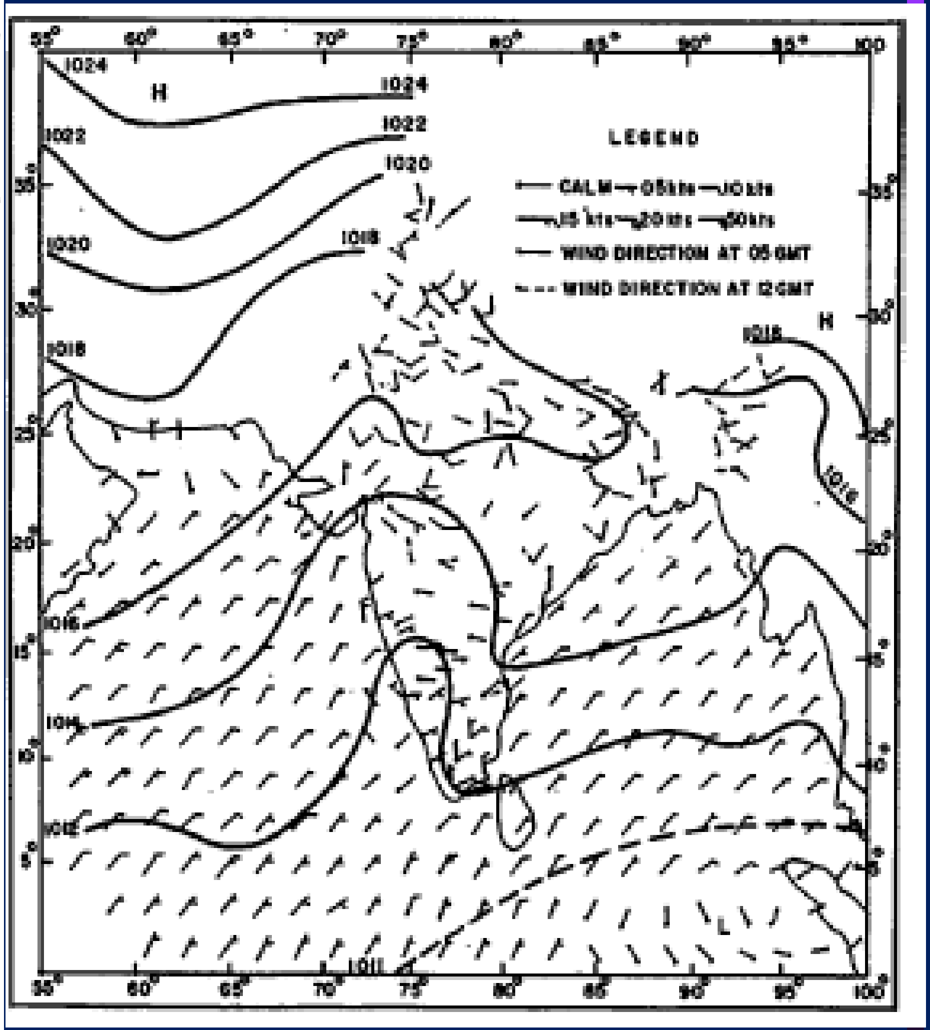
Monsoon Definitions:

- Seasonal variation in the direction of winds
- Seasonal variation of rainfall-wet summers, dry winters
- Seasonal variation of the rainfall is far more important to the billions in the monsoonal regions of the world.

Seasonal variation of the direction of the mean pressure, surface wind

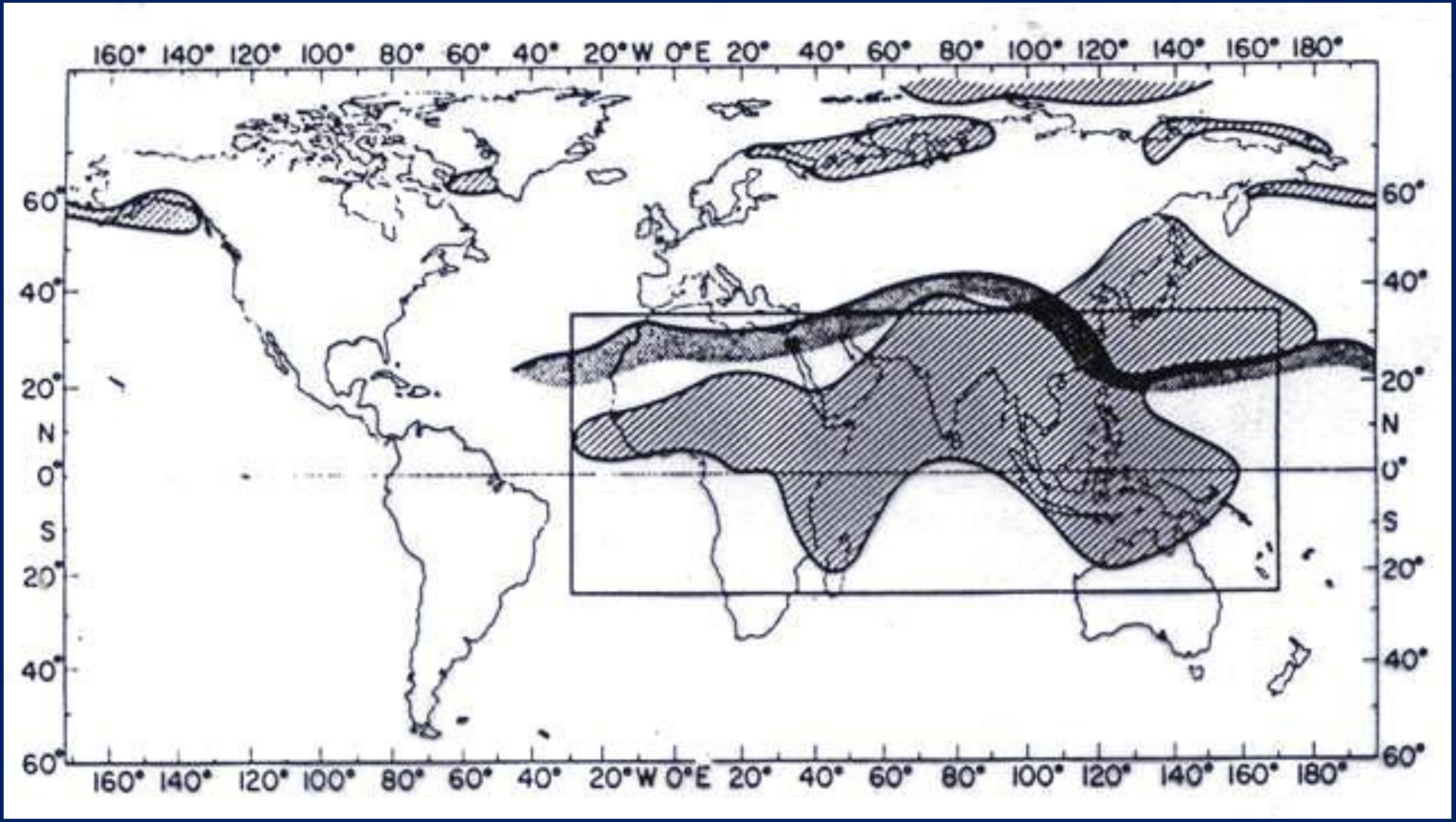
July | November





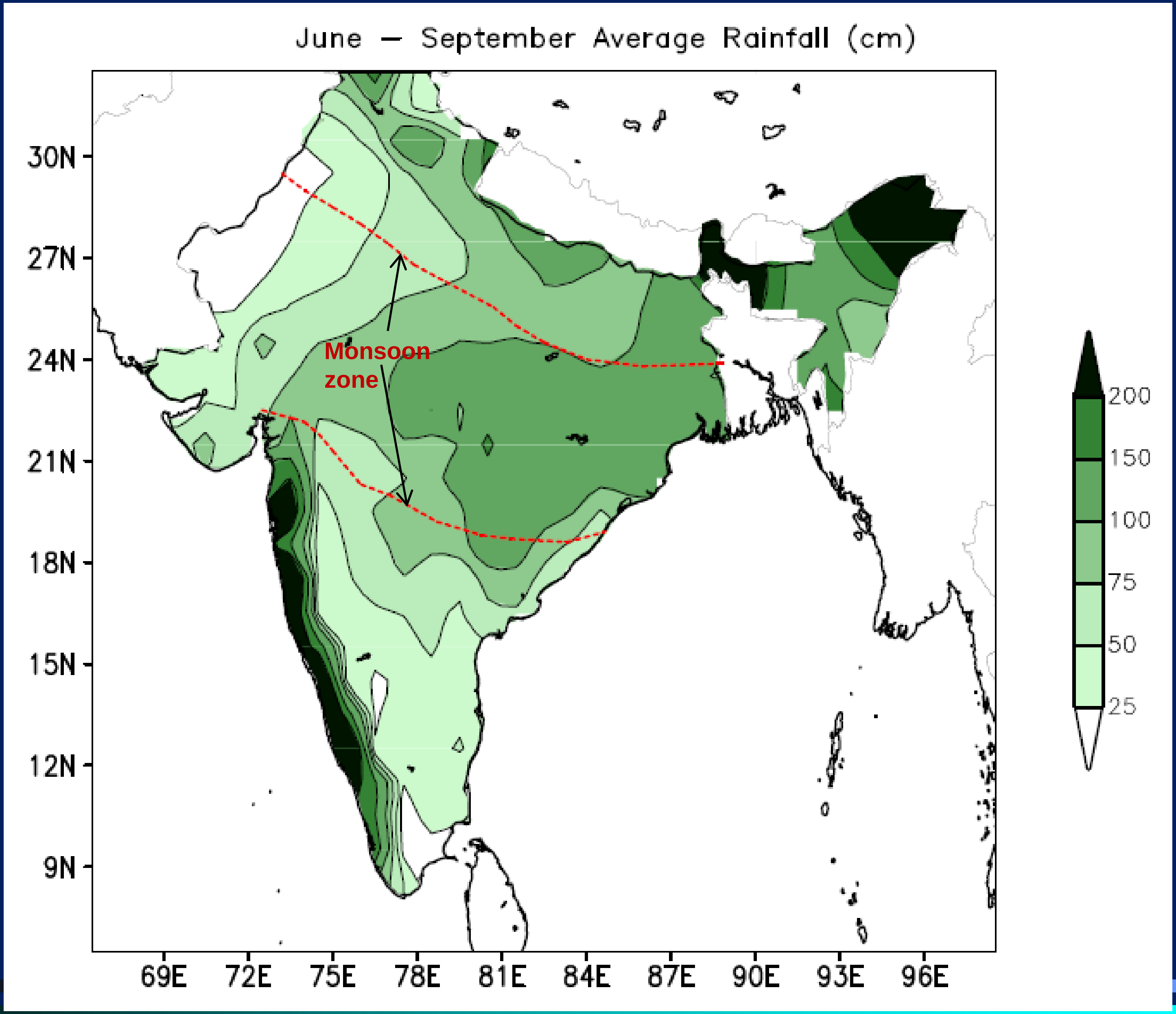
"Southwest monsoon" (*Misnomers*) "Northeast Monsoon"

Monsoonal Regions of the World: Ramage



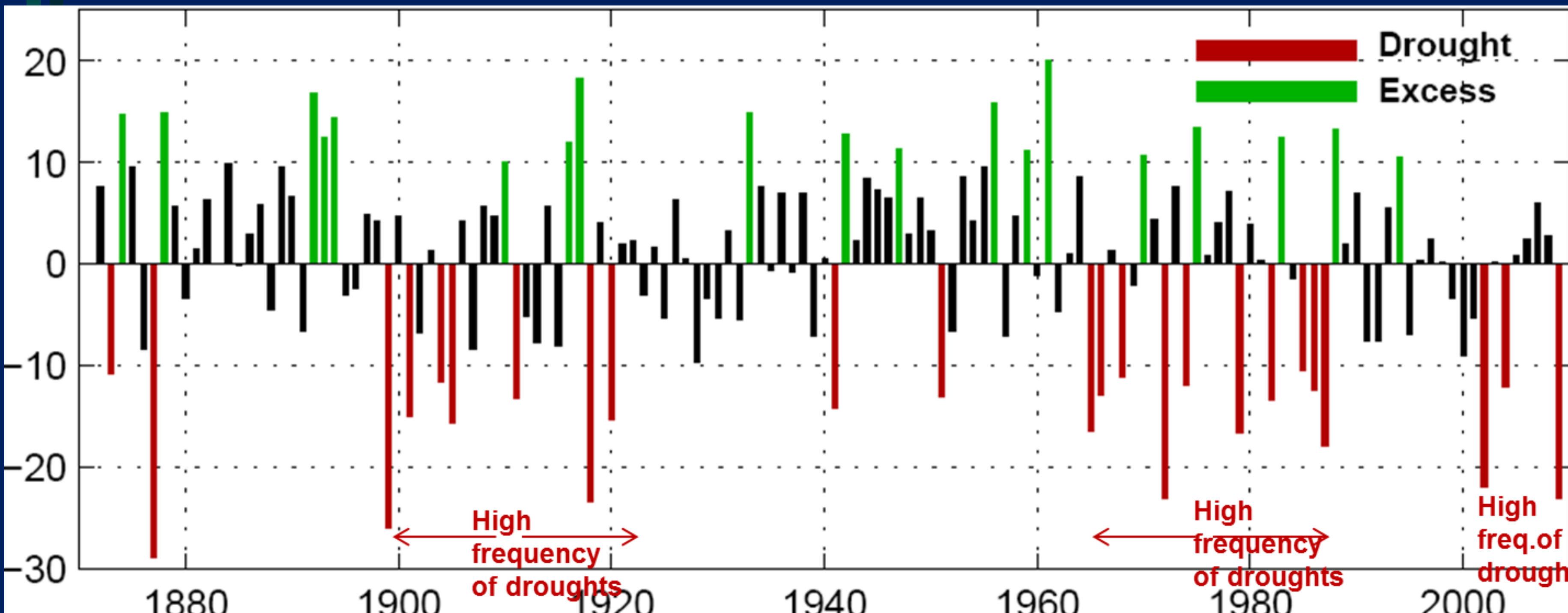
Indian region is near the centre

Spatial Pattern of the mean summer monsoon rainfall (cm)



- It is seen that the mean rainfall pattern during the summer monsoon is characterized by a major rain-belt over the ‘monsoon zone’ (marked by the red-dashed line), with the rainfall decreasing northwestward from the maximum over the eastern part. Identifying the system responsible for this large-scale monsoon rainfall has been addressed since 1686. I shall talk about our understanding of this critical issue today.
- In addition, heavy rainfall occurs along the west coast of the peninsula and over the northeastern region.
- .

Interannual Variation of the anomaly of ISMR (as % of the mean) during 1876-2010



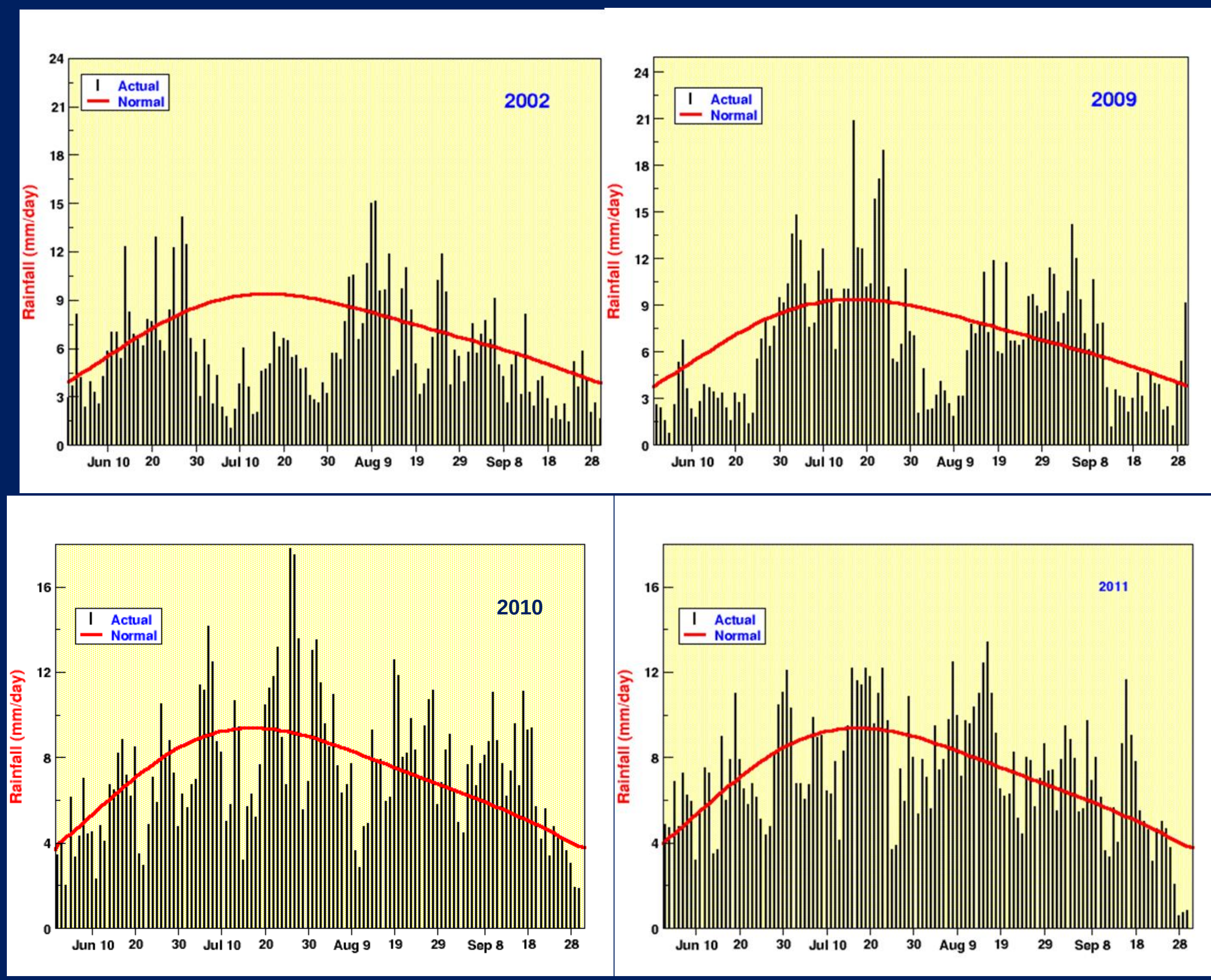
Drought: ISMR anomaly <-10% of the mean

Excess rainfall seasons: ISMR anomaly >10% of the mean

Frequent droughts during 1899-1920 (7 in 21 years) ;1965-87 (10 in 28years) and again since 2002,

less frequent during 1878-98 (0 in 21years); 1921-64 (2 in 44 years)

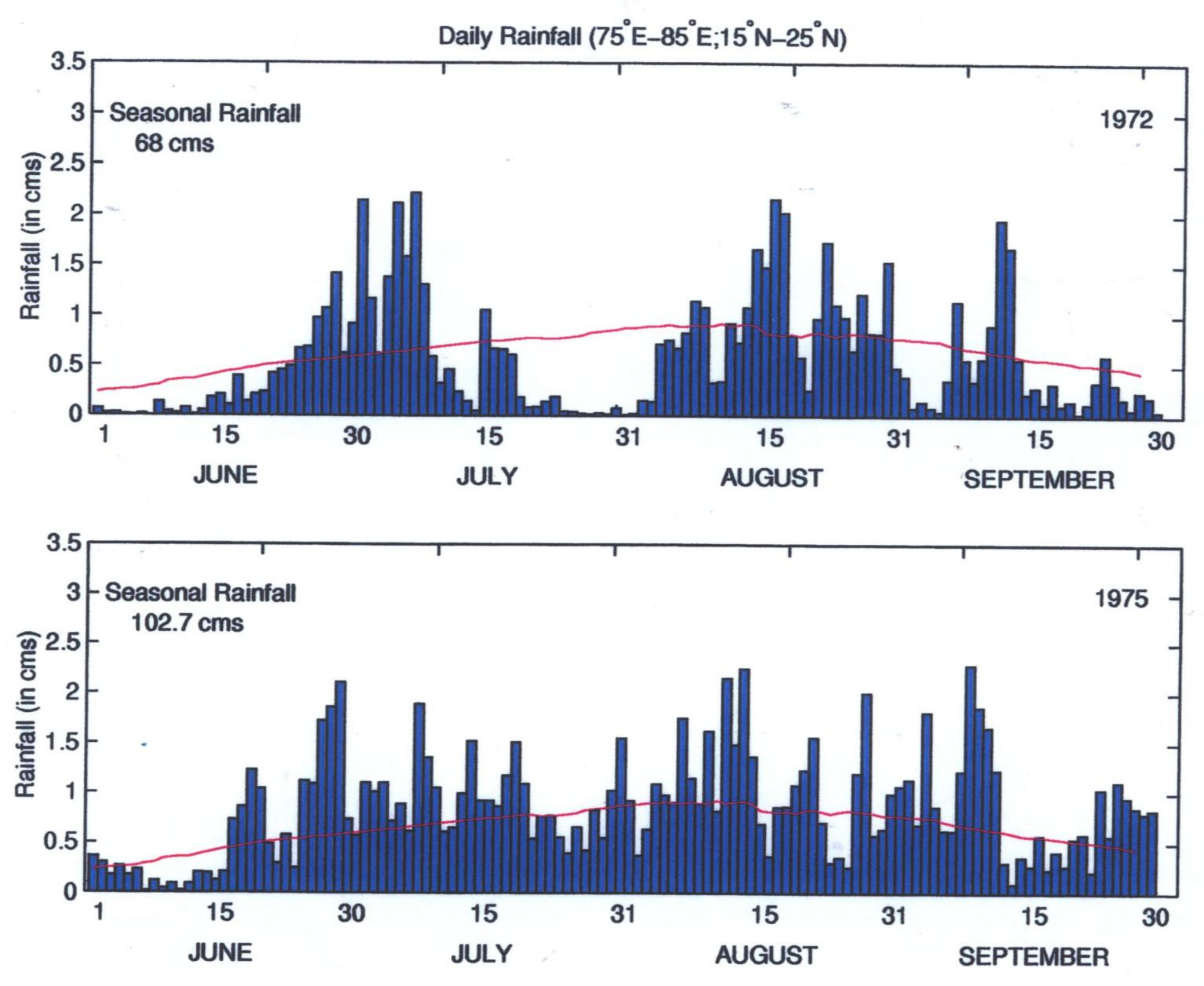
Intraseasonal variation



Droughts: ISMR deficit >20%

Normal monsoon seasons ISMR: 2% above normal

Variation of the daily rainfall over central India



Drought

Excess Rainfall season

System responsible for the monsoon

- Two hypotheses
- The first hypothesis first proposed in 1686 attributes the monsoon to a system special to the monsoonal region
- The second hypothesis attributes the monsoon to a larger amplitude seasonal response of a system which is also present elsewhere over the tropics

First Hypothesis

Over three hundred years ago, in 1686, Edmund Halley (better known for the comet named after him) published a paper entitled

“An historical account of the trade-winds and monsoons observable in the seas between and near the tropics with an attempt to assign the physical cause of the said winds”

***Phil. Trans. Roy. Soc. London vol16*, p153-168 (1686)**

in which he suggested that the primary cause of the monsoon was the differential heating between ocean and land.

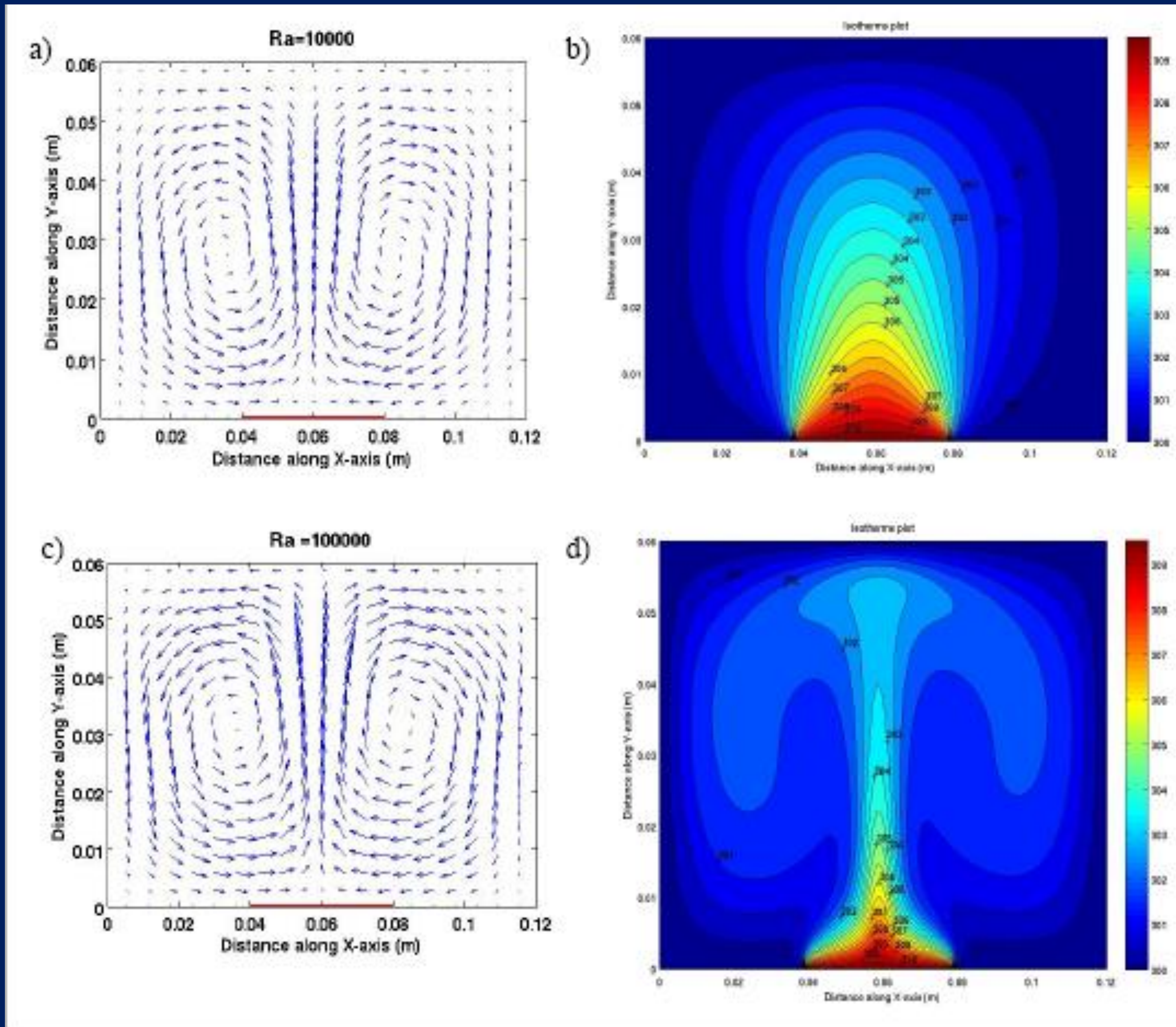
Differential heating, according to Halley, would cause pressure differences in the atmosphere and winds blowing from the high pressure to the low pressure.

Monsoon – A Gigantic Land-Sea Breeze?

- Halley and many scientists after him considered the monsoon to be a gigantic land-sea breeze in which the ascent of air (and hence clouds and rainfall) over the heated land is generated by the land-ocean temperature contrast.

- In 1735 Hadley modified the theory to incorporate the impact of the Coriolis force arising from the rotation of the earth, (which is important for the spatial scales of thousands of kilometers characterizing the monsoon circulation) on the direction of the winds .
- Thus the zeroth order model is

Response of a fluid to differential heating from below



Benard convection

Implications for variability: expect the ascent/rainfall to increase with increasing land-ocean temperature contrast.

However, observations of the space-time variations of the monsoon over the Indian region are not consistent with this expectation.

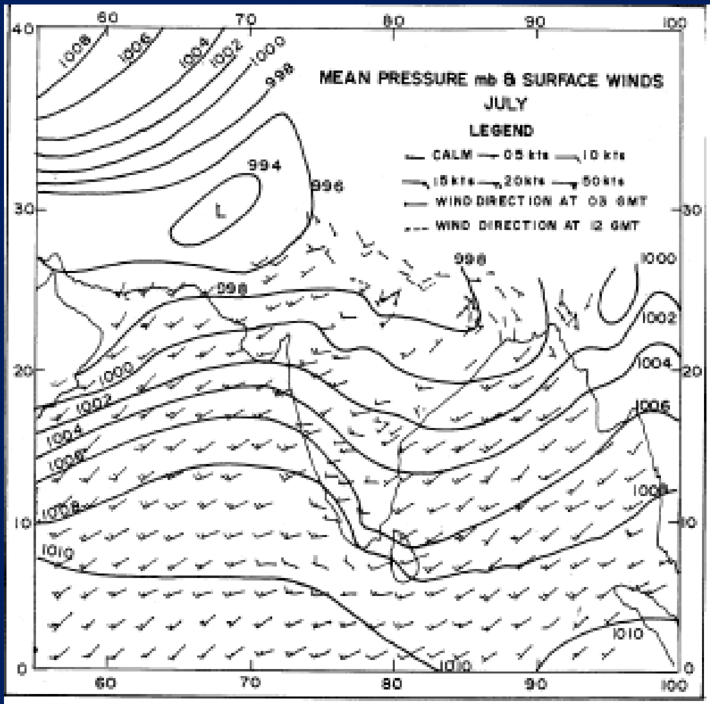
This was first pointed out by G. Simpson

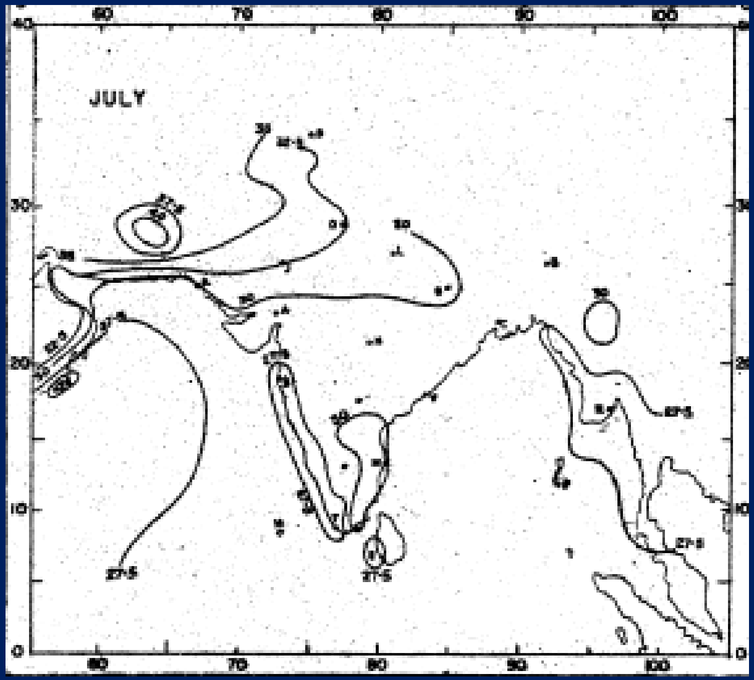
(‘The South-West Monsoon’, QJRMS, Vol.17, pp.150–73, 1921 **). In his words**

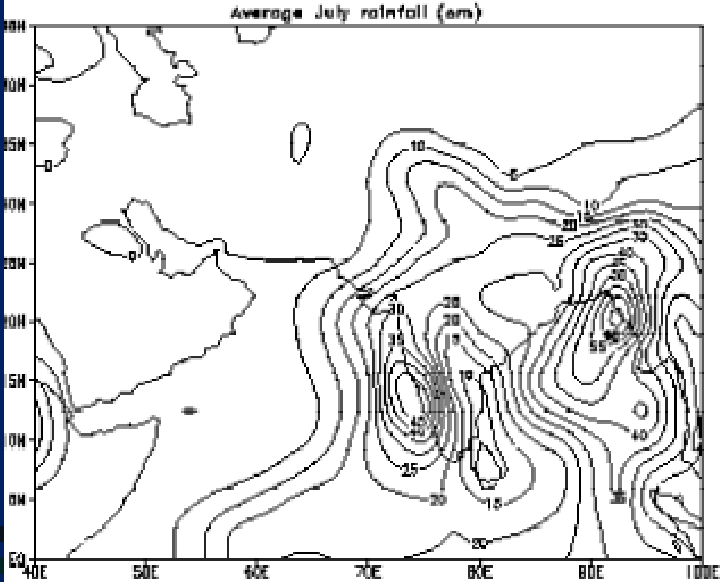
“I believe very few educated people would have any difficulties in giving an answer to the question what is the cause of the monsoon?

- ***They would refer to the high temperature over the land compared with that over the surrounding seas; would speak of ascending currents of air causing an indraft of sea-air towards the interior of the country.***

- ***It is only when one points out that India is much hotter in May before the monsoon sets in than in July , when it is at its height – or draws attention to the fact that the hottest part of India – the northwest gets no rain at all during the monsoon –***


MEAN PRESSURE mb & SURFACE WINDS
JULY
LEGEND
CALM
WIND DIRECTION AT 03 GMT
WIND DIRECTION AT 12 GMT

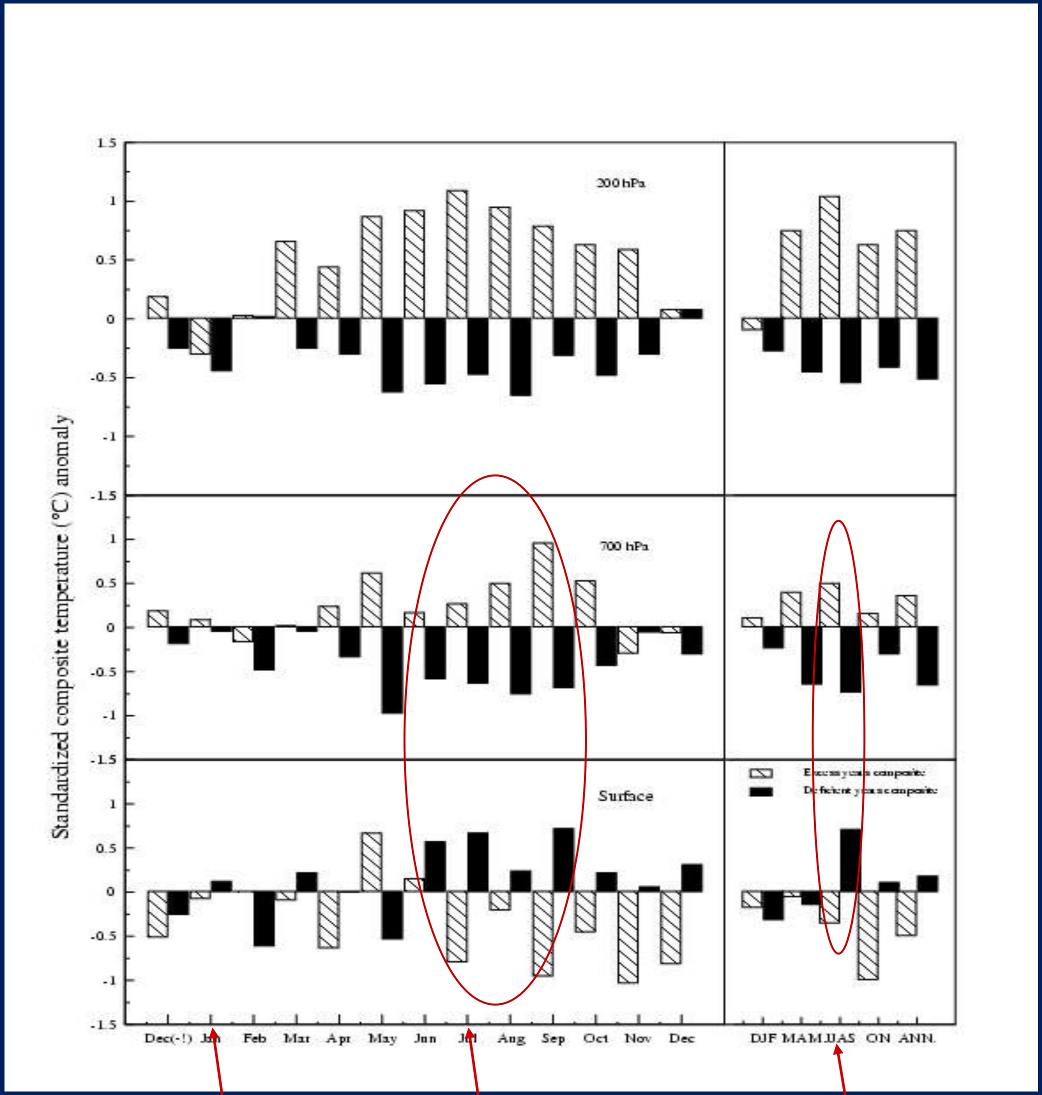

JULY


Average July rainfall (cm)

- ***or shows by statistics that the average temperature is much greater in years of bad rains than in years of good rains, that they begin to doubt whether they know the real cause of the monsoon.”***
- **Such statistics was generated by Kothawale & Rupakumar (2002) who showed that the surface temperature anomaly is positive for droughts and negative for excess monsoon seasons (next slide)**

Temperature anomalies for seasons with deficit rainfall (solid) & excess rainfall (hatched)

Note that deficit (excess) rainfall is associated with warmer (cooler) surface temp. and cooler (warmer) temp at 700 and 200hpa levels.



200 hpa

700 hpa

Surface

Jan

Jul

JJAS

Kothawale & Rupakumar 2002

This is consistent with our experience in the rainy season, that days without rain are hotter than rainy days. Clearly, rather than the land surface temperature determining the amount of rainfall via the impact on the difference between land and ocean temperature, the land temperature is determined by the rainfall (or lack thereof).

Thus, the observations suggest that the land surface temperature varies in response to the variation in rainfall and it is not appropriate to consider land-ocean temperature contrast as a cause of the monsoon rains. In other words, the observations are not consistent with the land-sea breeze hypothesis.

Several scientists, to this day consider the differential heating between land and ocean to be the primary cause of the monsoon.

For example :

1. ‘The elementary monsoon’ by P J Webster in ‘Monsoons’ edited by J. Fein and Pamela Stephens

Wiley- Interscience 1987;

2.‘Effect of tropical topography on global climate’ by G. A. Meehl, Ann. Rev. Earth Planet. Sci 1992

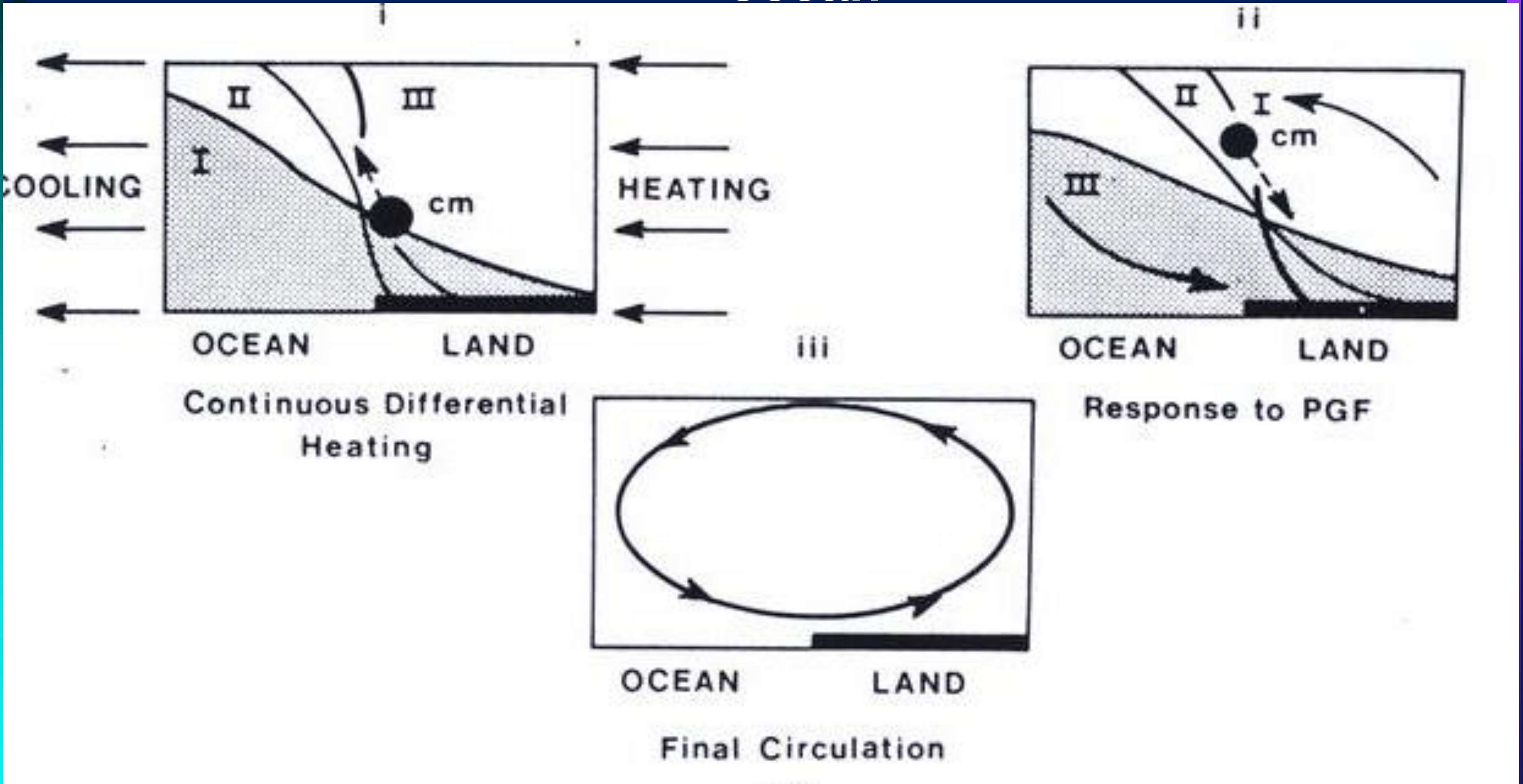
It is also thus discussed included in most textbooks e.g. James, I. N. Introduction to circulating atmospheres, Cambridge University Press 1994

Webster* (1987) considered the zeroth order model of the monsoon to be a response to the differential heating associated with land-ocean temperature contrast.

Then he added the effects of moisture and rotation.

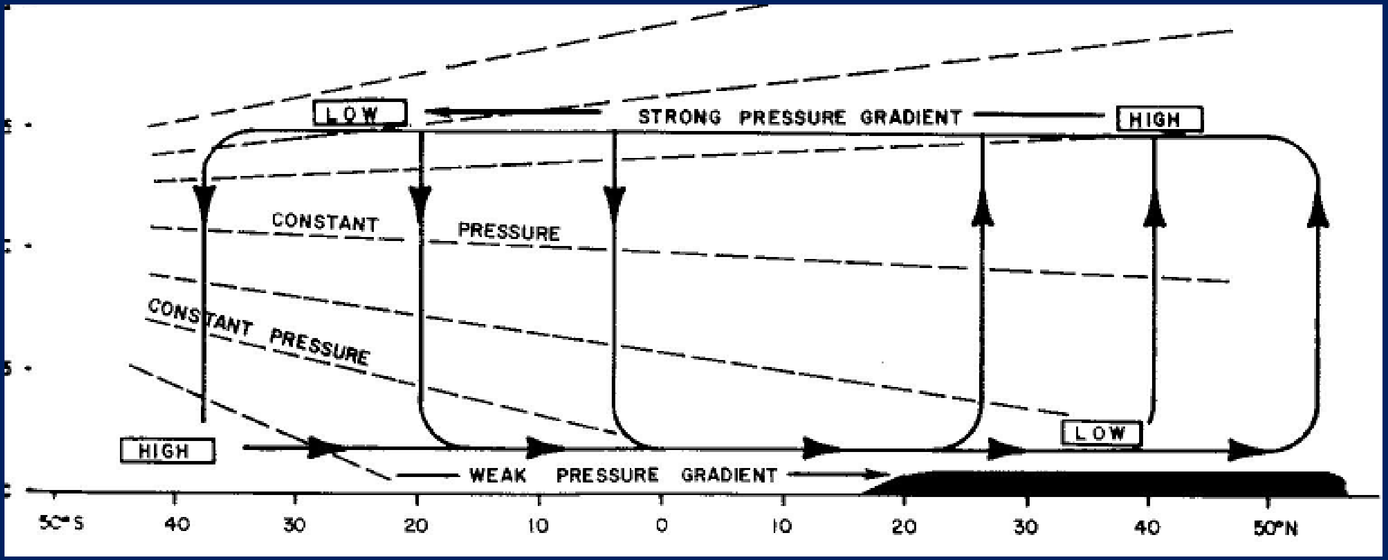
***'The elementary monsoon' P J Webster (1987) in Monsoons edited by Fein and Stephens.**

Impact of continuous differential heating over land and ocean

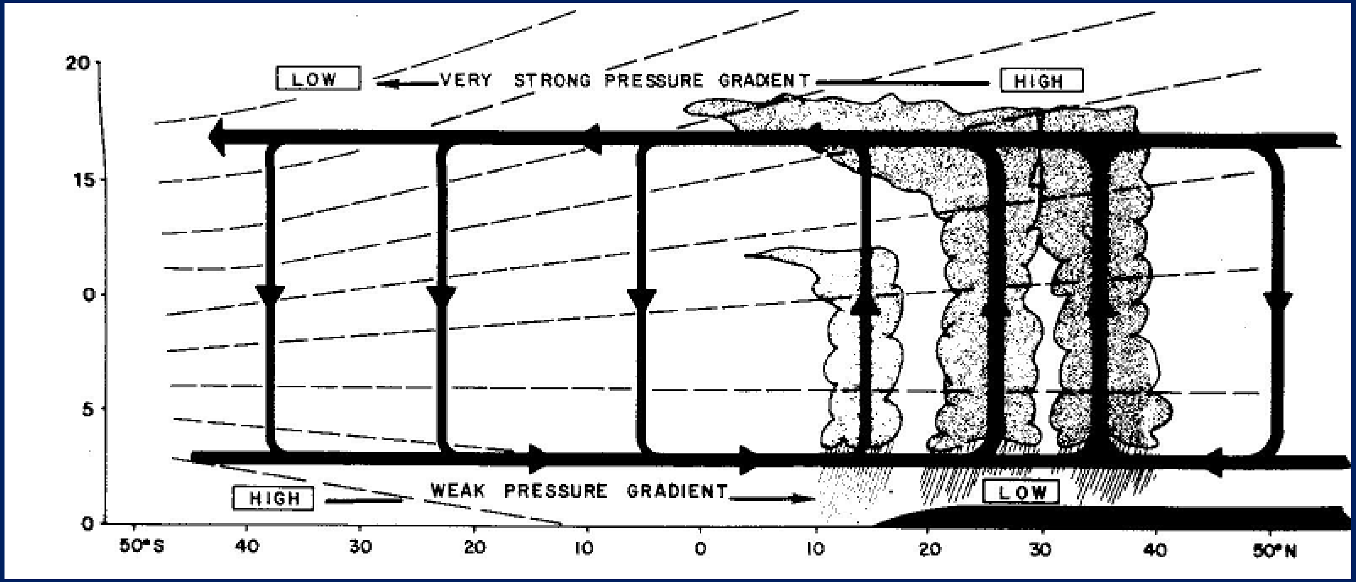


(b)

From



Dry monsoon

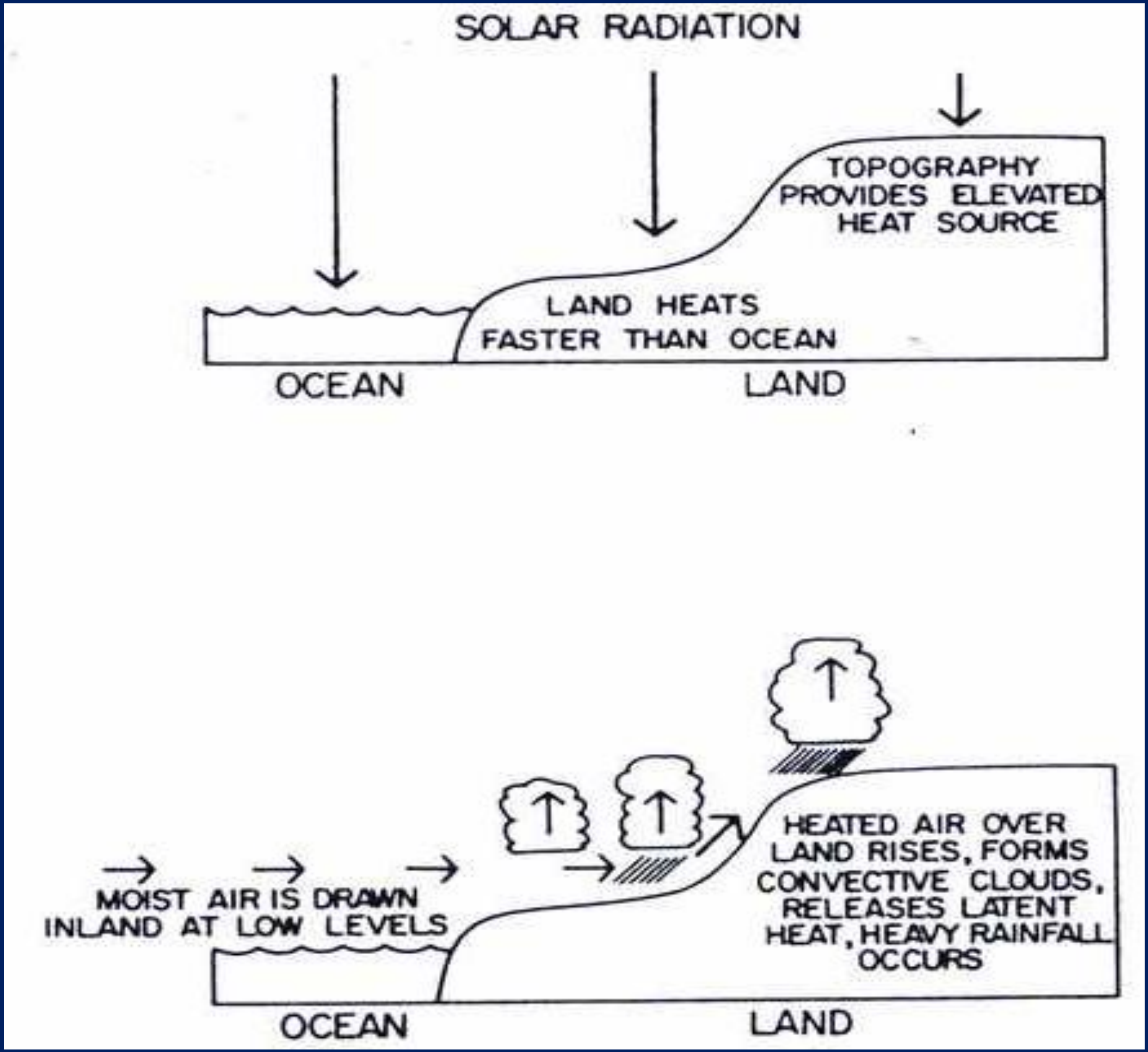


Moist monsoon

Webster 1987

Meehl (Rev. Earth Pla. Sci, 1992) added another important factor viz. topography.

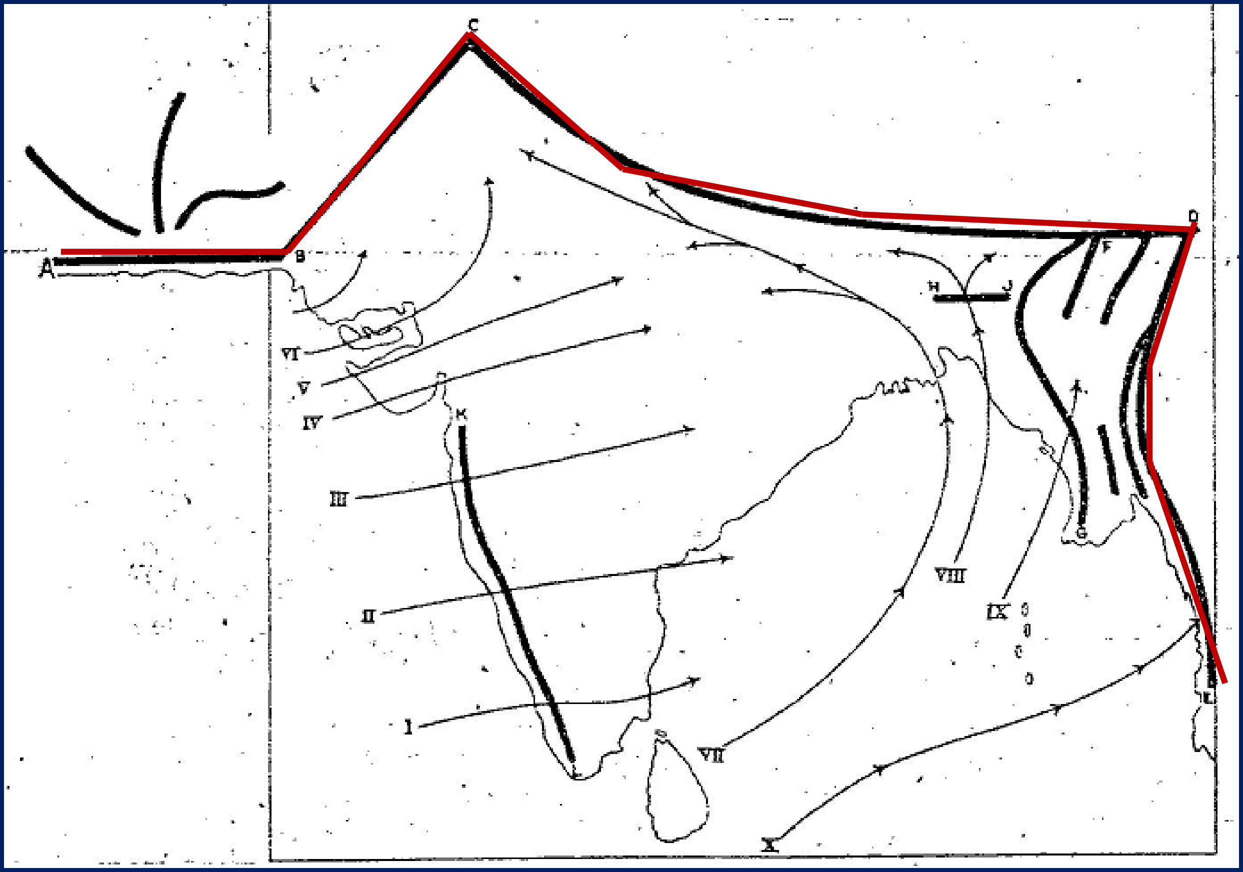
“Tropical topography can intensify the solar heating over land by providing an elevated heat source. This magnifies the regional scale land-sea temperature contrast and facilitates the onset and maintenance of monsoon regimes that can produce convective rainfall and latent heating.”



From Meehl 1992

Why was Simpson's criticism ignored?

Perhaps, because it was in a paper in which he proposed an alternative hypothesis, which was not acceptable. He suggested that the mountain-ranges (in red)



are equivalent to two sides of a box into which the air streams through the other two sides. There are no openings in these two sides.

According to him ‘the heavy rain (characterizing the monsoon) is caused by the inflow of large quantities of damp warm air into a region where, on account of the peculiar distribution of mountain ranges, it is forced to ascend and in consequence deposit its moisture as rain.’

The actual temperature over the Indian land area is not directly responsible for the ascensial currents which cause the rain; on the contrary in the regions where the rainfall is prevented, the temperature is abnormally high, while the greatest rainfall is accompanied by low temperatures.’

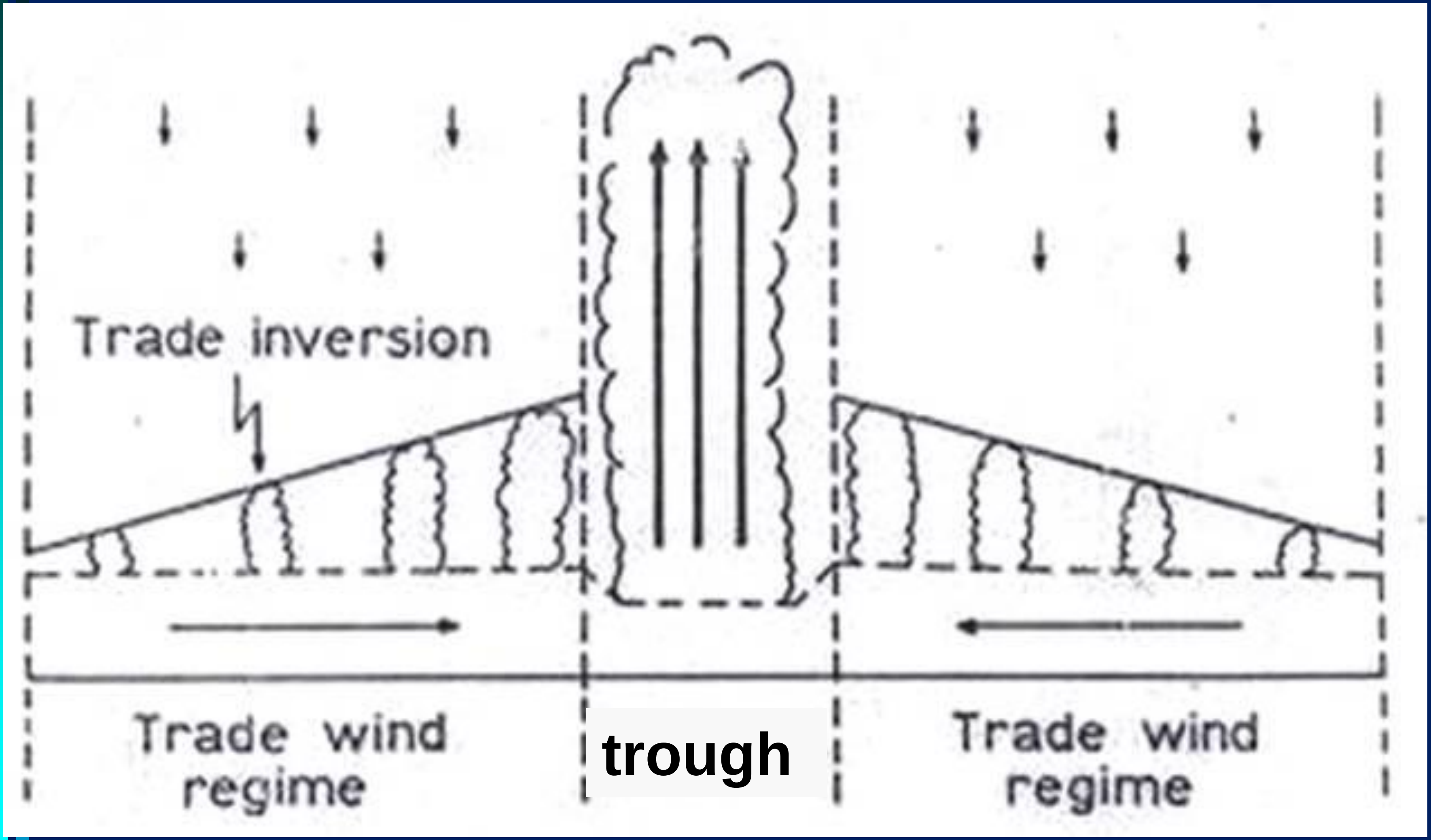
In any event, Simpson's valid criticism of the land-sea breeze model for the monsoon appears to have been ignored by almost all the scientists.

Not surprisingly, in several papers (e.g. Ramanathan et al for aerosol impact) it is claimed that since there is an impact on the land-sea temperature contrast, there will be an impact on the Indian monsoon.

Alternative hypothesis

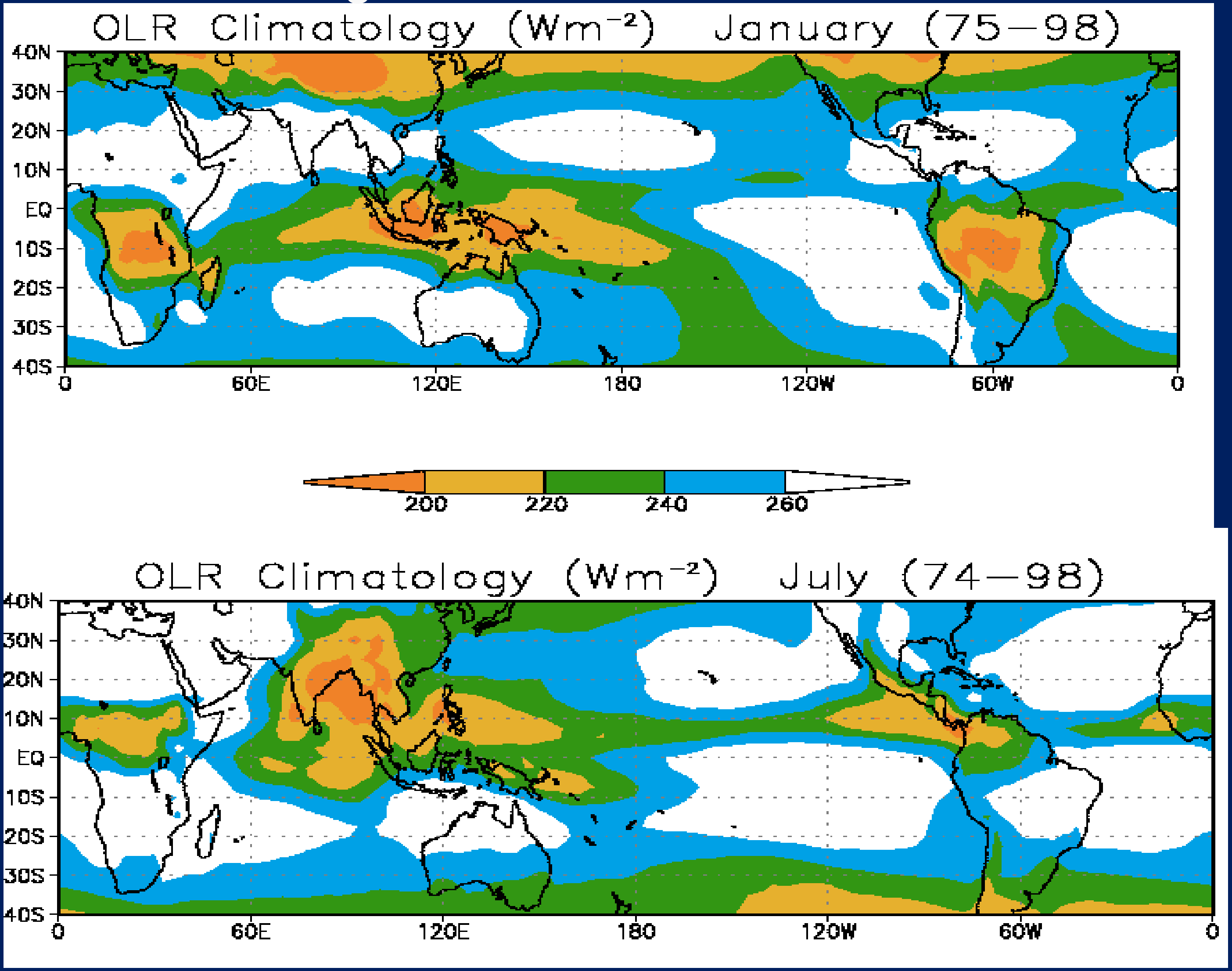
- According to the second hypothesis, the monsoon is a manifestation of the seasonal variation of the tropical circulation in response to the seasonal variation of the solar radiation.
- The monsoon is attributed to the seasonal migration of the ITCZ (a la Charney) or the equatorial trough (a la Riehl) or near equatorial trough (a la Ramage) i.e. rising limb of the Hadley cell, onto the monsoonal region in the summer.
- I believe that this was Charney and Riehl's perception of the monsoon since 1970s.

Hadley cell: schematic picture



However, there have been serious objections to attributing the monsoon to seasonal migration of the ITCZ.

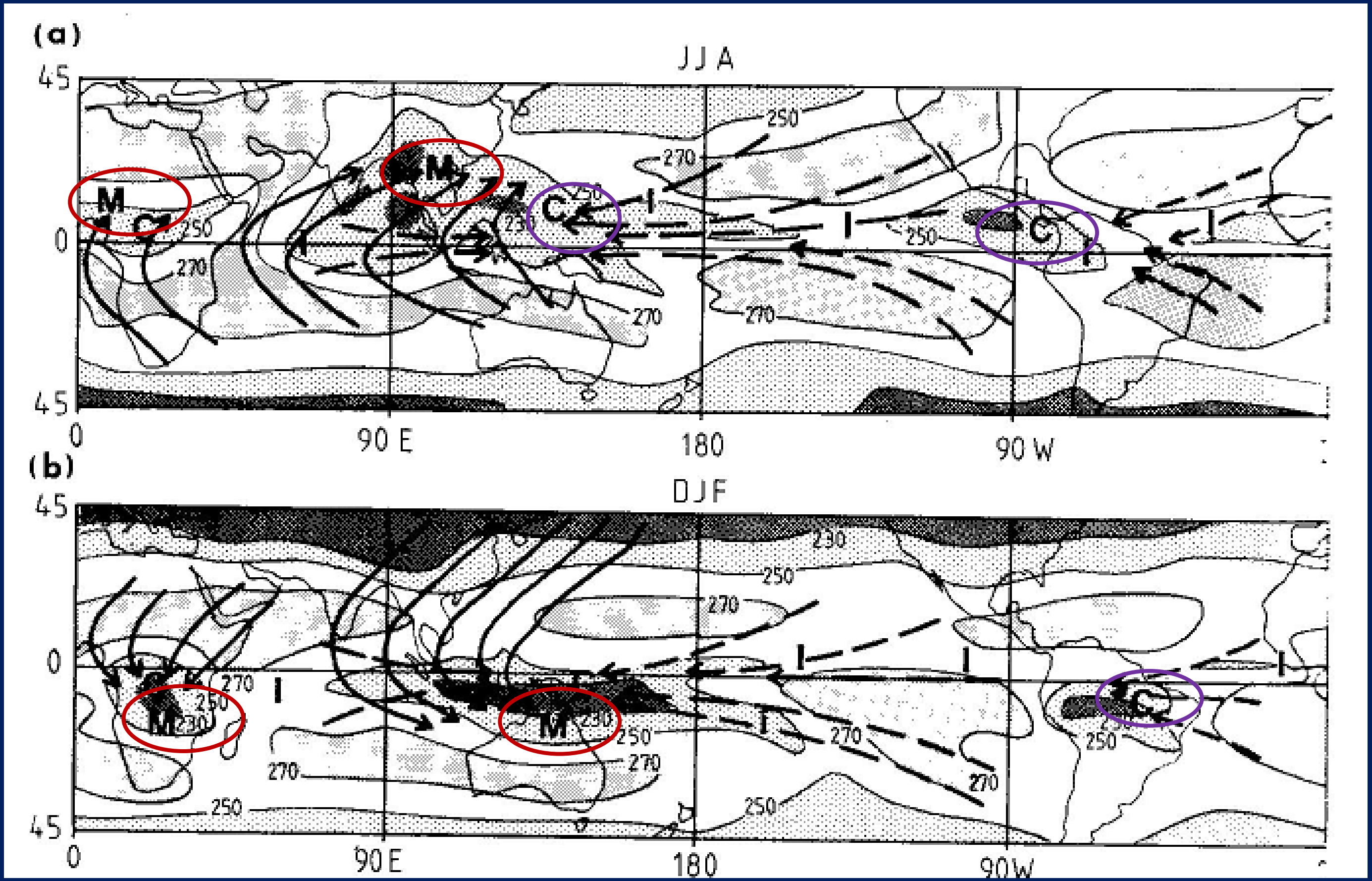
Note the large latitd-extent of the low OLR region in July over 70E-100E



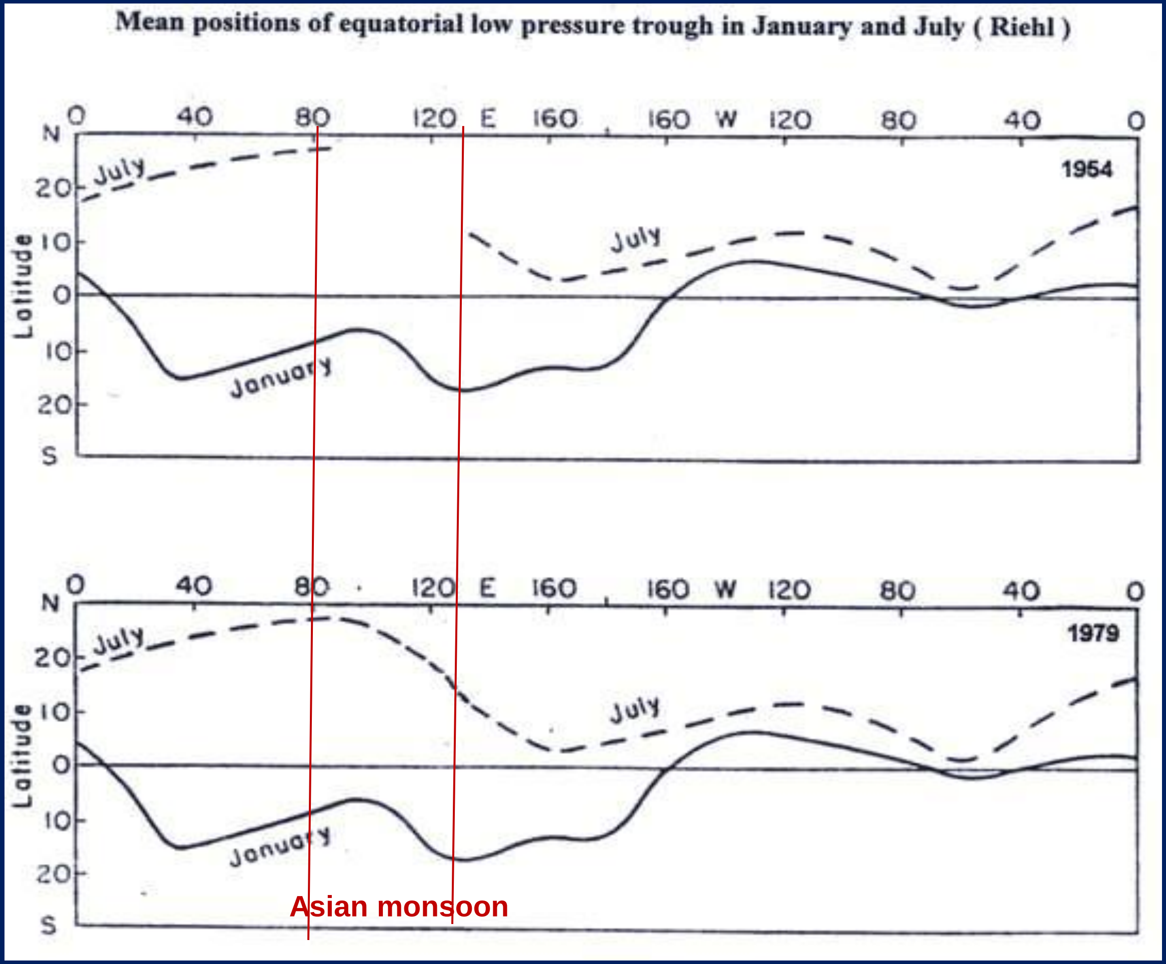
Murakami 1987 (in Monsoon Meteorology edited by Chang and Krishnamurthy, Oxford univ. Press) states

“Over the Indian Ocean, a persistent, belt-shaped distribution of low IR values can be seen mainly during the winter (December to February) season along the area connecting northern Madagascar and Sumatra. The lack of a similar distribution during the summer (June to August) season indicates that the ITCZ over the Indian Ocean changes its existence drastically from winter to summer .”

In the depiction by Webster (1987, The variable and interactive monsoon in Monsoons ed. by Fein and Stephens) of the tropical OLR patterns and streamlines, the monsoonal regions (denoted by M) are shown as distinct from those associated with the canonical ITCZ (denoted by C).



It appears that even Riehl got convinced that the basic system over the monsoonal regions was the equatorial trough sometime between 1954 and 1979



- **Sikka and Gadgil's* (1980) study of the daily (i) satellite imagery over the Indian longitudes and (ii) the variation of the 700 mb trough, an important feature of the monsoon circulation which is associated with moist convection, showed that the organized moist convection associated with the monsoon trough can be attributed to a continental ITCZ over the region.**

- ***Sikka DR and Sulochana Gadgil, 1980. On the maximum cloud zone and the ITCZ over India longitude during the Southwest monsoon. Mon. Weather Rev.,108, 1840-53***

Indian monsoon

- **Sikka and Gadgil (henceforth SG) showed that:**
- **(i) In satellite imagery the cloud-band over the Indian region during the summer monsoon looks very similar to that associated with the classic ITCZ over the Pacific and also that over the equatorial Indian Ocean in the pre-Monsoon (April) .**

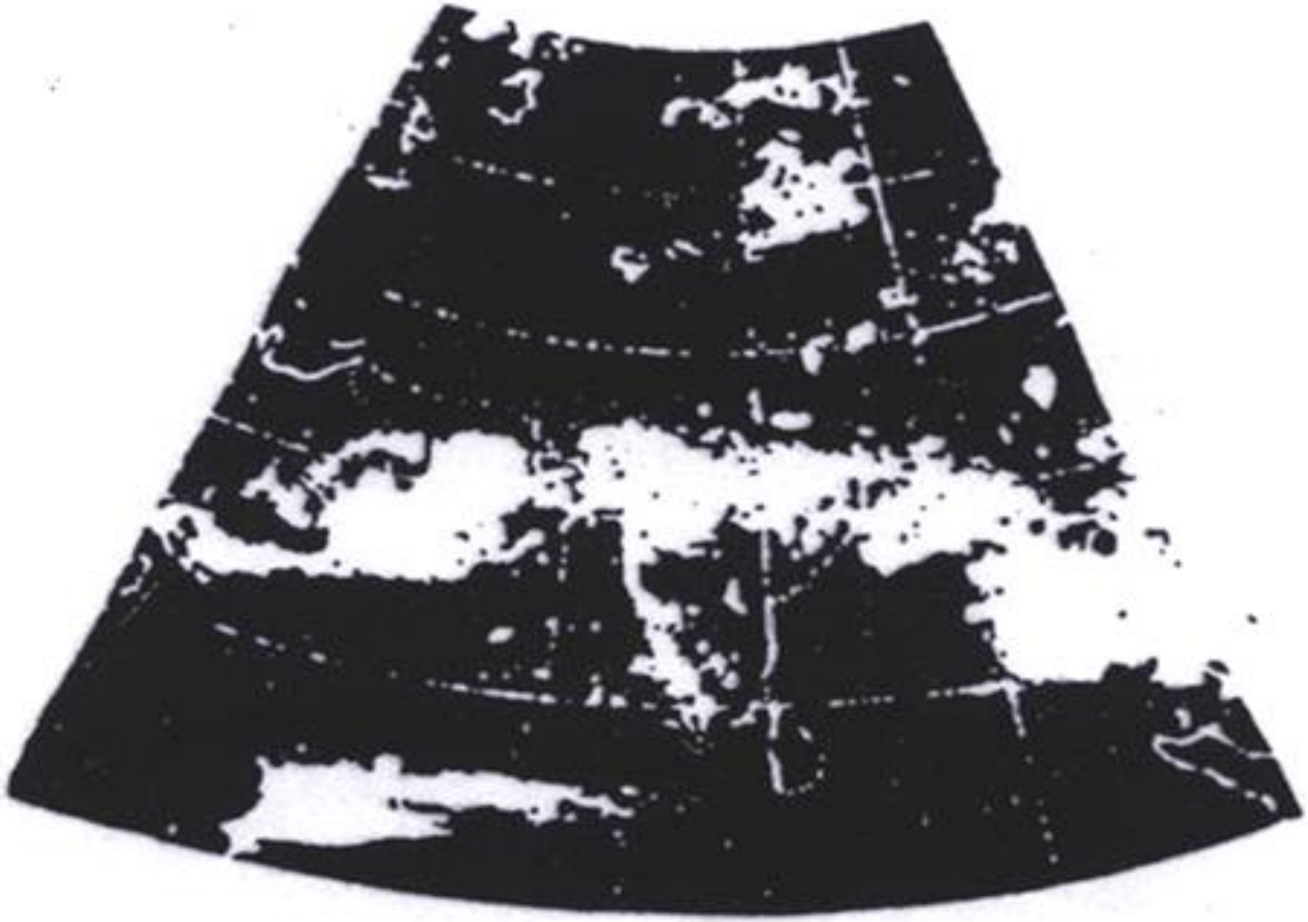


Fig 6. Satellite imagery of an active monsoon day (8th july 1973).

ITCZ over the Pacific

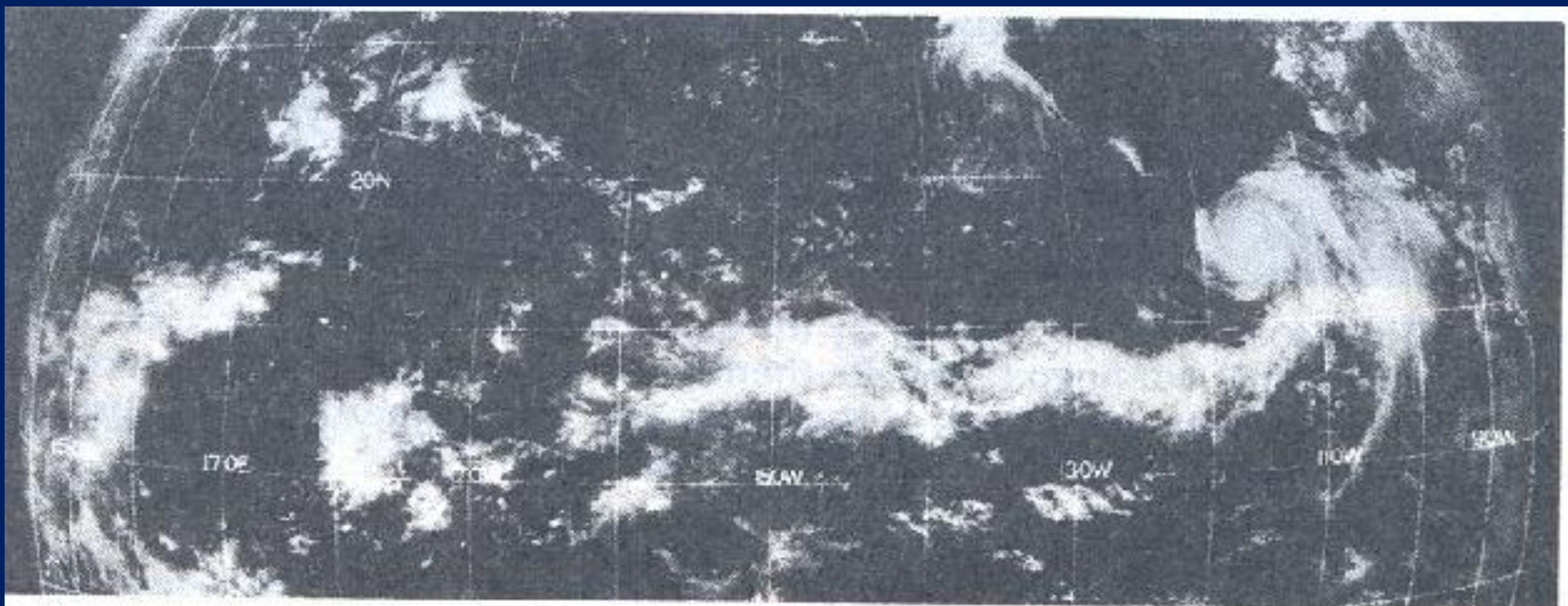
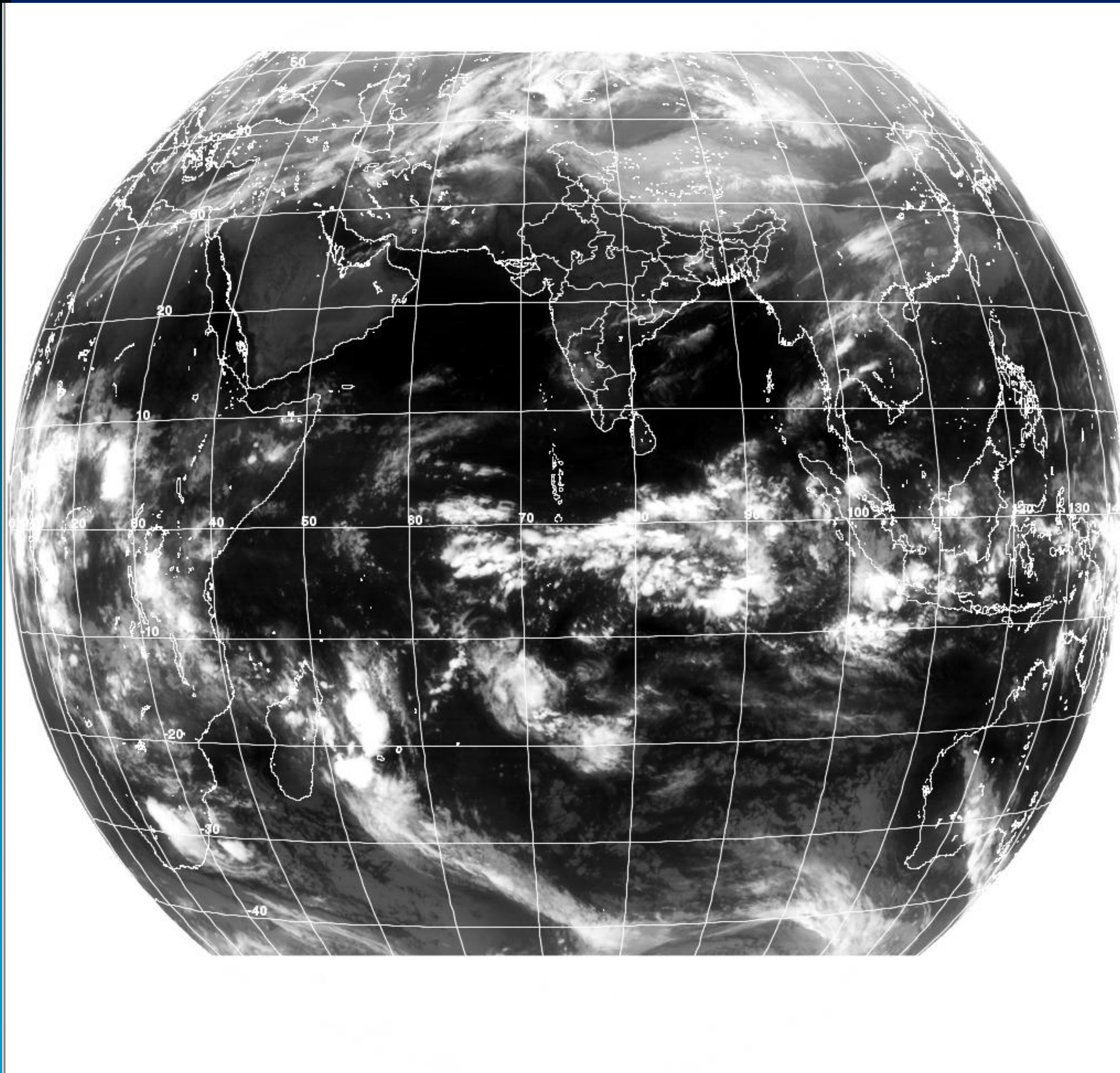
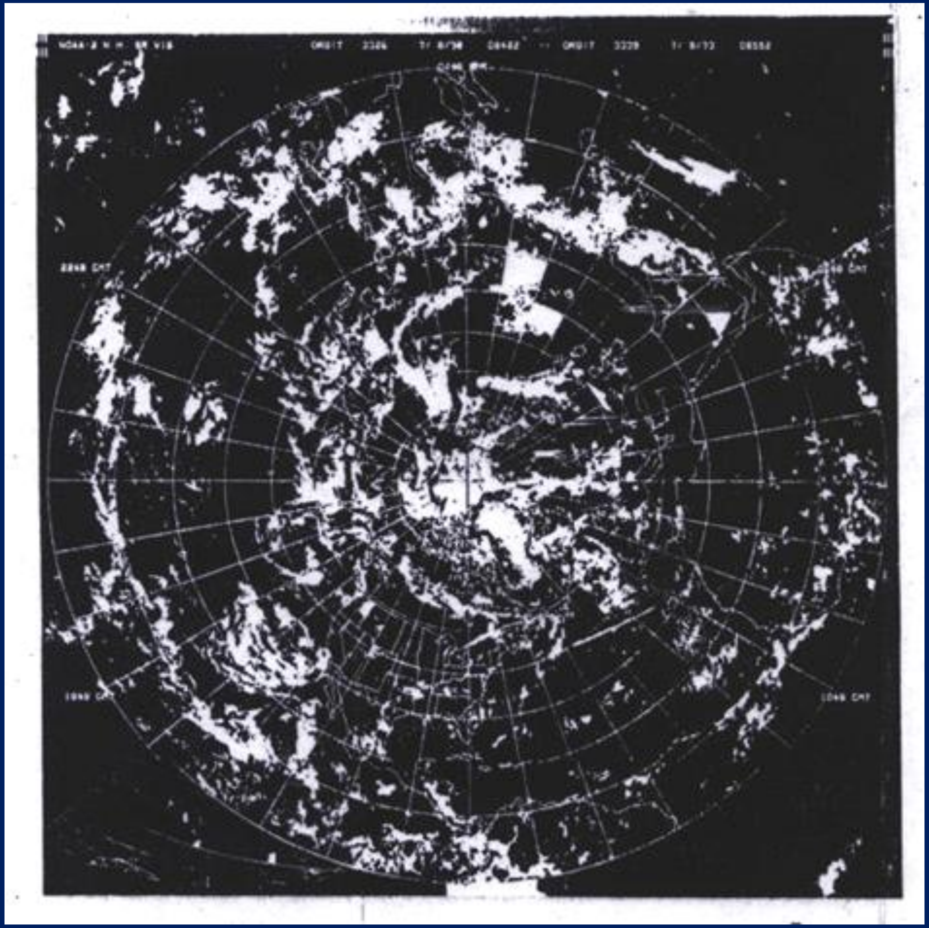


Fig 7 of Srinivasan & Gadgil



ITCZ over the equatorial Indian Ocean 16 March 2010

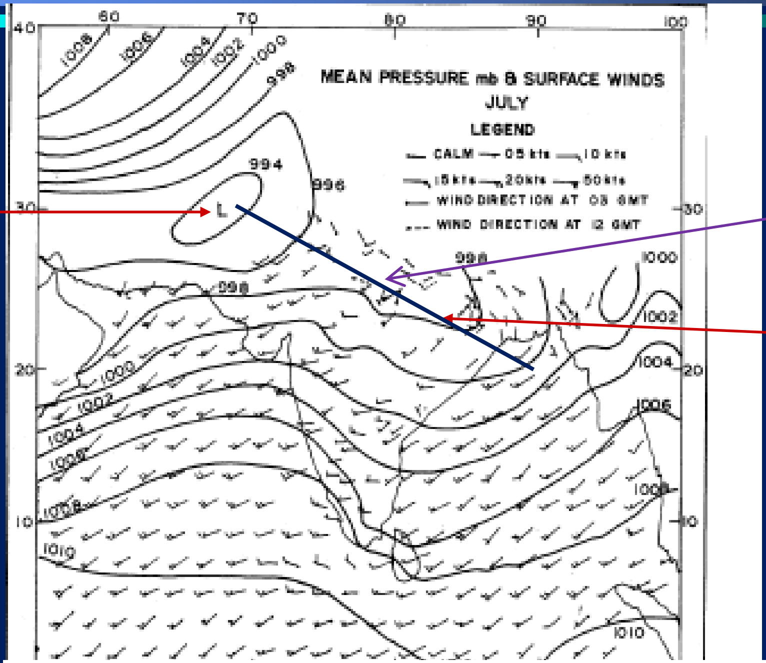
In fact, the cloud-band over the Indian region often extends eastward over the tropical Pacific and on occasion, as far as the east Pacific.



- **Intertropical/tropical convergence zones (ITCZ/TCZ)**

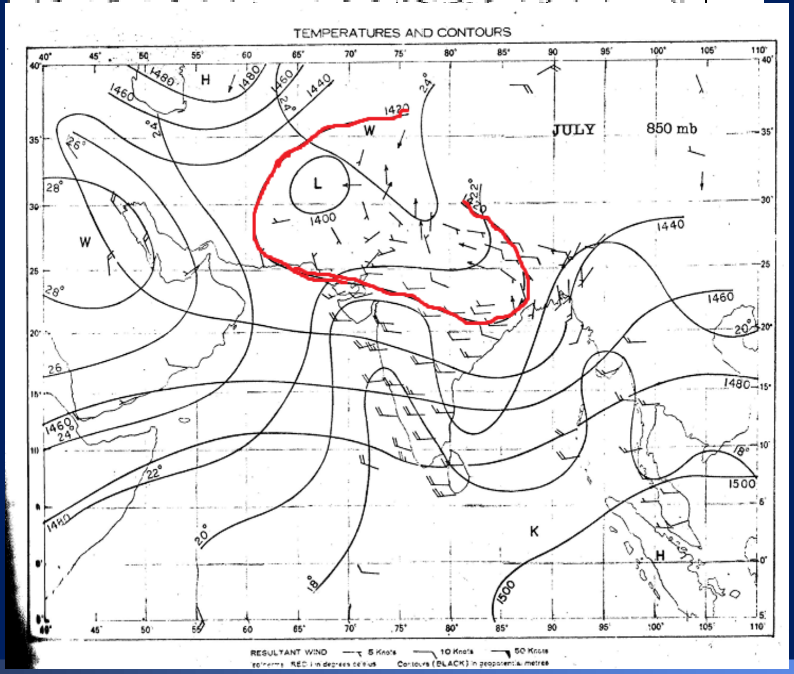
- **Note that, intense convergence in the boundary layer (which is associated in rotating systems with) cyclonic vorticity above the boundary layer, deep convection and heavy precipitation are considered to be important attributes of the ITCZ by Charney.**
- **However, while cyclonic vorticity at 850 mb is a necessary condition for organized convection, it is not a sufficient condition. It can also be associated with a heat low/trough. Heat lows/troughs are characterized by a shallow overturning cell with ascent from the surface restricted to the lower 2 kms or so and fair weather with no rainfall.**

Heat low



Surface trough

Dynamic low (TCZ)



850mb

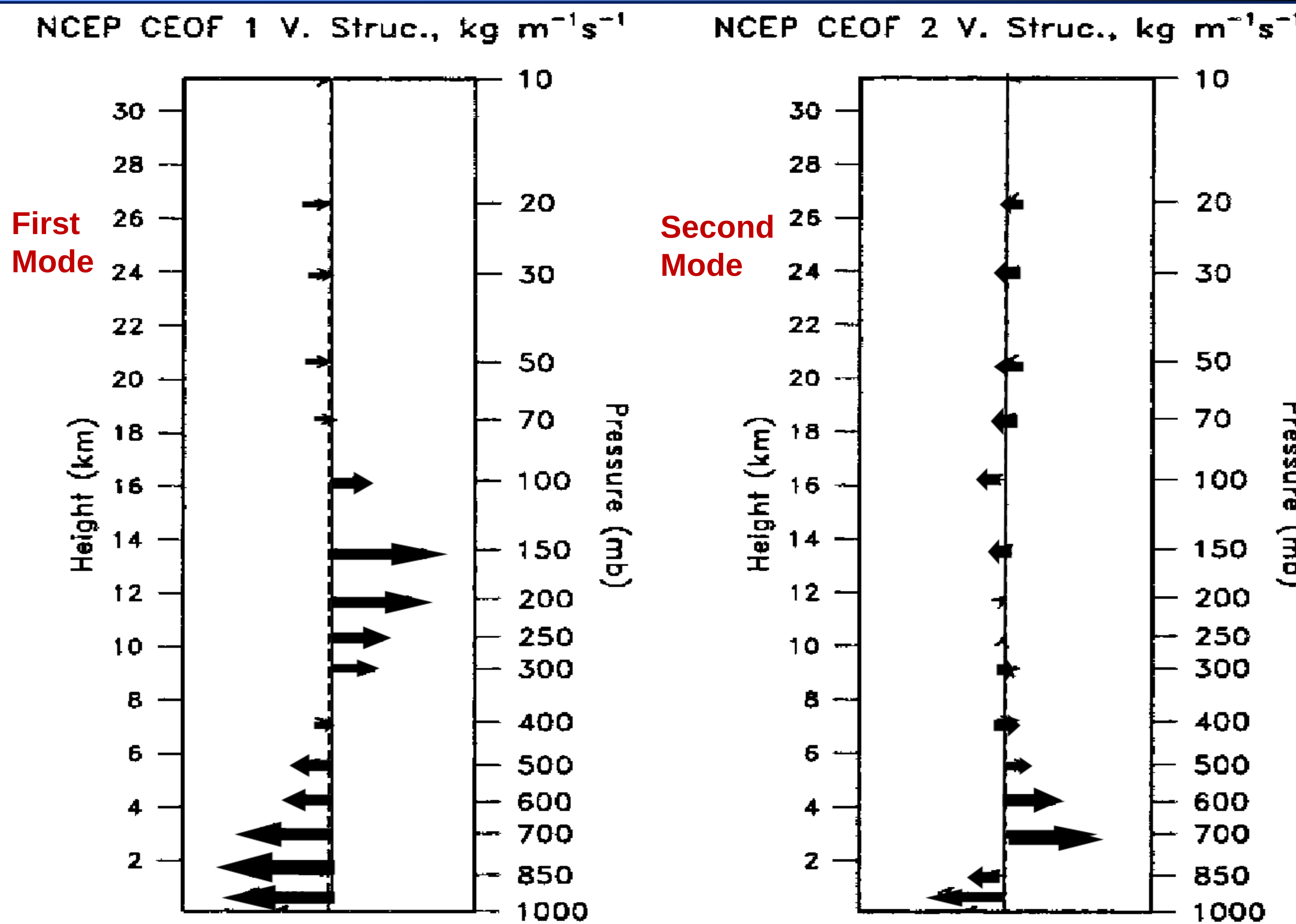
An analysis which brings out rather nicely the different patterns of overturning associated with the surface trough in the tropics is given in a paper:

"The Global Monsoon as seen through the Divergent Atmospheric Circulation"

By

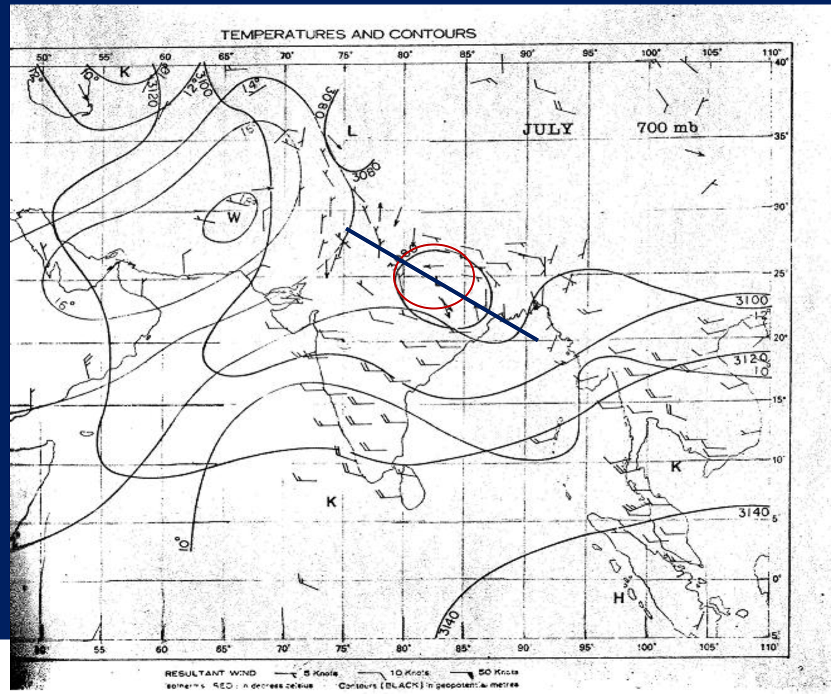
Kelvin E. Trenberth, David P. Stephaniak and Julie M. Caron

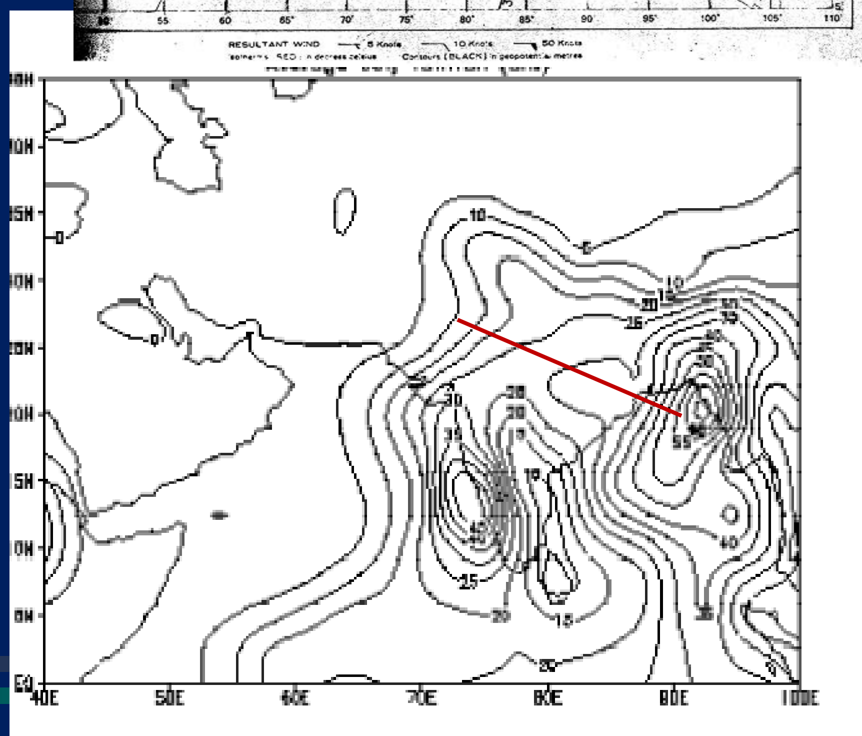
Journal of Climate (2000) 13:3969-3992


NCEP CEOF 1 V. Struc., kg m⁻¹s⁻¹
First Mode
Height (km)
Pressure (mb)
NCEP CEOF 2 V. Struc., kg m⁻¹s⁻¹
Second Mode
Height (km)
Pressure (mb)

60%

20%





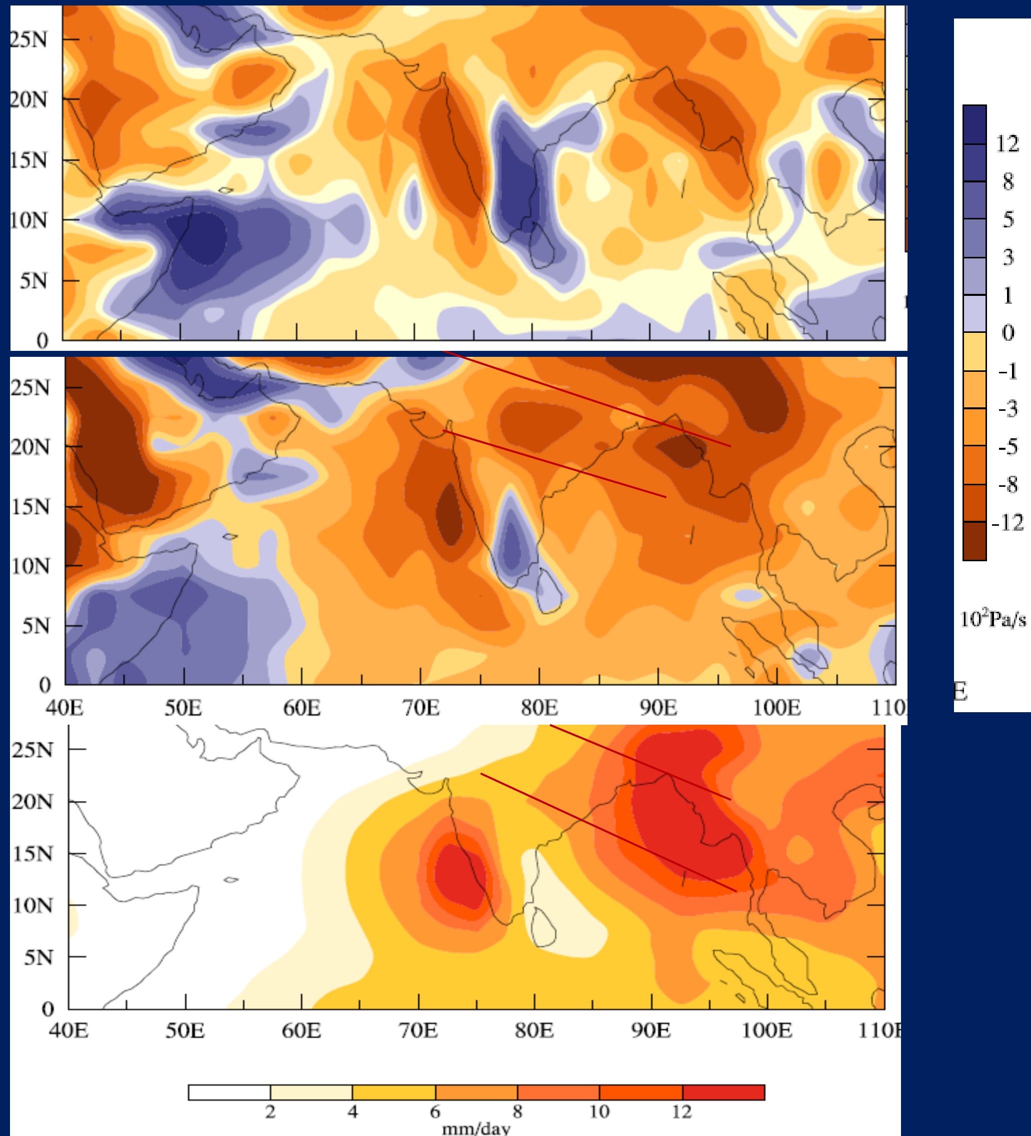
The 700mb trough was known to be associated with the maximum non-orographic rainfall. Hence SG studied the variation of the 700mb trough.

July

vertical velocity
at 850 hpa
(ERA-40)

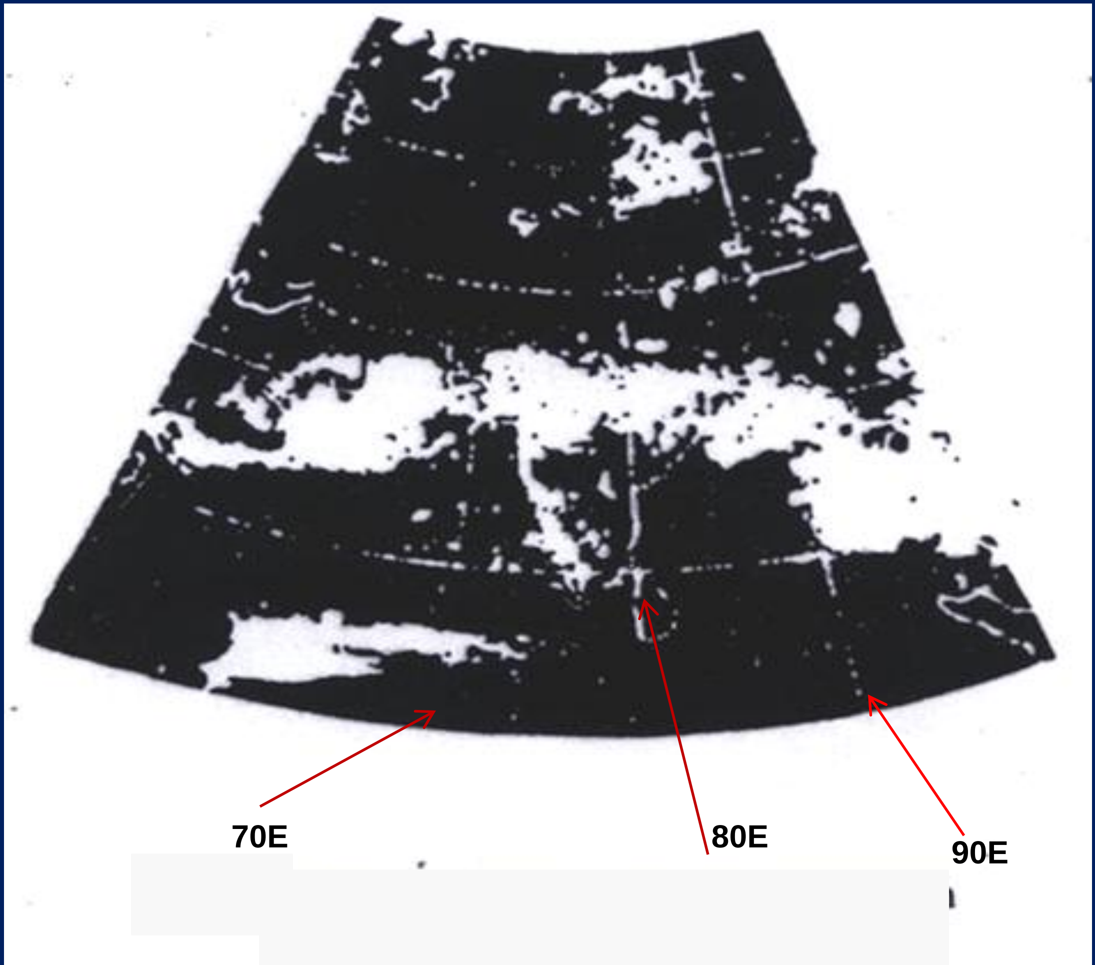
Vertical velocity
At 700 hpa
(ERA-40)

Rainfall (GPCP)



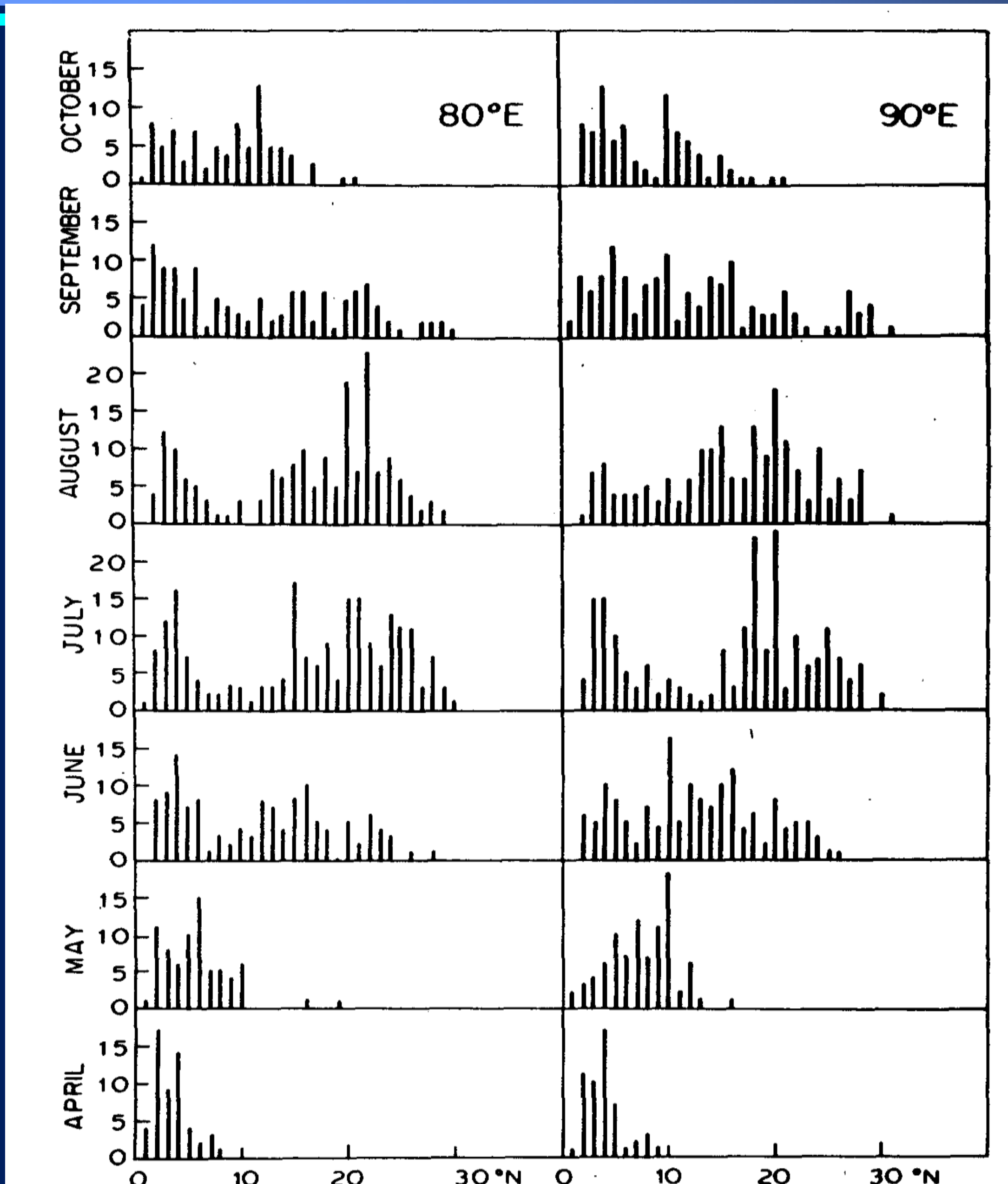
The 700mb trough zone is associated with cyclonic vorticity and convergence and maximum non-orographic precipitation over India.

- **SG studied the daily variation of the maximum cloud zone (MCZ) at 70^0,80^0,90^0E and 700 hpa during April-October 1973-77**



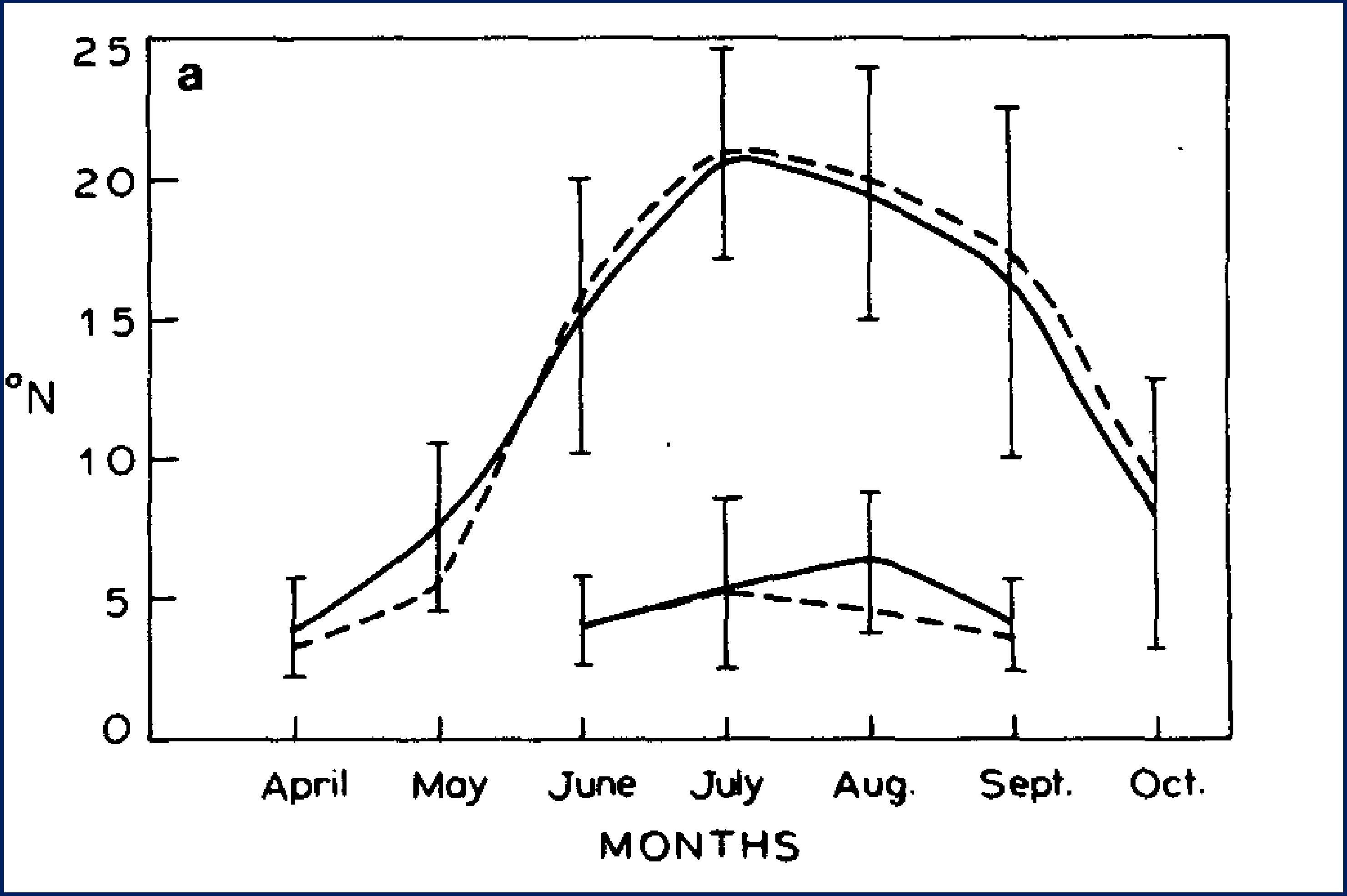
- **The MCZ is taken to be that cloud band which has the maximum brightness, which is predominantly zonal, and has a longitudinal extent of at least 10^0 (e.g. next slide).**
- **Daily values of the latitudes of the northern limit the axis and the southern limit of the MCZ were read off at longitudes 70^0,80^0,90^0E from the cloud mosaics for the period April to October for 1973-1977.**
- **The latitudinal position of the 700 mb trough at these longitudes was obtained from the daily weather charts prepared by the Poona Weather Central of IMD. The 700hpa level was chosen so that the heat trough at lower levels were not included.**

- **Important results**
- **I: Firstly, during June-September, there are two favourable locations for the cloud bands, one over the heated subcontinent and another over the warm waters of the equatorial Indian Ocean.**
- **The low-frequency belt between 7and 13^0 N separates the northern MCZ from the southern one. SG took the minimum occurrence along 90^0E in this band i.e. 7^0N in June and September and 13^0 and 11^0 in July and August, respectively, as the dividing latitude between the two MCZs.**



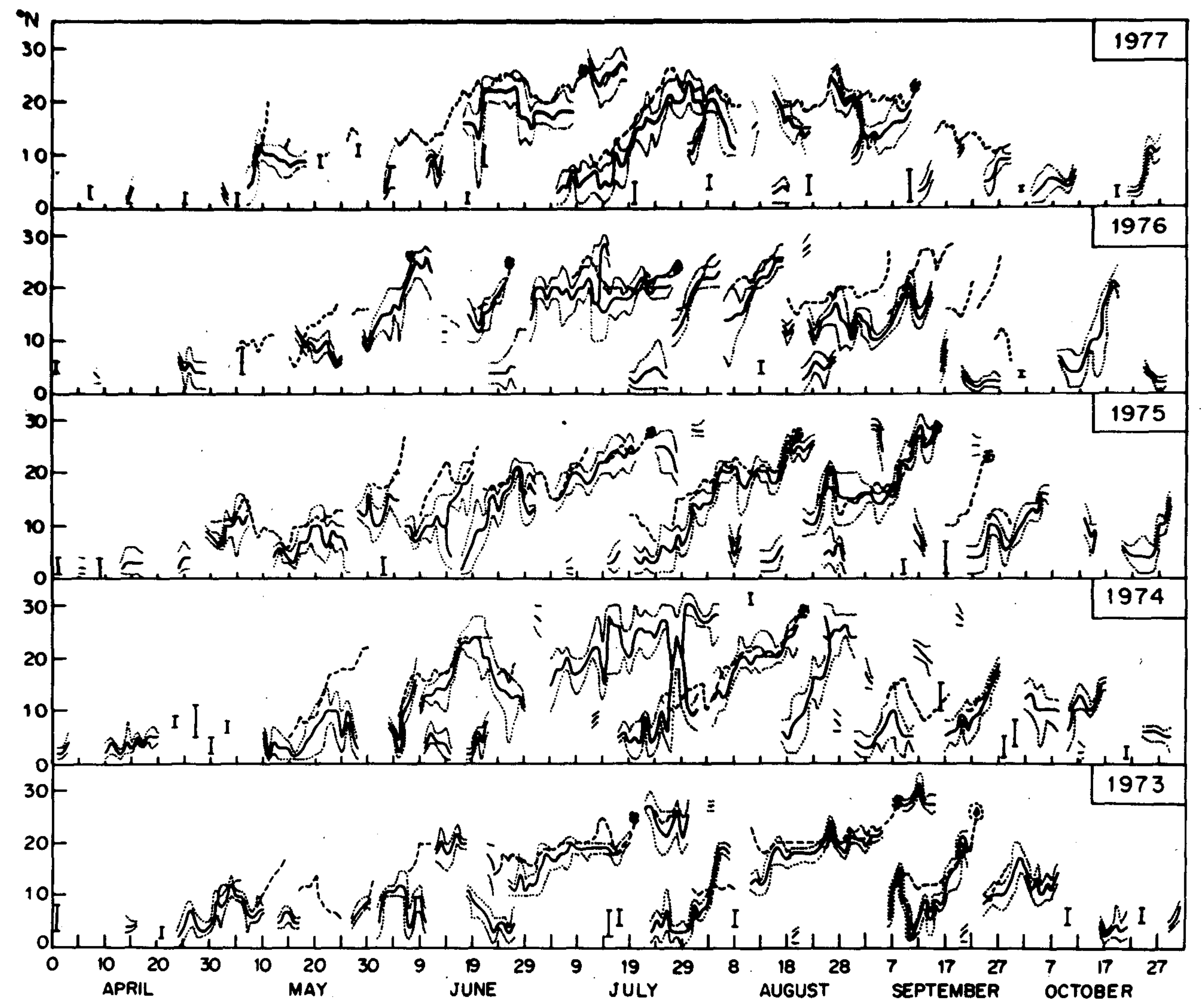
Monthly mean of the number of days on which the number of days on which the axis of the cloud-band occurred at different latitudes along 80^0 E and 90^0E for 1973-77

Seasonal variation of the location of the cloud bands



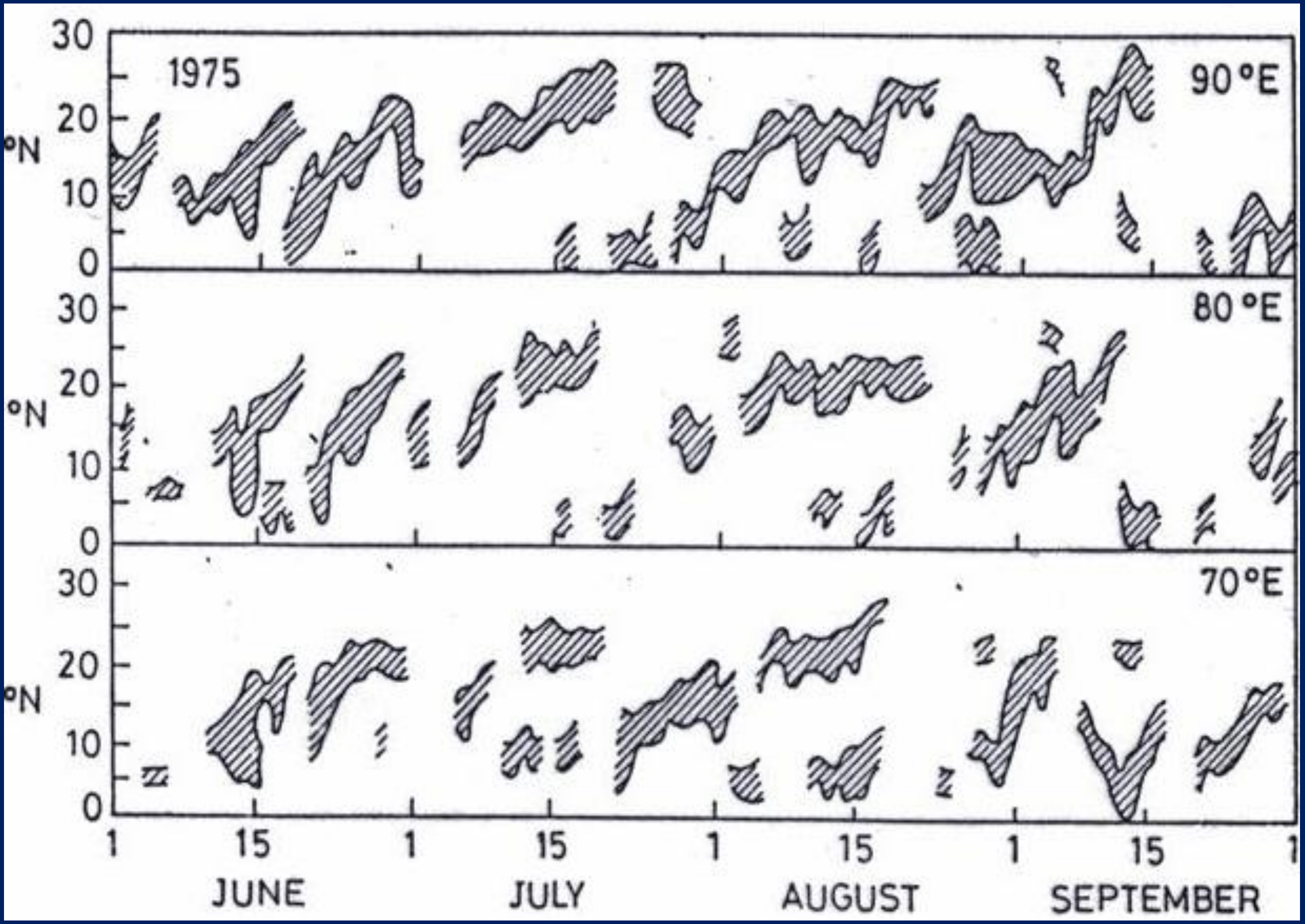
Note that a cloud band over the equatorial Indian Ocean persists throughout the summer monsoon season.

- II: The most prominent feature of the daily variation of the MCZ is a series of northward propagations of the cloud bands from the equatorial Indian Ocean onto the Indian region.
- These propagations are also seen in the daily variation of the 700hpa trough. There is a high correlation between the axes of the MCZ and the 700 hpa trough on a day-to day basis.
- Rate of northward propagations about 1degree per day i.e. a little over 1 m/sec i.e. of the same order of magnitude as MJO.

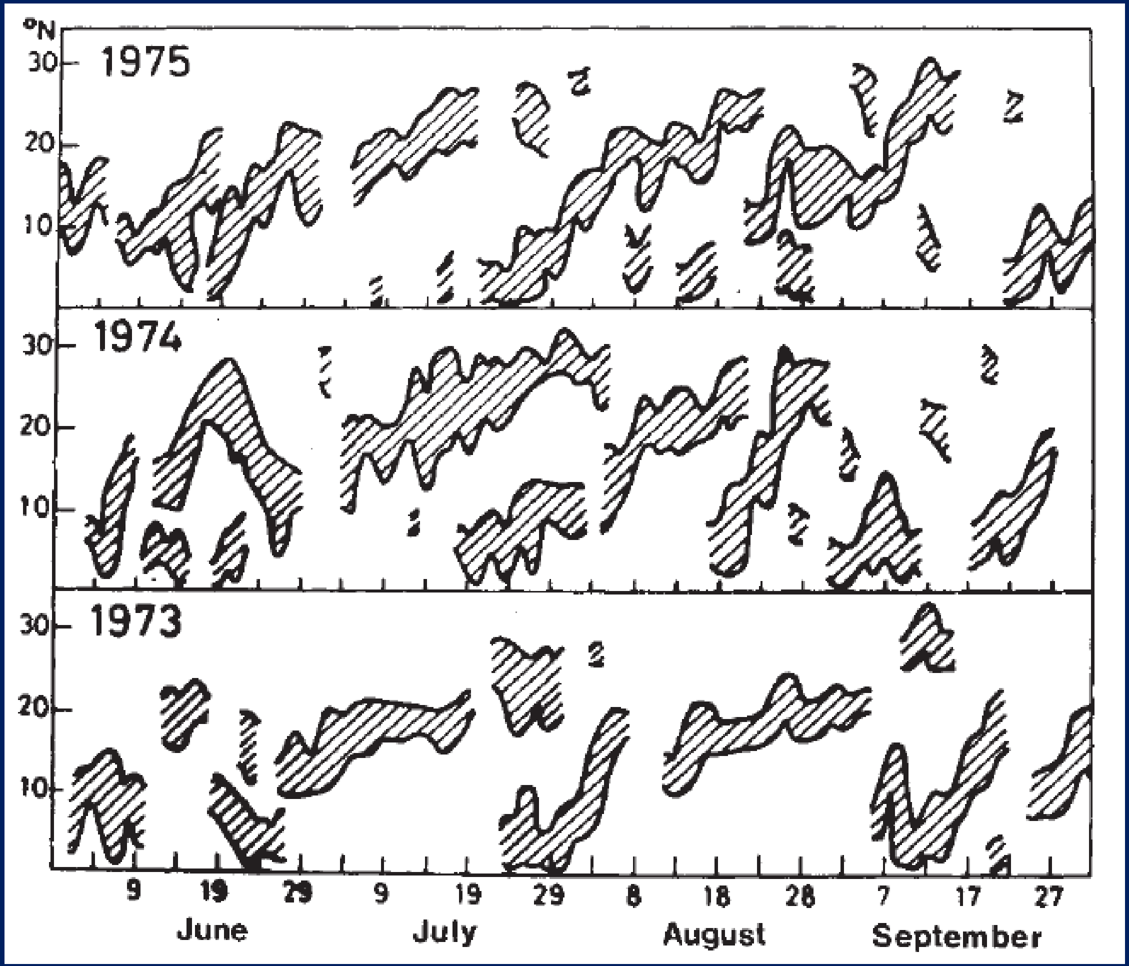


1:Axis of the MCZ (solid line)
2: northern and southern limits (dotted lines)
3. 700mb trough (dashed line)

Variation of the cloud-bands along 70^0,80^0, 90^0E during June-September 1975

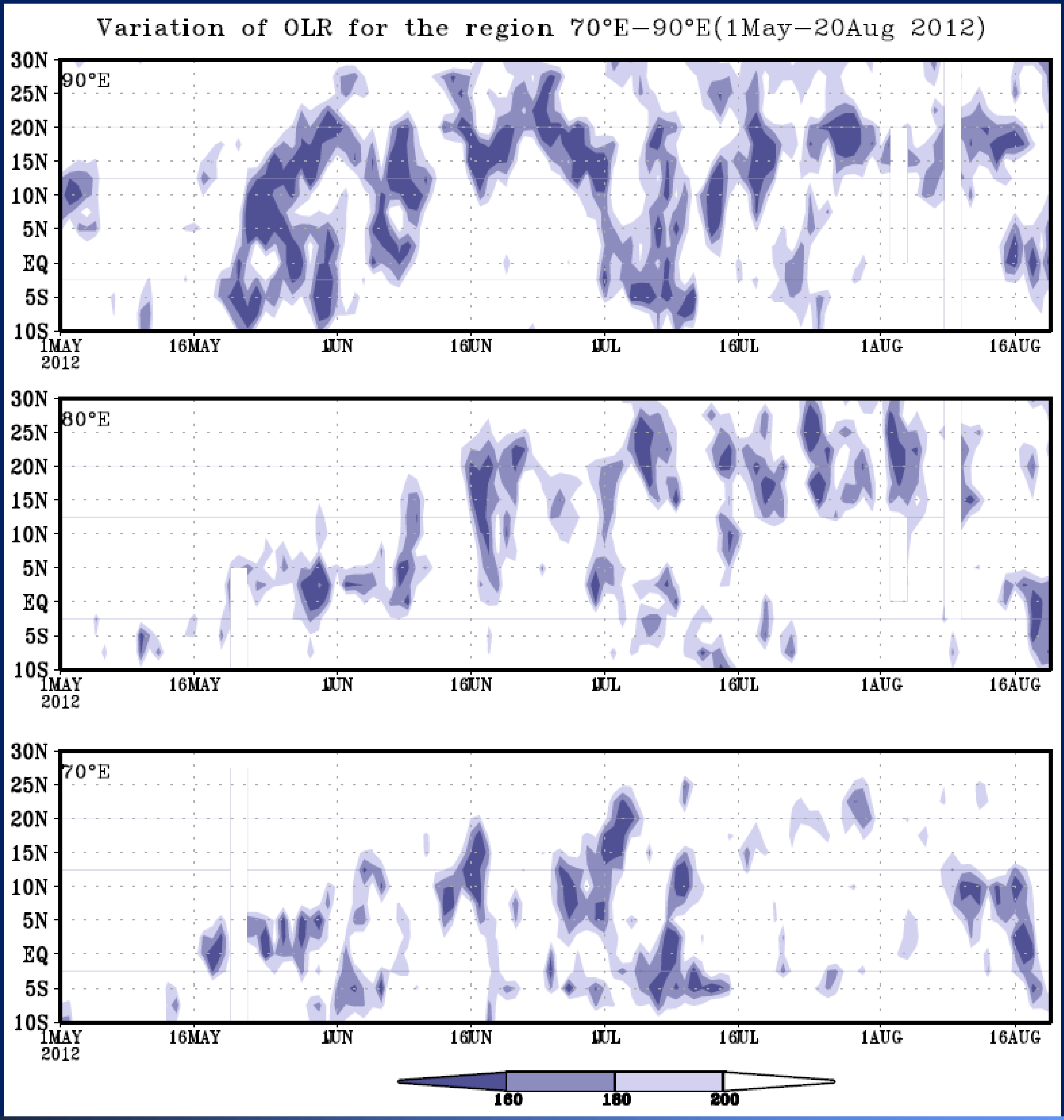


Note that the northward propagations are coherent across 70^0-90^0E



Variation of the location of the cloud band at 90^0E during 1973,74,75

Note that the northward propagations occur every year, irrespective of whether it is a good monsoon (such as 1975) or a drought (such as 1974).



Variation of OLR for the region 70°E–90°E(1May–20Aug 2012)
90°E
80°E
70°E
30N
25N
20N
15N
10N
5N
EQ
5S
10S
1MAY
2012
16MAY
1JUN
16JUN
1JUL
16JUL
1AUG
16AUG
160
180
200

Thus

(i) the MCZ associated with an active monsoon day resembles that associated with the canonical ITCZ

(ii) The MCZ over the Indian region is associated with cyclonic vorticity at 850 and 700 hpa

(iii) There is a high correlation between the axis of the MCZ and that of the 700 hpa trough (which is known to be associted with intense convergence in the lower troposphere (Anjaneyalu 1969) and maximum non-orographic rainfall (raghavan 1973).

SG concluded

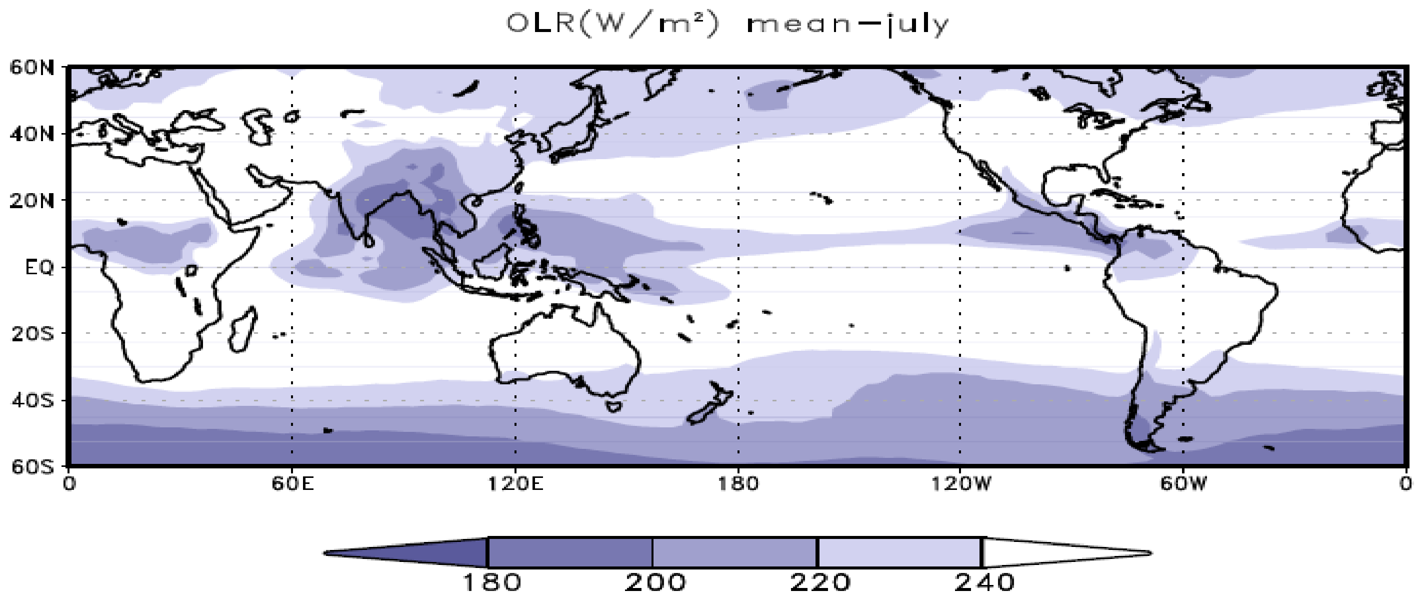
"Putting all this together, it becomes clear that the organized moist convection associated with the monsoon may be attributed to a continental ITCZ over the region. This surmise is consistent with the characteristics of an ITCZ viz. the presence of a prominent zonally oriented region of moist convection in the tropics associated with high cyclonic relative vorticity and convergence. Thus the monsoon MCZ could be considered as a manifestation of a continental ITCZ and the secondary MCZ of an oceanic one".

They noted that “Since on occasion there are two MCZs simulteneously present over the same longitudinal belt, it is clear that convergence in only one of them can be intertropical. ”

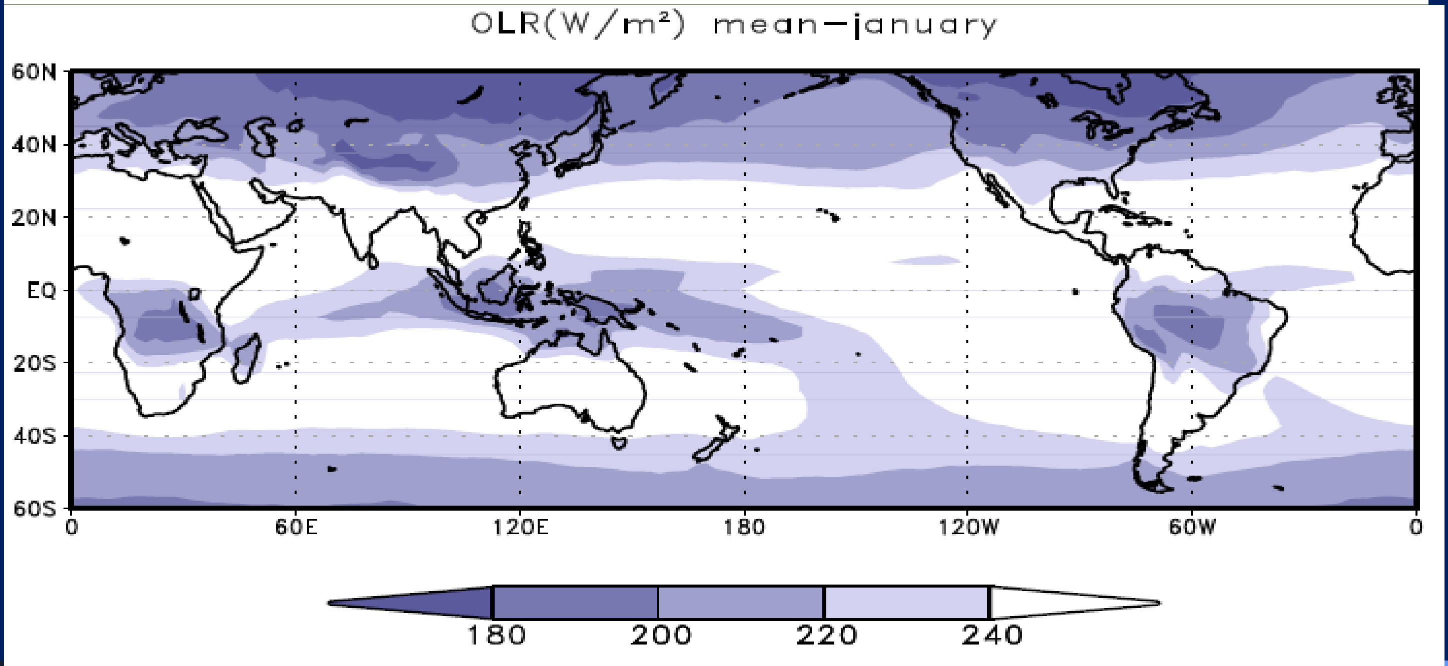
Now we use the term tropical convergence zone (TCZ) to denote such a system and the monsoon attributed to a continental TCZ (CTCZ) over the Indian region (Gadgil 1988).

- If the monsoon is indeed associated with a CTCZ over the Indian region (as suggested by SG), why does the mean July OLR pattern indicate a low OLR region of much larger latitudinal extent than over the Indian longitudes in the boreal summer than the low OLR regions elsewhere or in the boreal winter as pointed out by Murakami?

- This is because of two special features of the intraseasonal variation over the Indian longitudes during the summer monsoon: the presence of two TCZs-the oceanic as well as the continental one and northward propagations of the oceanic TCZ.
- Thus intraseasonal variation plays an important role in determining the monthly/seasonal patterns over this region.



OLR(W/m²) mean–july
60N
40N
20N
EQ
20S
40S
60S
0
60E
120E
180
120W
60W
0
180
200
220
240



OLR(W/m²) mean–january
60N
40N
20N
EQ
20S
40S
60S
0
60E
120E
180
120W
60W
0
180
200
220
240

- The MCZ is associated with intense cyclonic vorticity at 850 and 700 mb and moist convection and rainfall (Sikka 1977, Gadgil 1988).
- Note the presence of synoptic scale systems embedded in the MCZ.
- Northward propagations often involve propagations of synoptic systems over the Arabian Sea and Bay of Bengal which get connected with a zonal band.

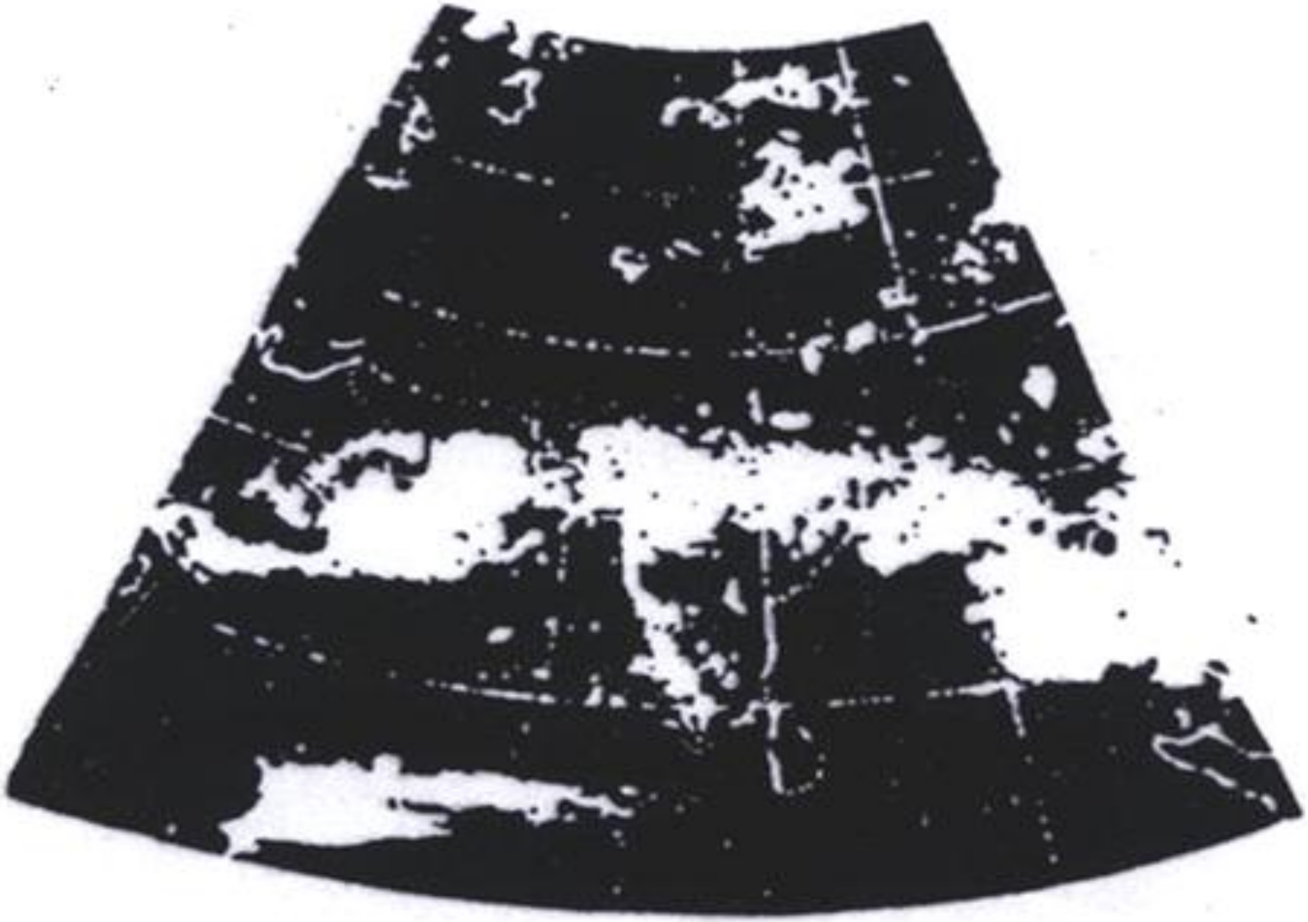


Fig 6. Satellite imagery of an active monsoon day (8th july 1973).

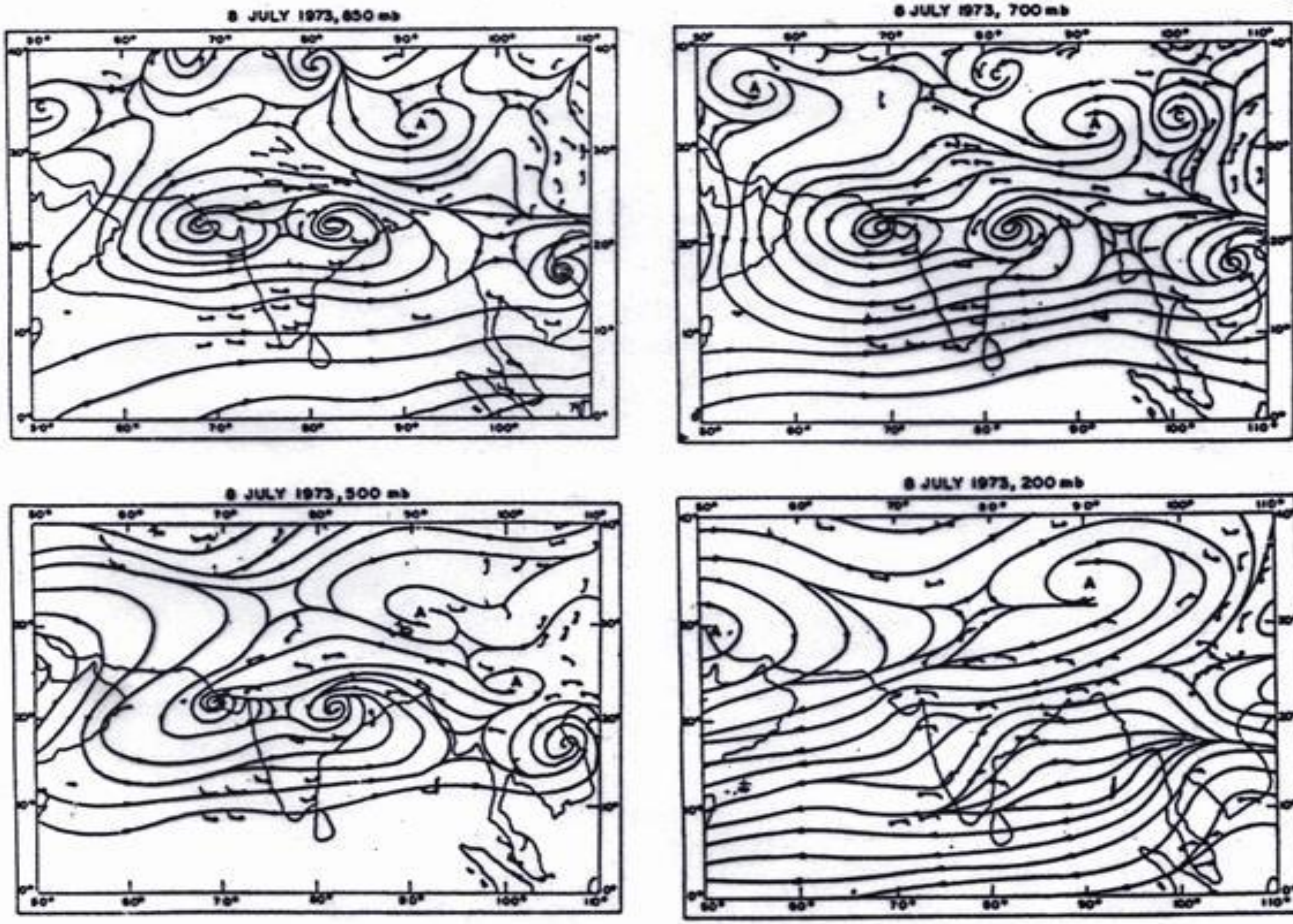
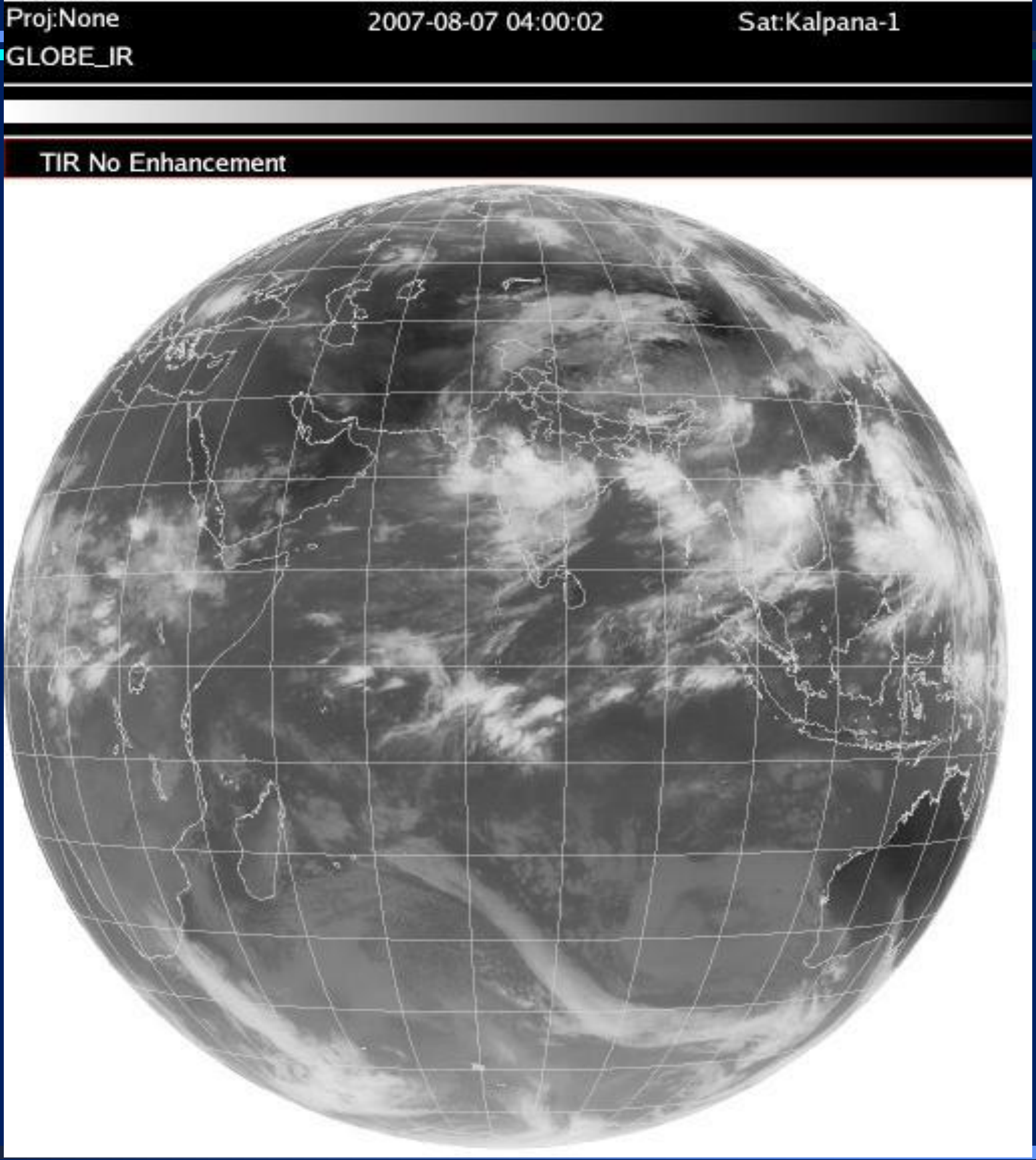


Fig. 1. Circulation pattern at different levels on 8 July 1973.

Another example



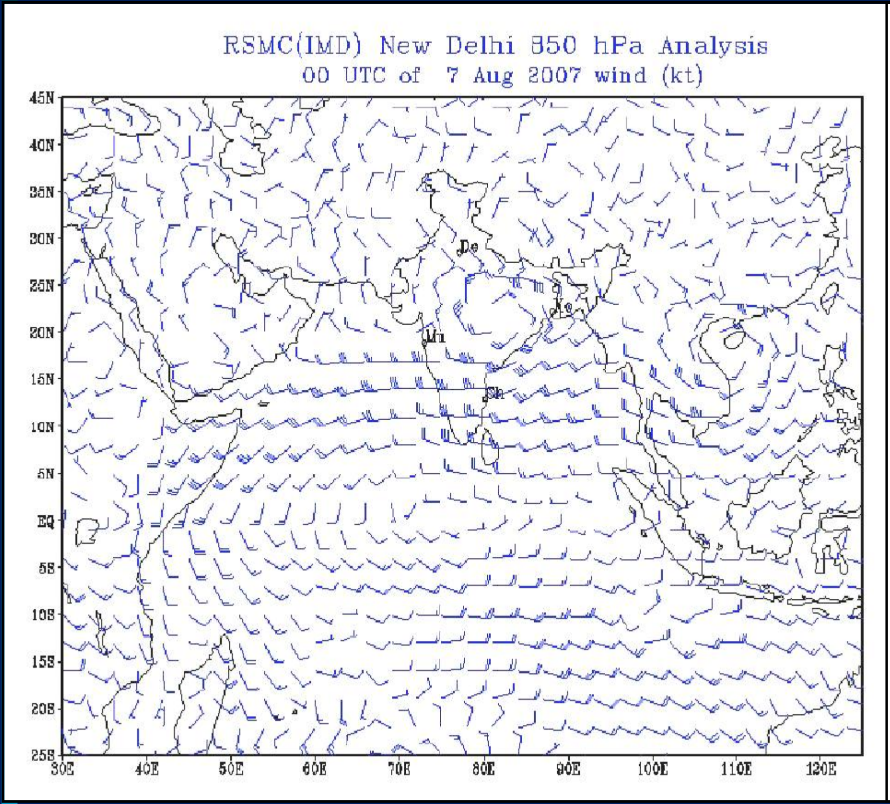
7August

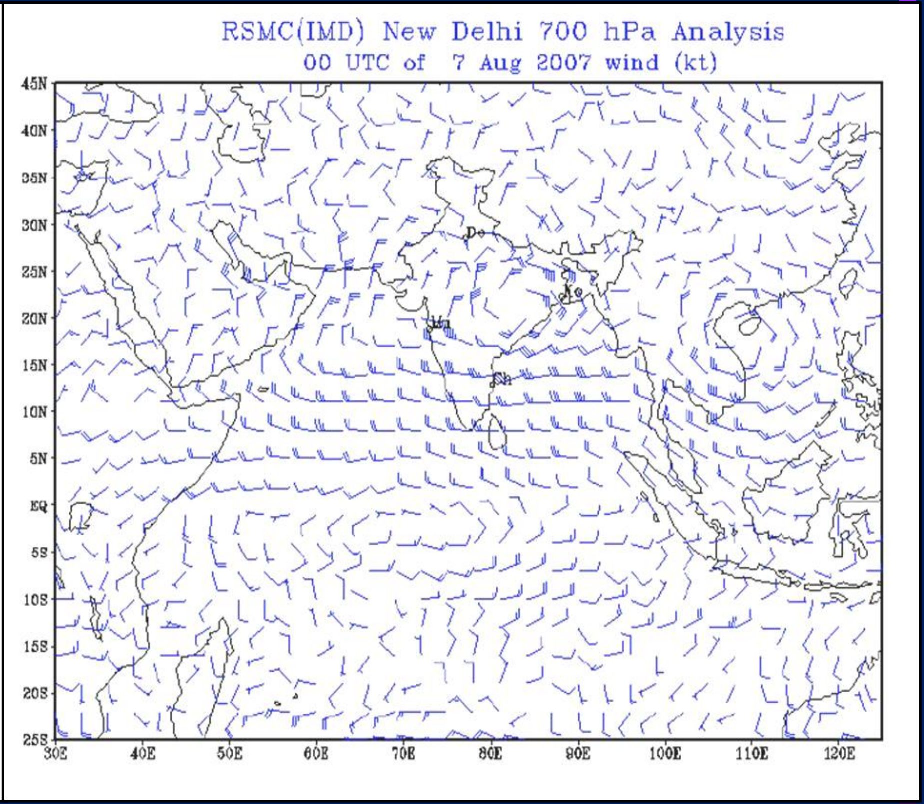
2007

Analysis of winds for 7 August 2007

at 850hpa

at 700 hpa

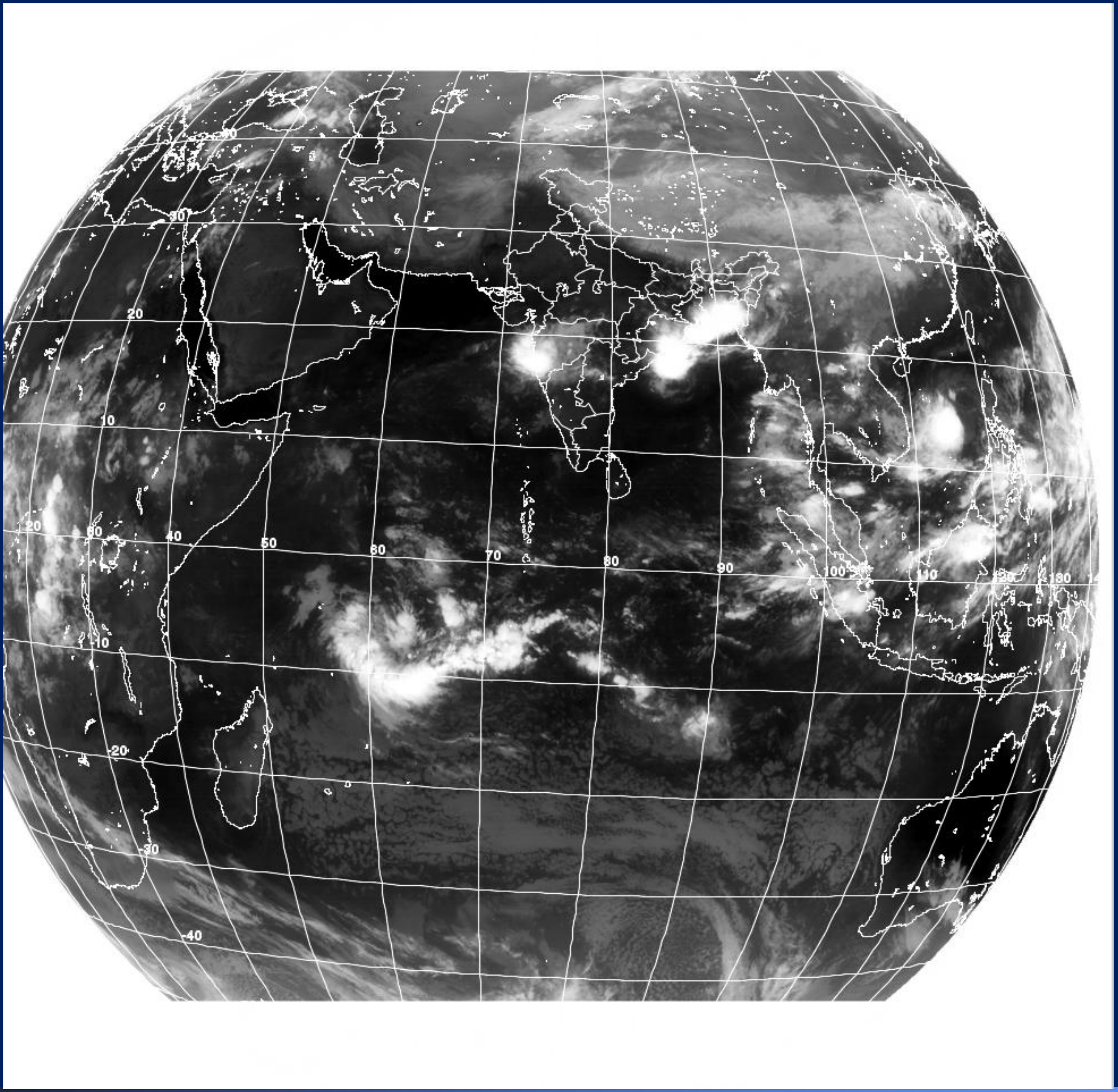




Multi-scale

- The synoptic scale systems embedded in the TCZ generally have meso-scale systems embedded in them.
- This monsoon season we saw meso-scale systems in isolation as well.
- Riehl’s remark about ITCZ versus hurricanes can be extended to meso-scale systems as well

Multi-scale convection : meso, synoptic, planetary



- Why two TCZs over the same longitudinal belt?
- Multiple equilibria-
- Over the heated subcontinent or warm equatorial Indian Ocean
- Nature chooses a combination of the two.
- However, a solution with only the oceanic TCZ and desert (like the Sahara) over the Indian monsoon zone is a valid solution. e.g. UKMET, MeteoFrance models
- Role of moist pre-conditioning? Role of Tibetanorography?

- **The SG study showed that the equatorial TCZ plays an important role in maintaining the CTCZ over the monsoon zone. However, the relationship of the CTCZ to the equatorial TCZ is complex. There is competition between the two TCZs over the same longitudes.**
- **This complex relationship has important implications for monsoon variability on intraseasonal and interannual scales . One example is the role of EQUINOO in interannual variation of the monsoon. Another is the role of EEIO convection in breaks.**

Variability of the CTCZ

- Processes which lead to variability of oceanic TCZs e.g. cloud heating of mid-troposphere leading to a decrease in CAPE etc. + processes special to CTCZ such as land surface processes.
- Interactions with the TCZs over the eq. Indian Ocean, central Pacific and Western Pacific

- It appears that Blanford first suggested in 1886 (i.e. 200 years after Halley) that the monsoon is associated with the occurrence of a system which is seen over the equatorial Indian Ocean in the spring (i.e. ITCZ or equatorial trough).

Rainfall of India : A Monograph

by

Henry F Blanford,

Meteorological Reporter to the Government of India

Indian Meteorological Memoirs, 1886

- “During these spring months , on the Bay of Bengal and the Arabian Sea , the winds are light, frequently alternating with calms and somewhat variable; ----
- The change that ensues at the end of May or in June, when the surrounding seas are swept by a strong monsoon current, and heavy and continued rain sets in on the coasts of India, is very marked, and has long been recognized in popular language as ‘the burst of the monsoon’.
- The essential cause of the change appears to be that during the spring months , the sea-winds which feed the storms of that season are the relatively damp but by no means saturated air of the surrounding seas; or if saturated, at least not so to any considerable vertical height above the sea surface .

- **But in more southerly latitudes, in the neighbourhood of the equator, is a belt of the atmosphere corresponding to the doldrums of the Atlantic, into which the southeast trades of the South Indian Ocean pour a steady supply of almost saturated air.**
- **At all times of the year, more or less convection goes on in this belt*, as proved by its raininess in all the seasons; and consequently it affords a great reservoir of air, which, up to an indefinite height above the sea surface, borders at all times on a state of saturation.**
- ***what we refer to as the ITCZ or the equatorial trough***

- Now it appears to be the eventual rush of this air towards the region of low pressure, developed over India gradually during the spring months, that constitutes the burst of the monsoon. Once started , the energy of its movement is sustained by the condensation of its own copious vapour; by the latent heat so set free.
- The energy of convection furnished by the heated atmosphere of the plains, is competent only to keep up the feebler indraught that obtains during the spring months; and indeed even this indraught is maintained partly by the moderate condensation of cumulus and local thunderstorms, fed by the vapour it brings.

- The solar heat , directly absorbed by the dry land atmosphere or taken up from the heated ground, bears much the same relation to the general air movement, as the pull on the trigger does to the propulsion of the rifle ball.
- It determines the disturbance of atmospheric equilibrium but it does not furnish the energy of the of the resulting air stream. That energy is supplied in the latent heat of the indrawn vapour.
- So long as this supply is small and limited to the shallow stratum of air immediately fed by the evaporating surface beneath it, so long is the air movement feeble and interrupted.

- **And it is only when the barometric gradient from south to north has become sufficiently great to tap the great reservoir of latent energy, supplied by the evaporation of the southeast trade zone , that the air current becomes strong and sustained, constituting the summer monsoon; sustained, too, long after the heated land surface has been in a great measure quenched and cooled by the rainfall." (p119)**

- Thus, more than 125 years ago, Blanford had first suggested that the Indian summer monsoon is associated with the appearance over the Indian region of the TCZ from the equatorial Indian Ocean.
- It is surprising that neither Simpson nor the following generations of meteorologists including Webster, Meehl etc. took note of this hypothesis by Blanford (which I believe, was also conceived independently by Riehl and Charney in the late 70s) nor of Sikka and Gadgil's proof of the validity of this hypothesis and to this day we teach Halley's theory of the monsoon as a gigantic land-sea breeze.

Thank you

Blanford was thus a proponent of what I have called the second hypothesis. However, he did not believe that the monsoon was a manifestation of the seasonal migration of the equatorial rainy belt. Rather in his view, ‘the equatorial belt of constant rainfall exists across the monsoon region and is not bodily transferred northward to India and southward to Australia with the annual March of the sun in declination is a well established fact---rainfall registers of the Malay Archipelago show that while in the neighbourhood of the equator the season of the heaviest and most frequent rainfall is from November to January, there is no month in which the precipitation does not amount to at least 3 to 4% of the annual total. In fact during the monsoon, the whole region between the equator and the Himalayas is more or less one of precipitation and may be regarded rather as an extension and broadening out of the normal equatorial rainy zone, with a northward transfer of its maximum and a partial concentration in northern India, rather than a bodily transfer of the zone northward to Southern Asia.' (page 74)

This remains a rather apt description of the low OLR region over the Indian longitudes during the summer monsoon which Murakami also commented on.