The Physics of the Monsoon

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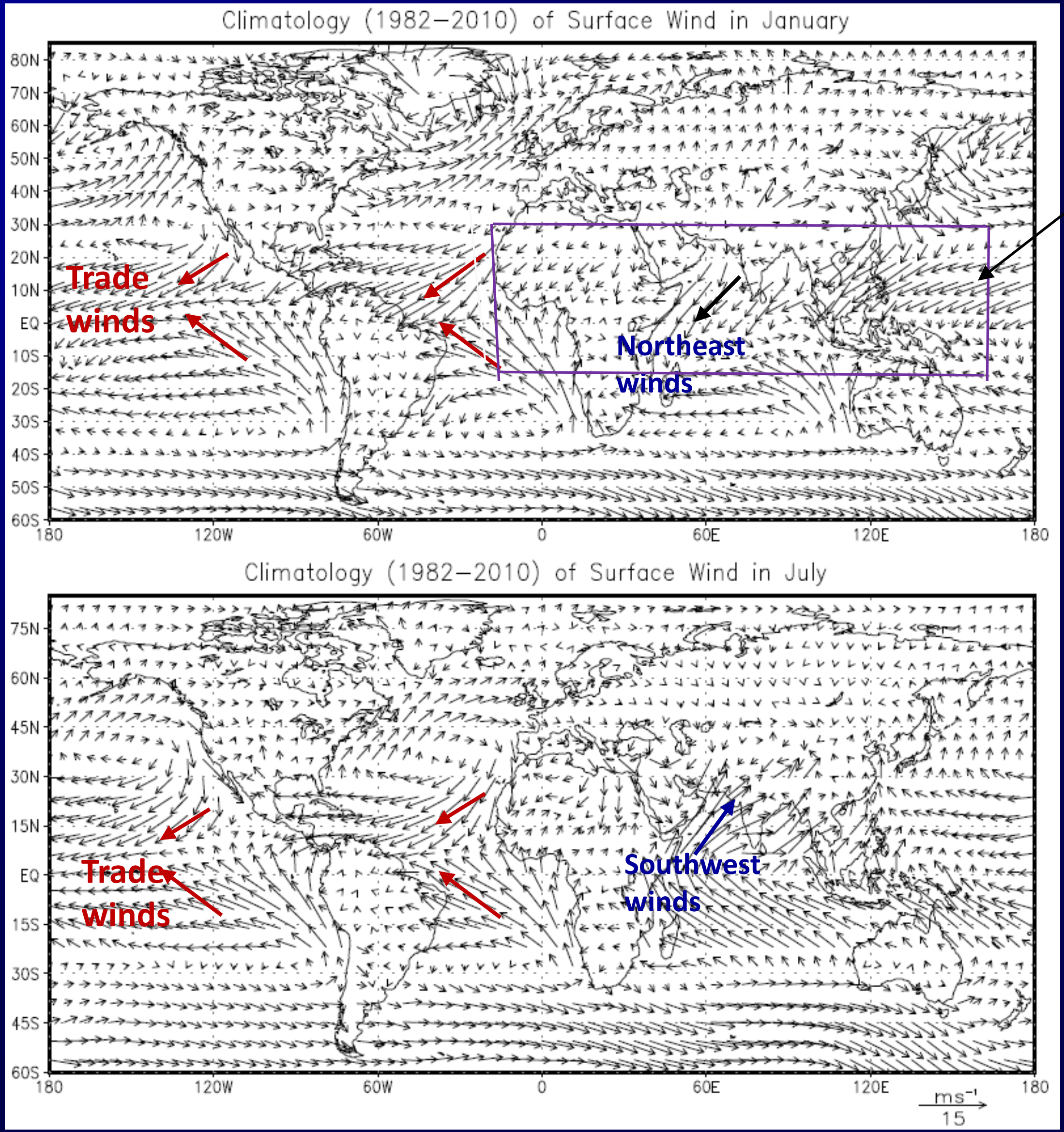
4 December 2019
IITM

Traditional definition of the monsoon

January

July

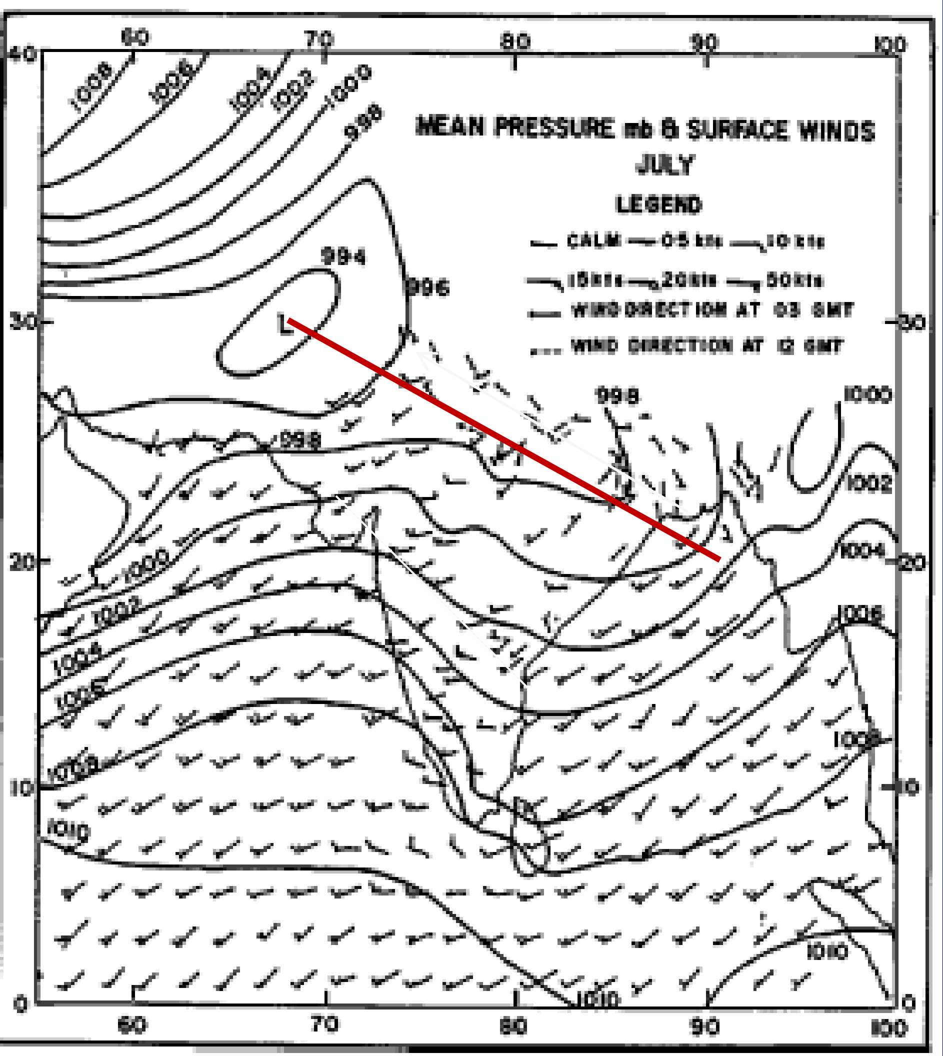


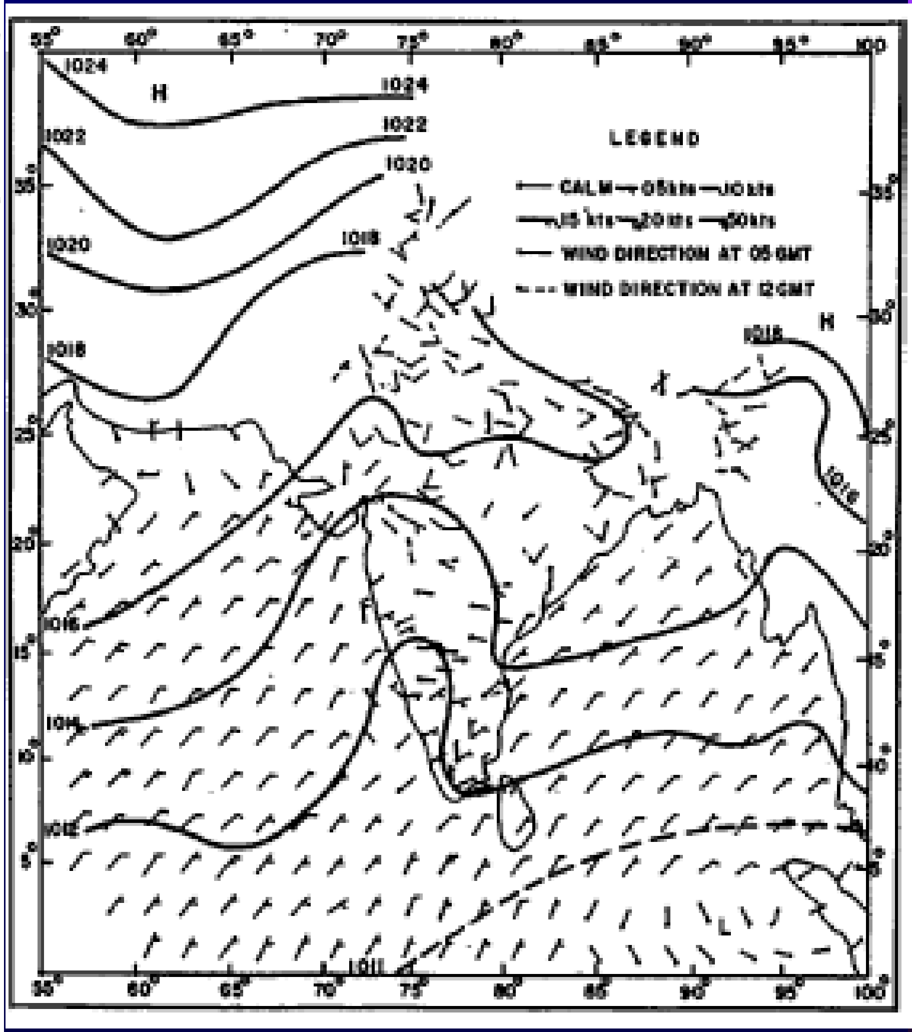
Monsoonal regions based on **large variation in the direction of surface winds with season**

Average surface winds

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

July | **November**

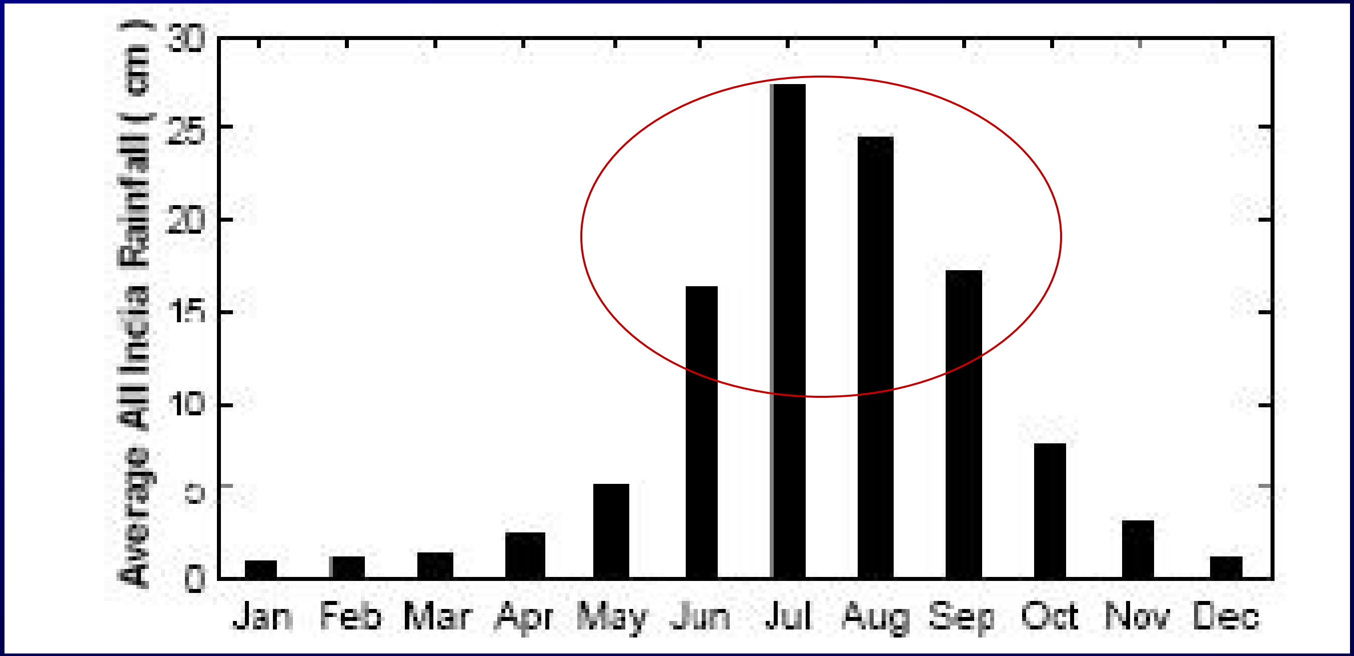




"Southwest monsoon" (*Misnomers*) "Northeast Monsoon"

However, for us the variation of the rainfall with the season is of far greater interest than the seasonal variation of the wind.

Monthly average rainfall over the Indian region

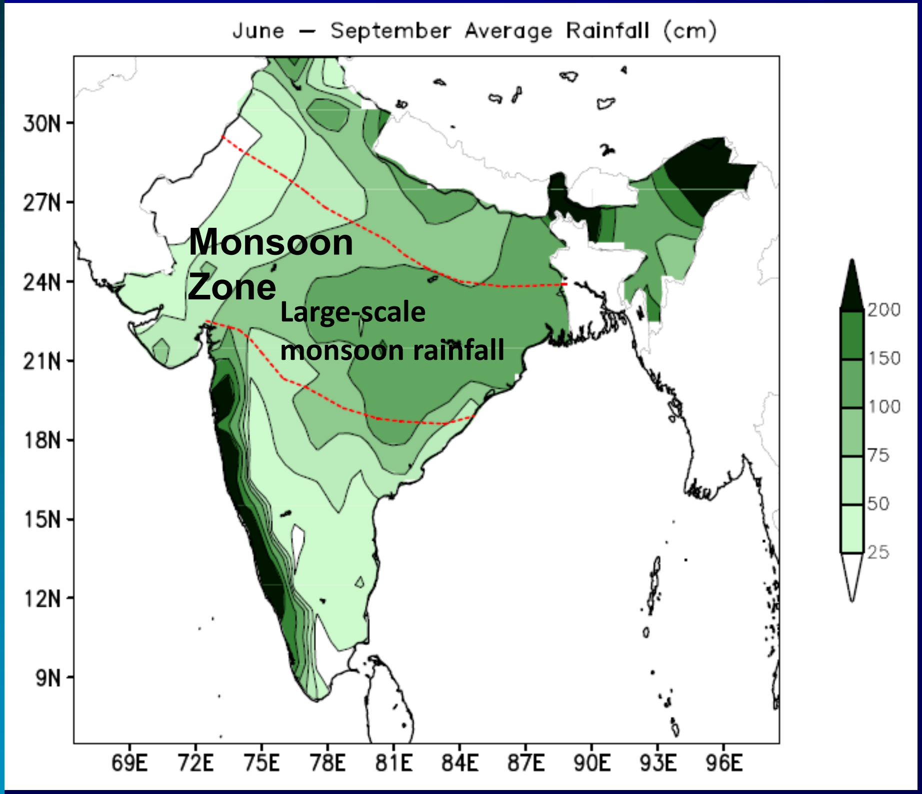


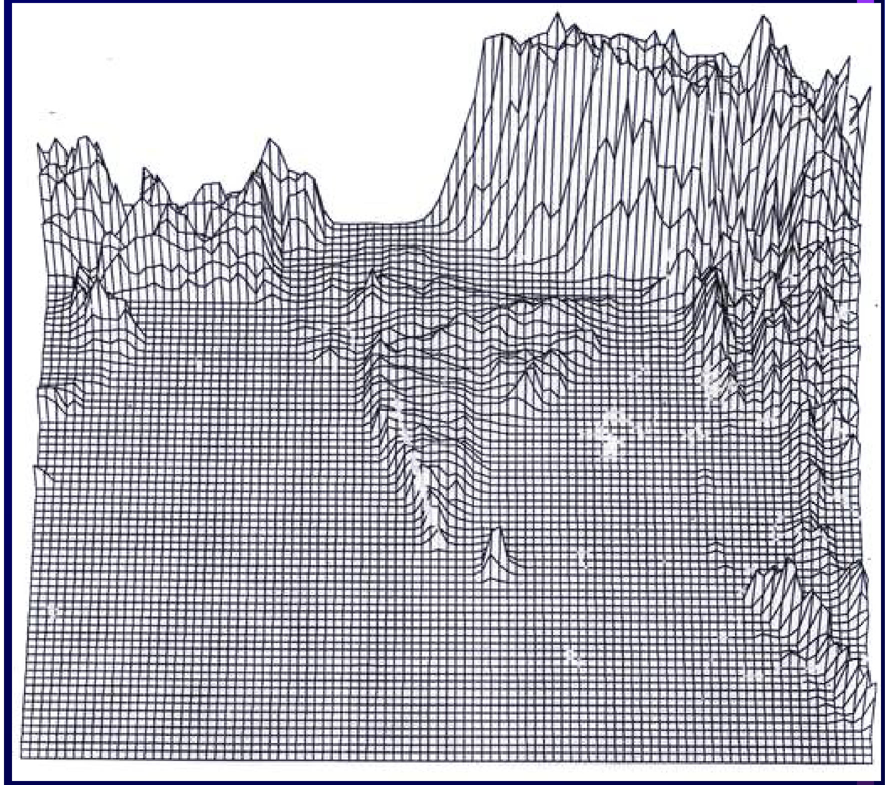
June-September- the summer monsoon season,

in which most of the rainfall occurs.

In common parlance: Monsoon: the rainfall we get in the monsoon season

Spatial Variation of the Summer Monsoon rainfall





Rainfall during June-September averaged over the Indian region-the Indian summer monsoon rainfall (ISMR)

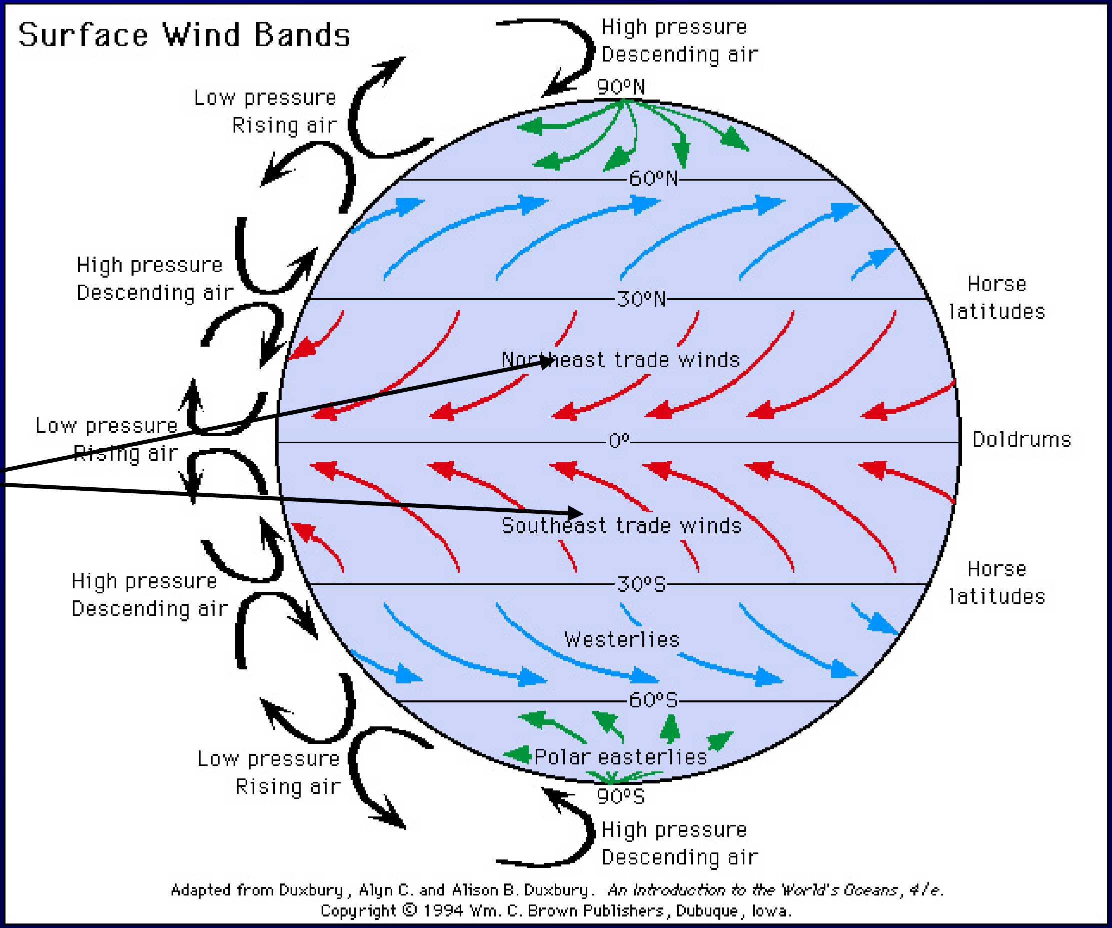
Evolution of our understanding of the basic system responsible for the monsoon

First step towards understanding the Physics of the Monsoon:

Understanding of tropical circulation and rainfall. I consider first the axisymmetric component of tropical circulation i.e. the general circulation of the atmosphere: circulation averaged over all longitudes.

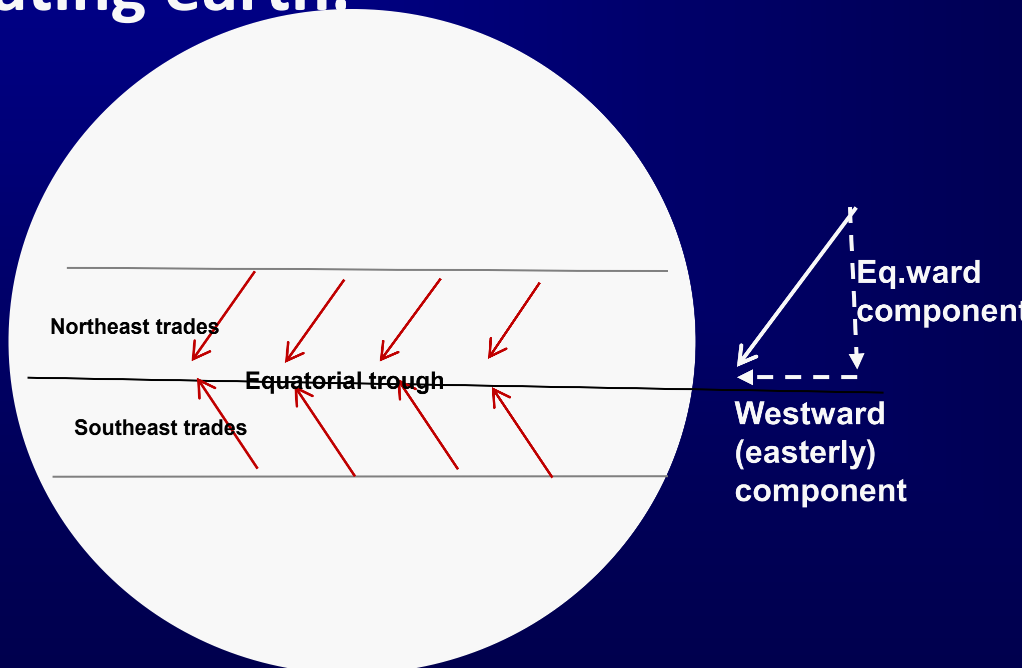
The observed annual average of the zonally averaged circulation: General circulation of the atmosphere

Major feature over the tropics: Trade winds



Idealized surface winds over the tropics

Trade winds: The westward/easterly component of Trade winds has intrigued scientists for centuries as it implies that winds blow in the opposite direction to the rotating earth.



Earlier studies focused on the easterly component but equatorward component is also important

Some basic facts (known to the scientists for over 3 centuries)

- Basic source of energy for the atmospheric/tropical circulation: the radiation from the Sun.
- However, the atmosphere is almost transparent to solar radiation which passes through unhampered by the atmosphere to be absorbed by the surface of the earth- be it land or ocean.
- Thus the atmosphere is driven by the heating of the lower boundary. This heating varies with latitude and nature of the earth's surface.
- If we consider the annual average, the maximum heating is over the equatorial regions.
- Also the earth rotates fastest at the lowest latitudes.

What causes the easterly component?

- Galileo Galilee (1564-1642) and Johannes Kepler (1571-1630) suggested: easterly component of the trade winds is due the failure of the earth's gaseous envelop to "keep up" with the speed of the earth's rotation. The air and the water are lagging behind and an earthbound observer experiences a westward-directed flow.

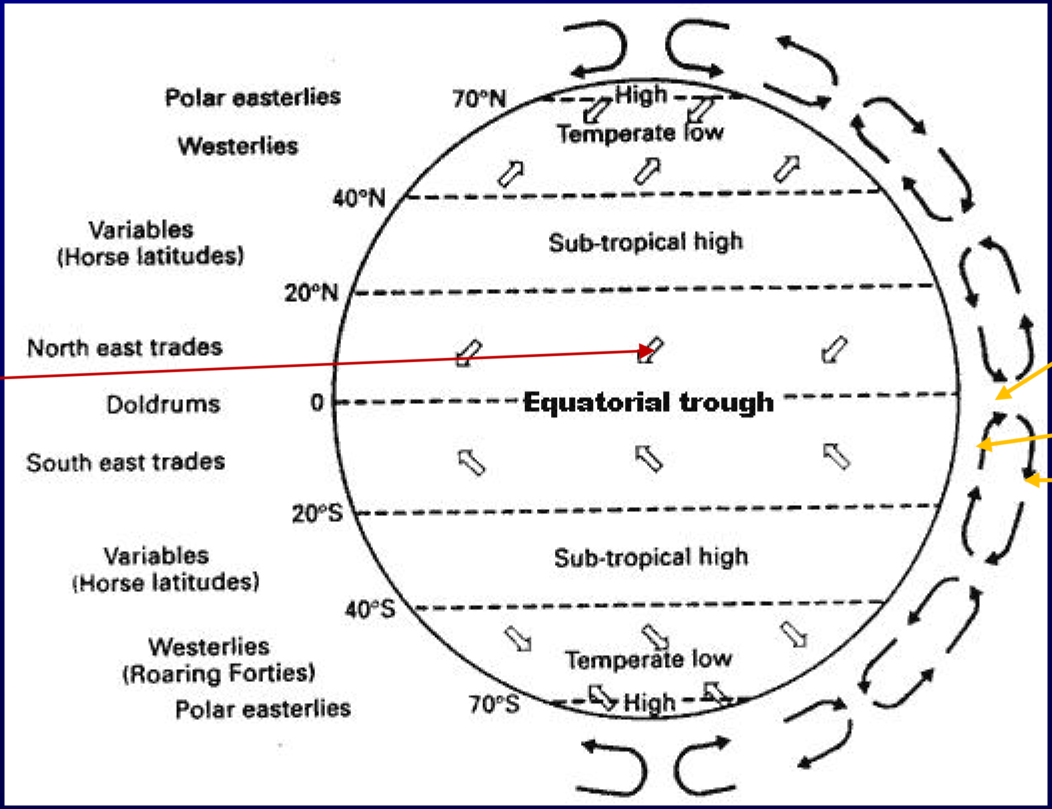
- However, Halley (1686) pointed out 'The Air being kept to the Earth by the principle *of Gravity* would acquire the same degree of *Velocity* that the Earth's surface moves with' i.e. what we call the no slip condition in fluid dynamics. Halley gave an alternative explanation for the easterly component of the trades which is also not correct.

- The correct explanation was given by Hadley (1735).
- Hadley attributed the easterly component, more than 50 years before the birth of Coriolis, to what we now call the Coriolis force, acting on the equatorward flow of surface winds. Since in the absolute sense earth's surface moves most rapidly eastward at the lowest latitudes, if the air were initially moving equatorward with no relative east/westward motion it would, in attempting to conserve its *absolute velocity (should have said angular momentum)* , arrive at lower latitudes moving westward relative to the earth.

Understanding the equatorward component, which is part of the vertical circulation, is very important

General circulation of the atmosphere

Surface circulation: Trade winds blow westward and equatorward.



Vertical circulation: Ascent over the equator, winds towards (away) from the equator at the surface (high levels)

- A major contribution to theories of tropical and monsoon circulation;

"An historical account of the Trade winds and Monsoon, observable in the seas between and near the tropics, with an attempt to assign the Physical cause of the said winds," Phil. Trans. 1686, 26, 153-168 by Edmund Haley.

- Based on an exhaustive survey of British ship logs, he compiled a near-global climatology of surface winds. These maps provided a remarkably accurate depiction of surface winds in the tropical oceans and, to a large degree, have stood the test of time.
- He presented a detailed and methodical account of trade winds as observed in three separate oceans and sought a common cause for them.

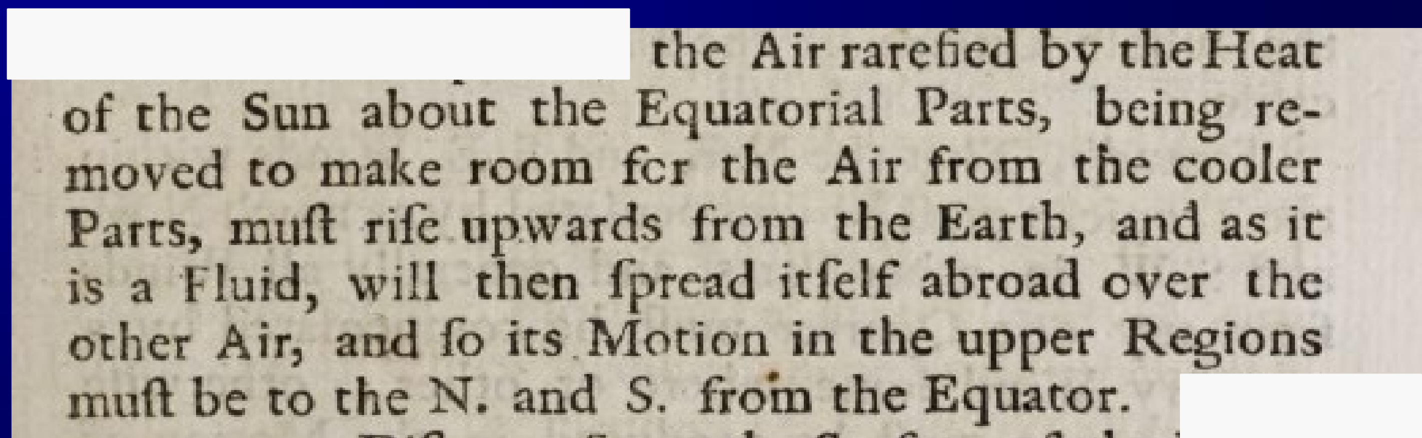
Equatorward component and the vertical circulation

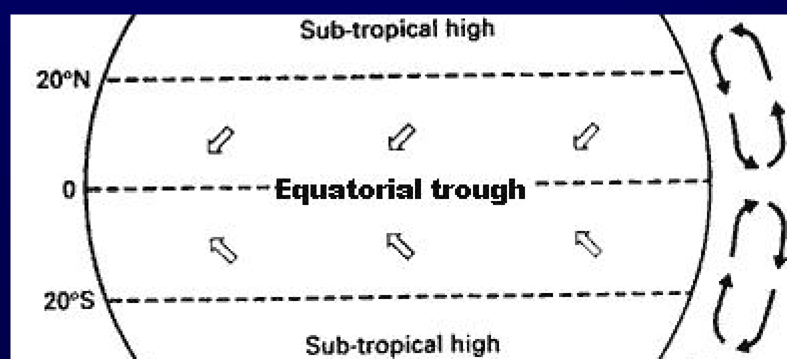
- Halley suggested causes for the equatorward component of the trade winds as well as the vertical circulation.
- Equatorward component:

(i) Air is most rarified over the most heated region i.e. the equator

- (ii)On either side of the equator “ The air which is less rarified or expanded by heat, and consequently more ponderous, must have a motion towards those parts thereof, which are more rarified and less ponderous to bring it to an equilibrium.”
- Halley’s theory for the equatorward component of the trades has stood the test of time.

- **The vertical circulation of tropical air, moving towards the equator near the surface and away from the equator at higher levels was also explained by Halley.**

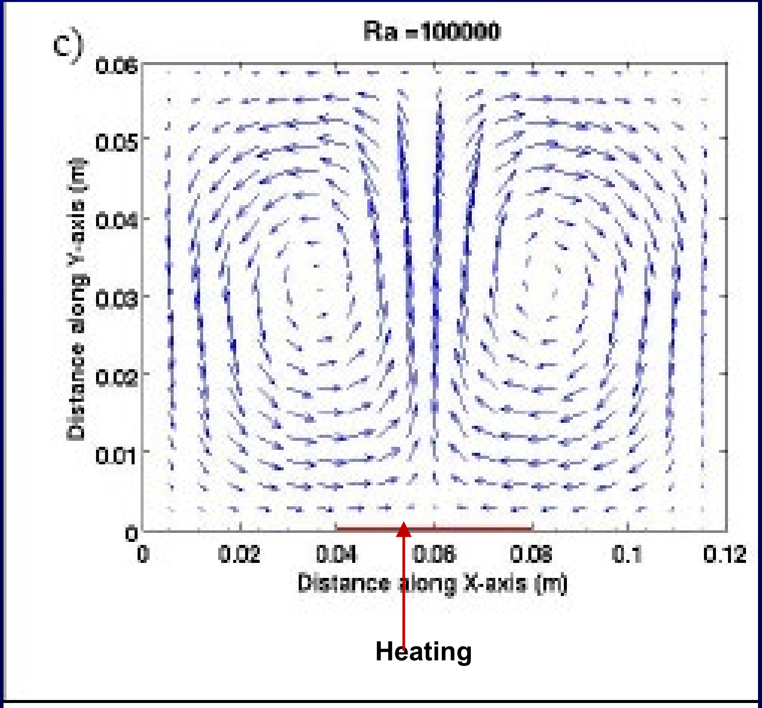

the Air rarefied by the Heat of the Sun about the Equatorial Parts, being removed to make room for the Air from the cooler Parts, muſt riſe upwards from the Earth, and as it is a Fluid, will then ſpread itſelf abroad over the other Air, and ſo its Motion in the upper Regions muſt be to the N. and S. from the Equator.



This explanation is believed to be correct even today.

- In concordance with Halley, Hadley (1735) concluded that the distribution of solar heating would lead to a general rising motion in lower latitudes and sinking motion in higher latitudes, the circuit being completed by equatorward motion at low levels and poleward motion aloft. This cell is now called the Hadley cell.

Fluid converges to the maximum heating



Benard Convection: the Porridge problem

It is shown that the strength of the ascent increases with increased temperature gradient .

Implication for large-scale rainfall:

- The major focus in all these earlier studies was on tropical circulation . This is because of the high demand from sailors for information on the nature of the surface winds over different oceanic regions. Even the monsoon was defined on the basis of seasonal variation of the surface winds and the two seasons June-September and October-December are still called Southwest and Northeast monsoons based on the direction of the surface winds over the surrounding oceans. I shall mention later why these are misnomers.
- However, for people living in the monsoonal regions as well as other tropical regions, the associated the deep clouds and rainfall are of far greater importance. In fact, deep clouds have a large impact on the circulation.

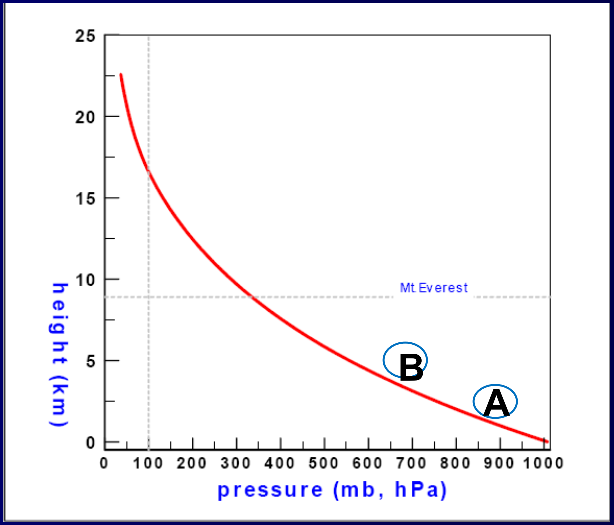
Relation between the circulation and rainfall in the tropics

Some basic facts about convection/clouds in the tropical atmosphere

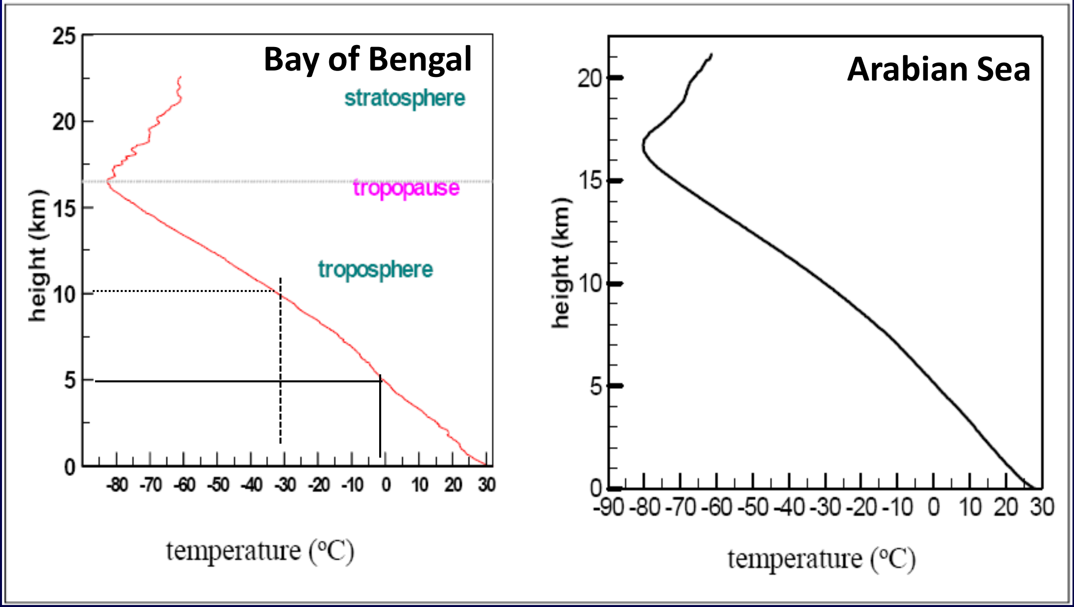
- Even at the surface of the ocean, the relative humidity is only about 80%.
- The relative humidity decreases with height since the source of water vapour is the ocean.
- How much water vapour air can hold, decreases with air temperature, hence as air cools the relative humidity increases.
- Hence if a moist air parcel is somehow cooled beyond a threshold, saturation occurs and clouds can form.
- Such cooling can occur if the air ascends. So the vertical component of the circulation is important and ascent of surface air critical.

Conditional Instability of the tropical atmosphere

Consider a parcel of air which is made to rise adiabatically from a level A to a higher level, B. It will expand, because the pressure is lower at the level B.



Lapse rate:
Temp diff/height diff= about 30^0C/5km =6^0C/km



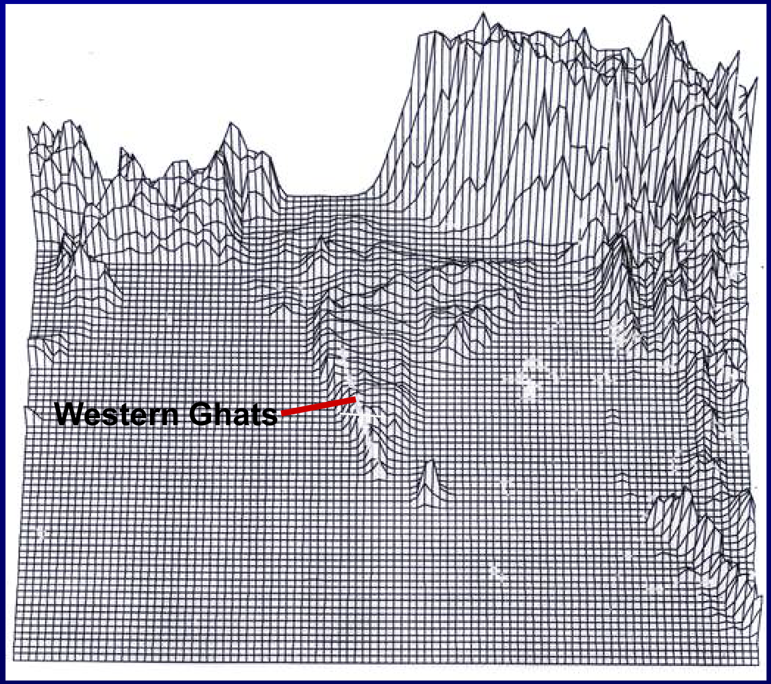
Curtsey G S Bhat

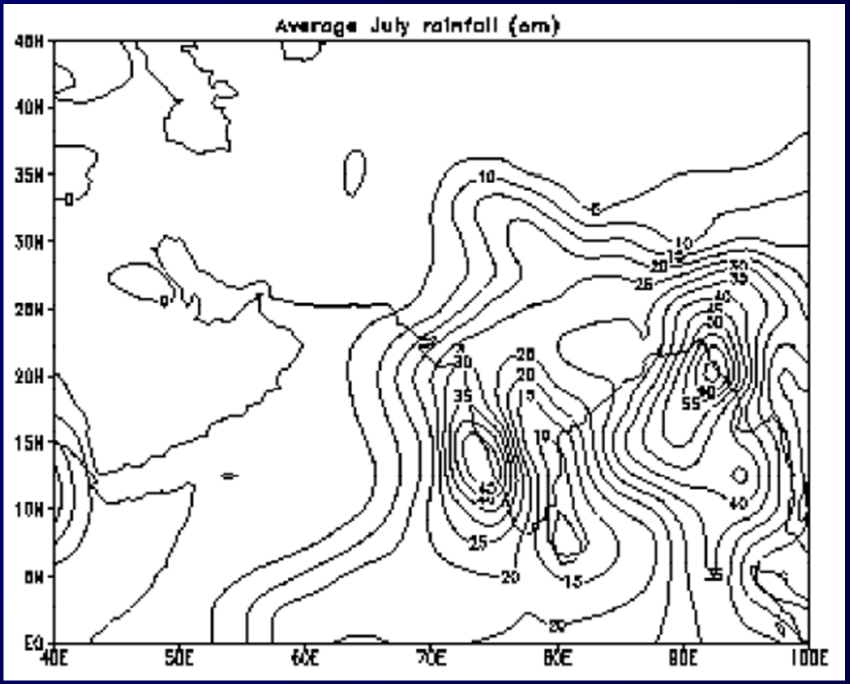
- If a parcel of dry air is lifted adiabatically, it will cool at the rate 10 ^{0}C/km i.e. more rapidly than the surrounding air i.e. parcel is cooler , hence denser and will return to its original level. **Thus the tropical atmosphere is stable relative to vertical displacement of dry parcels.**
- If the parcel is moist, as it cools its relative humidity increases and if lifted to a certain level, it becomes saturated. Beyond this level, water vapour condenses and latent heat is released. This prevents it from cooling as rapidly as a dry parcel and in fact it cools at the rate of about 4.5^{o} C per km i.e. < the environmental lapse rate of about 6^{o} C per km. **Thus the tropical atmosphere is unstable with respect to vertical displacement of moist air beyond the lifting condensation level.**
- **Hence the tropical atmosphere is said to be conditionally unstable.**

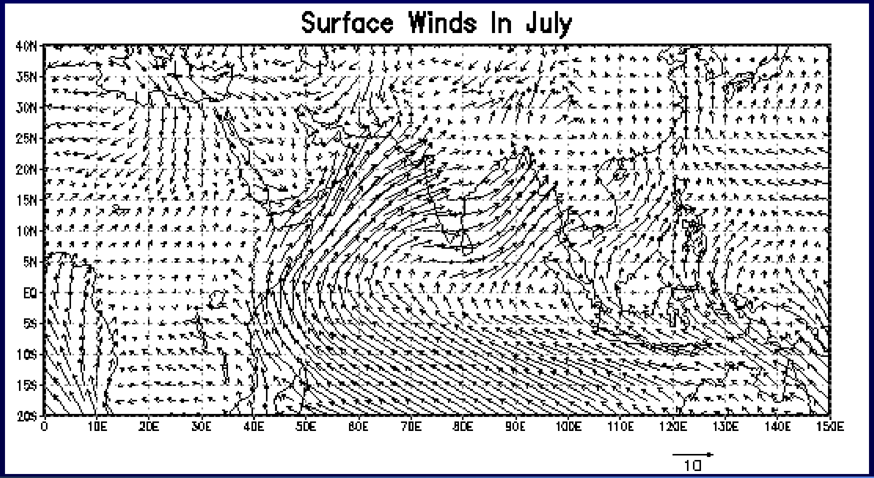
- **Cumulus clouds (horizontal scale of about 5kms) are a manifestation of the gravitational instability and convective overturning in an atmosphere whose lowermost layer is moist i.e. conditional instability.**
- **In an elegant treatment of this instability by one of the greatest minds in the field- J Bjerknes: *Saturated adiabatic ascent of air through dry-adabatically descending environment, Quar. J. R. Met. Soc., Vol.64, 1938,* it was assumed that the energy released by the buoyancy forces in the cloud has to be used in the work done in the downward flow against a stable gradient in the cloud-free region. It was shown that the ratio of this work to the energy released in cloud is minimum for the cloud with maximum velocity of ascent i.e. minimum area. Thus the thinnest clouds would grow the fastest.**

- **Given the increasing impact of entrainment of dry air with decreasing radius of the clouds , Charney (*Planetary Fluid Dynamics in Dynamic Meteorology, P Morel D Reidel rel, ed., 1973)* deduced that the scale which would grow the fastest would be around 5km i.e. scale of the cumulus cloud.**
- **Recent studies (G S Bhat,1998, The dependence of cloud mass flux and area cover on convective and large scale processes, J. Atmos. Sci., pp. 2993-2999,and references therein) suggest that over a large fraction of the tropical atmosphere which is cloud-free, descent occurs because of the radiative cooling of air which balances the heating associated with adiabatic compression.**
- **In any event, the argument that the smallest scale will be selected holds in this case as well.**

For convection, a critical feature is the ascent of moist surface air up to the level of lifting condensation. Such an ascent can be forced by orography

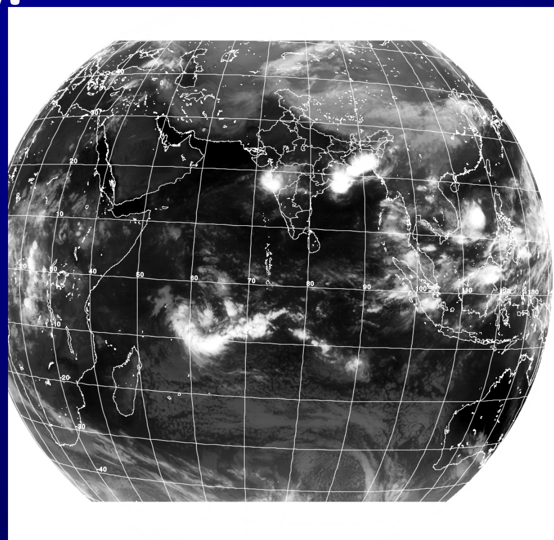


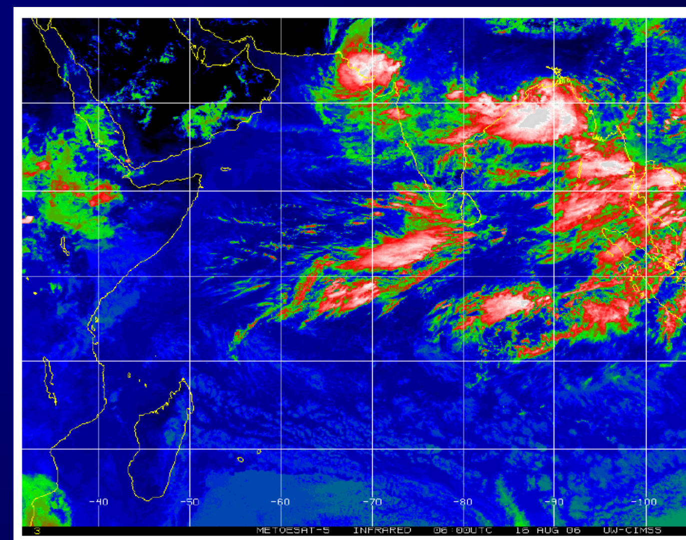




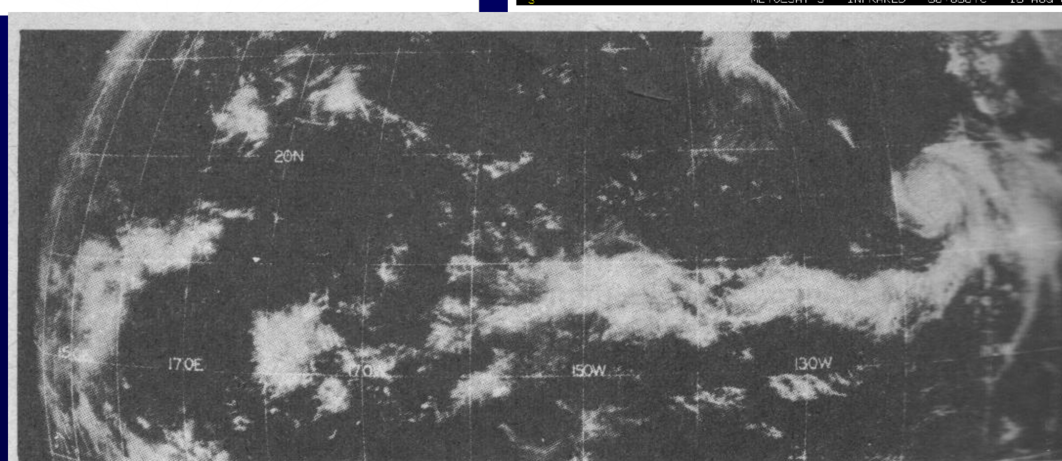
- **Organized rainfall over regions where topography does not play an important role, is generally associated with meso, synoptic and planetary scale systems which are clearly seen in satellite imagery.**

Meso-scale





Synoptic -scale



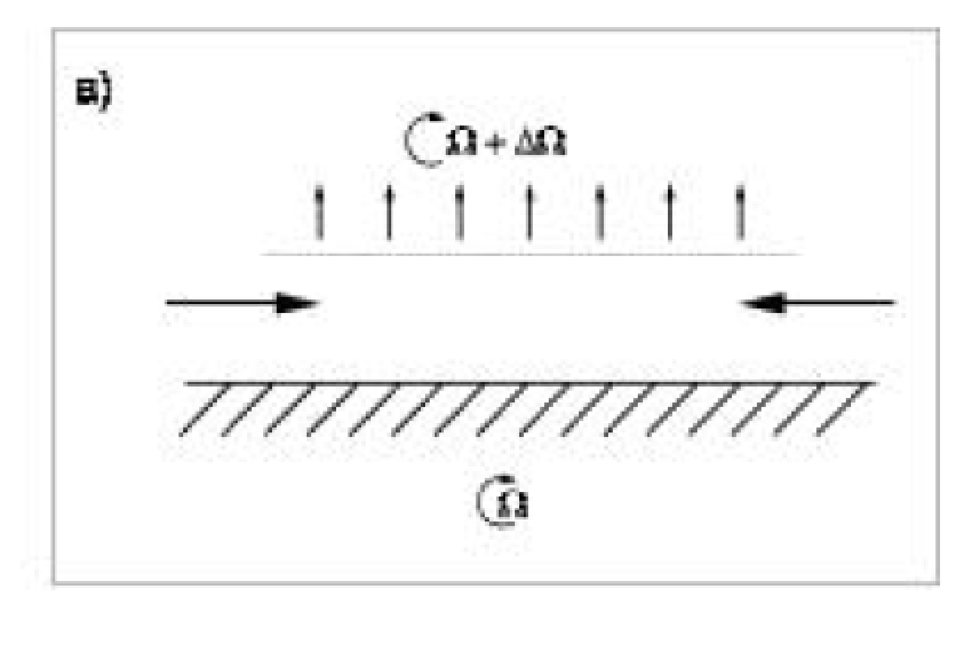
One of the earliest pictures of the ITCZ over the Pacific (Riehl 1969)

- It is important to note if we consider the conditional instability of the tropical atmosphere, then the scale that grows the fastest will be the cumulus scale. The horizontal extent of an individual cumulus is around 5kms.
- How then can the synoptic scale cloud system grow and intensify? In other words, how could convection over the larger scales be selected for since in a moist tropical atmosphere the cumulus scale must always win in the competition?
- This question was first posed by Charney and Eliassen (1964) for understanding why cyclones form and intensify in the conditionally unstable tropical atmosphere. They suggested that the key was in Cooperation rather than competition.

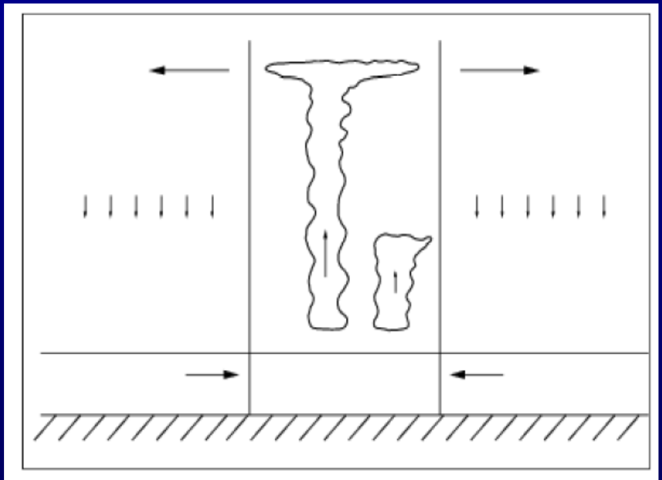
Ascent of the moist surface air up to the level at which condensation begins, is required for clouds to form.

Special feature of rotating systems

- Cyclonic vorticity above the boundary layer in a rotating system (Ekman layer) results in convergence in the boundary layer and ascent of the air from the boundary layer, often up to high levels.



This ascent can lead to genesis of clouds over the region of synoptic/planetary scale when the air is moist. Clouds lead to heating in the mid-troposphere which intensifies the low implying a positive feedback.

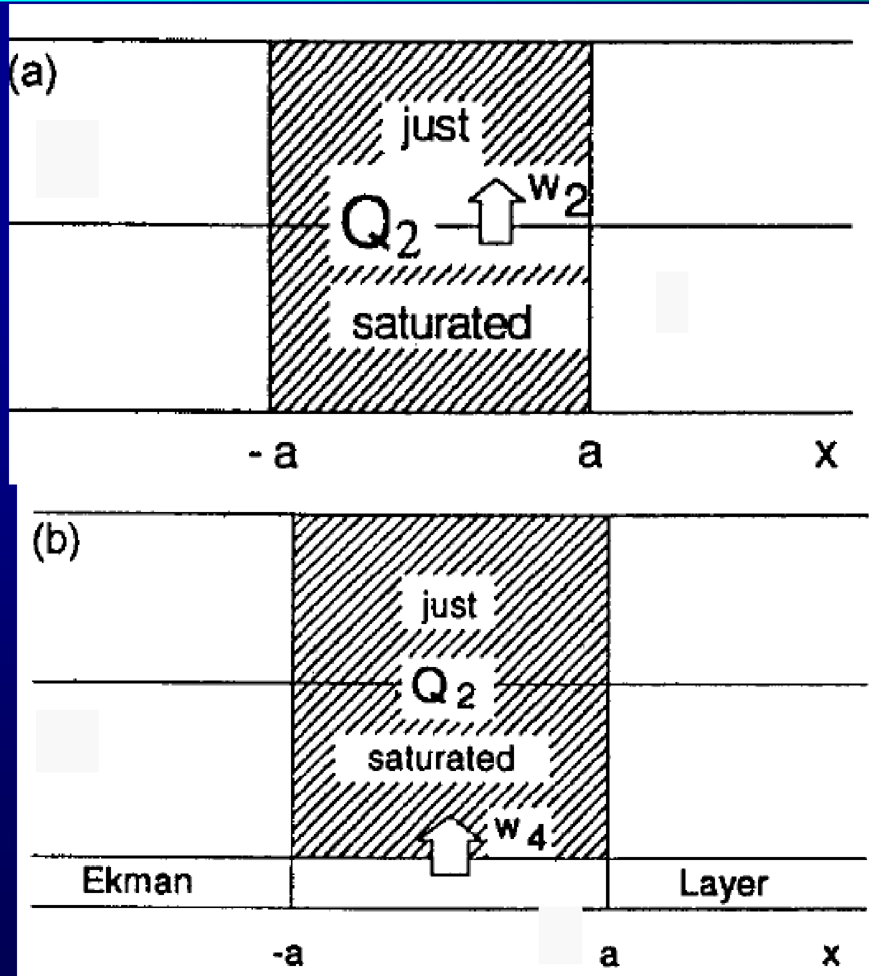


Low pressure system associated with cyclonic vort. above PBL assoc. low level convergence and ascent -> deep clouds-> mid-tropospheric heating-> intensification of the low/cyclonic voticity

This feedback between the low level convergence associated with cyclonic vorticity above the boundary layer and convection is the key element of the Charney and Eliassen (1964)'s Conditional instability of the second kind (CISK) (to distinguish it from that of the first kind which gives rise to cumulus clouds).

CIFK: Bjerknes, Lilly problem

Charney's CISK



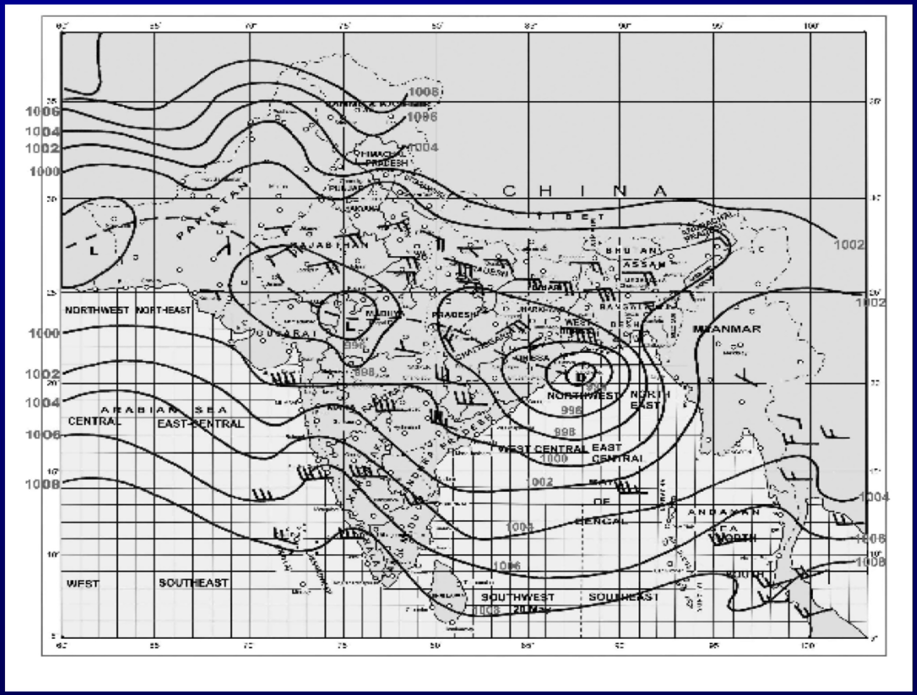
Q=heating proportional to W=velocity of ascent

Q proportional to W=upward velocity on top of the Ekman layer, which is proportional to the relative vorticity

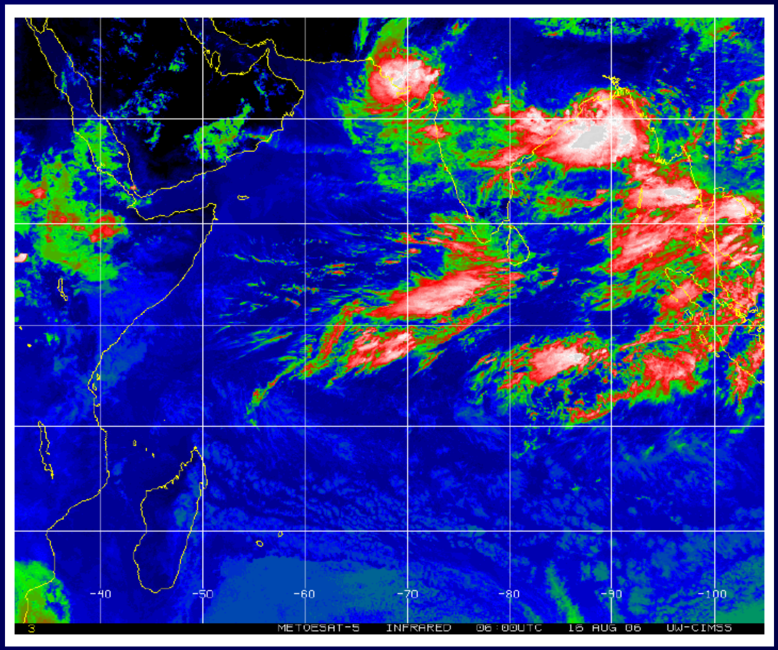
Critical features of the multiscale interaction proposed by Charney are intense low level convergence associated with cyclonic vorticity above the boundary layer, intense convection and rainfall. I shall discuss the evolution of ideas about CISK and the controversies at the end.

Organization of the cumulus clouds on synoptic /planetary scales

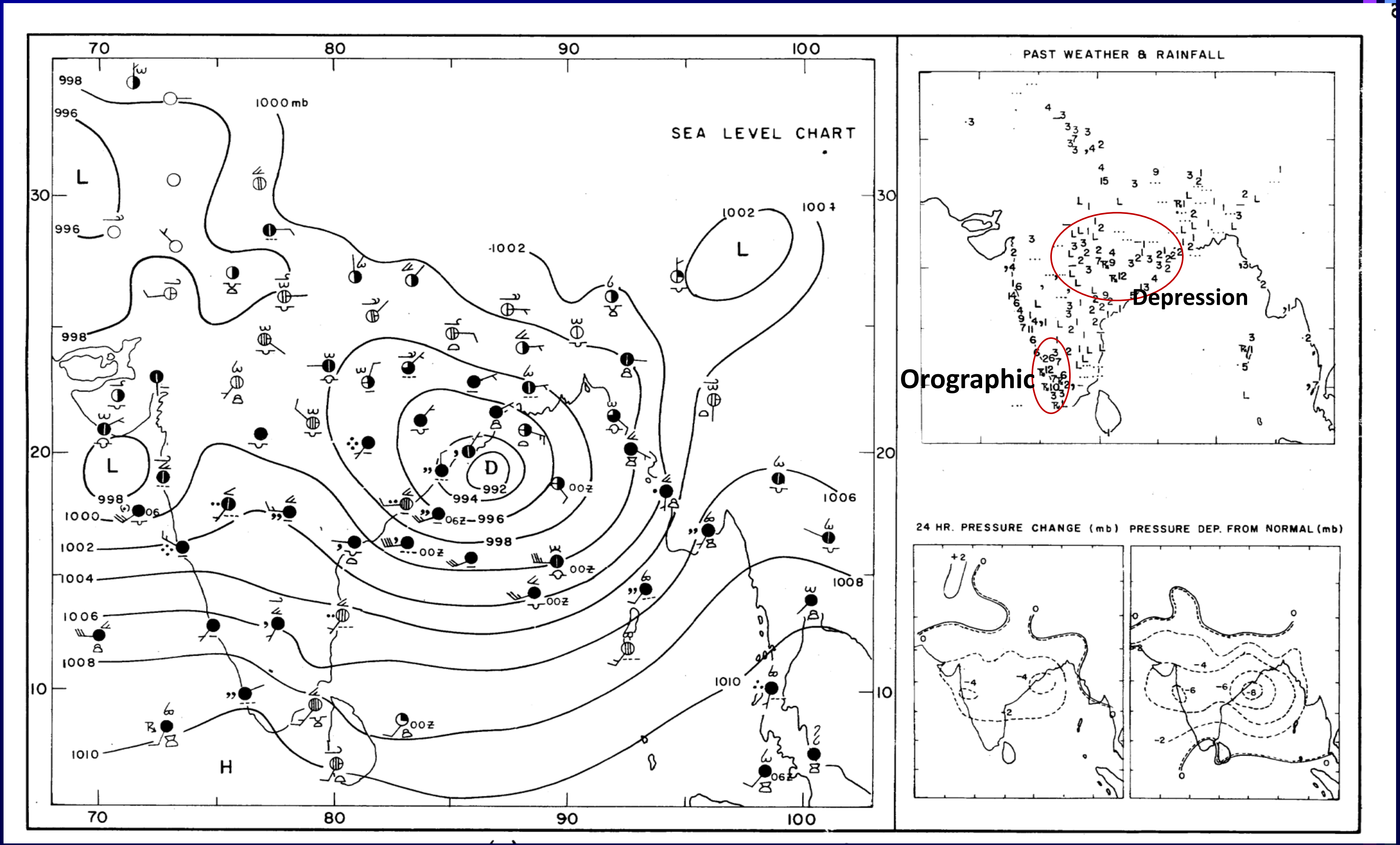
Weather map for 16 August 2006.



Satellite picture for 16 August 2006



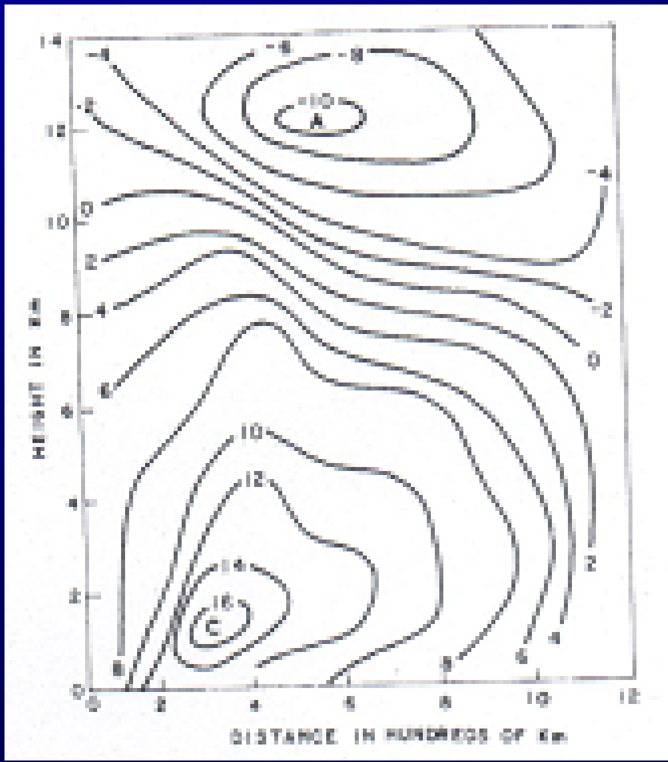
. Colours indicate the height of the radiating surfaces (cloud top, when there are clouds). White is for minimum temperature (i.e. maximum height of the cloud top), green for somewhat higher temperature (shallower clouds) and red is generally cloud free.



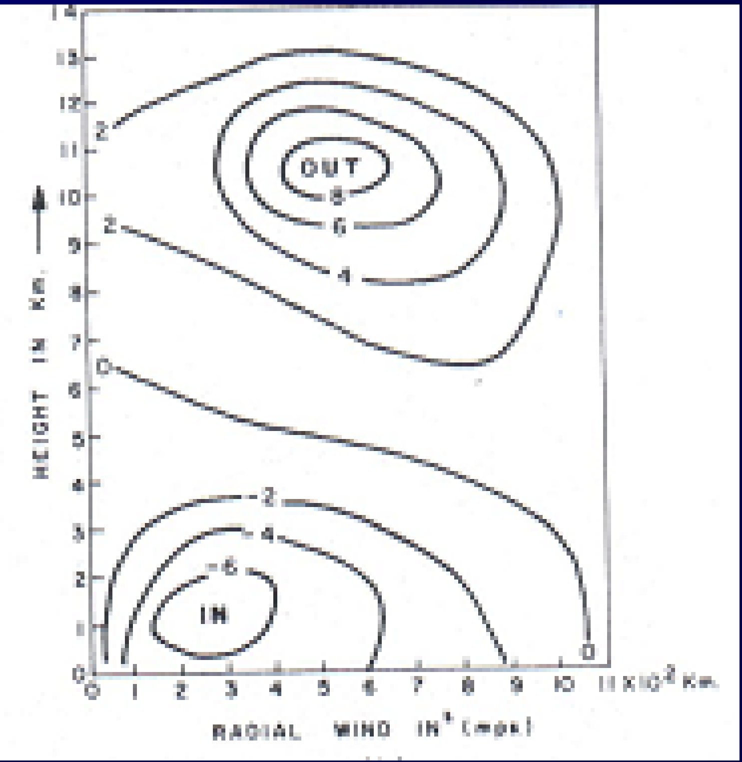
Synoptic charts 0300 GMT 6August 1964

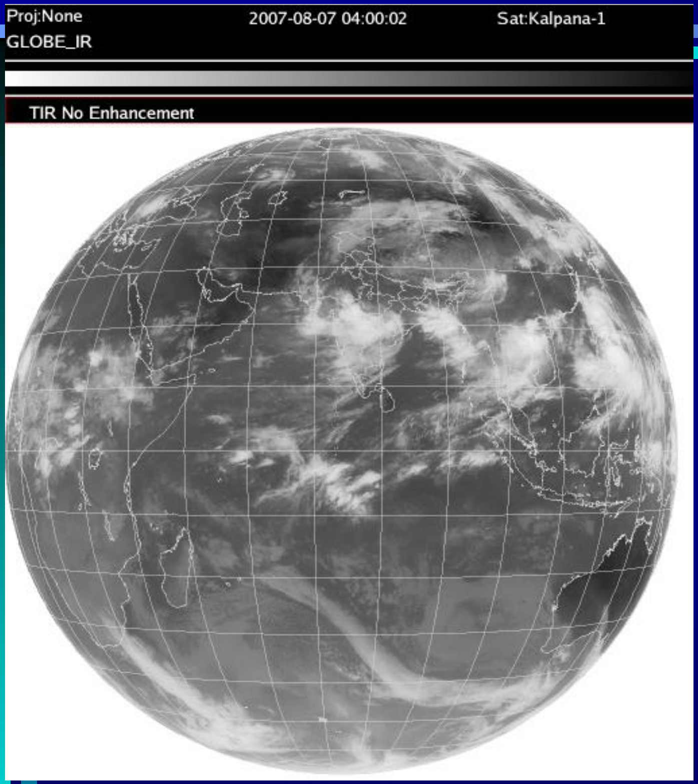
Composite depression:
horizontal and vertical variation of

tangential wind (m/sec)



radial wind (m/sec)





7August 2007

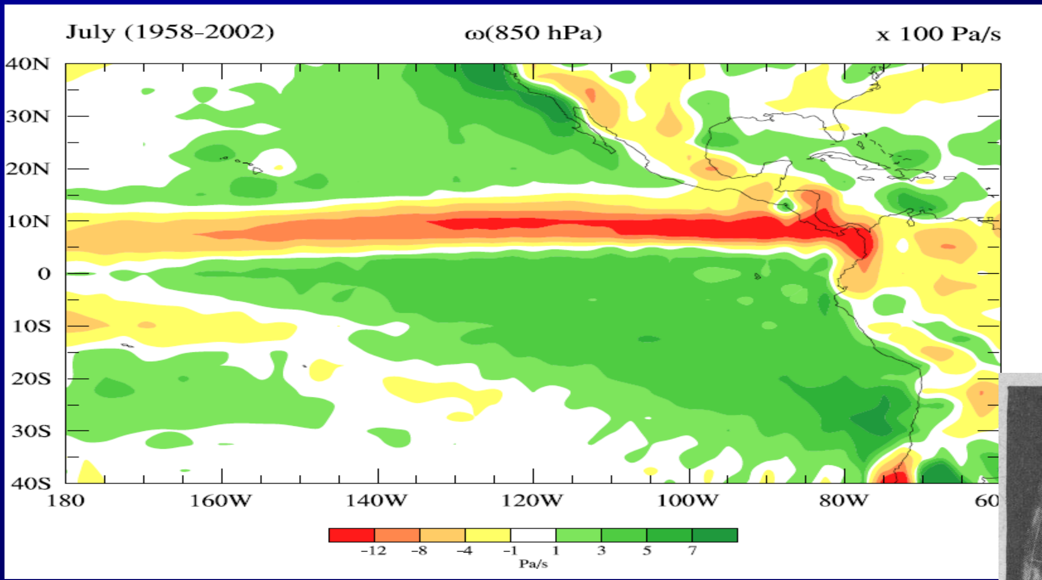
The intense blobs embedded in the planetary scale cloud band are synoptic scale systems;

Distinguishing attribute of the synoptic/planetary scale cloud systems is the cyclonic vorticity above the atmospheric boundary layer (i.e. at 850 hpa) extending up to and beyond 700 hpa and intense convergence in the boundary layer.

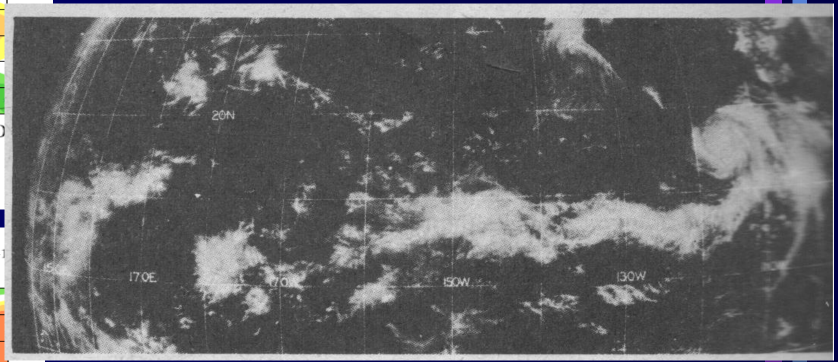
850 hpa **700 hpa**

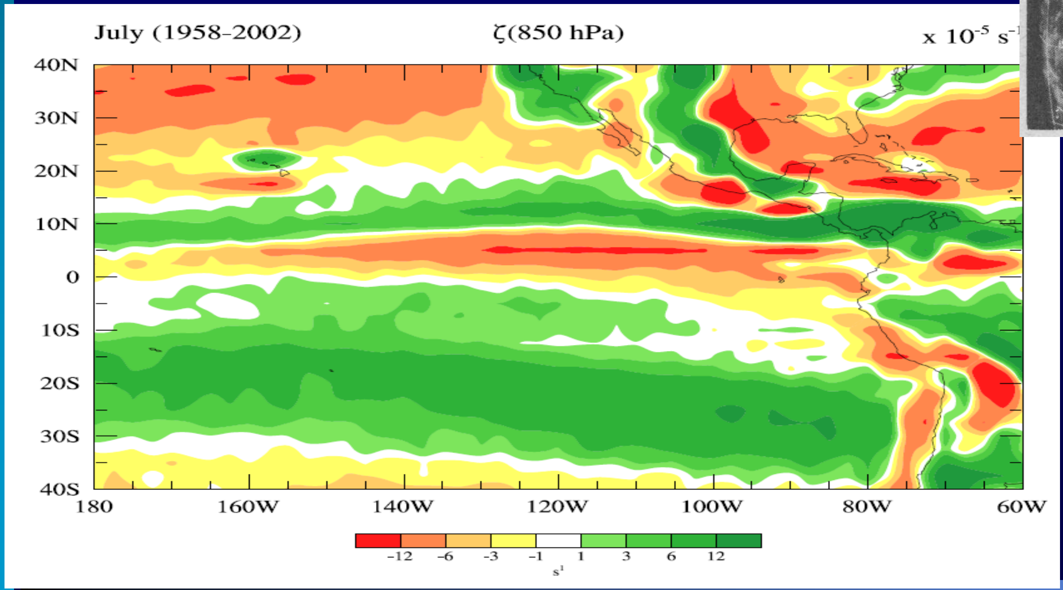
Planetary scale:ITCZ

July



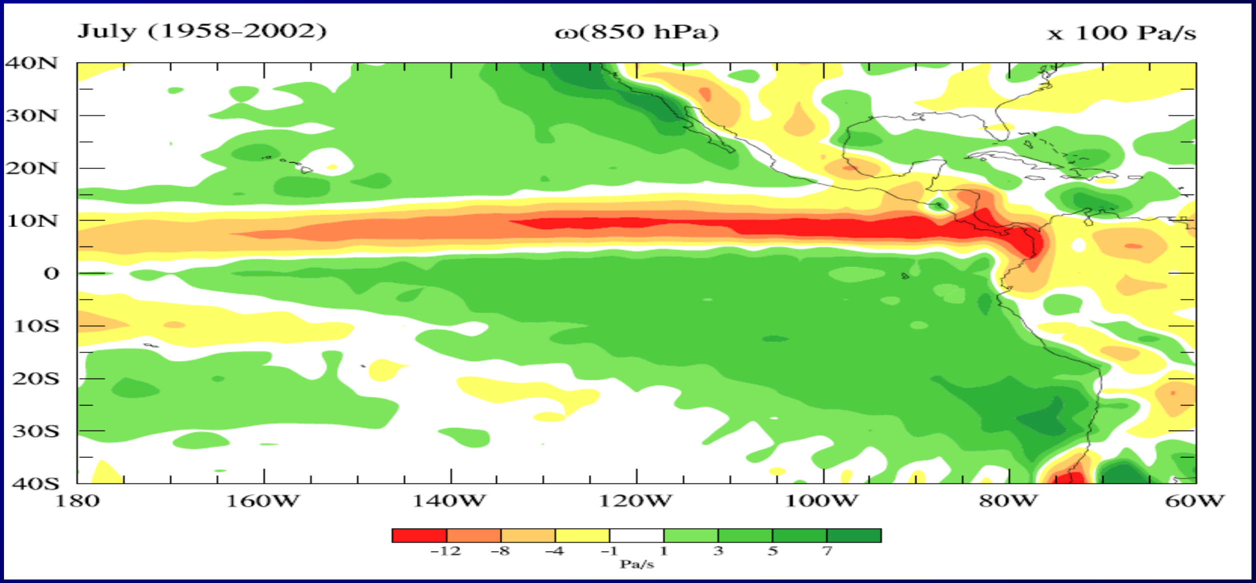
Vertical velocity : -ve values for upward

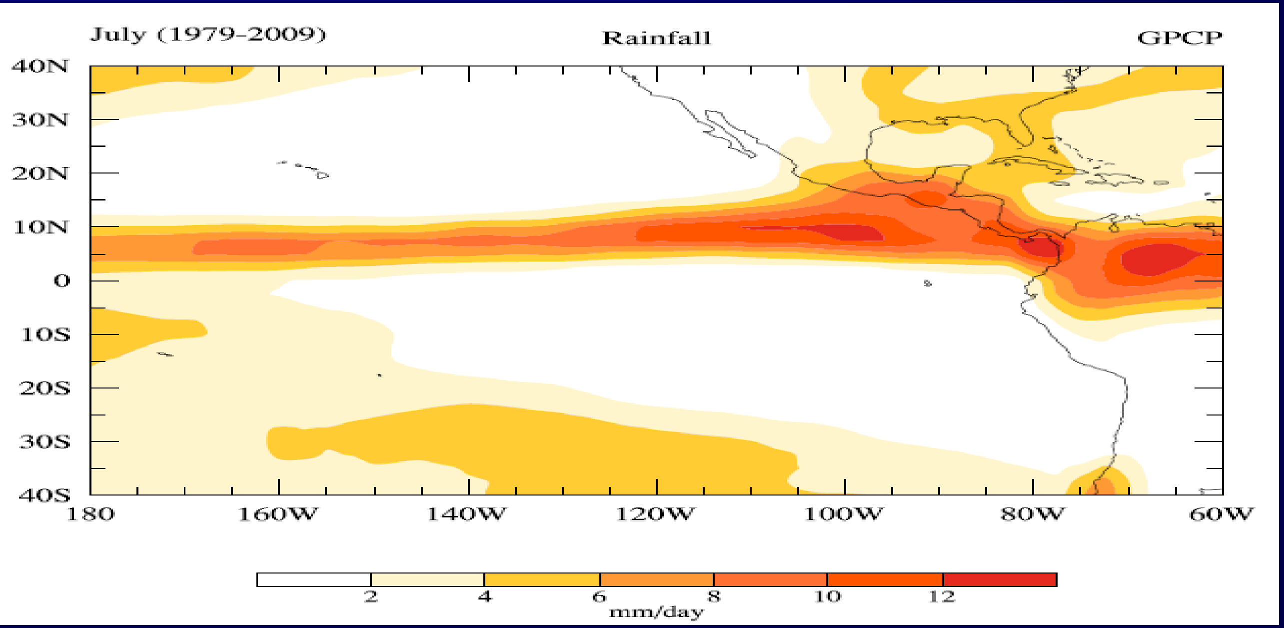




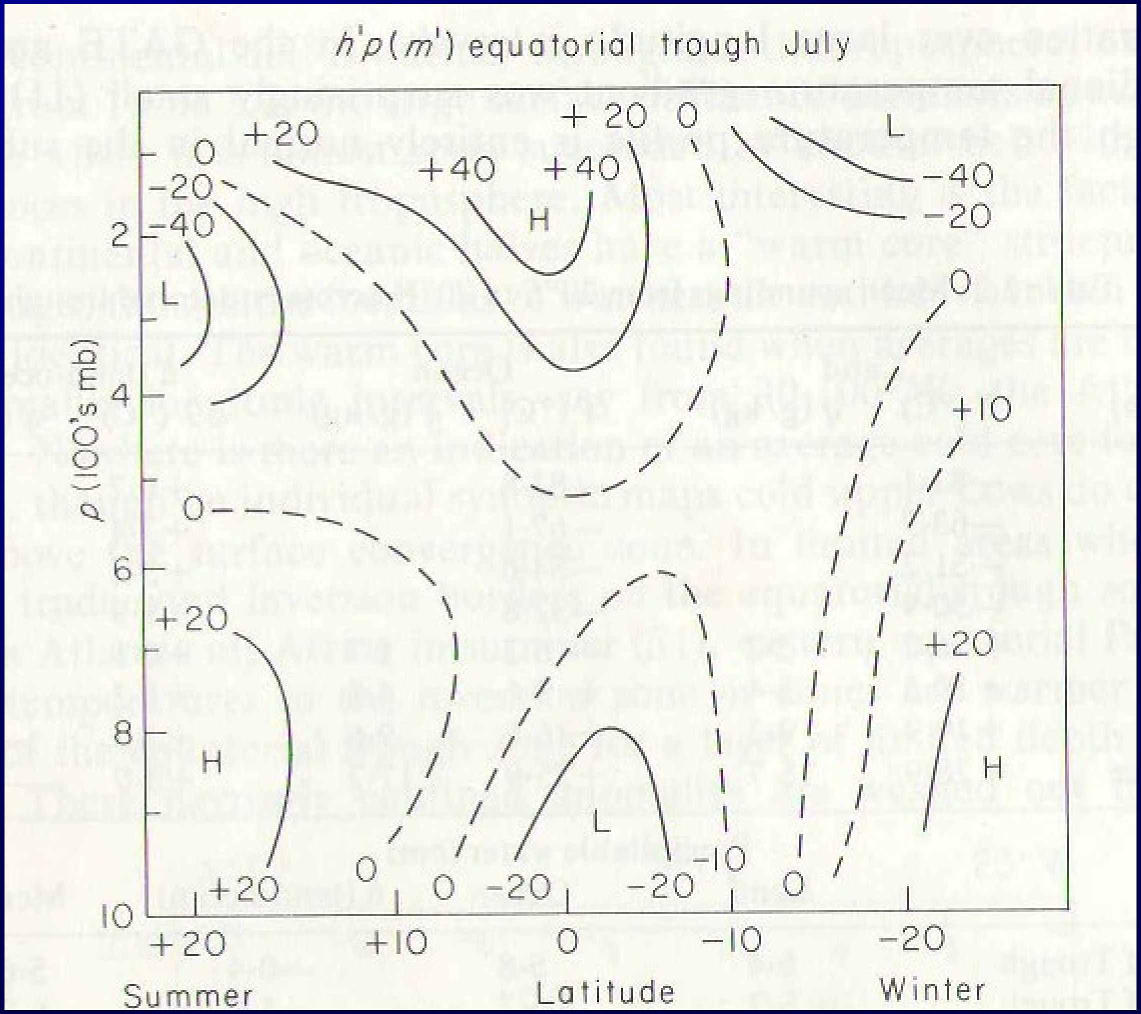
Voticity above the boundary layer

July


July (1958-2002)
ω(850 hPa)
x 100 Pa/s
40N
30N
20N
10N
0
10S
20S
30S
40S
180
160W
140W
120W
100W
80W
60W
-12
-8
-4
-1
1
3
5
7
Pa/s


July (1979-2009)
Rainfall
GPCP
40N
30N
20N
10N
0
10S
20S
30S
40S
180
160W
140W
120W
100W
80W
60W
2
4
6
8
10
12
mm/day

Pressure distribution relative to the equatorial trough



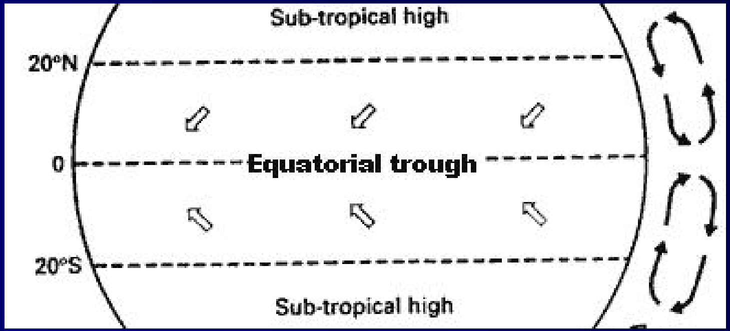
ITCZ-Charney 1971

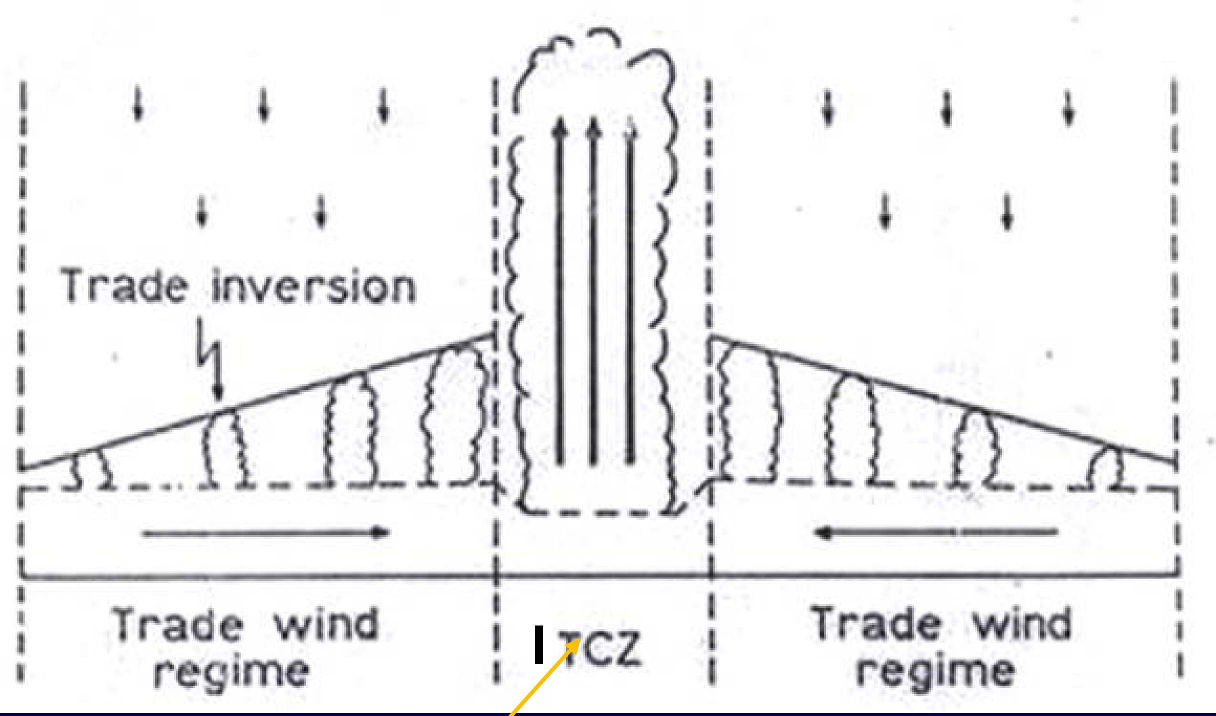
The important attributes of the ITCZ are considered to be:

- intense convergence in the boundary layer which is associated with cyclonic vorticity above the boundary layer,
- ascent of moist air throughout the troposphere and
- deep moist convection and heavy precipitation

Tropical circulation and rainfall

If the ascent of the surface moist air over the equatorial region is strong enough, the result is the Hadley cell.





Hadley cell

Intertropical Convergence Zone (ITCZ)

Theories of the monsoon

- **Halley's land -sea breeze model**
- **Alternative theory for the basic system responsible for the monsoon considered to be the Intertropical Convergence Zone (ITCZ) or the equatorial trough ITCZ (whose origins can be traced to Blanford's (1886) remarkably perceptive analysis)**

Detailed discussion in :

'The monsoon system: Land–sea breeze or the ITCZ?'

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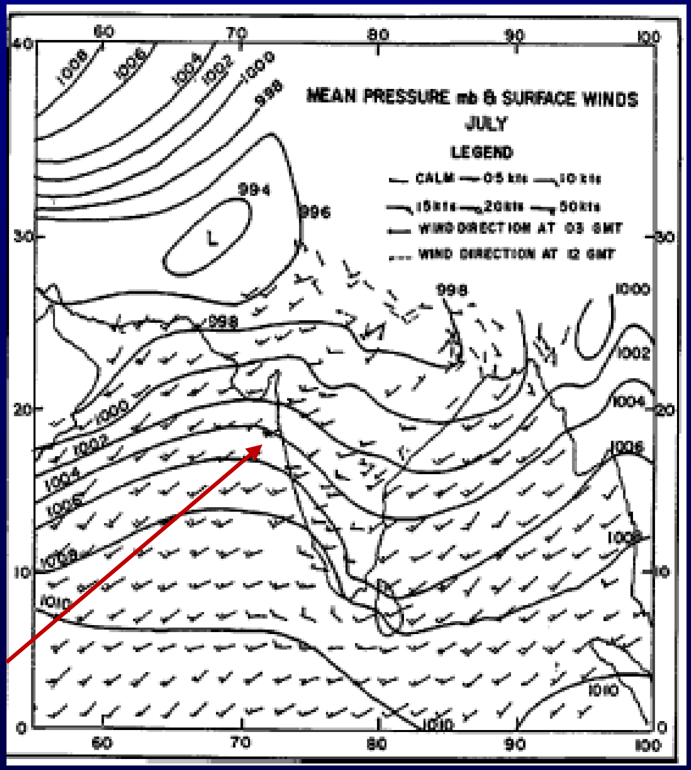
J. Earth Syst. Sci. **(2018) 127:1**

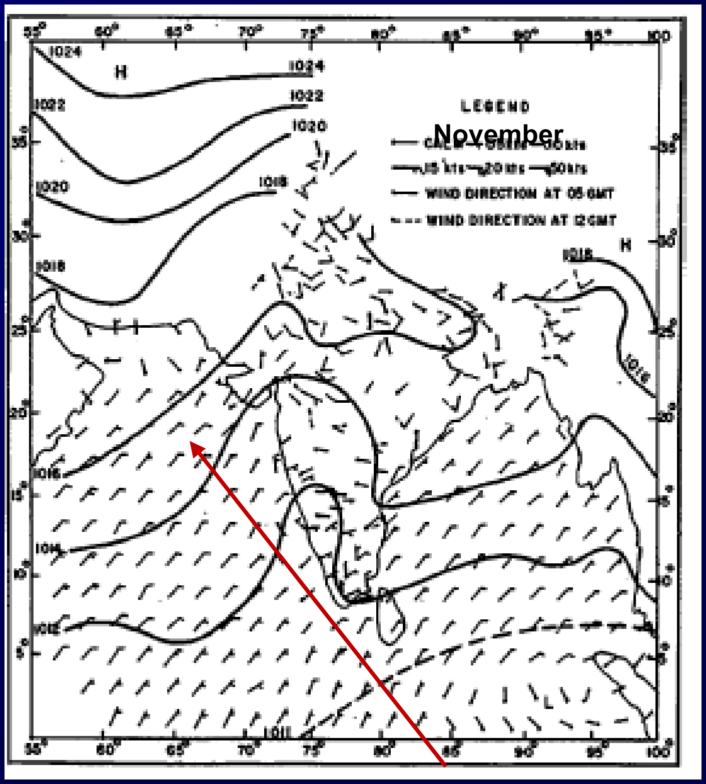
https://doi.org/10.1007/s12040-017-0916-x

Halley'theory for the seasonal variation of surface winds : the monsoon (according to him)

MEAN PRESSURE AND SURFACE WINDS

July | November





Winds from the Southwest | from the northeast

- In the summer,,

Land hotter than ocean=>

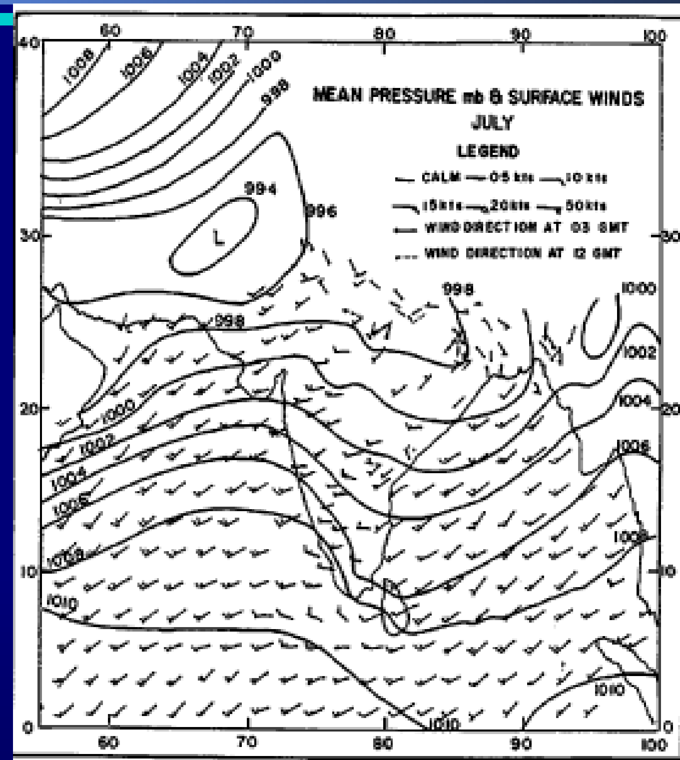
Pressure low over land,

high over ocean;

Hence winds from ocean

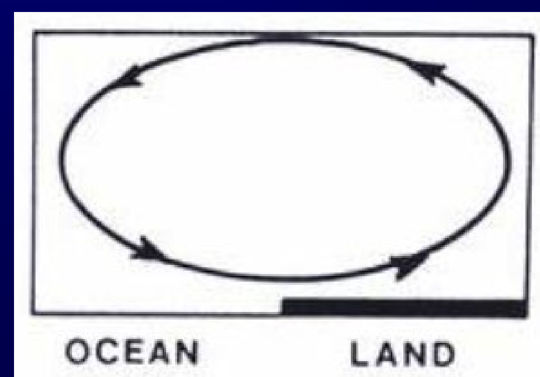
to land i.e. Westerly

instead of easterly



- Land-Sea breeze

Impact of continuous differential heating over land and ocean



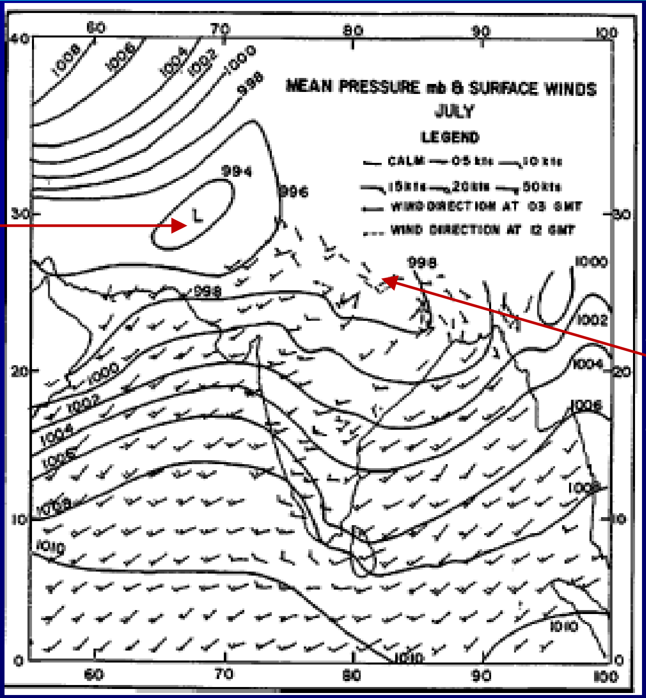
Land is hotter than the ocean

- Expect ascent to increase with increase of land-ocean contrast

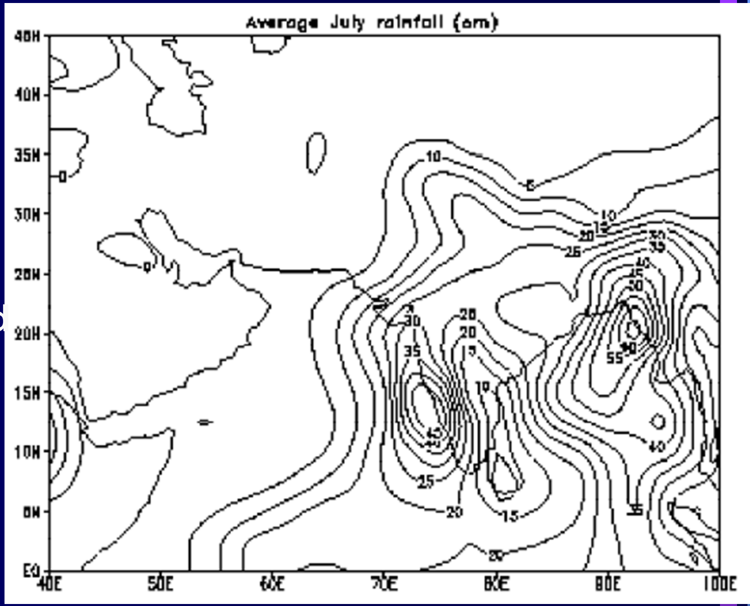
How deep is the vertical cell driven by surface heating gradients?

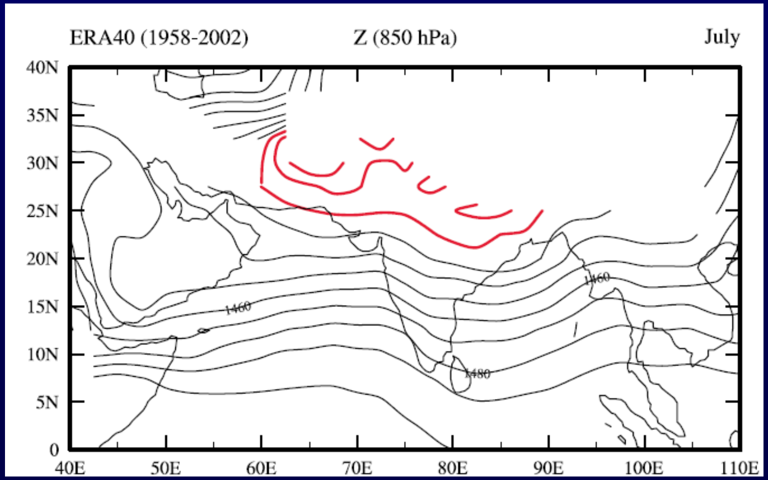
- In a study of the axisymmetric circulation of the tropical atmosphere driven by heating gradients at the bottom boundary, it has been shown that the vertical ascent associated with the low pressure generated by the surface heating does not extend beyond 3 kms from the bottom i.e. the vertical cell is rather shallow. This is called a **heat low**.
- A deep cell extending throughout the troposphere, occurs only when there is heating in the mid-troposphere associated with the latent heat released when clouds form and rainfall can occur-Hadley cell. The low at the surface for such a case is the **dynamic low.**

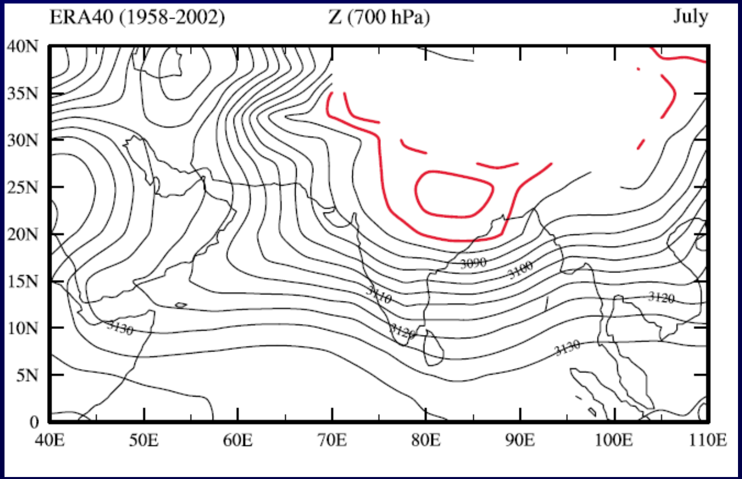
Heat low:ascent only upto 850 hpa



Dynamic low ascent up to and above 700hpa







- Although Halley never mentioned the rainfall associated with his land-sea breeze model, if the ascent is strong enough to produce rainfall, the implication of the Halley model is that the variability of this rainfall is related to variability of land-ocean contrast.
  Simpson (1921), first then Kothawale & Rupakumar (2002), Gadgil et. al (2018) have shown out that the relationship between land-ocean contrast is opposite to this expectation. Land temperatures respond to rainfall and are lower for higher rainfall.
  Clearly, the time has come to abandon the notion that the land-sea contrast is the primary cause of the monsoon.
  Yet it remains a popular theory, found in text books & papers. It is also used to deduce impacts on monsoon rainfall of glbal warming which would involve land warming faster than the ocean in prestigious IPCC reports.

- What then is the basic system responsible for the monsoon?
- Many other hypotheses have been suggested including one by Simpson himself, but the one that has now been established is that: the basic system is the same that is associated with large-scale rainfall over the non-monsoonal regions of the tropics viz, the ITCZ. (Sikka and Gadgil 1980, Gadgil 1988).

Monsoon and the ITCZ

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. 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.

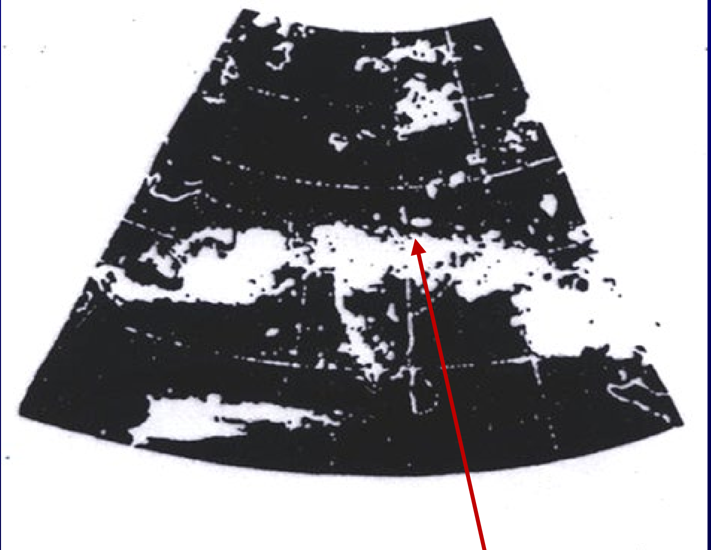
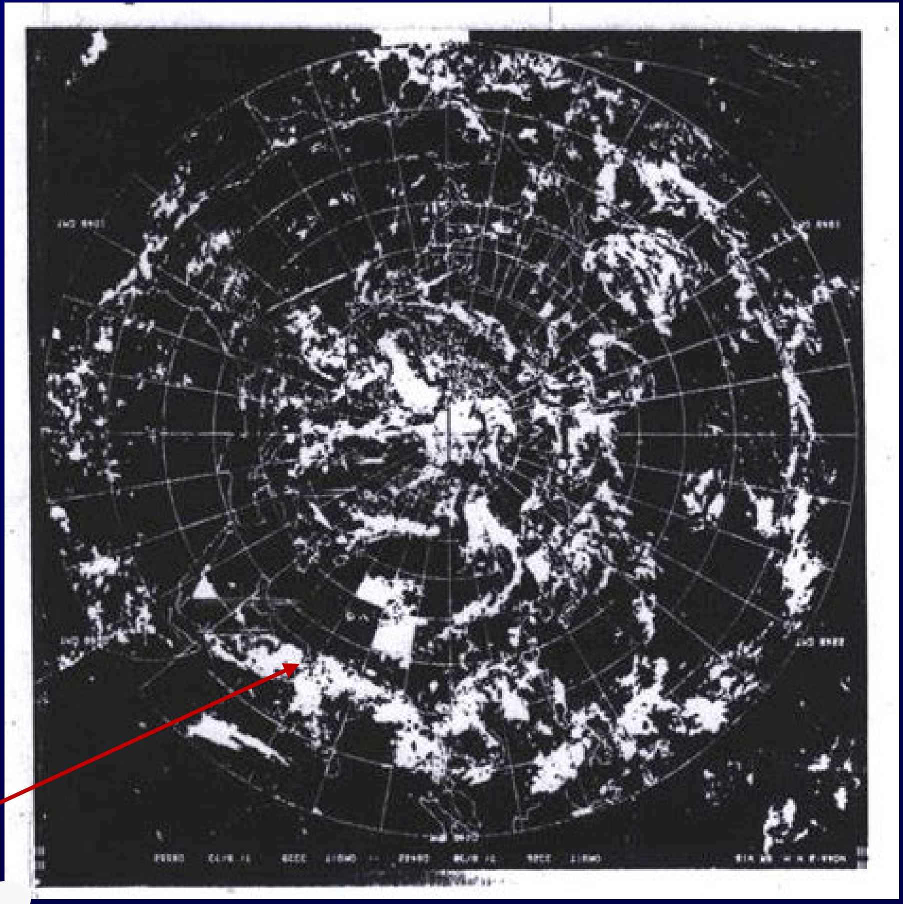


Fig 6. Satellite imagery of an active monsoon day (8th july 1973).



A zonal (east-west) cloud band over the Indian region is seen on an active monsoon day (8July1973)

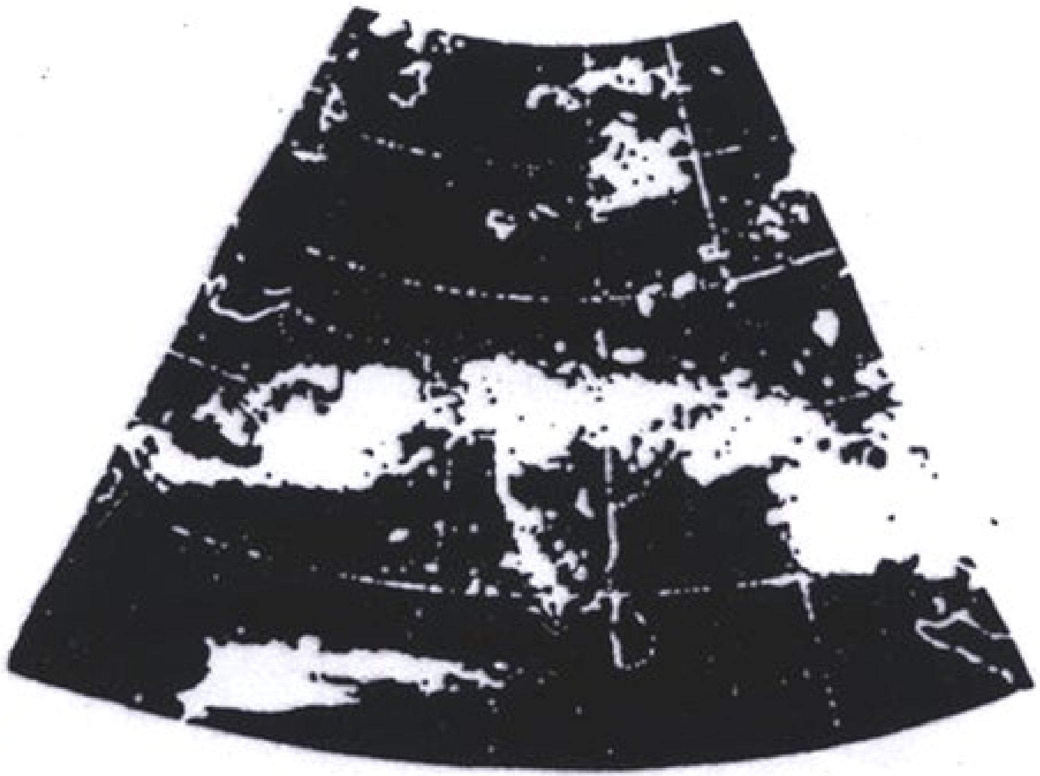
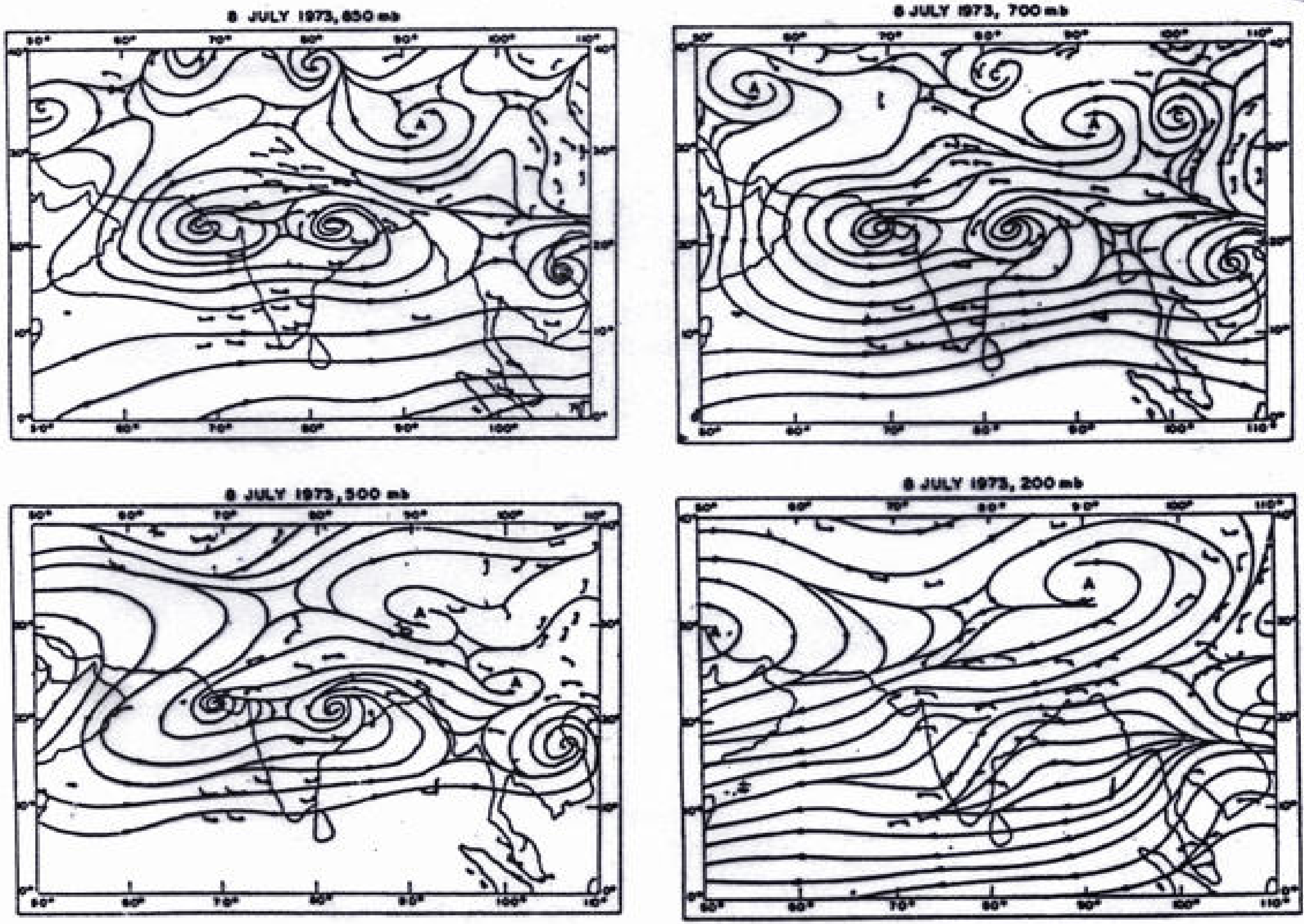


Fig 6. Satellite imagery of an active monsoon day (8th july 1973).

Sikka and Gadgil 1980



Circulation pattern at different levels on 8 July 1973.

Sikka and Gadgil (SG) showed that

(i)The maximum cloud zone (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 associated with intense convergence in the lower troposphere (Anjaneyalu 1969) and maximum non-orographic rainfall (Raghavan 1973).

(iv) Since the MCZ has all the attributes of the ITCZ (a la Charney), Sikka and Gadgil concluded 'It becomes clear that the organized moist convection associated with the monsoon may be attributed to a continental ITCZ over the region.'

Monsoon and the ITCZ

- The seasonal variation of the rainfall over the monsoonal regions is associated with the seasonal variation in the location of the ITCZ in response to the seasonal variation of solar heating. Monsoon is thus a manifestation of this seasonal variation of the ITCZ.
- Thus all the feedbacks characterizing an ITCZ over the oceans + those special to land surface processes will lead to monsoon variability.

Special features of the ITCZ over Indian longitudes during the summer monsoon

- Two favorable zones for the occurrence of the ITCZ, one over the heated continent and another over the warm waters of the equatorial Indian Ocean. The MCZ occurs intermittently over one or other or both throughout the summer monsoon.

Special features of the ITCZ over Indian longitudes during the summer monsoon

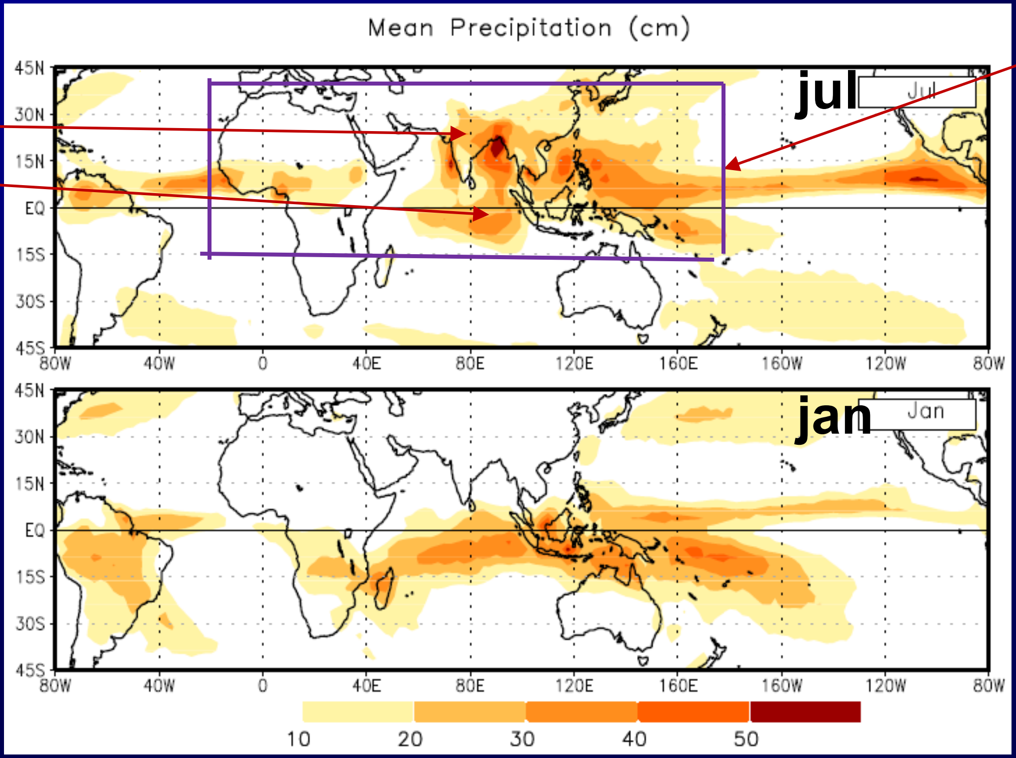
Over the Indian longitudes, there are two favorable zones for the occurrence of the ITCZ, one over the heated continent and another over the warm waters of the equatorial Indian Ocean. The MCZ occurs intermittently over one or other or both throughout the summer monsoon.

Since the convergence over both the equatorial Ocean and the continent cannot be intertropical, we refer to the as continental (CTCZ)and oceanic tropical convergence zones. The first special feature is thus:

1. Occurrance of two TCZs: CTCZ one over the heated continent and another oceanic ITCZ over the equatorial Indian Ocean. The two are also seen as maxima in the mean July rainfall.

Mean Rainfall in January and July

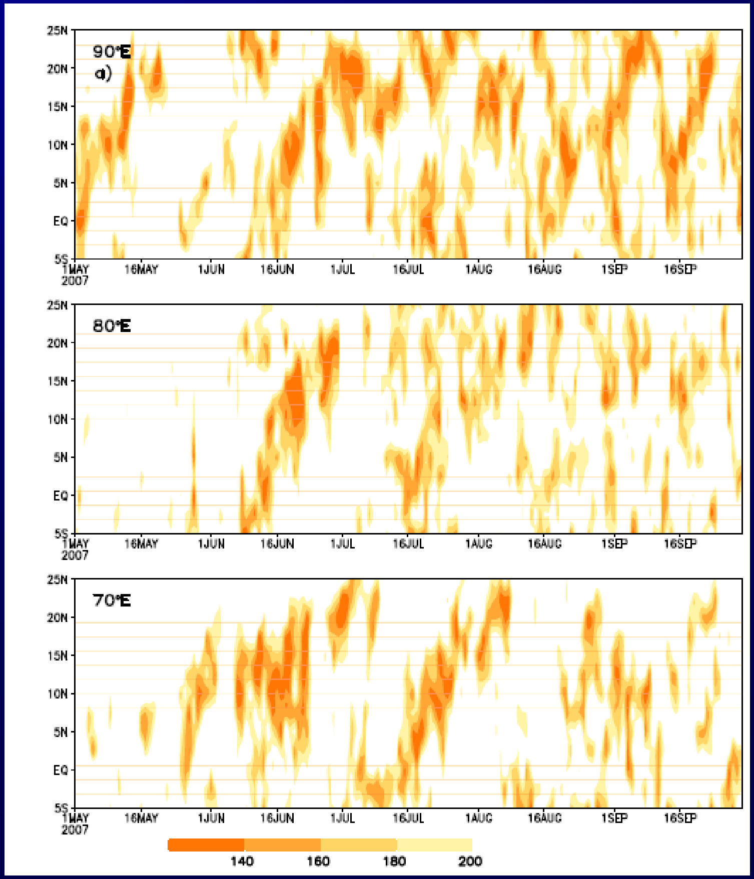
CTCZ
Oceanic TCZ



Monsoonal Regions of the world (*based on seasonal variation in the direction of the wind)*

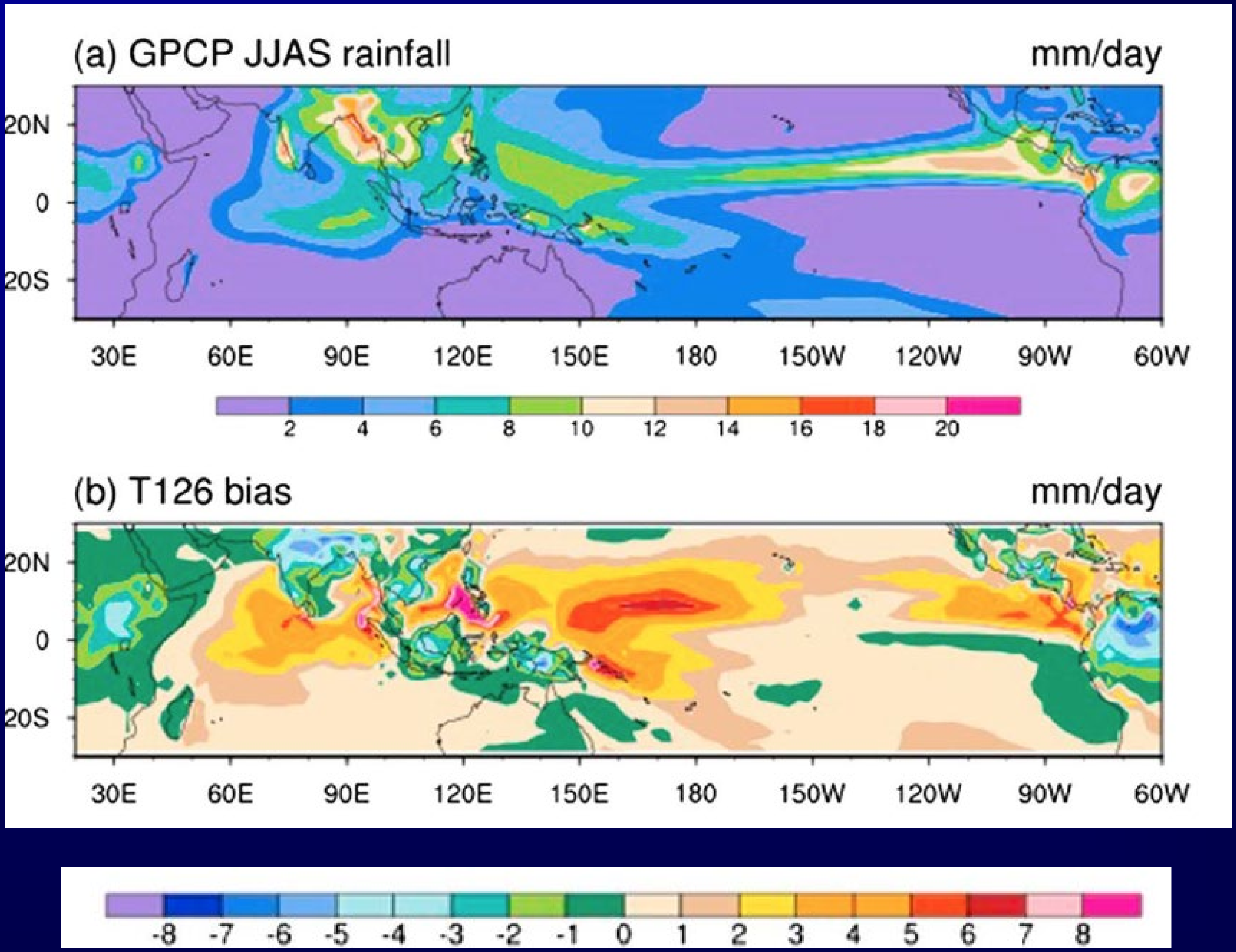
Although the basic system responsible for large scale rainfall is the same as for the non-monsoonal regions, the amplitude of the seasonal variation is much larger.

2. Northward propagations the oceanic TCZ culminating over the monsoon zone over the subcontinent at interval of 2-6 weeks throughout the summer season. Thus the oceanic TCZ is a lifeline of the CTCZ and since it maintains the CTCZ with such propagations

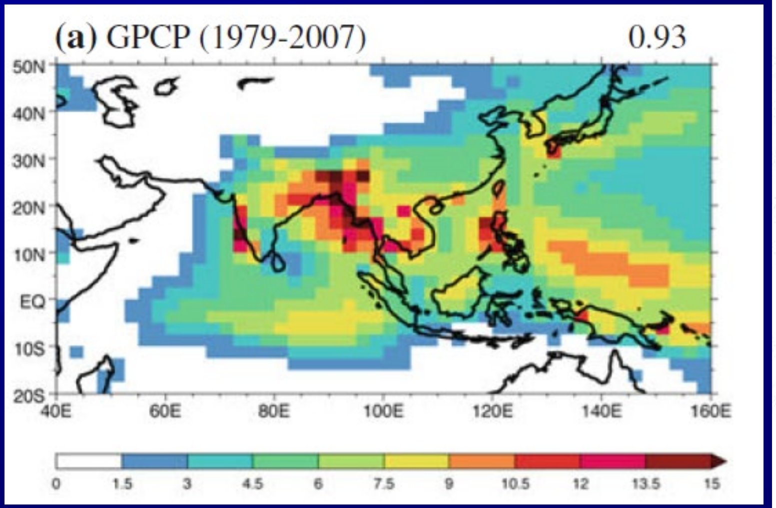


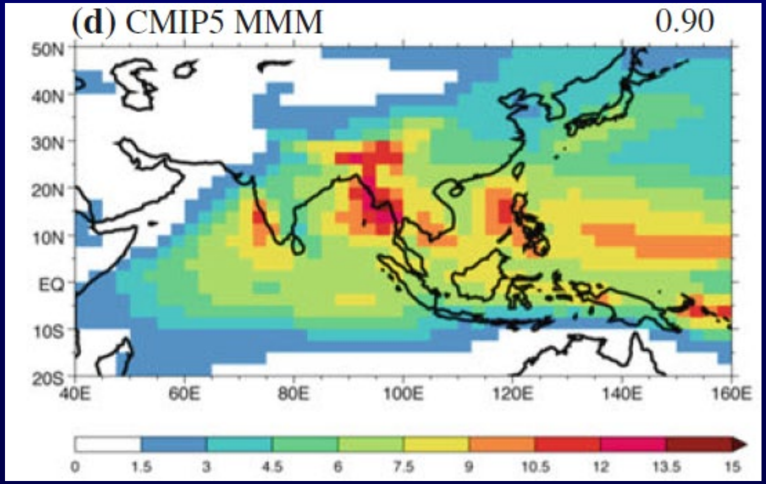
Daily variation of latitudinal belts with low OLR along 70^0, 80^0 and 90^0E during May-September, 2007

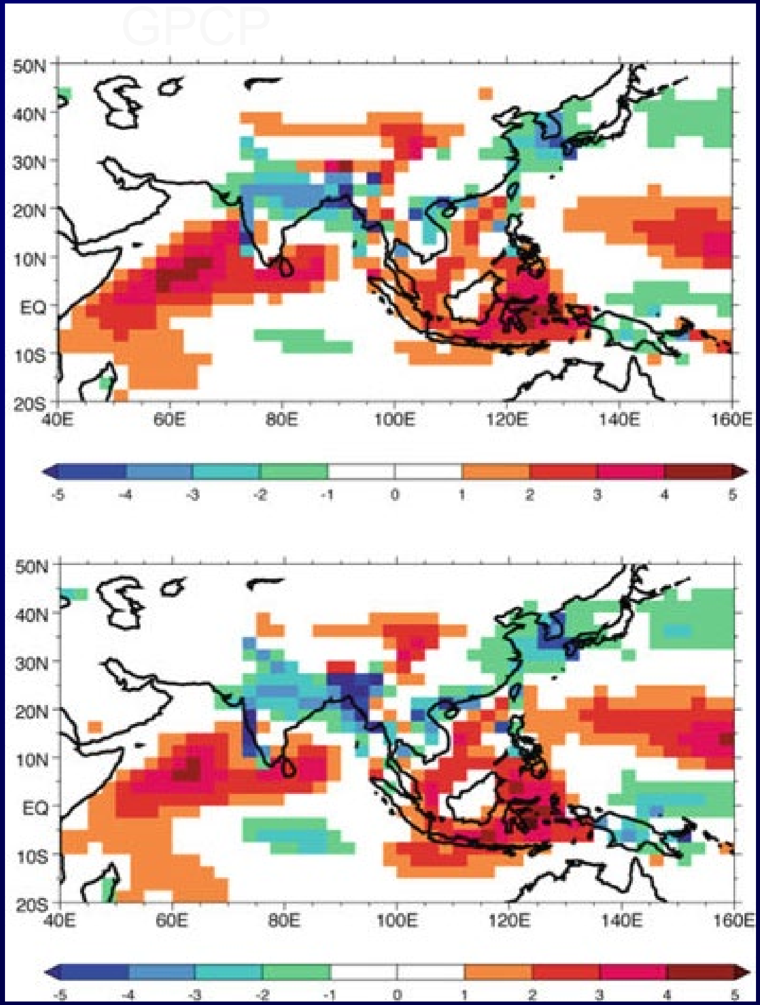
Problems faced by the models-the oceanic TCZ winning the competition with CTCZ



CMIP5 MMM – GPCP







CMIP3 MMM – GPCP

CISK

- Charney and Eliassen (1964) and Charney (1973) viewed the organization of convection over the synoptic scale (as in a tropical cyclone) or over the planetary scale (as in the cloud band associated with a intertropical Convergence Zone-ITCZ, examples of which we have seen in the satellite imagery) as a manifestation of an instability (CISK) in which these larger scales are selected for.
- However, after Charney and Eliassen suggested the hypothesis, Sarachik and Israeli showed that there was no selection for a large scale mode as suggested by Charney and Eliassen.
- So there is a major problem in calling this interaction between the cumulus and synoptic and larger scales as CISK

- Also, the linear theory of CISK proposed by them has been widely criticized since the 1980s. It has been suggested that it fails to take into account the non-linear feedbacks/ processes which are needed to explain the dynamics of a mature tropical cyclone.
- However, the possibility of viewing the synoptic scale cyclone as a manifestation of CISK was revived by the work of Srinivasan and Smith who showed that selection for a large scale mode occurs if there is a lag between convergence and rainfall as suggested by Emmanuel.
- So it appears that the jury is still out on whether the interaction can be considered to be associated with an instability.

- However, as I understand it, the key element of the ITCZ physics is the positive feedback involved between low-level convergence (associated with cyclonic vorticity above the boundary layer), ascent and clouding.
- The concept of co-operative interaction between the cumulus and larger scales proposed by Charney and Eliassen is still widely accepted. In Ooyama's words "the spirit of CISK as the cooperative intensification theory is valid and alive."
- However, there has been another approach viz. the Quasi-equilibrium (QE) approach. I would like to share with you a comment from one of the leaders in the field about my JESS paper on monsoon and the ITCZ. "One key thing I would have liked discussed is just what induces the TCZ to finally move north and bring rain to India. The current way of

thinking (or maybe it is just the current way of talking) would invoke the quasi-equilibrium (QE) Theory and say it is when moist static energy over the land gets high enough. Though of course it does not tell us what makes it high enough.

On what might be a related matter, I was reminded that your work (1984) about the ~27.5C cutoff for convection does somewhere also say that above that threshold it is a matter of low level convergence. The QE mafia have made "CISK" a dirty word, but the QE models and CISK models do about the same thing. It may just come down to the idea that once the boundary layer air is potentially buoyant enough to rise to the top, all that matters is low level convergence, so over the Indian sector all that matters is convergence."

Some food for thought!

Thank you