12.708: Topics in Paleoclimatology

MONSOONS: PAST, PRESENT, & FUTURE

Olivier MARCHAL & Delia OPPO

One Definition of the Monsoon

- Monsoon climates are found where a tropical continent lies poleward of an equatorial ocean

- There are characterized by:
  - dry winters & very wet summers
  - reversal of wind direction:
    * equatorward-easterly flow in dry season
    * poleward-westerly flow after monsoon onset

Clift & Plumb (2008)

Near-Surface Circulation Patterns in Indian Monsoon Region

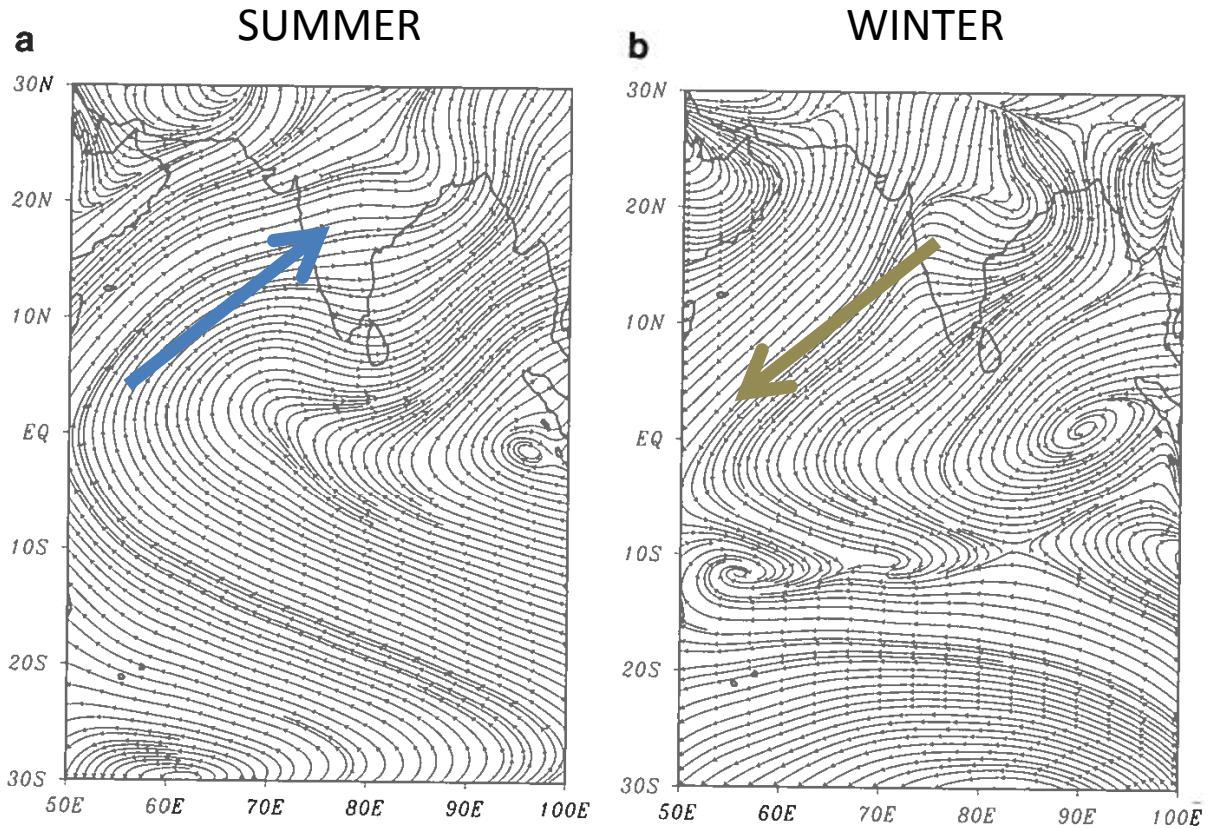
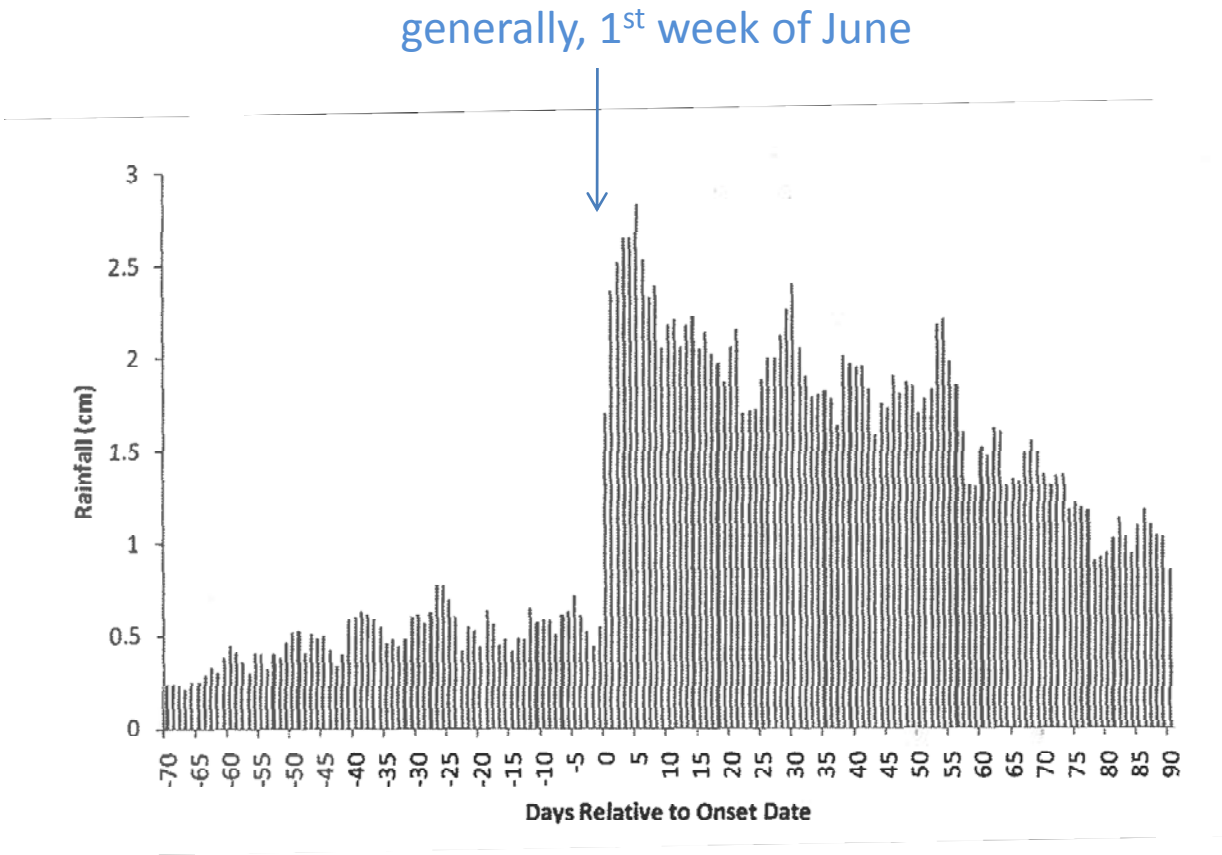


Fig. 5.1 Climatological 925 mb streamlines over the Indian monsoon region for the month of (**a**) July, and (**b**) January (Computed from NCEP-NCAR reanalysis)

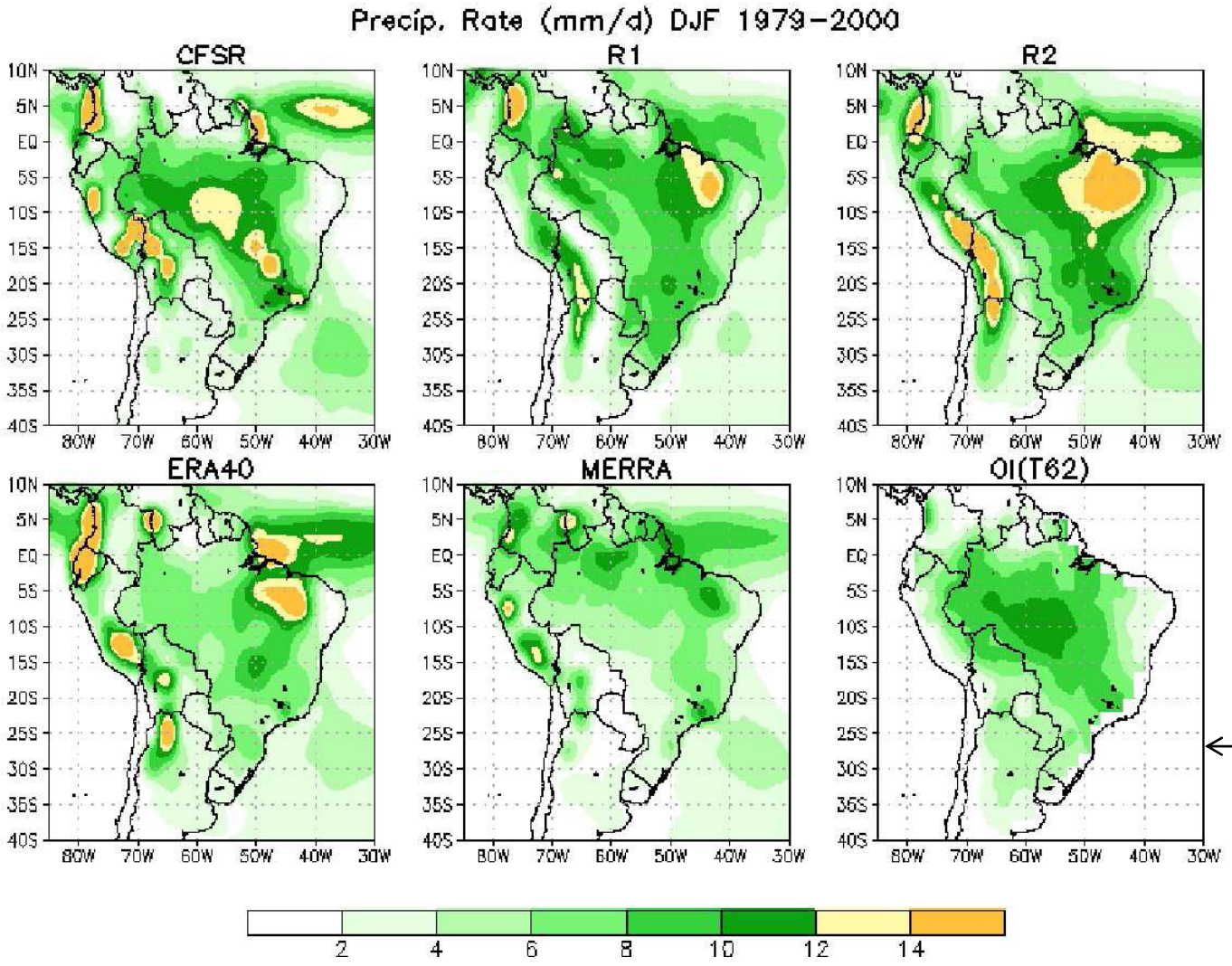
Krishnamurti et al. (2013)

Composite Record of Daily Rainfall at Kerala (SW India)



Krishnamurti et al. (2013)

South American Monsoon System



DATA-BASED ANALYSIS

Silva & Kousky (2007)

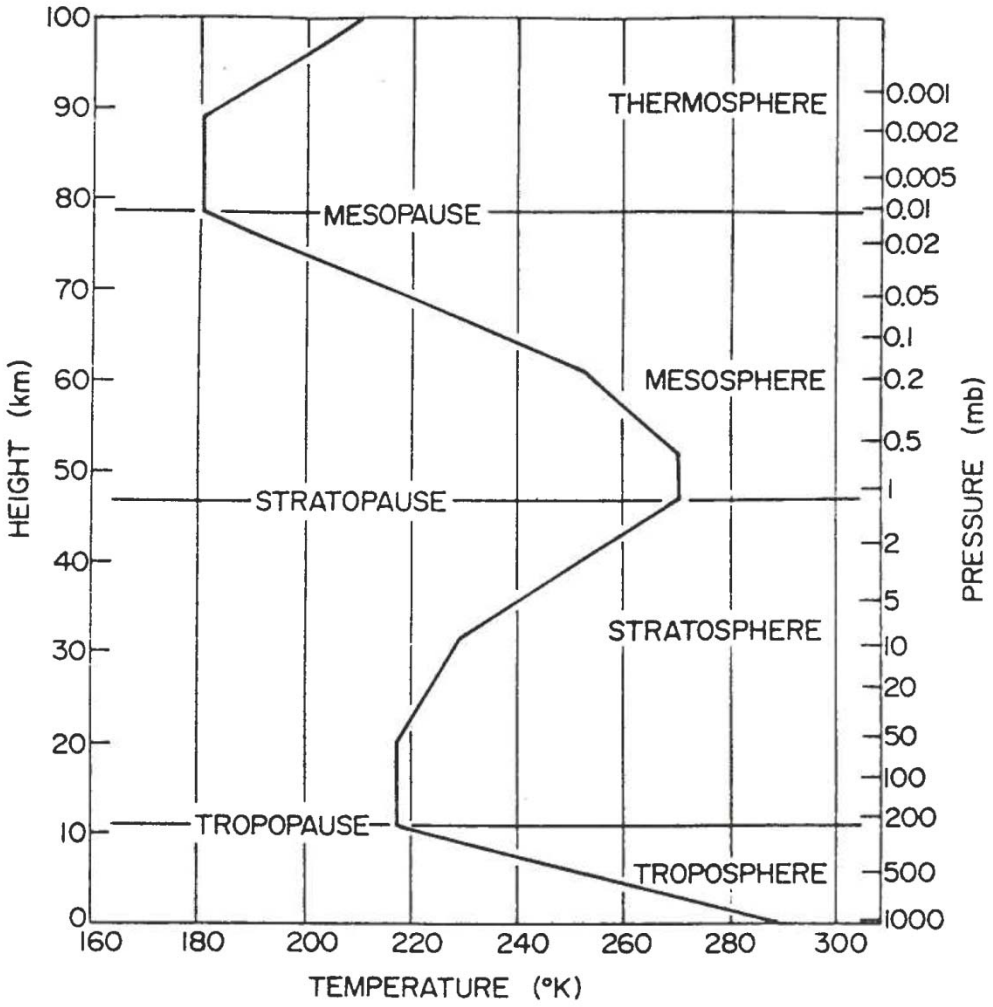
Regions affected by Monsoons

- South Asia and South East Asia
- Western Africa
- Northern Australia
- South America (Brazil, Bolivia, Paraguay)
- North America (Southern US and Mexico)

Silva & Kousky (2007)

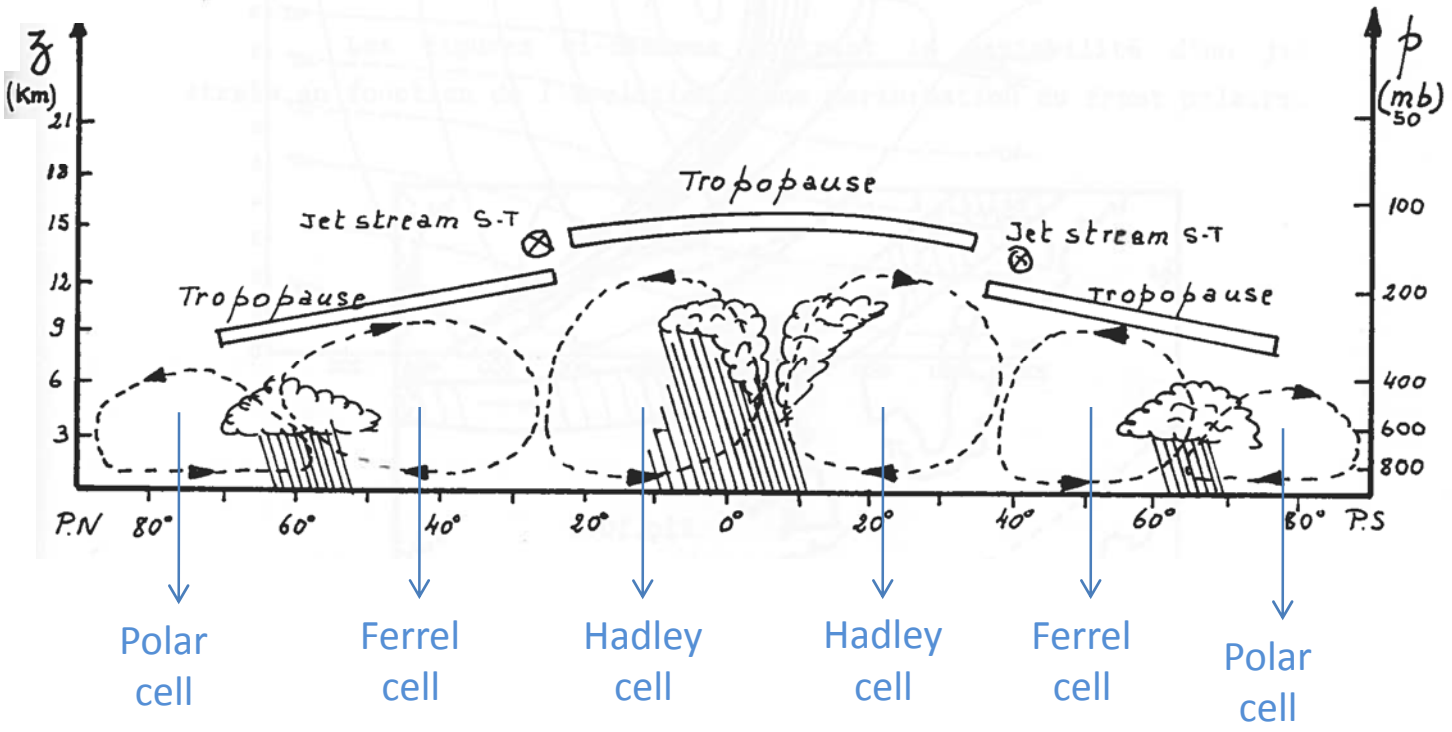
Part I: Rudiments of Tropical Meteorology

Idealized Temperature Profile in the Atmosphere



Peixoto & Oort (1992)

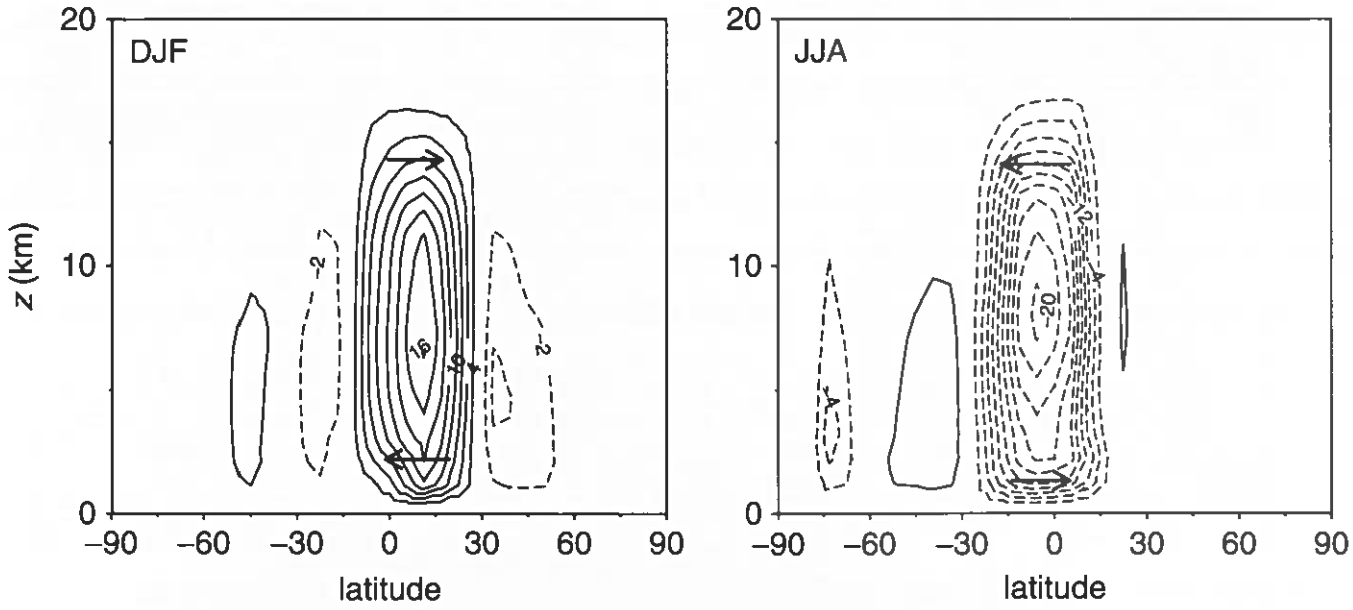
Schematic of Tropospheric Mean Circulation



F. Ronday (1990)

The Hadley Cell

mass streamfunction (10 kg/s)



Clift & Plumb (2008)

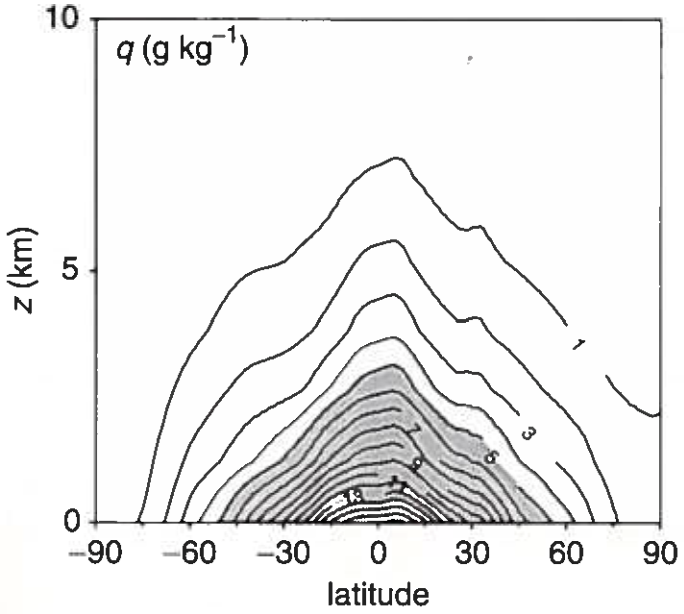
Humidity Indices

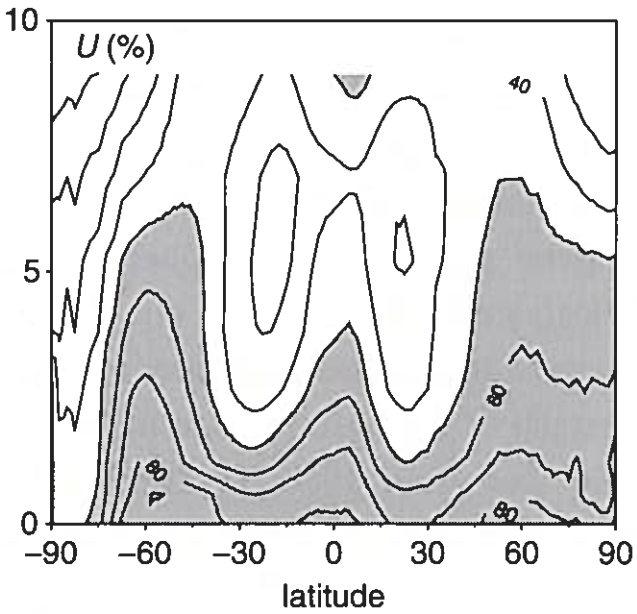
Specific humidity

$$q = \frac{m_V}{m}$$

Relative humidity

$$U = \frac{p_V}{p_{V,SAT}}$$





Clift & Plumb (2008)

The Clausius-Clapeyron Relationship

$$p_{V,SAT}(T) \approx p_{V,SAT}(T_0)\exp\left[\frac{L(T_0)}{R_V}\left(\frac{1}{T_0}-\frac{1}{T}\right)\right]$$

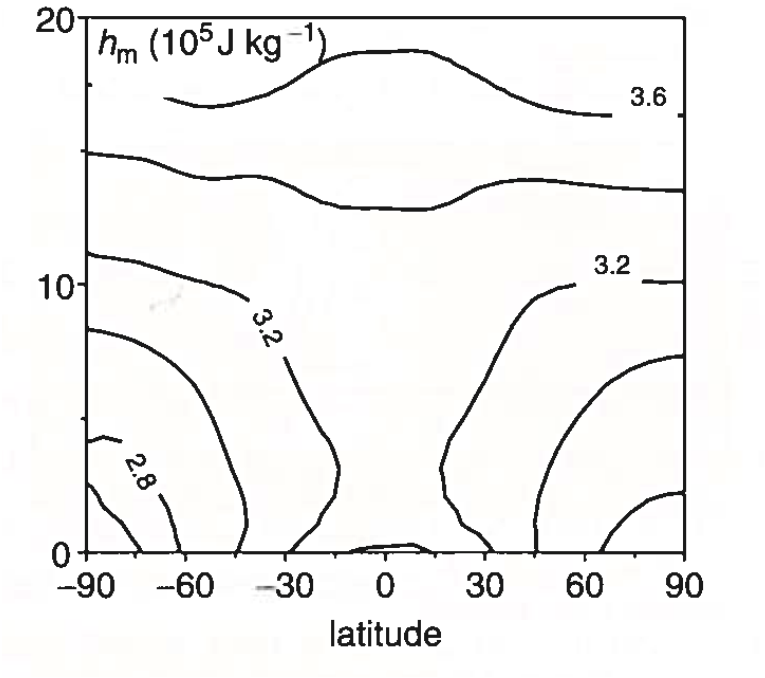
where

L	latent heat of vaporization
R_v	mass constant for water vapor
T_0	reference temperature

Saturation water vapor pressure increases quasi-exponentially with temperature

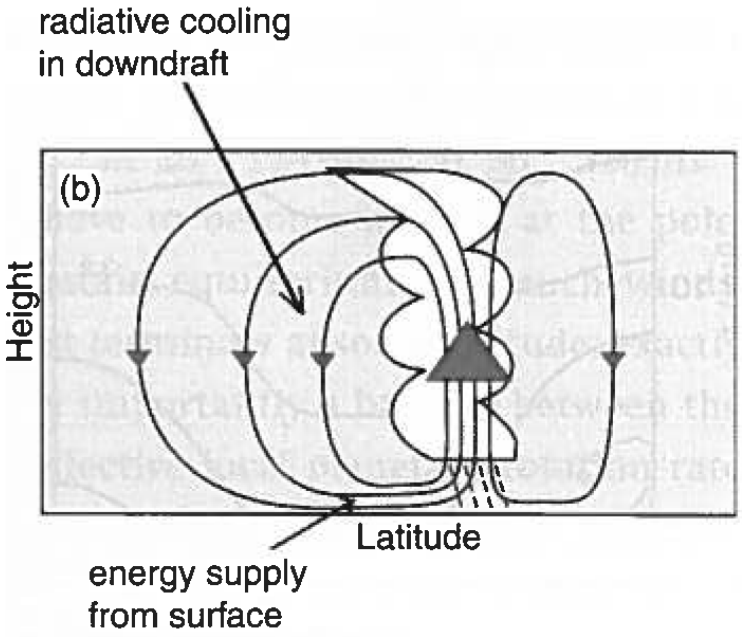
Moist Static Energy h_m

$$h_m = C_P T + gz + Lq$$



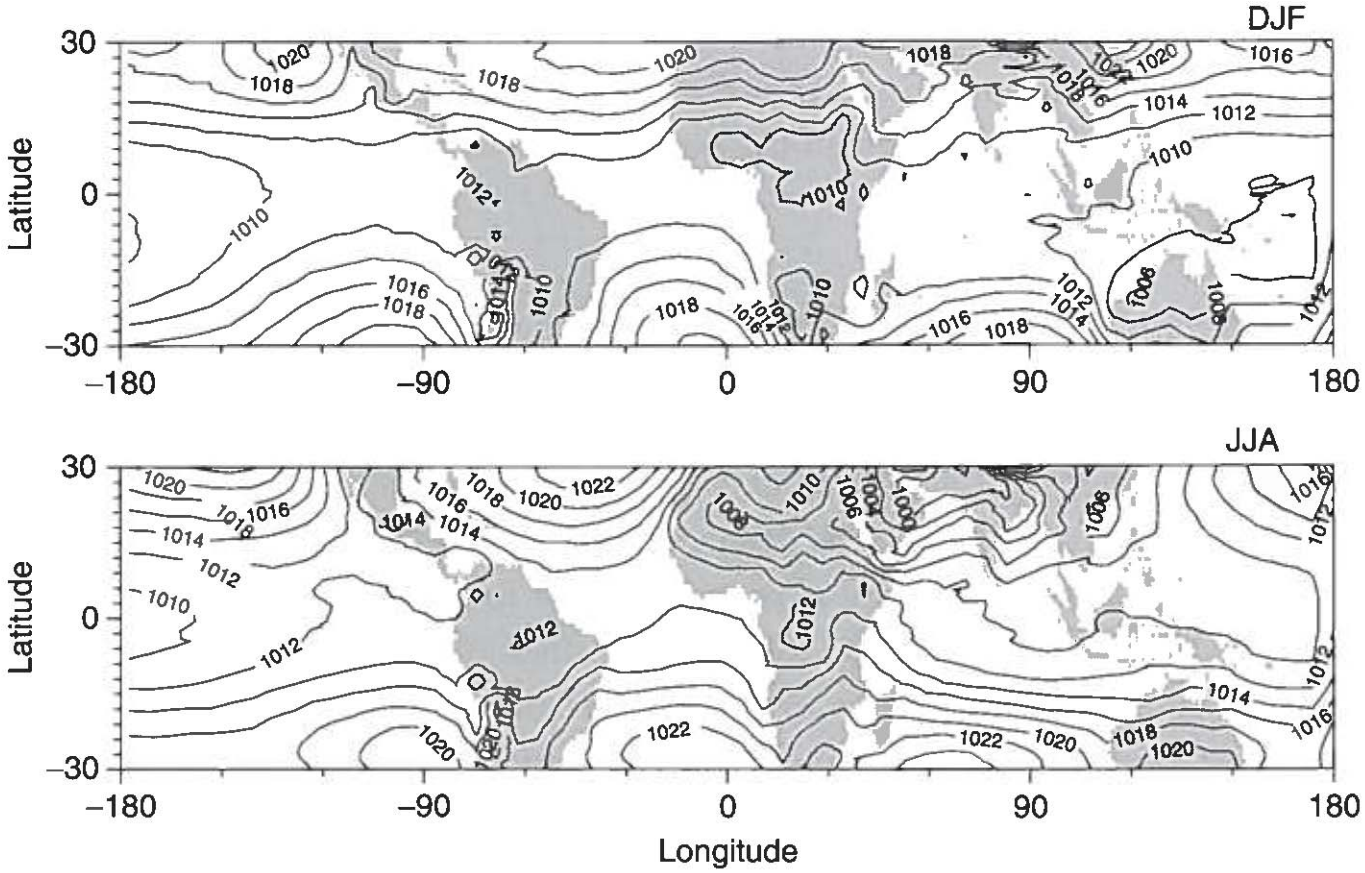
Clift & Plumb (2008)

Energetics of Hadley Circulation



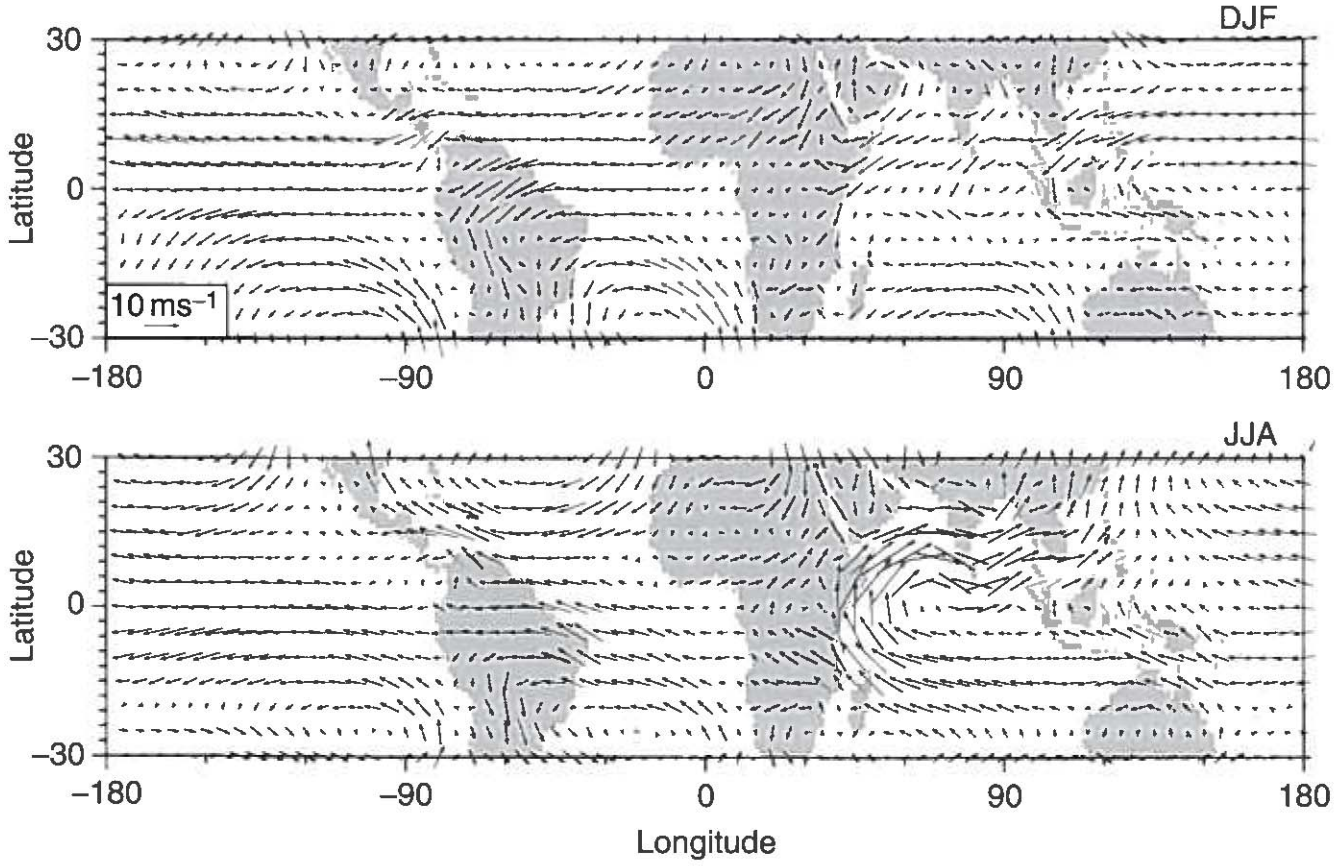
Clift & Plumb (2008)

Climatological Surface Pressure (hPa)



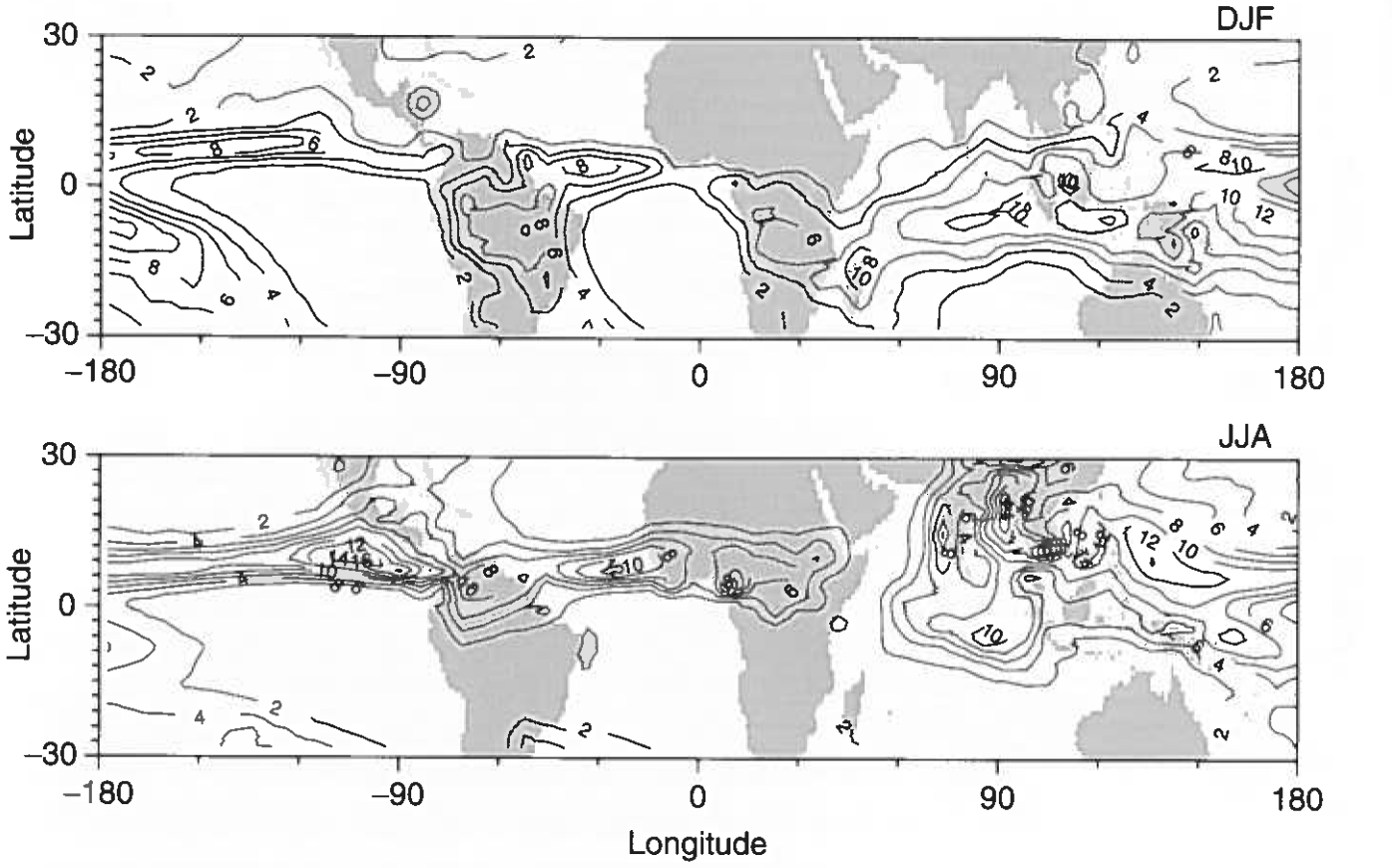
Clift & Plumb (2008)

Climatological Winds at 850 hPa



Clift & Plumb (2008)

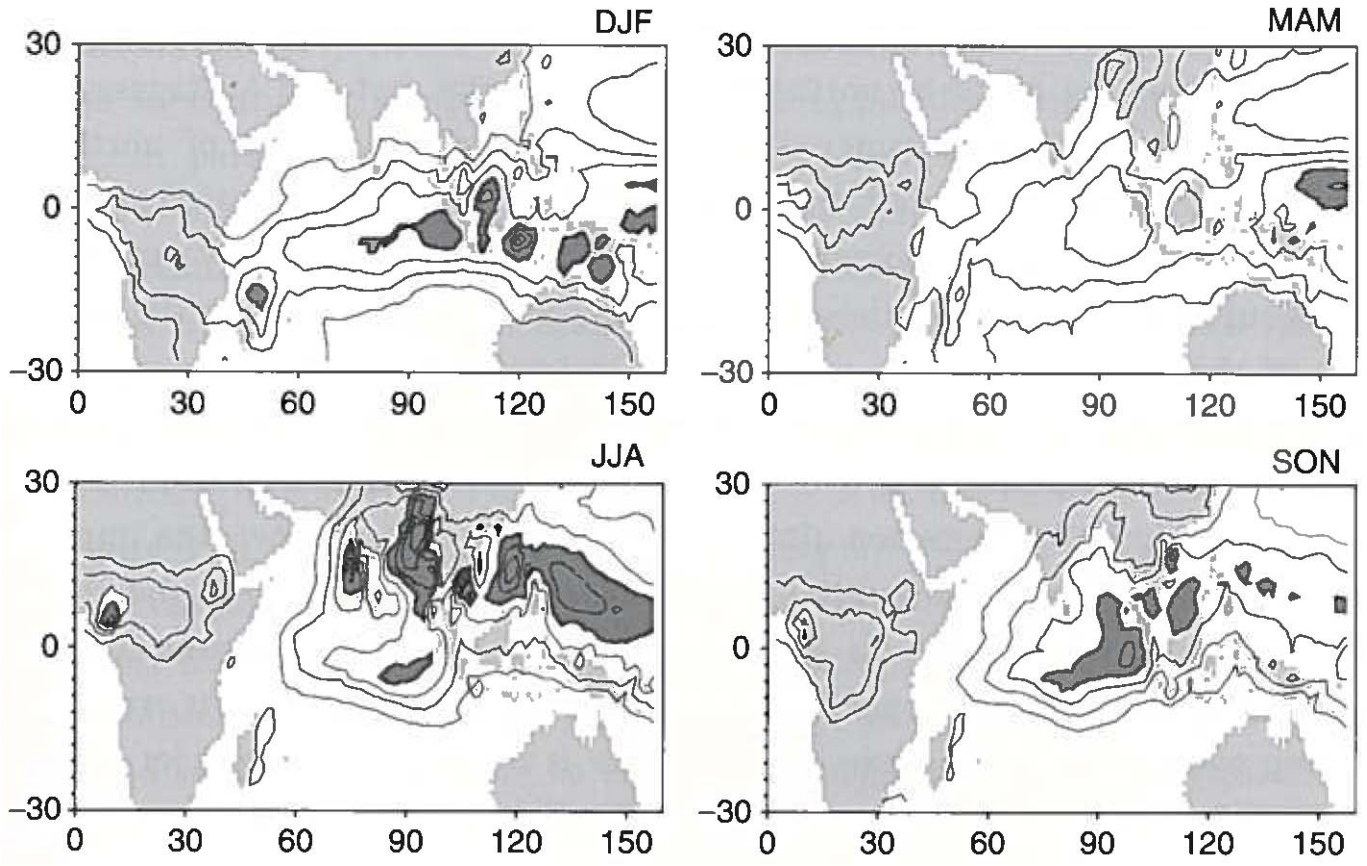
Climatological Rainfall (mm/day)



Clift & Plumb (2008)

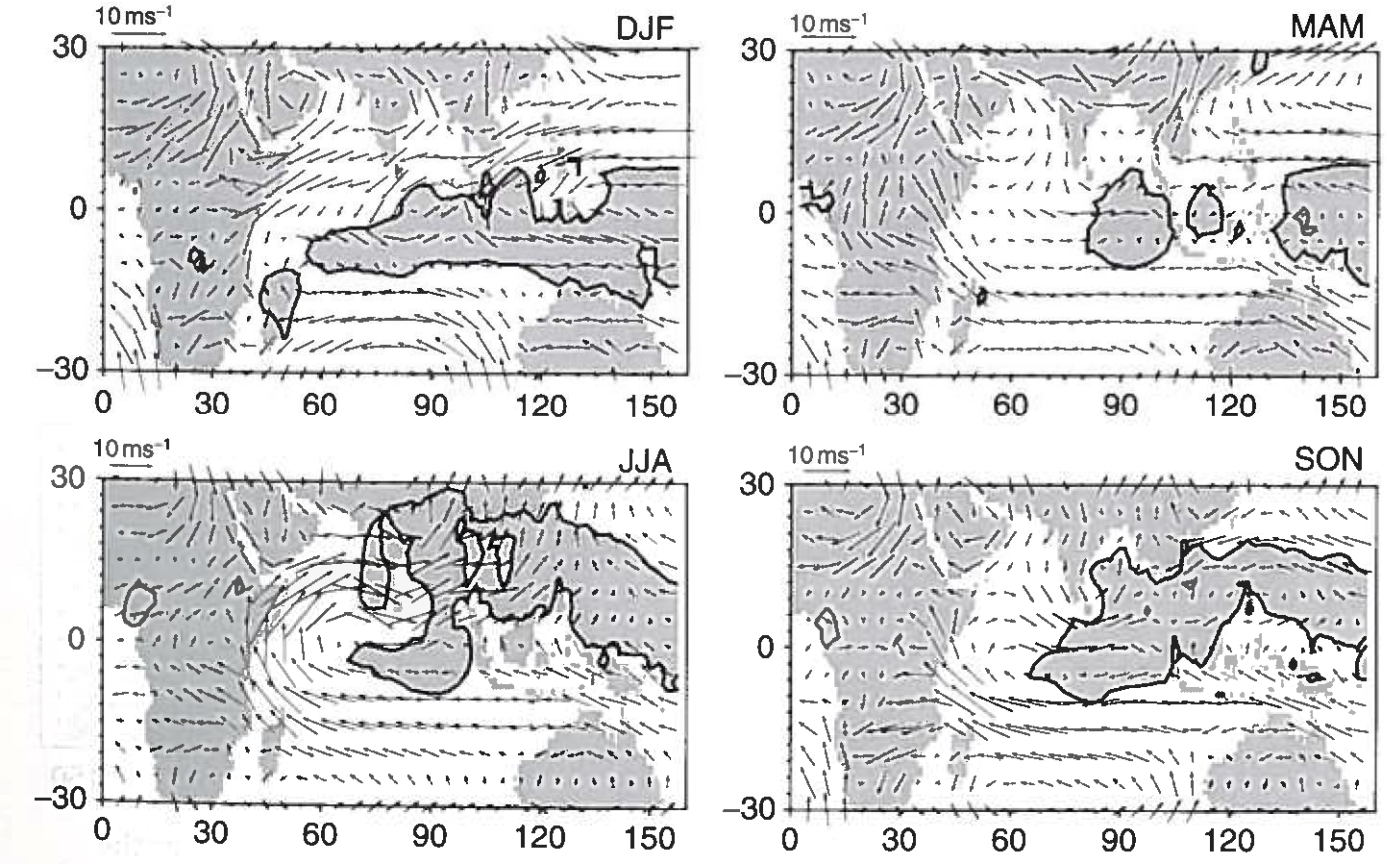
Part II: The Indian Ocean Monsoon System

Climatological Rainfall (mm/day)



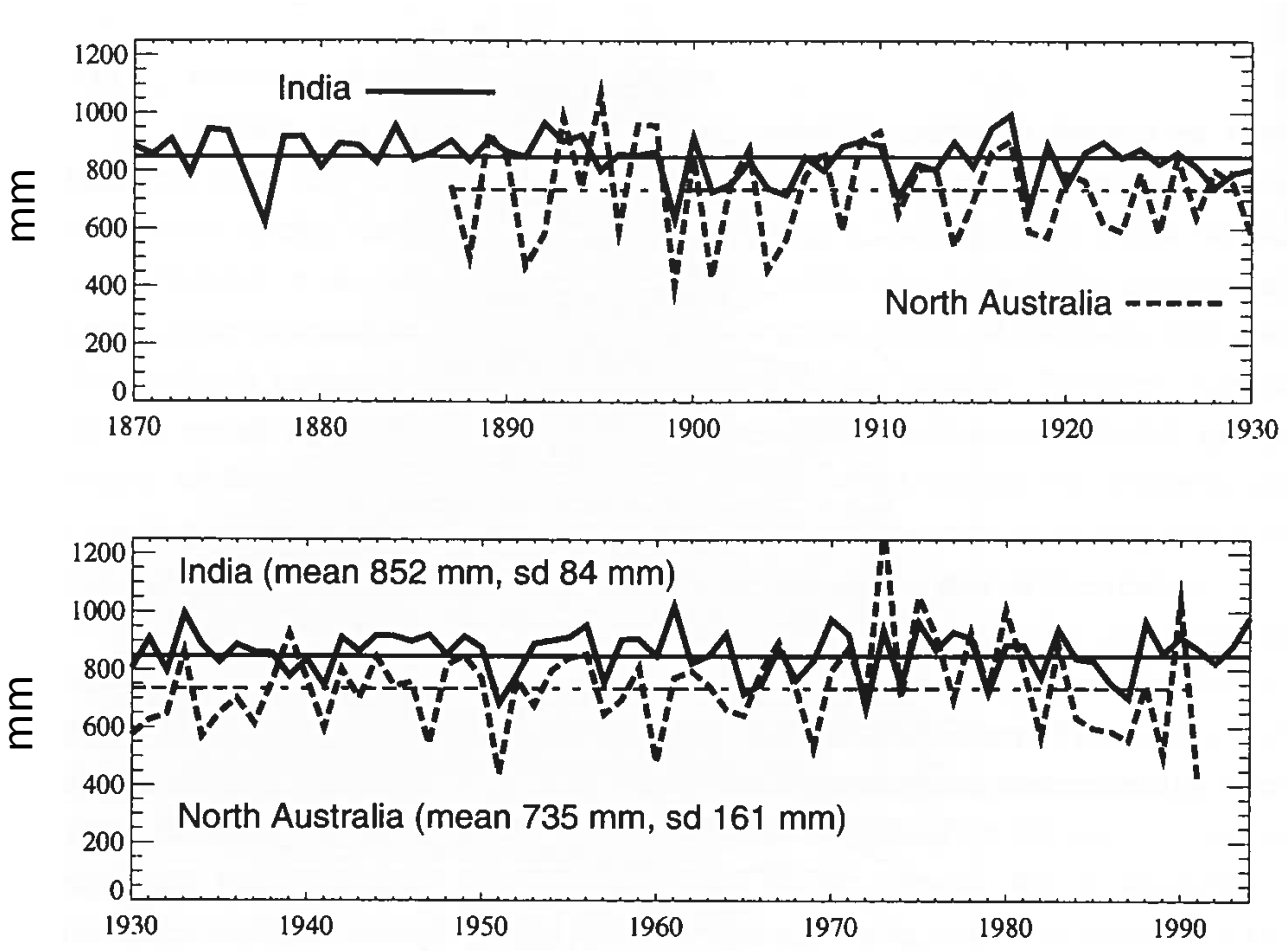
Clift & Plumb (2008)

Climatological Rainfall & Low-Level Winds



Clift & Plumb (2008)

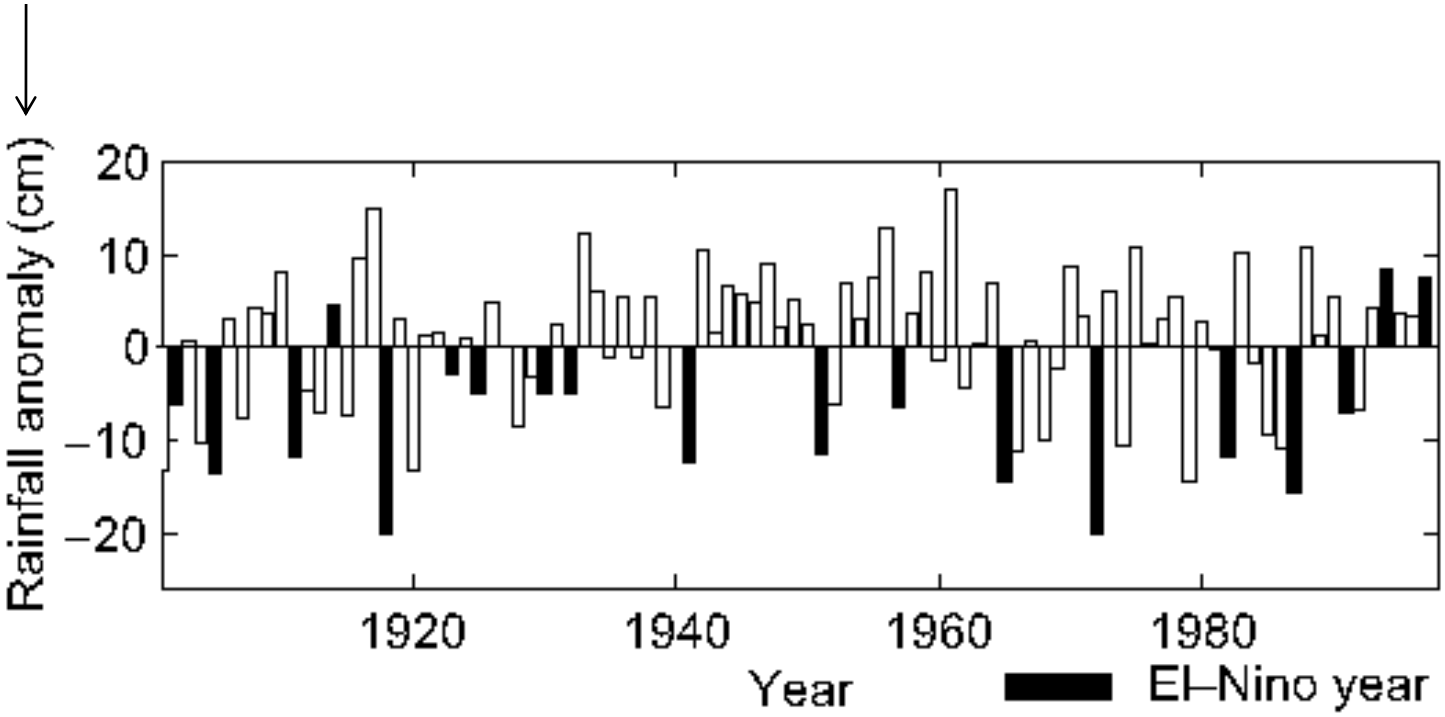
Inter-Annual Variability of Rainfall



Clift & Plumb (2008)

Relationship with El Niño

All-India summer monsoon rainfall



Gadgil (2003)

Part III: Theory of the Monsoons

Classical Hypothesis

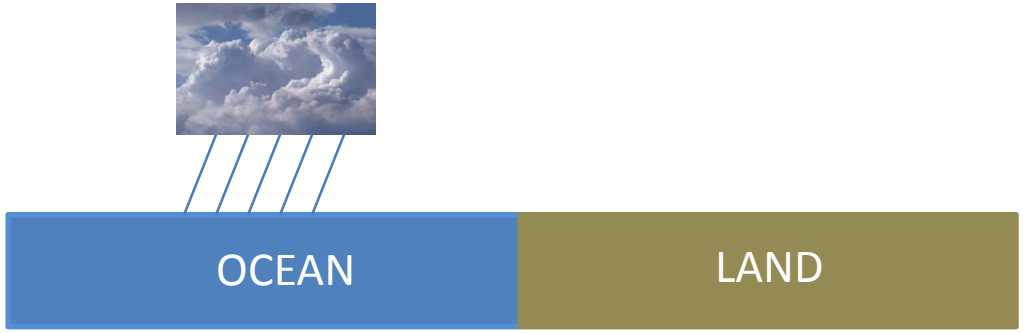
The monsoon results from a strong contrast in heating between ocean and land - It is a gigantic see breeze (Halley 1686)

Alternative Hypothesis

The monsoon is a substantial seasonal excursion of the ITCZ from the equator (e.g., Chao and Chen 2001; Gadgil 2003)

PRE-MONSOON CONDITIONS

h_m (ocean) > h_m(land)



moist static energy

$$h_m = C_P T + gz + Lq$$

MONSOON CONDITIONS

h_m (ocean) < h_m(land)

REFERENCES

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Gadgil S., *The Indian monsoon and its variability*, Annual Review of Earth and Planetary Sciences, 31, 429-467, 2003

Halley E., A historical account of the trade winds and monsoons observable in the seas and near the tropics with an attempt to assign a physical cause of the said winds, Philosophical Transations of the Royal Society of London, 16, 153-168, 1686

Krishnamurti T., Stefanova L., and Vasubandhu M., *Tropical Meteorology – An Introduction*, Springer, 421 pp., 2013

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Ronday F., *Meteorologie generale et introduction a la dynamique de l'atmosphere*, Institut de Recherches Marines et d'Interactions air-mer, Universite de Liege, Belgium, 318 pp., 1990 (ask O. Marchal to consult a copy)

Silva V. and Kousky V., The South American Monsoon System: Climatology and variability, in Monsoon Climatology, S.-Y. Wang (ed.), In Tech Publisher, available from http://www.intechopen.com/books/modern_climatology/the-south-american-monsoon-system-climatology-and-variability

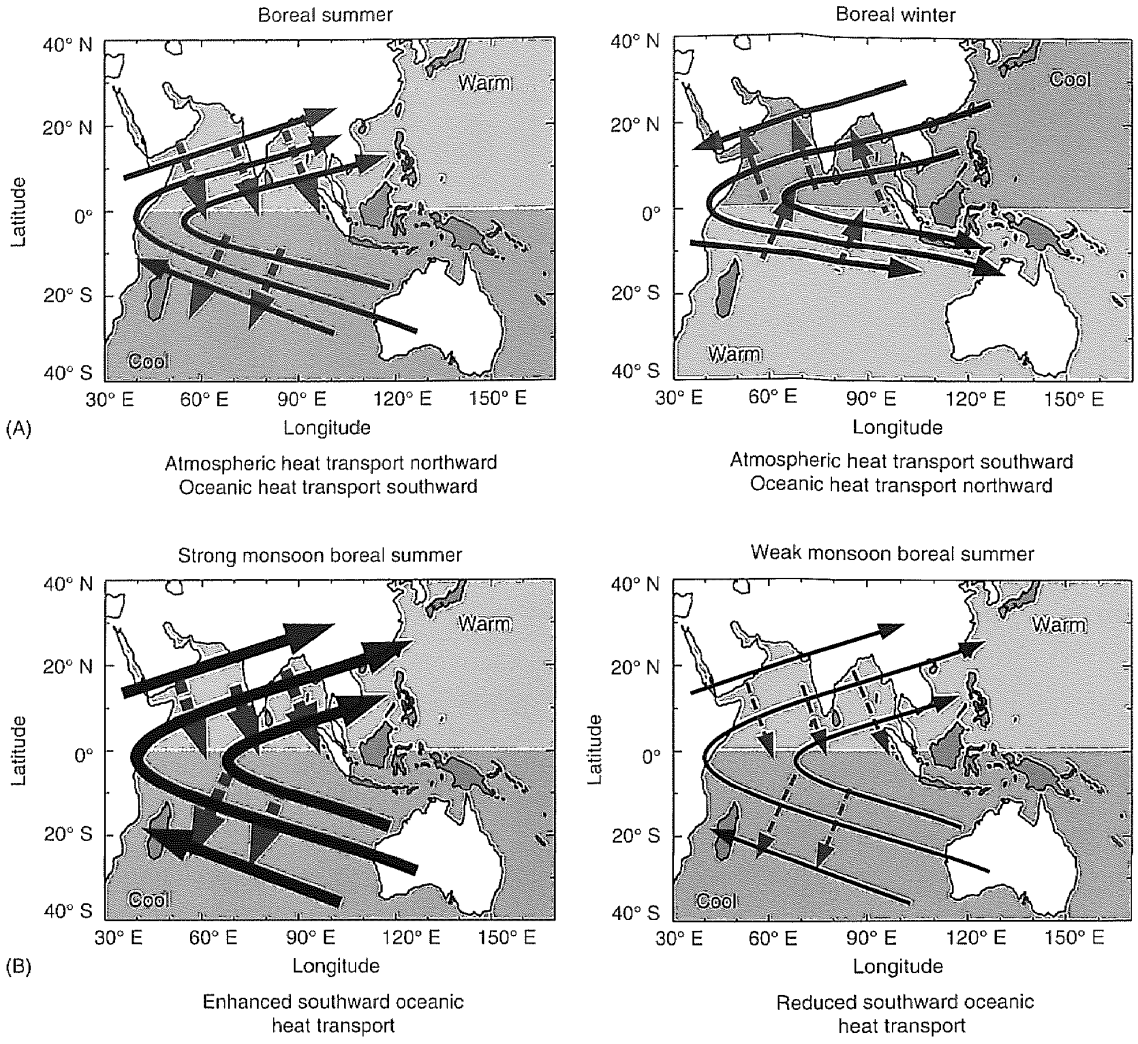
Webster P. and Fasullo J., Monsoons – Dynamical Theory, in Encyclopedia of Atmospheric Sciences, vol. 2, pp. 1370-1386, 2007

Webster P., The elementary monsoon. In Monsoons, J. Fein and P. Stephens (eds.), New York: John Wiley, pp. 3-32, 1987

Webster P., Magana V., Palmer T., Shukla J., Tomas R., Yanai M., and T. Yasunari, Monsoons: Processes, predictability, and the prospects for prediction, *Journal of Geophysical Research*, 103, 14451-14510, 1998

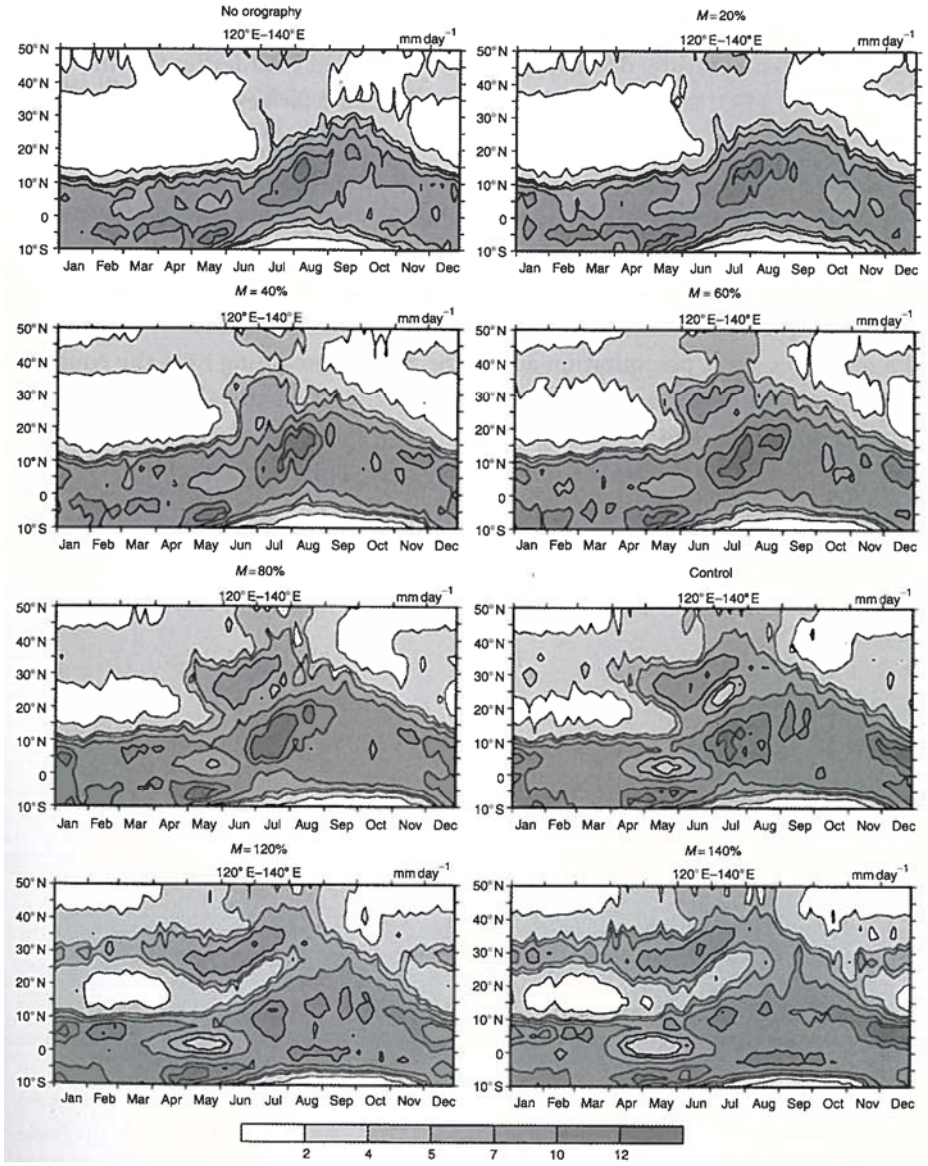
Back-up Slides

A Regulatory Model of the Monsoon



Webster & Fasullo (2007)

Role of Orography



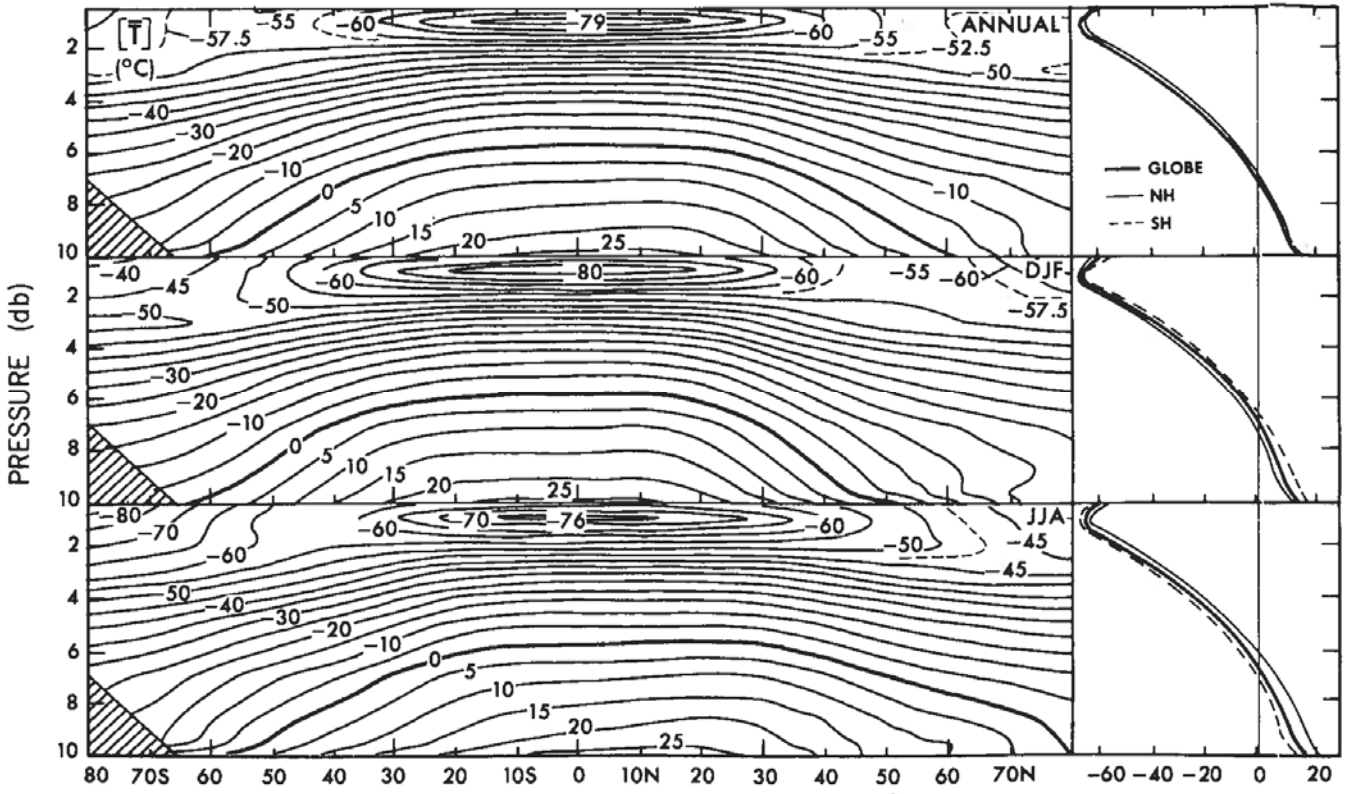
Clift & Plumb (2008)

One Definition of the Monsoon

- Prevailing wind direction shifts by at least 120^{o} between January & July
- Prevailing wind direction persists for at least 40% of the time in January & July
- Fewer than 1 cyclone-anticyclone alternation occurs every 2 years in either month in a 5^{o} latitude-longitude rectangle

Ramage (1971)

Zonal Mean Cross-Sections of Temperature



Peixoto & Oort (1992)

Regions affected by Monsoons

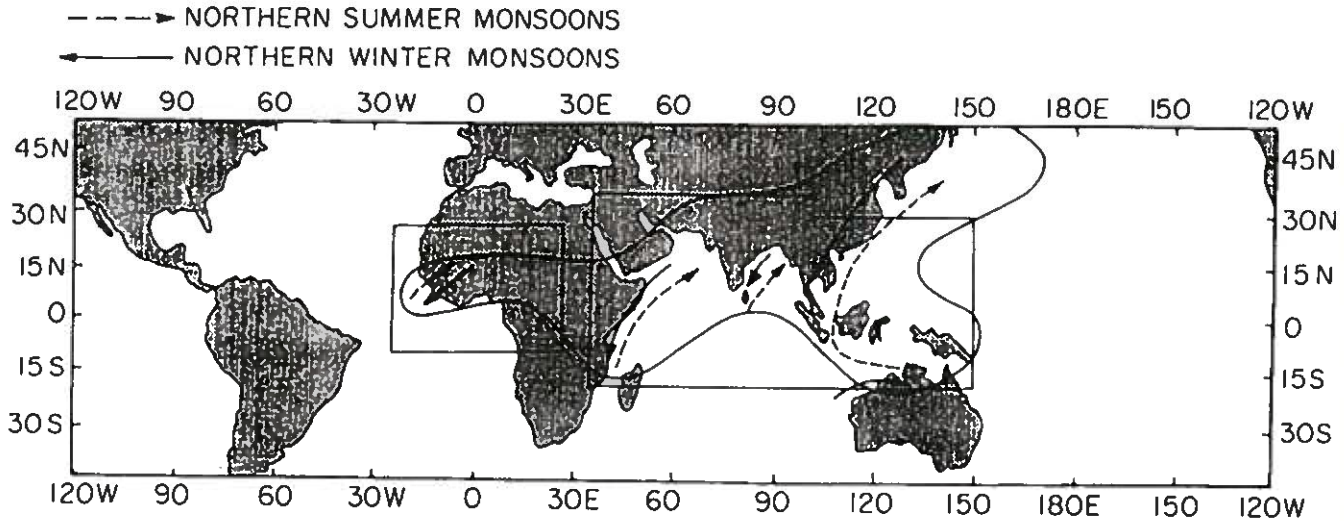


Fig. 5.2 Domain of monsoons (After Ramage 1971)

Krishnamurti et al. (2013)

Conservation of Angular Momentum

$$\frac{d\vec{M}}{dt} = \vec{R}\times\vec{F}$$

where $\vec{M} = \vec{R}\times\vec{u}_A = \vec{R}\times\left(\vec{u}_R + \vec{\Omega}\times\vec{R}\right)$

Consider $M = \hat{n}\vec{M}$

$$= uR\cos\phi + \Omega R^2\cos^2\phi$$

If $\vec{R}\times\vec{F} = 0$, then

$$\frac{d}{dt}\left(uR\cos\phi + \Omega R^2\cos^2\phi\right) = 0$$

or

$$\Omega R^2 = uR\cos\phi + \Omega R^2\cos^2\phi$$

$$u = \Omega R\frac{1-\cos^2\phi}{\cos\phi}$$

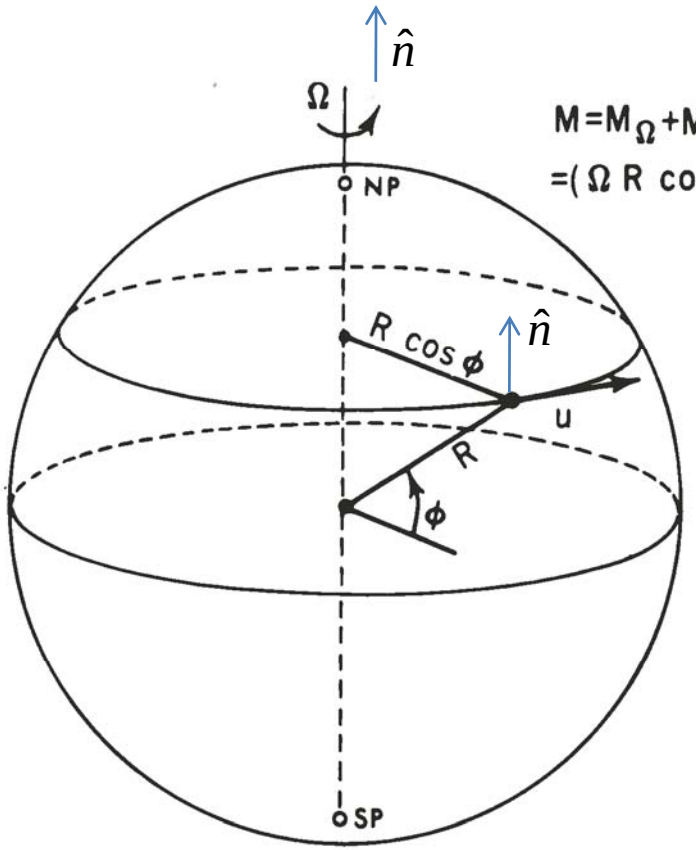
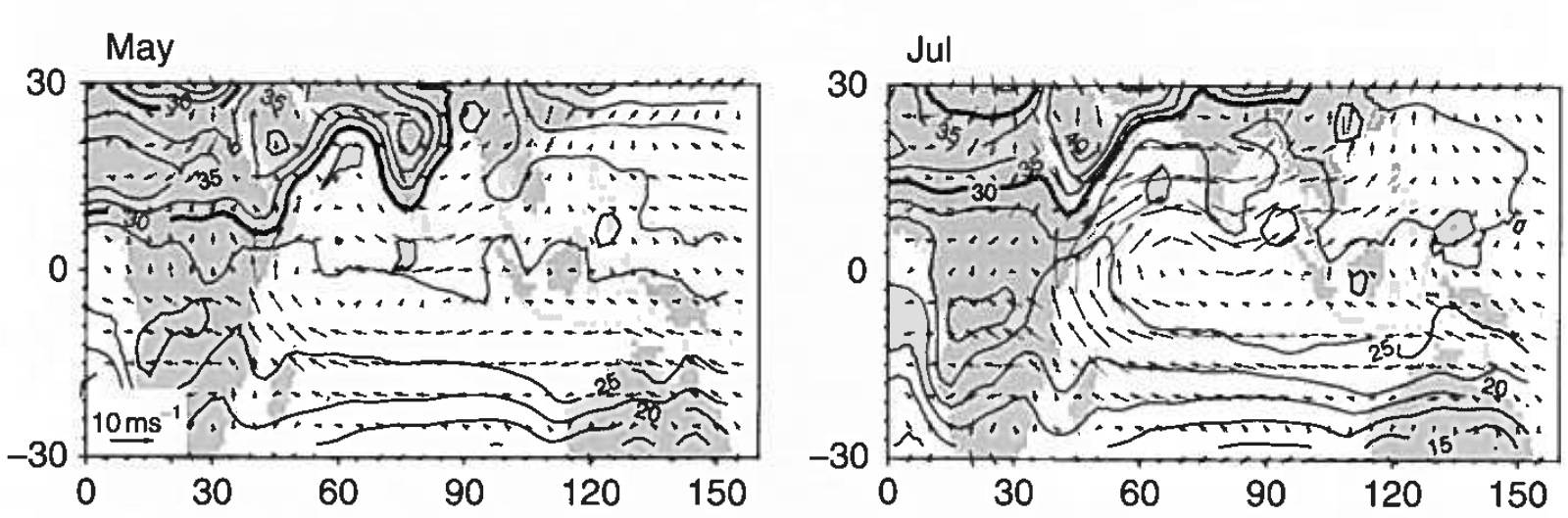


FIGURE 11.1. Schematic diagram of the angular momentum component around the earth's axis of rotation. NP = North Pole; SP = South Pole.

Peixoto & Oort (1992)

Climatological 1000 hPa Air Temperature & 850 hPa Winds



Clift & Plumb (2008)

Intra-Annual Variability: Active & Break Cycles

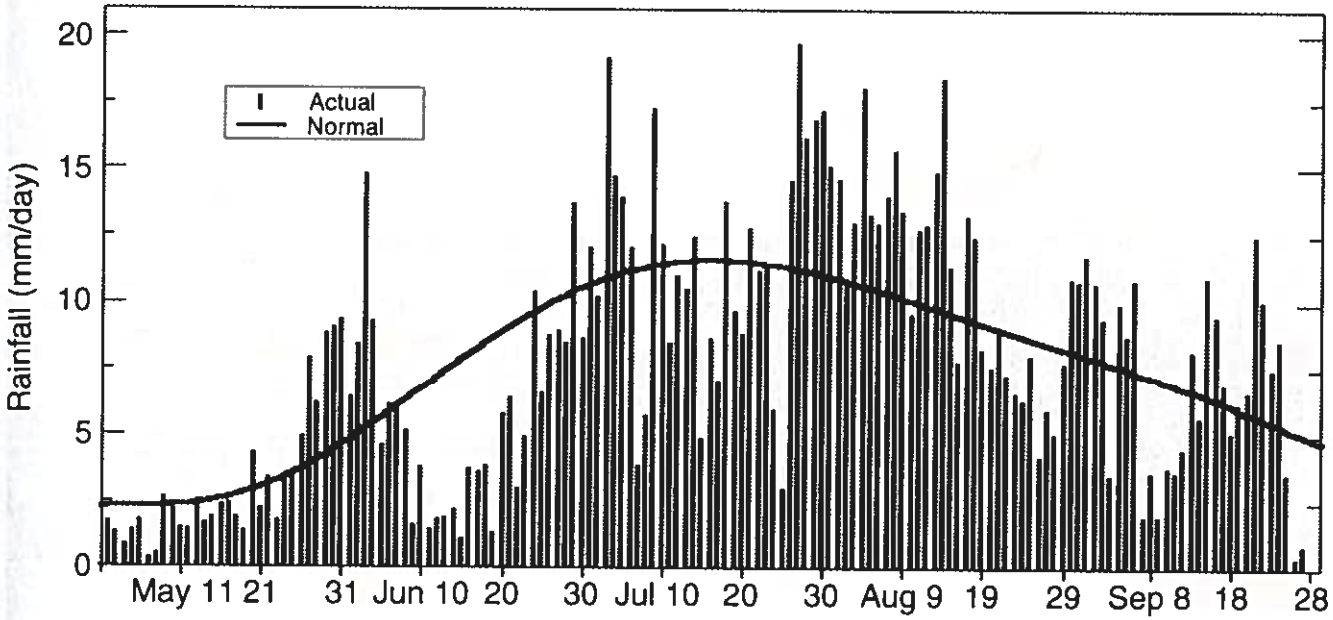
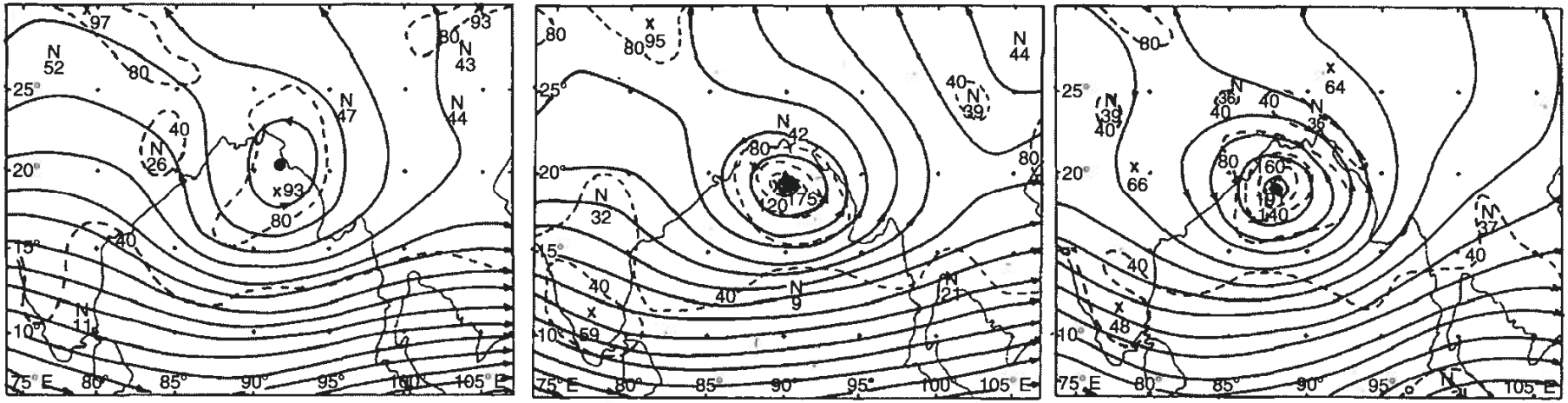


Fig. 5.26 Daily all-India observed rainfall for 2006 (*bars*) and climatological daily rainfall values (*line*) (From India Met. Department archive)

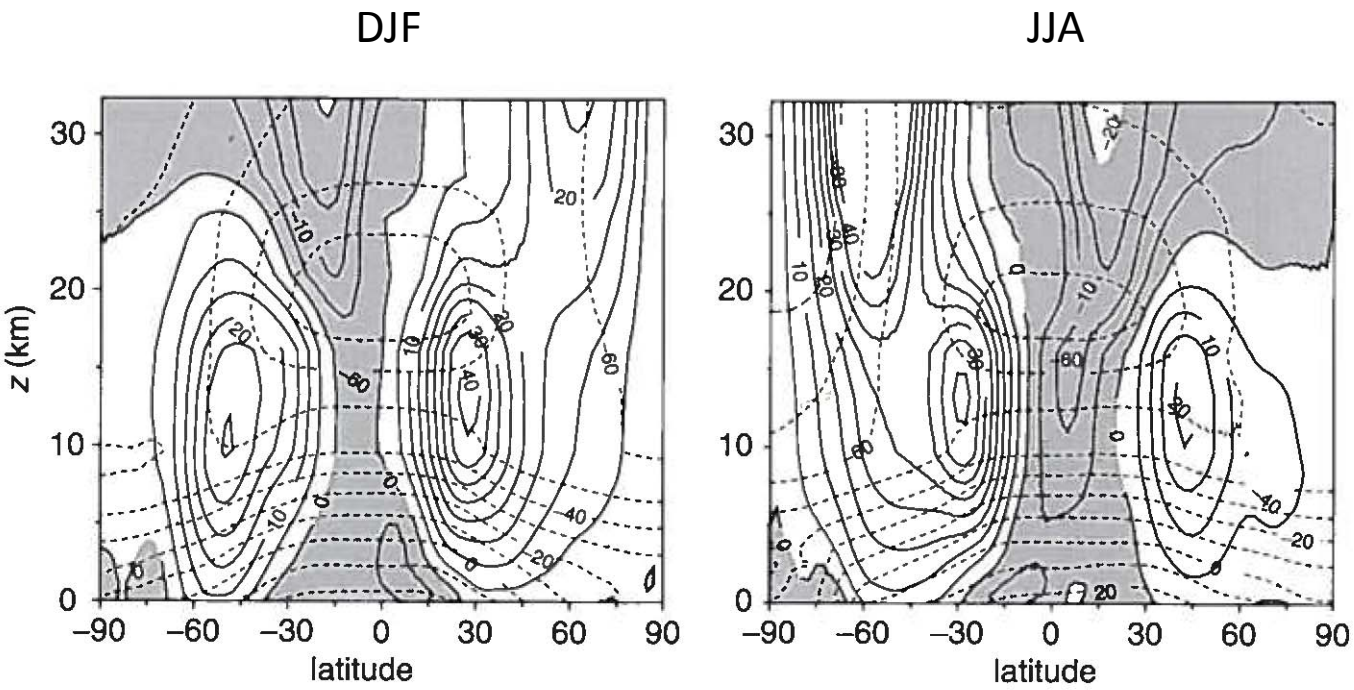
Krishnamurti et al. (2013)

Intra-Annual Variability: Monsoon Depressions



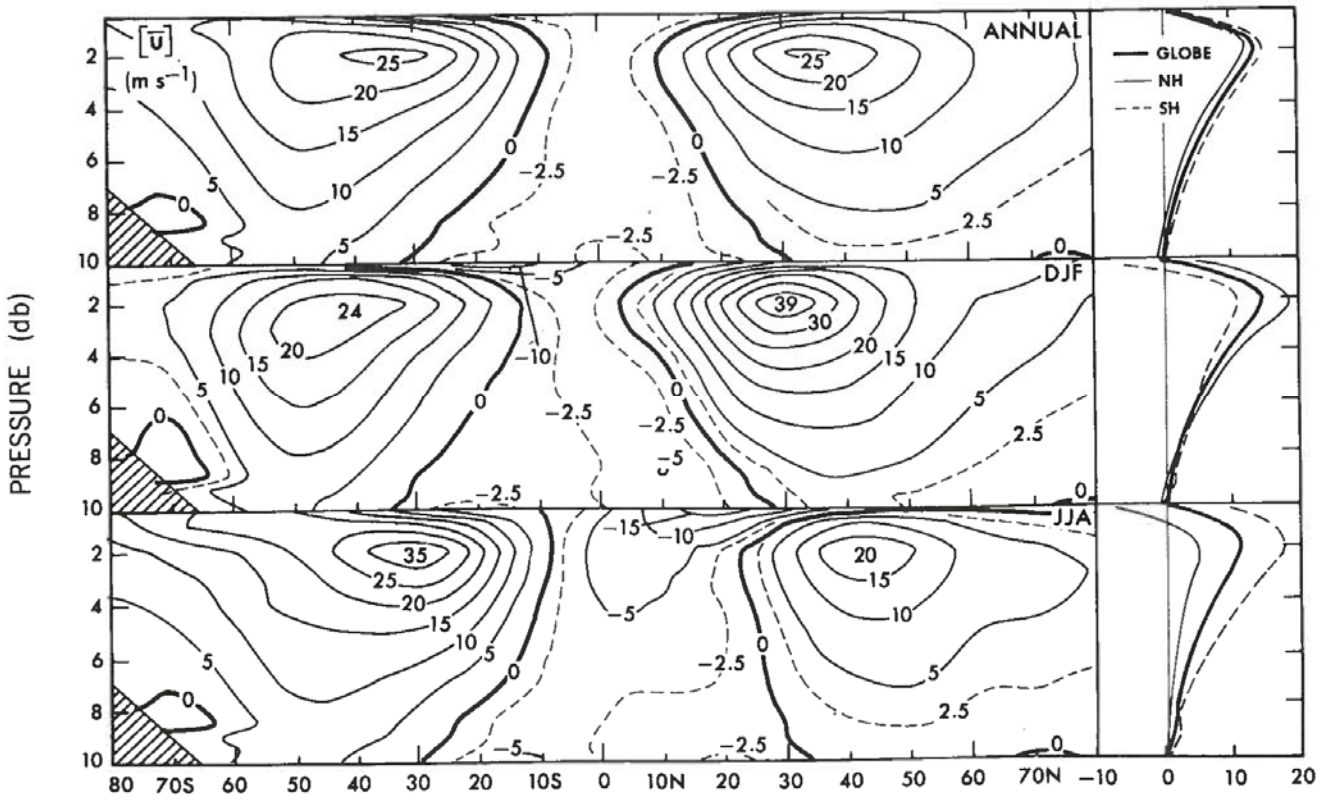
Clift & Plumb (2008)

Zonal Circulation



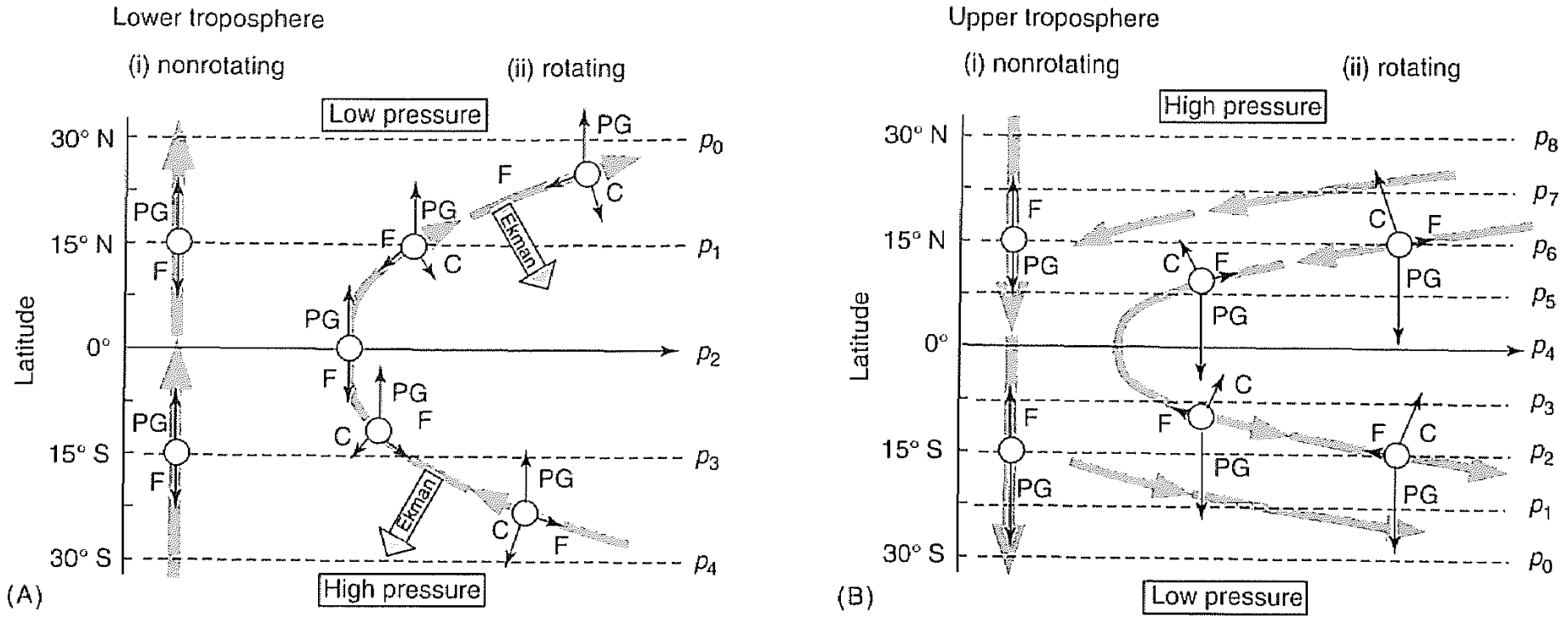
Clift & Plumb (2008)

Zonal Mean Cross-Sections of Zonal Wind

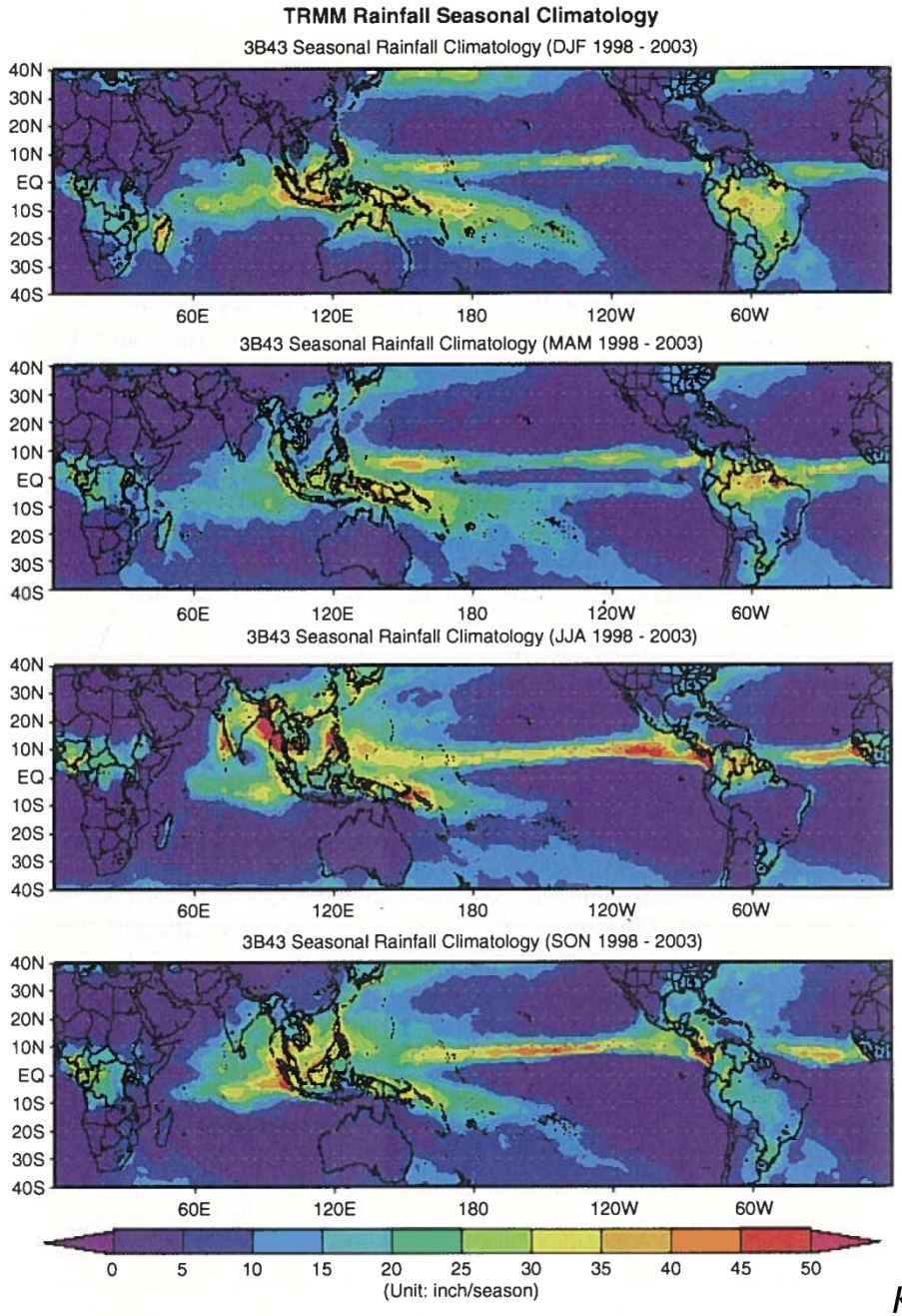


Peixoto & Oort (1992)

Schematic of Monsoon Circulations

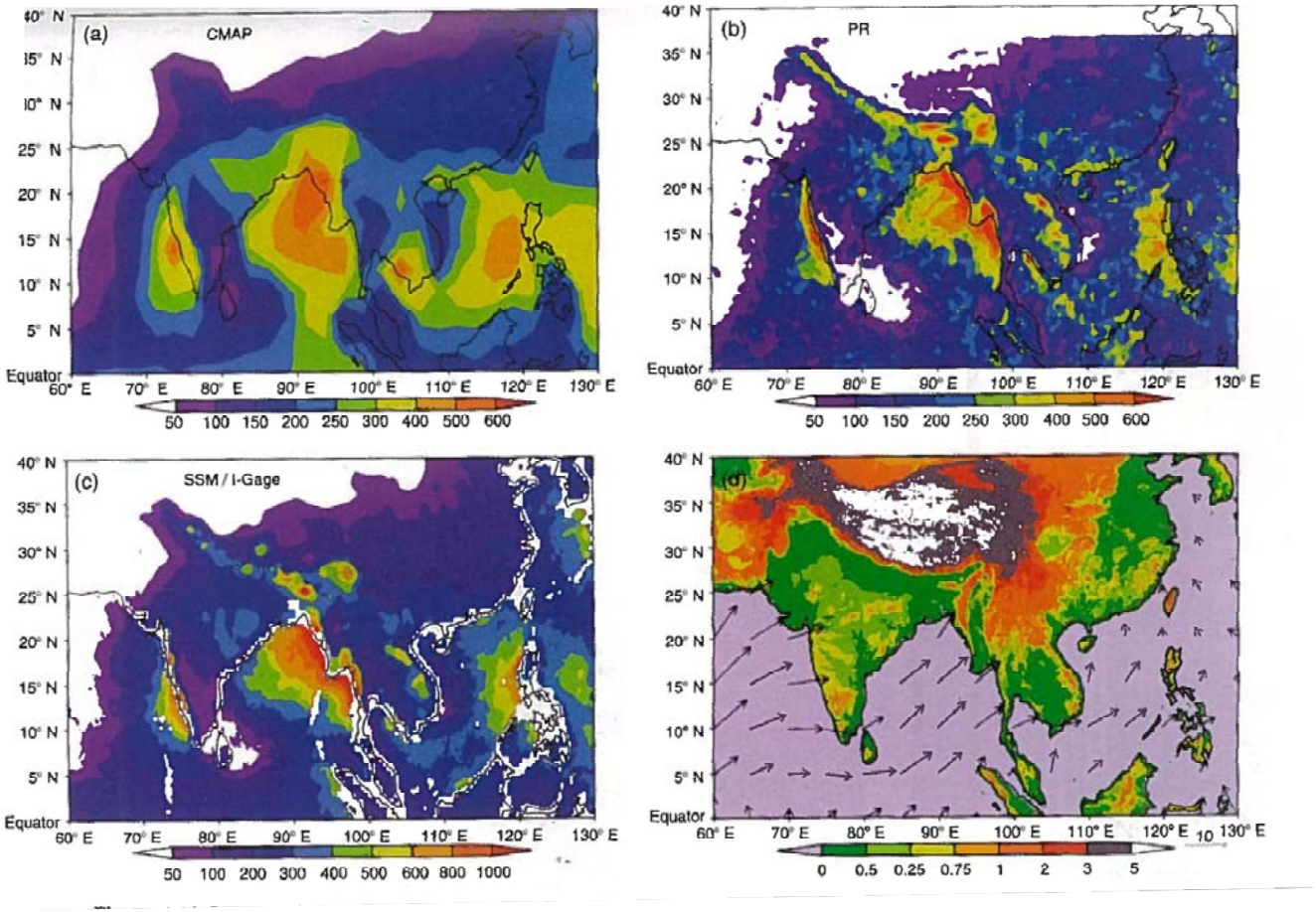


Webster & Fasullo (2007)



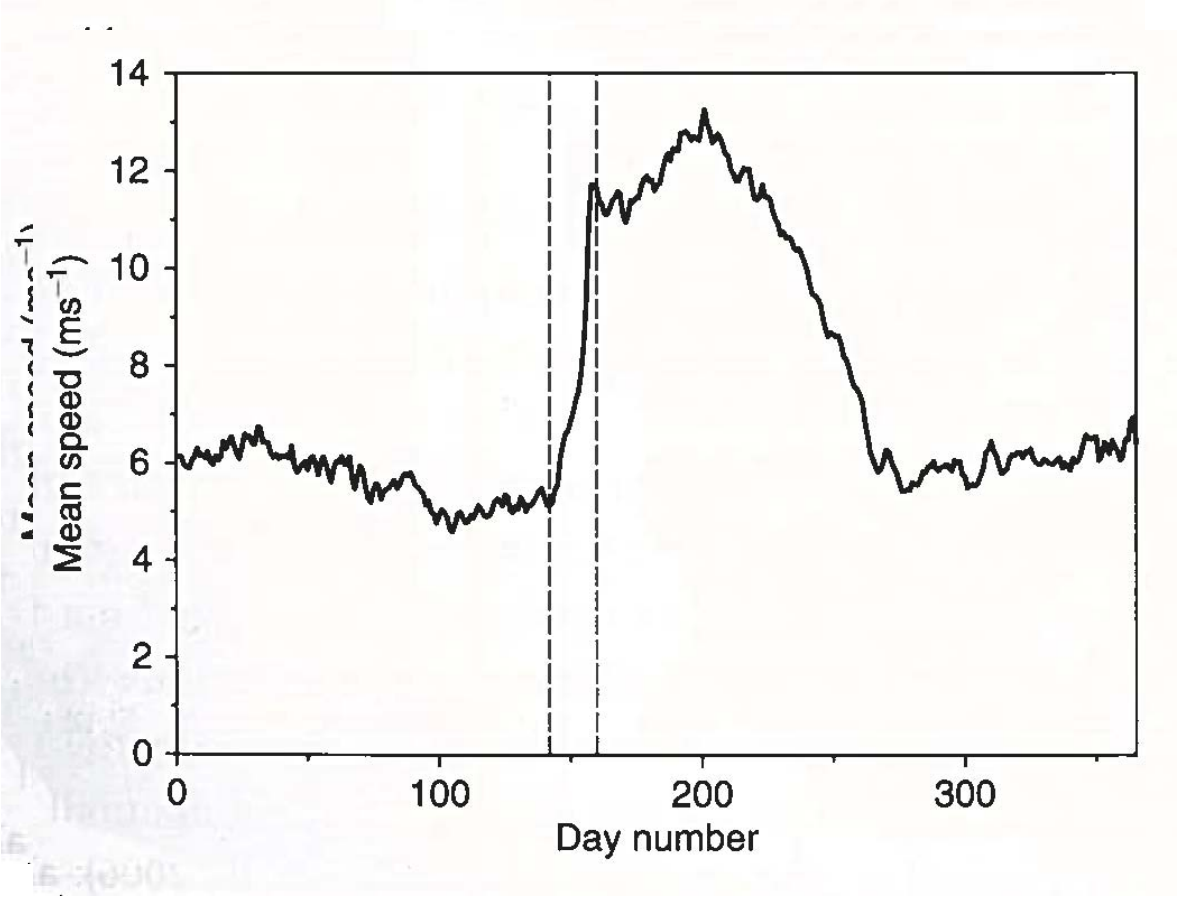
Krishnamurti et al. (2013)

Summertime Rainfall from Different Datasets



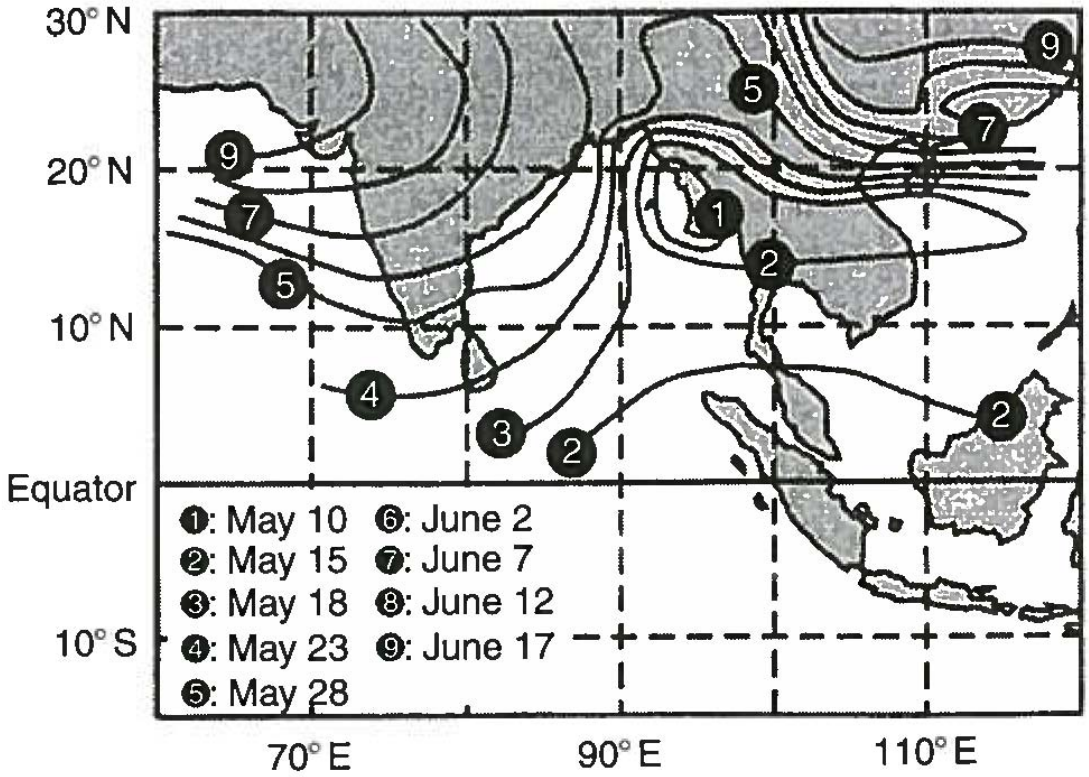
Clift & Plumb (2008)

Seasonal Evolution of Winds over the Arabian Sea



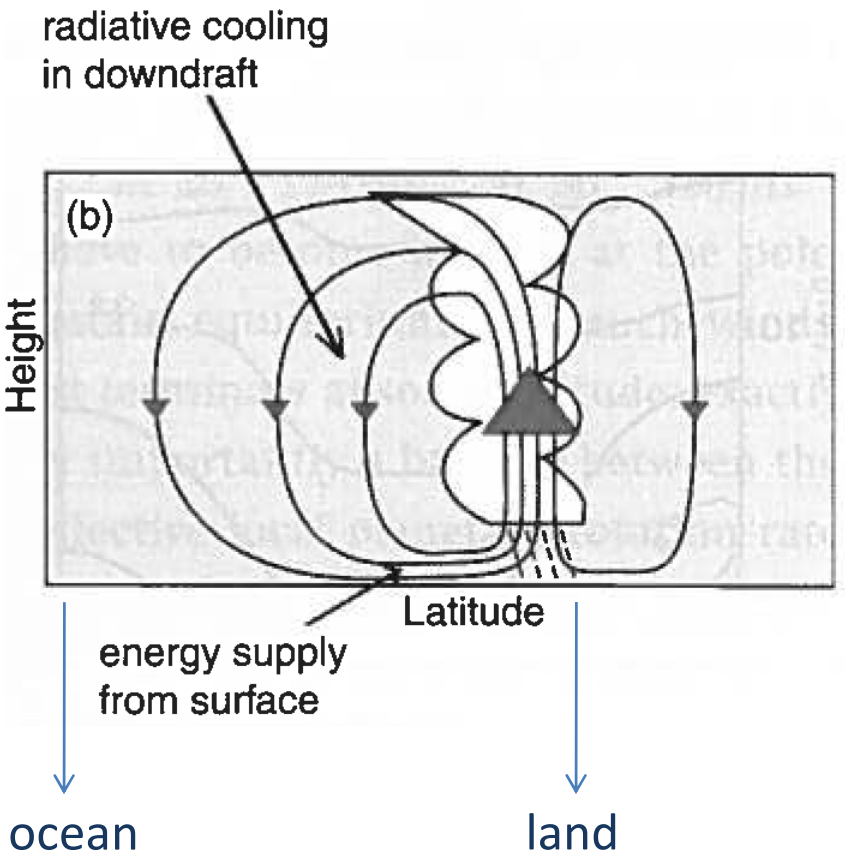
Clift & Plumb (2008)
Clift & Plumb (2008)

Progression of the Summer Indian Monsoon



Clift & Plumb (2008)

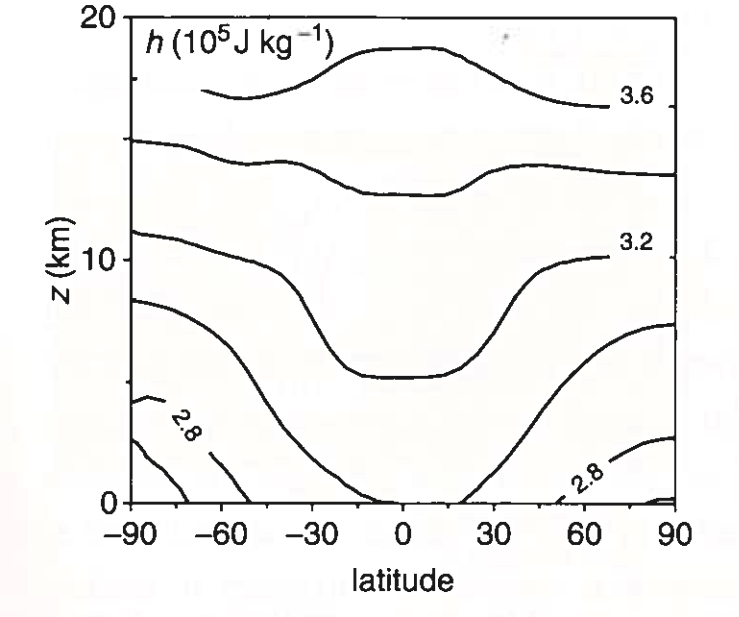
Role of Land-Sea Contrast



Clift & Plumb (2008)

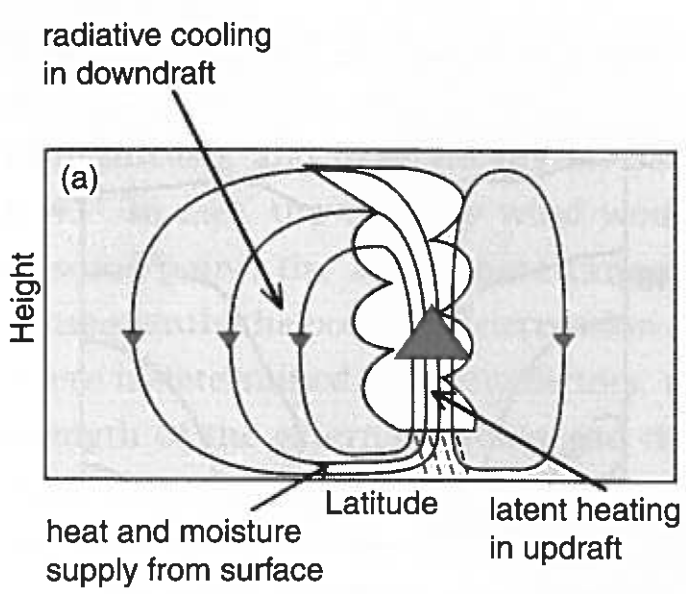
Dry Static Energy *h*

$$h = C_P T + gz$$



Clift & Plumb (2008)

Energetics of Hadley Circulation



Clift & Plumb (2008)