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)

generally, 1st week of June

Krishnamurti et al. (2013)
South American Monsoon System

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

\[ U = \frac{p_v}{p_{v,\text{SAT}}} \]

\textit{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

Rainfall anomaly (cm)

Year

1920 1940 1960 1980

El-Nino year

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

$h_m \text{ (ocean)} > h_m \text{ (land)}$

monsoon conditions

$h_m = C_p T + gz + Lq$

MONSOON CONDITIONS

$h_m \text{ (ocean)} < h_m \text{ (land)}$
REFERENCES


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


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)


Back-up Slides
A Regulatory Model of the Monsoon

(A) Boreal summer

Atmospheric heat transport northward
Oceanic heat transport southward

(B) Strong monsoon boreal summer

Enhanced southward oceanic heat transport

Webster & Fasullo (2007)
Role of Orography

Clift & Plumb (2008)
One Definition of the Monsoon

- Prevailing wind direction shifts by at least $120^\circ$ 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 $5^\circ$ latitude-longitude rectangle

*Ramge (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 \( \vec{M} = \vec{R} \times \vec{u}_A = \vec{R} \times (\vec{u}_R + \vec{\Omega} \times \vec{R}) \)

Consider \( M = \hat{n} M \)

\[ = uR \cos \phi + \Omega R^2 \cos^2 \phi \]

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

\[ \frac{d}{dt} (uR \cos \phi + \Omega R^2 \cos^2 \phi) = 0 \]

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)
Progression of the Summer Indian Monsoon

Clift & Plumb (2008)
Role of Land-Sea Contrast

Clift & Plumb (2008)
Dry Static Energy $h$

\[ h = C_p T + gz \]
Energetics of Hadley Circulation

Clift & Plumb (2008)