第五章：

大气环流中的纬向环流系统

5.2 Monsoon Circulation

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Outline

- Introduction
- Features of monsoon circulation:
  - an Indian monsoon example
- Monsoon dynamics
  - The land-sea contrast
  - The role of Orography, Tibet Plateau
  - Some GCM results
- On the East Asian monsoon
Introduction

- The definition of monsoon: a dramatic **seasonal reversal** of the low-level prevailing winds, precipitation and atmospheric circulation.

- The major monsoon systems of the world:
  - Asian monsoon
    - South Asian monsoon
    - East Asian monsoon
  - Australian (Indo-Australian) monsoon
  - West African monsoon
  - North and South American monsoon (controversial)
Introduction

- 65% of world’s population lives within monsoon;
- Monsoon precipitation is crucial to the life, food production, economy et al in these regions;
- Proper forecasting of location and quantity of precipitation is crucial to these regions.

Geographical Extent of the Global Surface Monsoons

The red, green, and blue areas indicate the tropical, subtropical, and temperate-frigid monsoons, respectively. The red and blue thick lines represent the ITCZ in summer and winter, respectively. (Li, J., and Q. Zeng, 2005)
Introduction

The formation of monsoon climate is closely related to the seasonal variation of the solar forcing and the seasonal migration of the planetary scale flow.

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Latent heat and water vapor

- Seasonal variation: strongest in the subtropics, monsoon regions

\[ e_s \approx 6.11 \times e^{\frac{L}{R_v}\left(\frac{1}{273} - \frac{1}{T}\right)} \]

\[ \text{LH} = Lq \]

\[ q = \text{RH} \times q^* \]
Features of monsoonal circulation:
-an Indian monsoon example
Features of monsoonal circulation: 
-an Indian monsoon example

The seasons of winter and summer might be better described as **dry** and **moist** seasons.

Figure 1.11 Climatological mean rainfall rate for the four seasons. The contour interval is 2.5 mm day\(^{-1}\); heavy shading denotes rainfall greater than 5-10 mm day\(^{-1}\). (from Clift and Plumb, 2008)
Features of monsoonal circulation: an Indian monsoon example

An obvious reverse of the prevailing winds

Somali Jet

Figure 1.12 Climatological mean low level (850 hPa) winds for the four seasons. The scale for the wind arrows is shown at the top left of each plot. The heavy lines mark regions of seasonal mean rainfall in excess of 7.5 mm day$^{-1}$.

(from Clift and Plumb, 2008)
Features of monsoonal circulation:

- An Indian monsoon example

The onset of the summer monsoon brings cooler surface temperatures to India and other areas that receive monsoonal precipitation, due to the increase in clouds as well as the increase in soil moisture that accompanies the precipitation. The data shows, as one might expect, that the lowest surface air temperatures in the monsoon region occur at the highest elevations. There is a large area of low (less than 280 K) surface air temperature on the Tibetan Plateau, and a large area of high (greater than 305 K) surface air temperatures on the Arabian Peninsula.

From an agricultural standpoint, the beginning of the precipitation associated with the Asian summer monsoon is probably one of the most anticipated events in the world. The onset of the monsoon is generally defined as the beginning of consistent rainfall of the monsoon season.

Figure 8.29: Observed 850 mb wind vectors for a) January, and b) July.

Accompanied is the reverse of whole atmospheric circulation.

Cross equator meridional overturning circulation.
Features of monsoonal circulation: - an Indian monsoon example

Bjerknes (1969) theorized that the cool, dry air of the trade winds is heated and moistened as it moves westward until it finally undergoes large-scale moist-adiabatic ascent over the Warm Pool. If there were no mass exchange with adjacent latitudes, a simple circulation would develop in which the flow is easterly at low levels and westerly at upper levels. When meridional mass exchange is considered, this simple picture has to be altered, because absolute angular momentum is exported to adjacent latitudes. Under steady-state conditions, the flux divergence of angular momentum at the equator must be balanced by an easterly surface wind stress. Thus surface easterlies on the equator are stronger than those imposed by the Walker circulation. The net result is that a thermally driven Walker cell is imposed on a background of easterly flow, the intensity of which depends on the strength of the angular momentum flux divergence.

Figure 8.37: JJA climatological 200 mb winds. The scale vector is 50 m s$^{-1}$.

Figure 8.38: Latitude-pressure plot of the JJA climatological zonal winds at 77.5 ºE. The contour interval is 5 m s$^{-1}$.

Strong vertical shear of zonal wind

(from Randall 2009)
Features of monsoonal circulation: -an Indian monsoon example

2. Description of the Monsoons
Ramage [1971] provided a rather strict definition of a monsoon and identified the African, Asian, and Australian regions as satisfying both a wind reversal and seasonal precipitation criterion. However, the Americas qualify as monsoon regions at least in terms of precipitation. In the following sections the various monsoon circulations will be described.

2.1. The Annual Cycle of the Monsoon

In Figure 6a the horizontal distribution of the 200-500-mbar layer mean temperature is plotted for boreal summer (Figure 6a left) and winter (Figure 6a right). The shaded region shows a mean temperature warmer than --26°C. During summer a planetary-scale warm air mass is centered on south Asia with the maximum average layer temperature (> --22°C) over the southern Tibetan Plateau, resulting in strong temperature gradients in both the north-south and east-west directions. A warm temperature ridge exists over the North American continent, and a deep temperature trough stretches from the west coast of North America to the central Pacific. A similar trough lies over the Atlantic Ocean. The upper tropospheric flow pattern during summer identifies clearly the thermal contrast between continents and oceans [e.g., Krishnamurti, 1971a, b]. The boreal winter presents a very different structure. A much smaller section of the globe (northeast of Australia) is warmer than --26°C. A Mean upper tropospheric (200--500 mbar) temperature (degrees Celsius) for the boreal summer (JJA), and boreal winter (DJF), averaged between 1979 and 1992. The boreal summer plot is based on calculations first made by Li and Yanai [1996]. Mean columnar temperatures warmer than --25°C are shaded.

(from Webster 1998)

Figure 6a. Mean upper tropospheric (200--500 mbar) temperature (degrees Celsius) for the boreal summer (JJA), and boreal winter (DJF), averaged between 1979 and 1992. The boreal summer plot is based on calculations first made by Li and Yanai [1996]. Mean columnar temperatures warmer than --25°C are shaded.
Features of monsoonal circulation: an Indian monsoon example

The sudden onset of south asian monsoon occurs between Julian day 146-160.

(from Clift and Plumb, 2008)

(from Molnar et al, 2010)
Features of monsoonal circulation:
-an Indian monsoon example

The sudden onset of south asian monsoon.

(from Webster 1998)
Features of monsoonal circulation: -an Indian monsoon example

High temperature

High temperature
Features of monsoonal circulation: 
am an Indian monsoon example

Stationary eddy transport $V_s \times 10^{14}$ W

Transient eddy transport $V_T \times 10^{14}$ W

Contribution from monsoonal circulation
Features of monsoonal circulation:
—an Indian monsoon example

- Stationary eddy transport $V_s (10^{14} \text{ W})$
  - JJA
  - DJF

- Transient eddy transport $V_T (10^{14} \text{ W})$
  - JJA
  - DJF
Features of monsoonal circulation: an Indian monsoon example

Intra-seasonal variation: exhibits peaks on 4-5 days, 10-20 days and 40-50 days

(from Randall 2009)
Features of monsoonal circulation:
-an Indian monsoon example

Obvious Inter-annual variation

Figure 1.18 Annual-mean rainfall (mm) showing all-India rainfall (solid) and north Australia rainfall (dashed). (Webster et al., 2005).
Features of monsoonal circulation:
-an Indian monsoon example

Inter-annual variation is related to the El Nino event and the Pacific SST.

Relatively weaker precipitation over India is always found in the El Nino years;

Relatively stronger precipitation over India is found in La Nina years.

(from Webster 1998)
Observed features

Summary:

- A monsoon climate is characterized by the obvious seasonal reversal of wind, precipitation and atmospheric circulation.
- From a global view: south asian monsoon is associated with the seasonal migration of ITCZ and Hadley circulation, which also plays an important role in the global meridional moisture and latent energy transport.
- South asian monsoon exhibits obvious sudden onset, with the low-level winds and the whole monsoonal circulation built in two weeks.
- Intra-seasonal variation: show periods in 4-5 days, 10-20 days and 40-50 days.
- Inter-annual variation: Relatively weaker precipitation occurs during El Nino years.
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Monsoon dynamics:

- land-sea contrast

- Thermal contrast: different (equivalent) heat capacity

- Moisture advection: provide source of precipitable water
-land-sea contrast

Thermal contrast:

\[ \rho_g C_{pg} H_{sur} \frac{\partial T_g}{\partial t} = F_{sur} + Q_{fx} \]

Determine the response time scale to surface heating

For ocean surface:
\[ \rho_g C_{pg} \sim 4 \times 10^6 \, Jm^{-3}K^{-1} \]
\[ H_{sur} \sim O(10m) \text{ to } O(100m) \]

For land surface:
\[ \rho_g C_{pg} \sim 1 \times 10^6 \, Jm^{-3}K^{-1} \]
\[ H_{sur} \sim O(1m) \]

fast response time scale
Monsoon dynamics:

- land-sea contrast

Thermal contrast:

Plumb and Hou (1992)
Monsoon dynamics: land-sea contrast

Thermal contrast:

- strength of circulation
- threshold of strong cross-equator meridional overturning circulation

Plumb and Hou (1992)

Numerical results for *axisymmetric* flow

strong heating:

weak heating: