

- Overview and description of major tropical monsoons



Goal: Describe the principal features and characteristics of monsoons

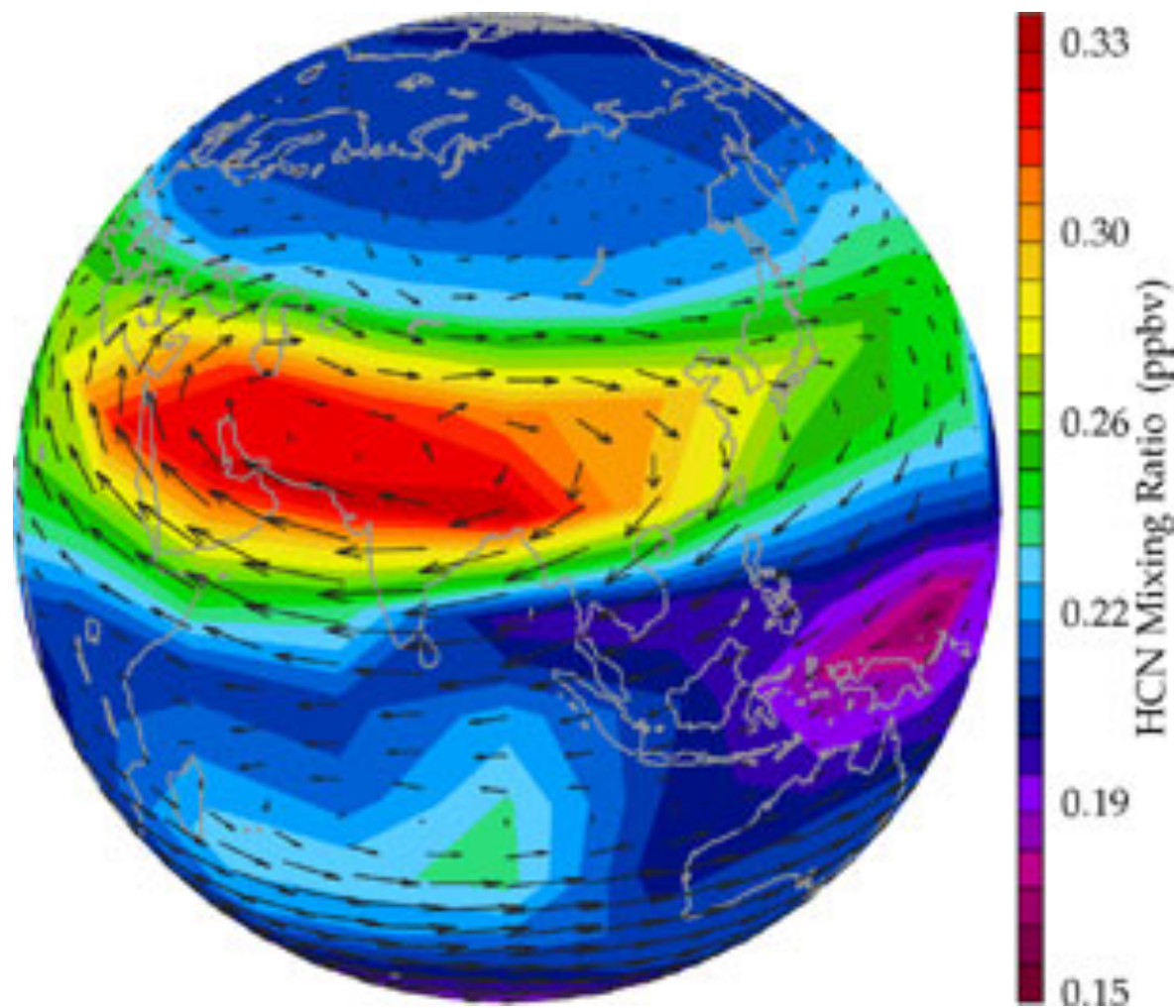
Published Online March 25, 2010
Science DOI: 10.1126/science.1182274

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REPORTS

Asian Monsoon Transport of Pollution to the Stratosphere

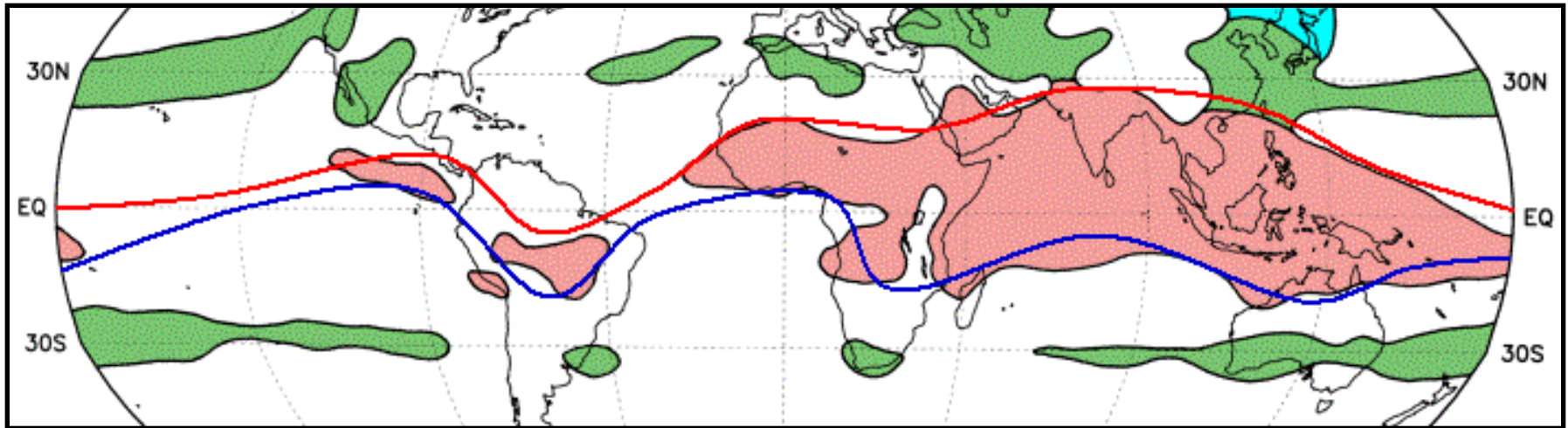
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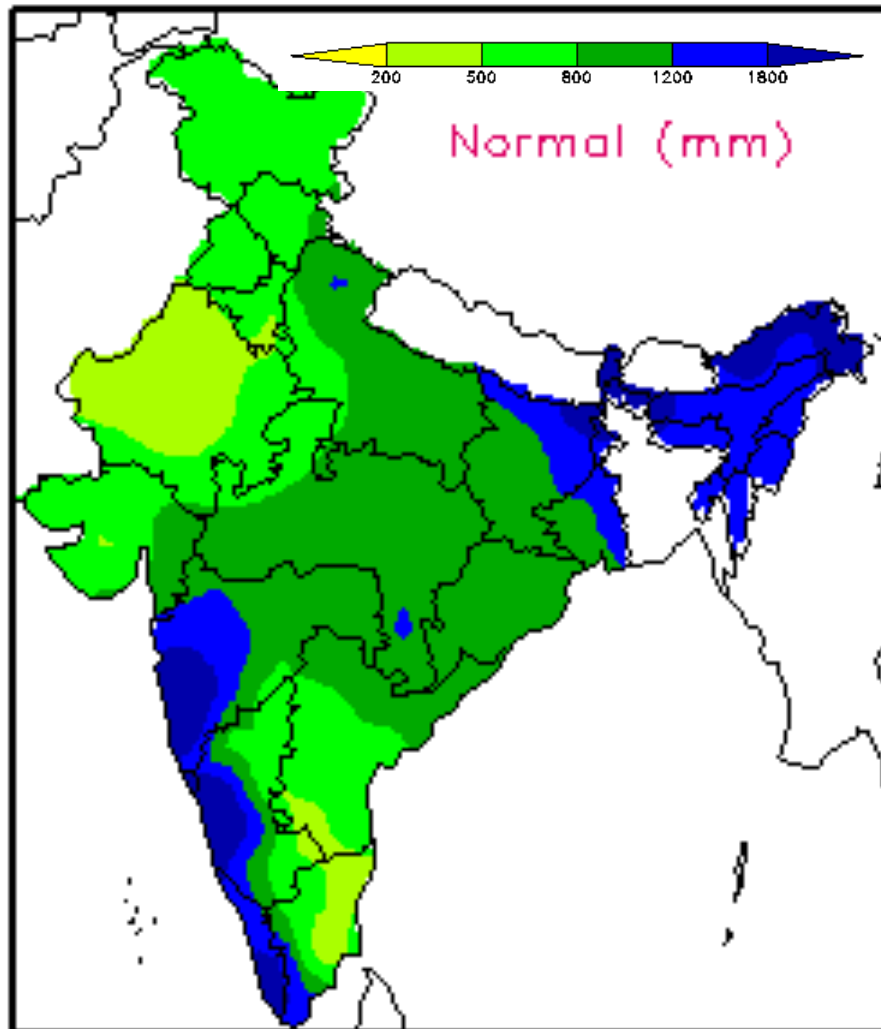
Monsoons: Overview

- Traditionally any seasonally-reversing wind pattern with accompanying changes in precipitation
 - Thus: wet monsoons and dry monsoons
- Etymology:
 - From the Portuguese *monção*, and the earlier Arabic *mawsim*, meaning “season” [also: Arabic-origin *mausam* means “weather” in Hindi]
- Major monsoon systems:
 - Asian [Indian/South Asian, East Asian, Western Pacific]
 - Australian
 - West African
 - North American
 - South American

Global distribution of monsoonal climates



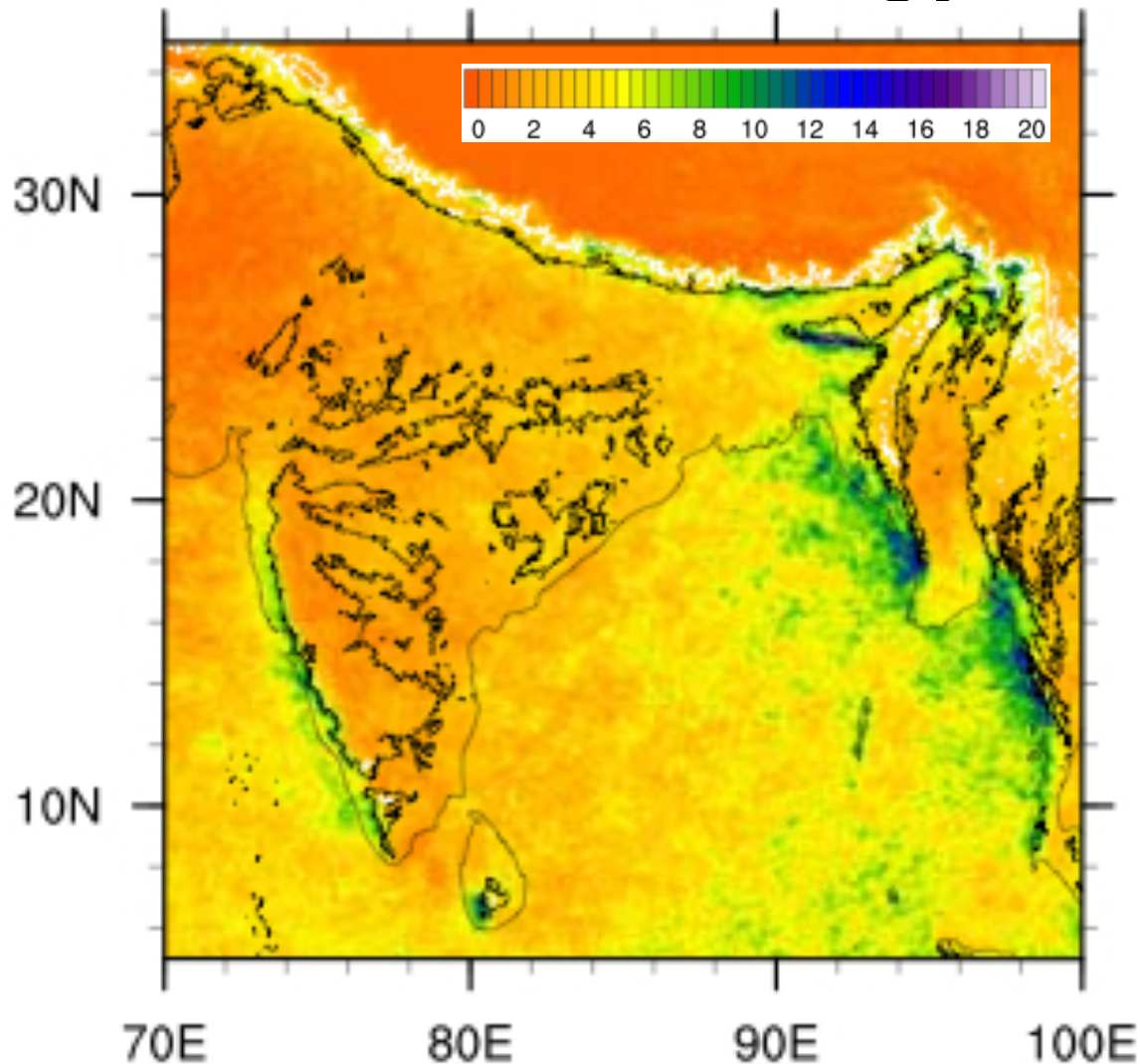
Indian monsoon precipitation



- The Indian monsoon season is defined as June-September [the plot shown is the seasonal accumulation of rainfall in mm]
- The highest climatological rainfall totals are occur over the southwest Arabian Sea coast (i.e., to the west of the western Ghats mountains) and over extreme eastern India
- A commonly used monsoon measure is the All India Rainfall Index (AIRI)

From the India Meteorological Department

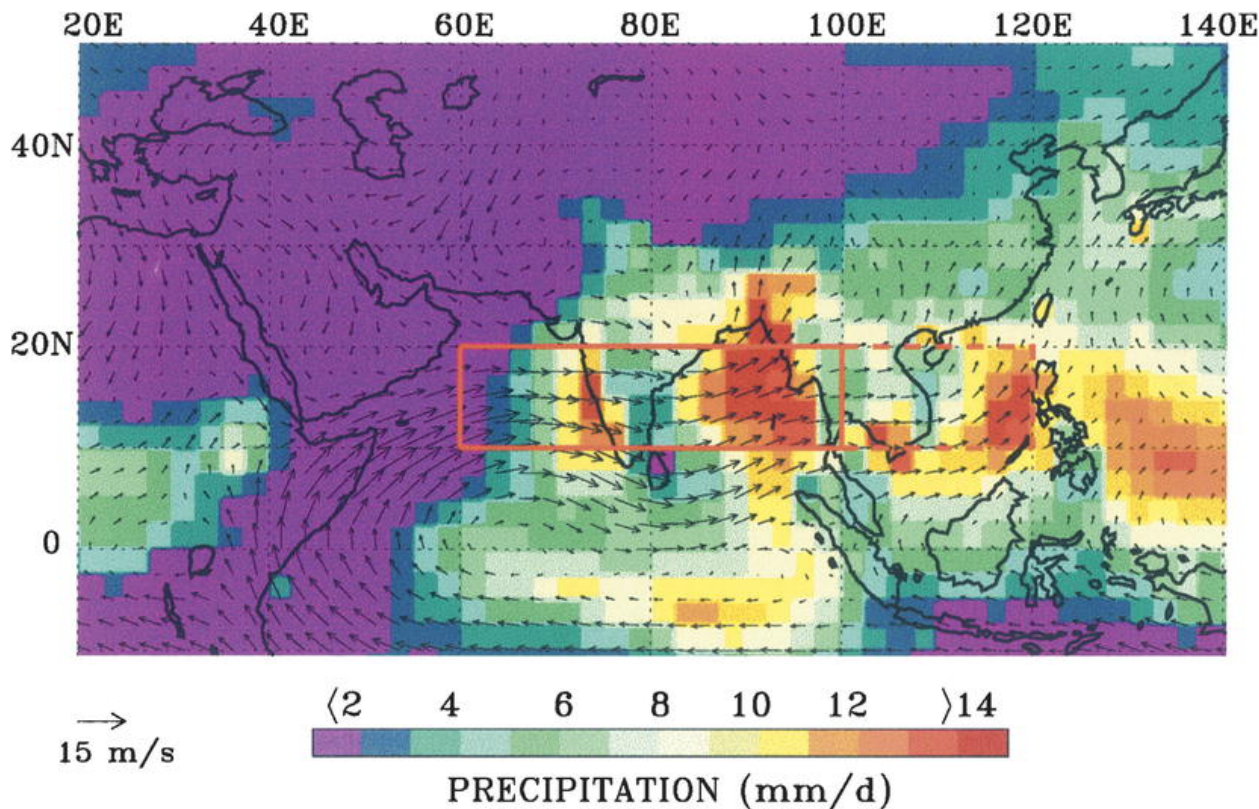
Very hi-resolution precip climatology for India



Nesbitt and Anders 2009

- TRMM satellite retrievals at 0.1° resolution
- Precipitation (shaded, in mm) and 500 m and 2000 m topography (black and white contours, respectively)
- Prominent co-location of most intense precipitation with topography

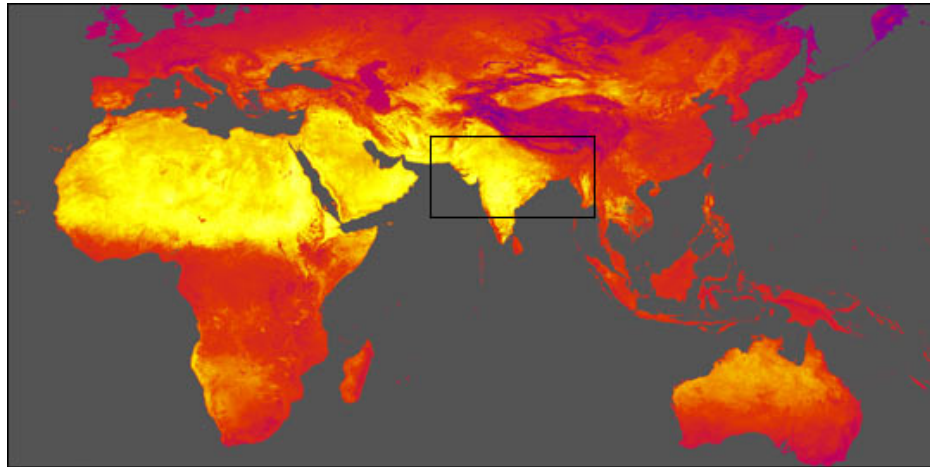
Broader structure of the South Asian monsoon



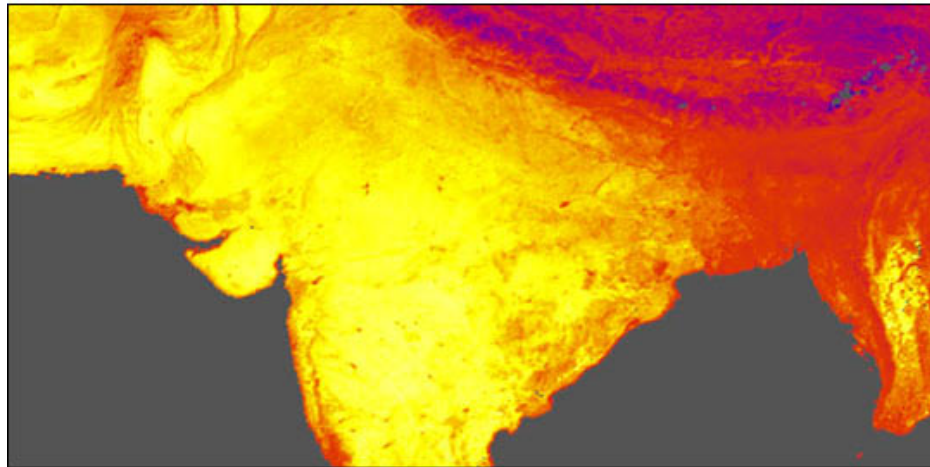
From Buermann et al. 2005

- 1979-1999 mean JJA CMAP precipitation (contours) and NCEP Reanalysis 850 mb horizontal winds (arrows) at 2.5° x 2.5° horizontal resolution
- The precipitation features previously evident over the Indian subcontinent are continuous with centers in the Arabian Sea and Bay of Bengal
- Note the low-level easterlies near the equator, westerlies over South Asia, and the southerly “Findlater” jet along the Somalian coast
- Extension of the monsoon into eastern Asia and the western Pacific

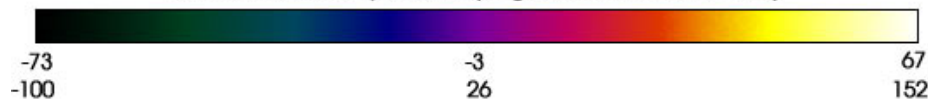
2003 Heatwave: A delay in monsoon advance



MODIS Land Surface Temperature May 2003



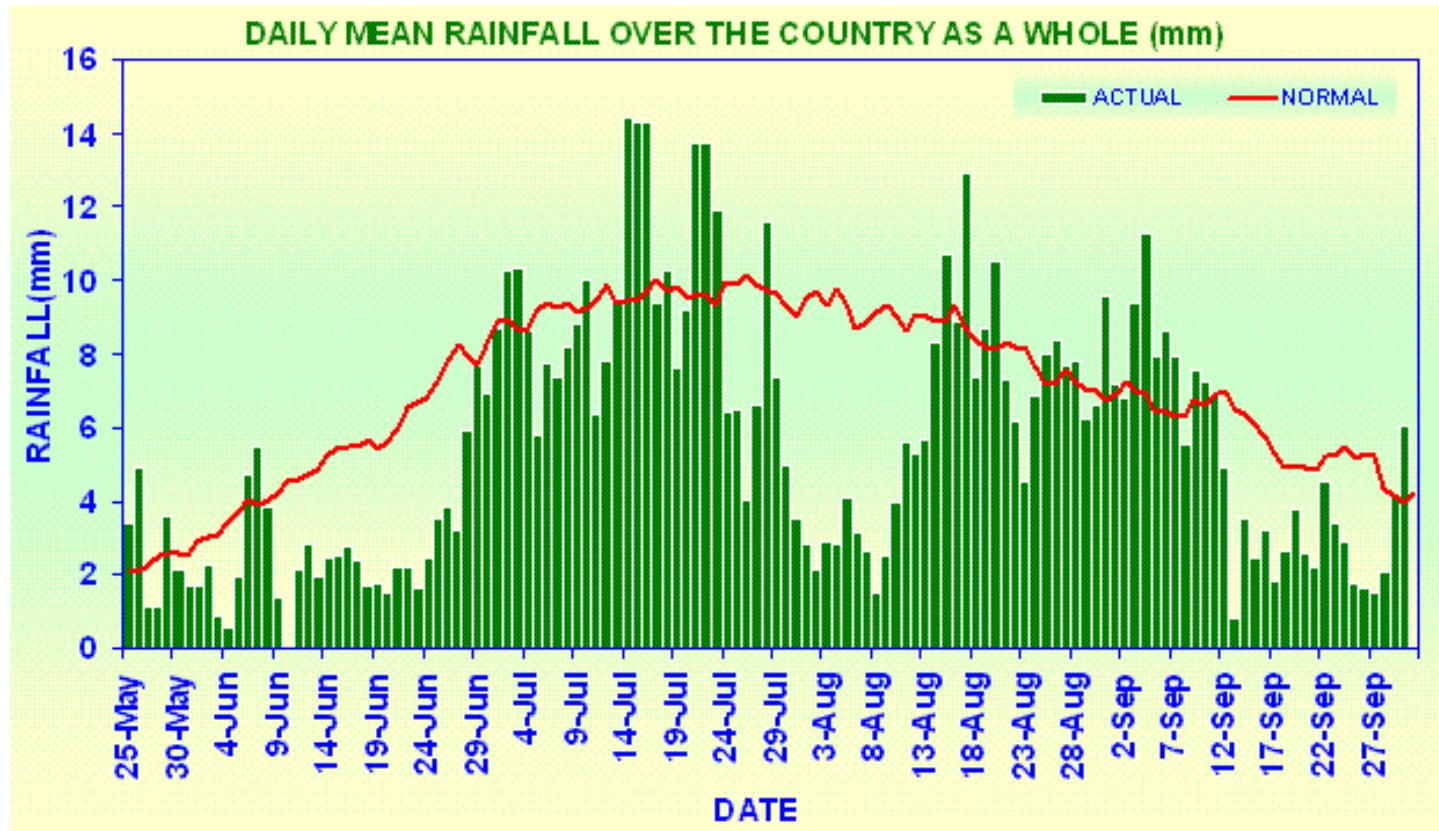
Land Surface Temperature (degrees Celsius/Fahrenheit)



- The pre-monsoon period (especially May) in India is typically characterized by high surface temperatures
- Especially hot conditions were in place in May 2003, resulting in nearly 1300 deaths
- The persistence of this event has been linked to a delay of ~1 week of monsoon advance

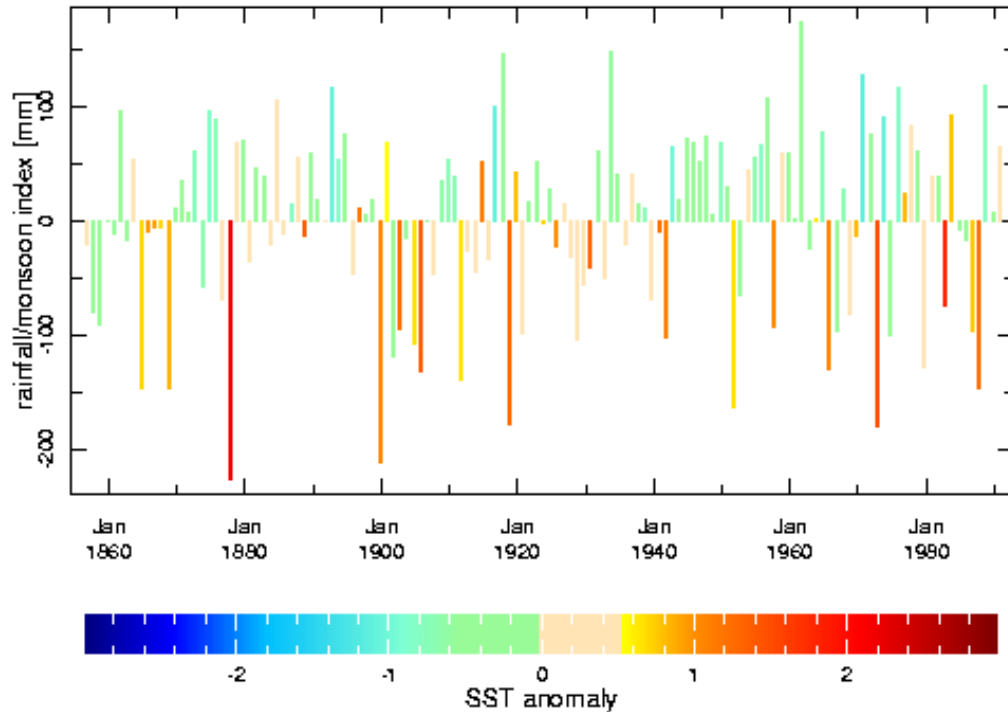
From NASA Earth Observatory Image of the Day (EOIOD) Gallery

AIRI for 2009



- Daily mean climatological AIRI is shown in red; daily mean values for 2009 are shown in green.
- Significant intraseasonal variability, with both “active” and “break” phases [Overall, 2009 was a below-average monsoon].

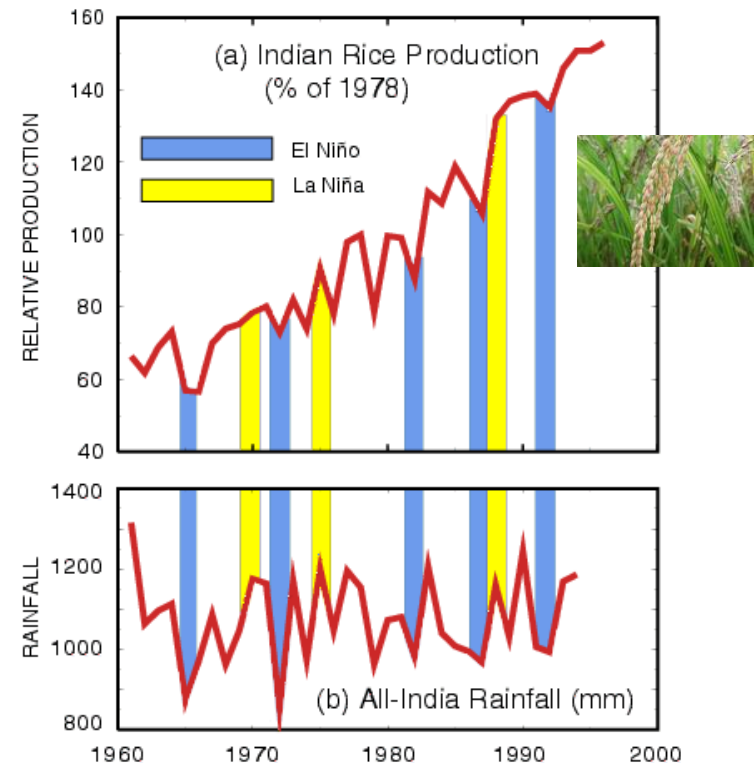
AIRI interannual variability



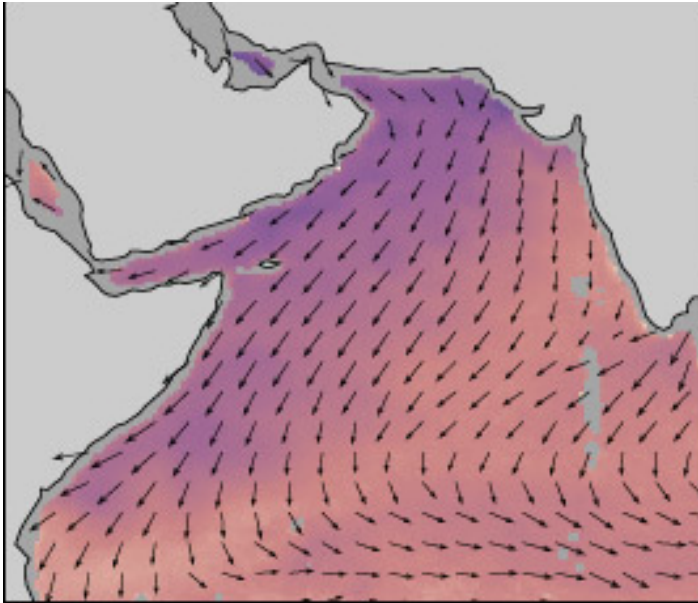
- **Kaplan et al. 1998** illustration of AIRI interannual anomalies (in mm) color coded by SSTs in the “NINO3” region [red = strong El Niño]. Note the mean value is ~850 mm, with a standard deviation of 80 mm.



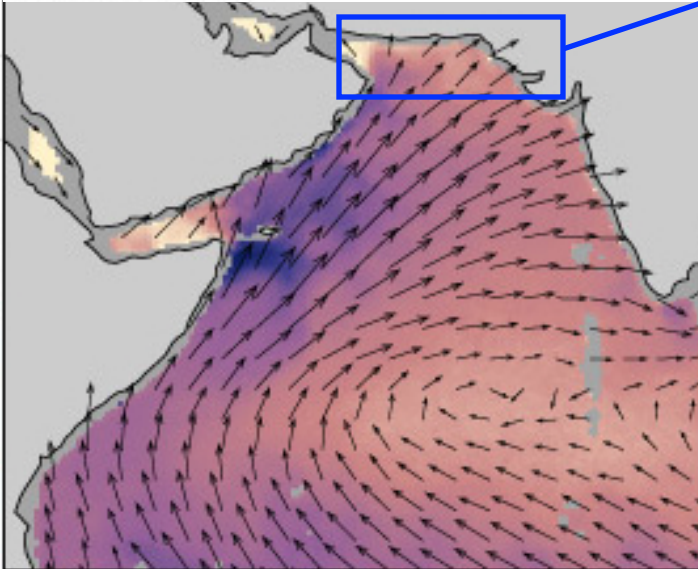
- Indian rice production (upper red curve; in % relative to 1978) and AIRI (lower red curve; in mm)



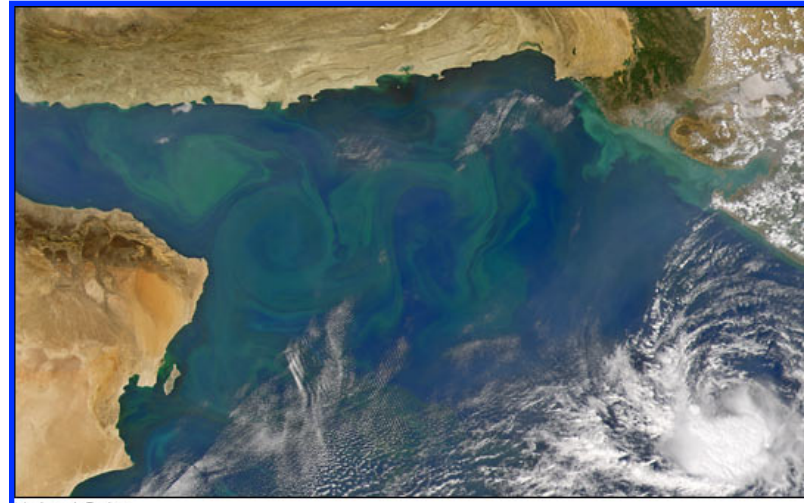
Seasonal wind reversal



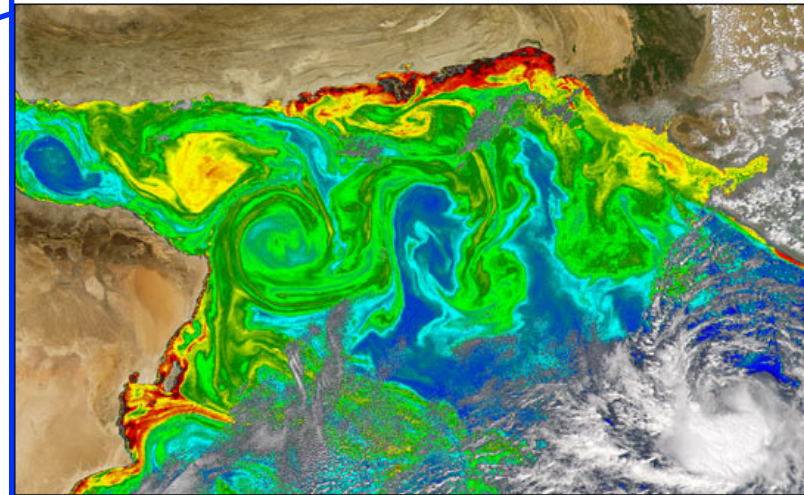
Winter Monsoon



Summer Monsoon



Natural Color

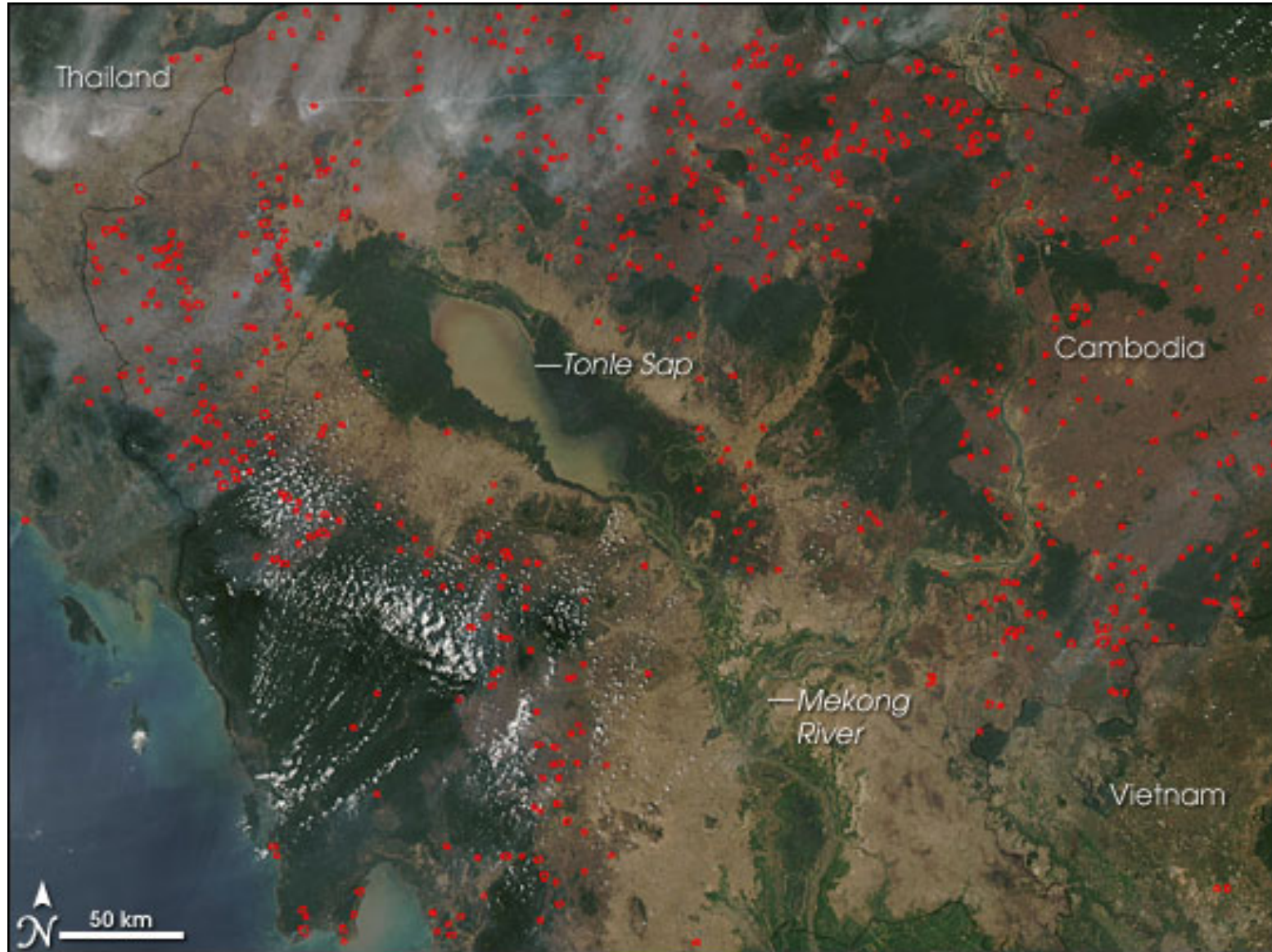


Chlorophyll Concentration

Ocean Chlorophyll Concentration (mg/m³)
0.05 1.0 10 50

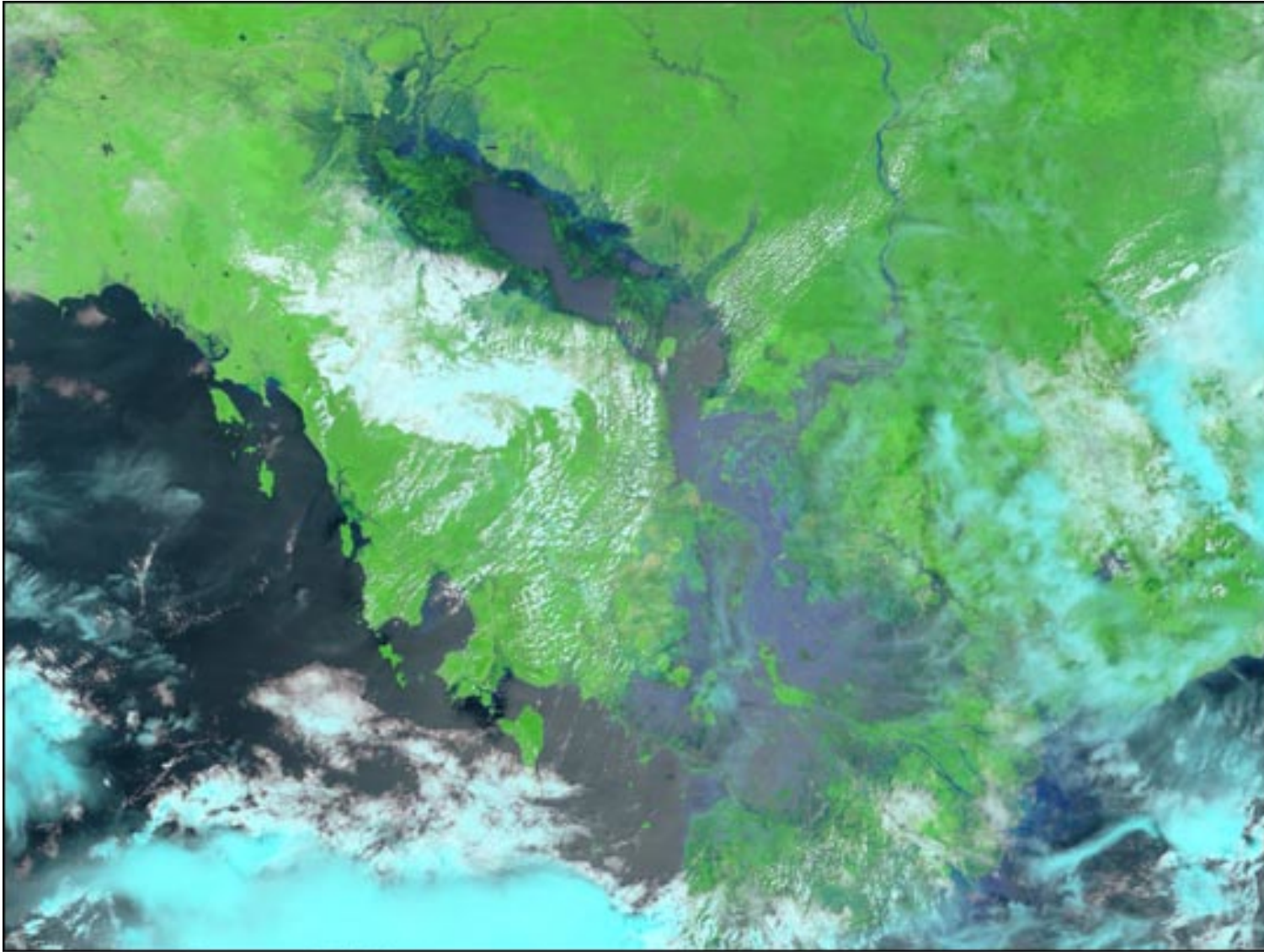
From NASA EOIOD

SE Asia dry monsoon



From NASA EOIOD

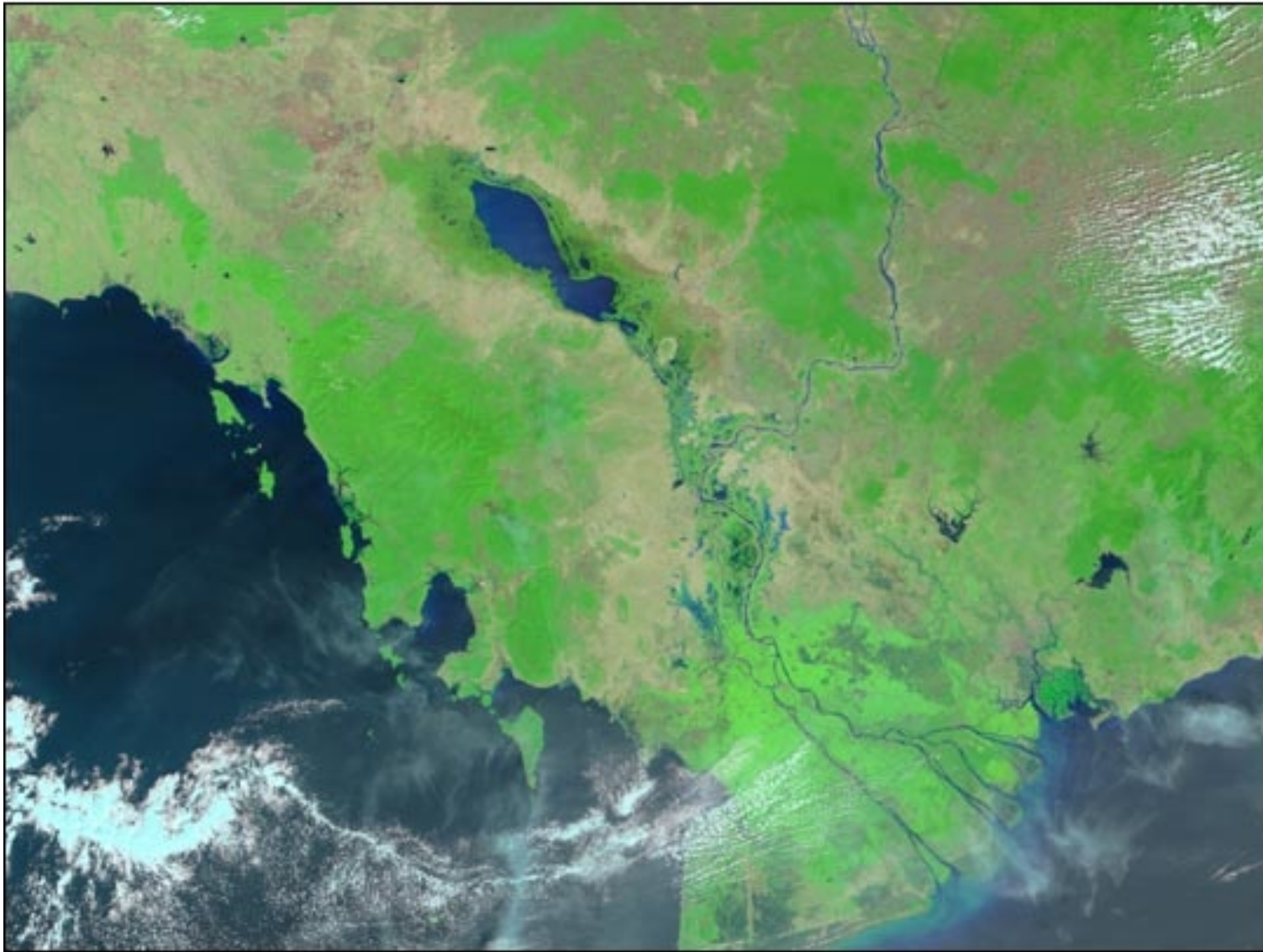
Seasonal change: Tonle Sap



Wet Season (October 9, 2002)

From NASA EOIOD

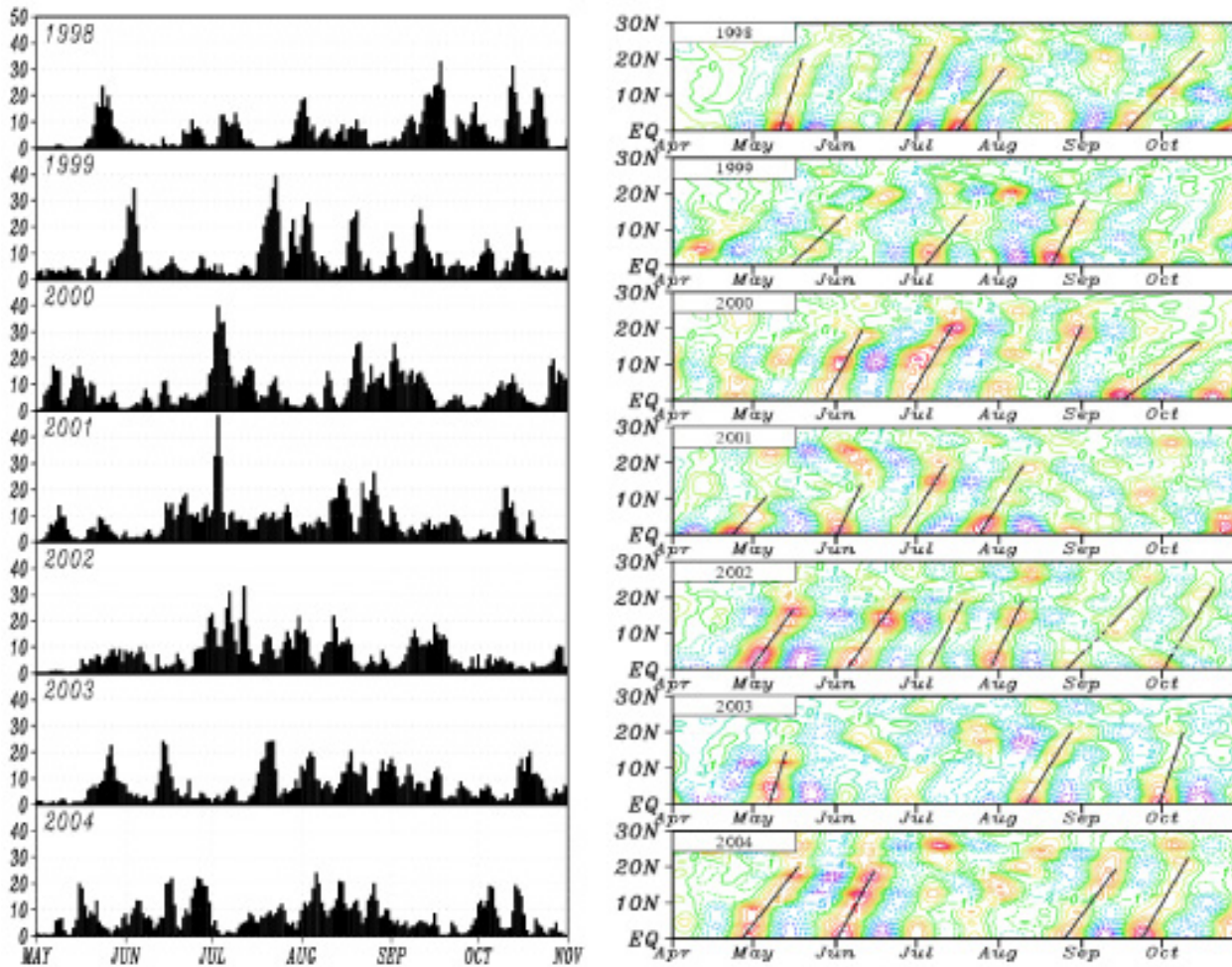
Seasonal change: Tonle Sap



Dry Season (January 29, 2003)

From NASA EOIOD

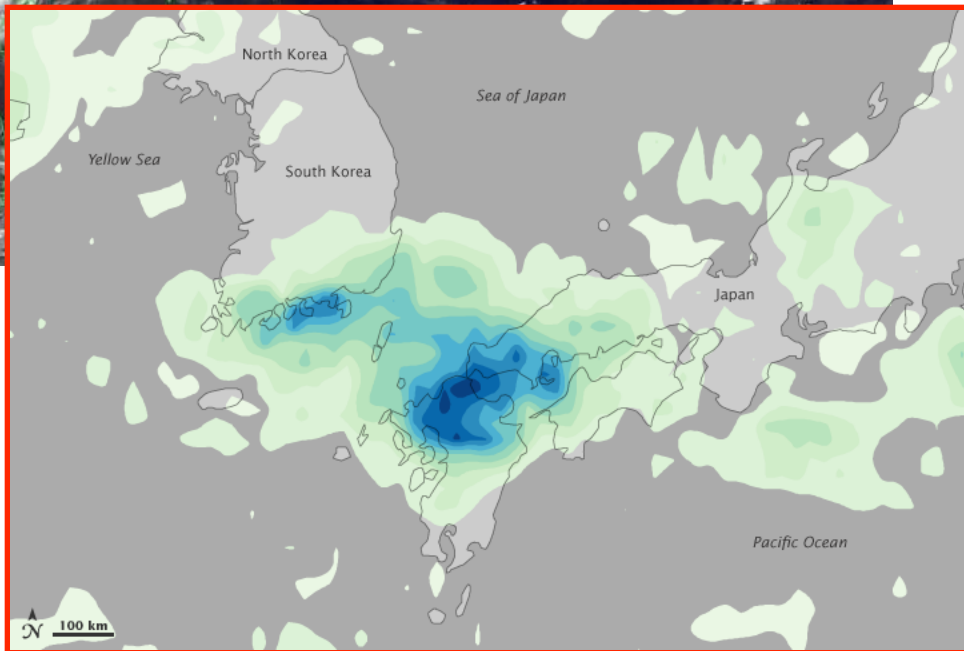
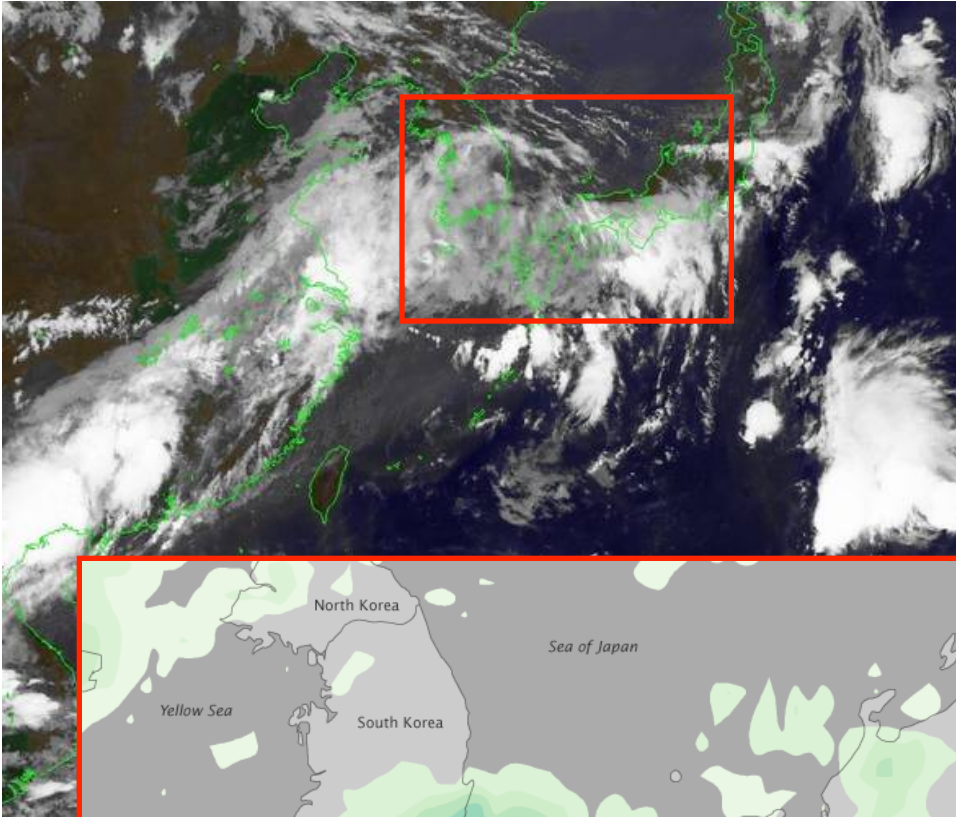
Western Pacific, 1998-2004



- Left: TRMM daily precipitation averaged over 115°E-140°E, 10°N-20°N
- Right: 20-50 day filtered precipitation averaged over 75°E-100°E
- Intraseasonal north(west)ward propagating features seen on the right, active/break periods on the left suggestive of monsoon modulation by MJO[?]

Fu et al , US CLIVAR [courtesy Dr. K. Kikuchi]

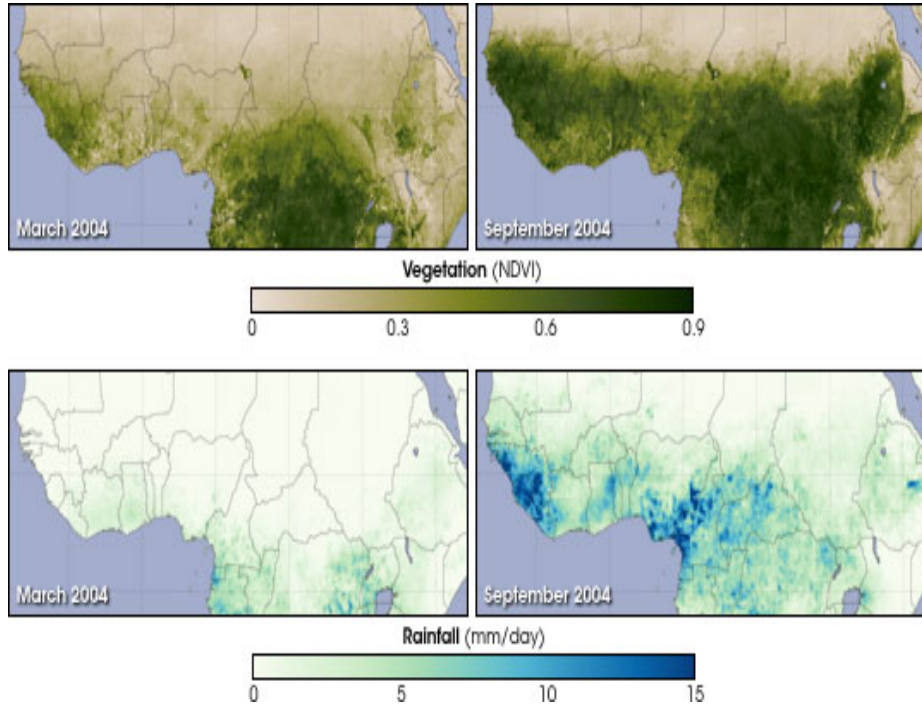
Mei-yu/bai-u front



- Quasi-stationary zonal rainfall feature on the northeast margin of the Asian monsoon
- Mei-yu means “plum rain” in Chinese, because of the arrival of rain in mid June: “When the rain falls on the ripe plums, there follows 40 days of rain.”
- While the rainy season is short (~30 days), it may account for 20% of the annual precipitation

From NASA EOIOD

West African monsoon

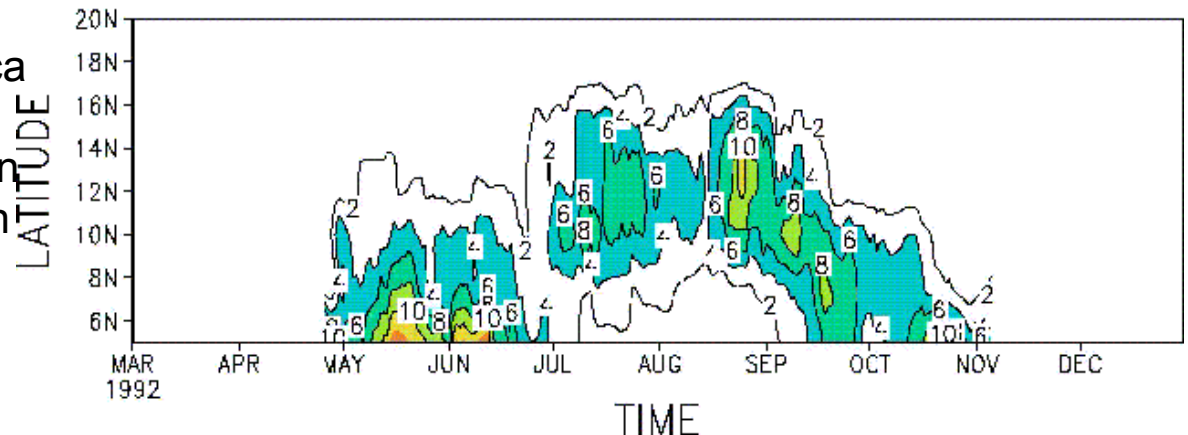


- Top panels: NDVI [satellite-derived measurement of “green-ness”] for March 2004 and September 2004
- Bottom panels: TRMM rainfall for March 2004 and September 2004

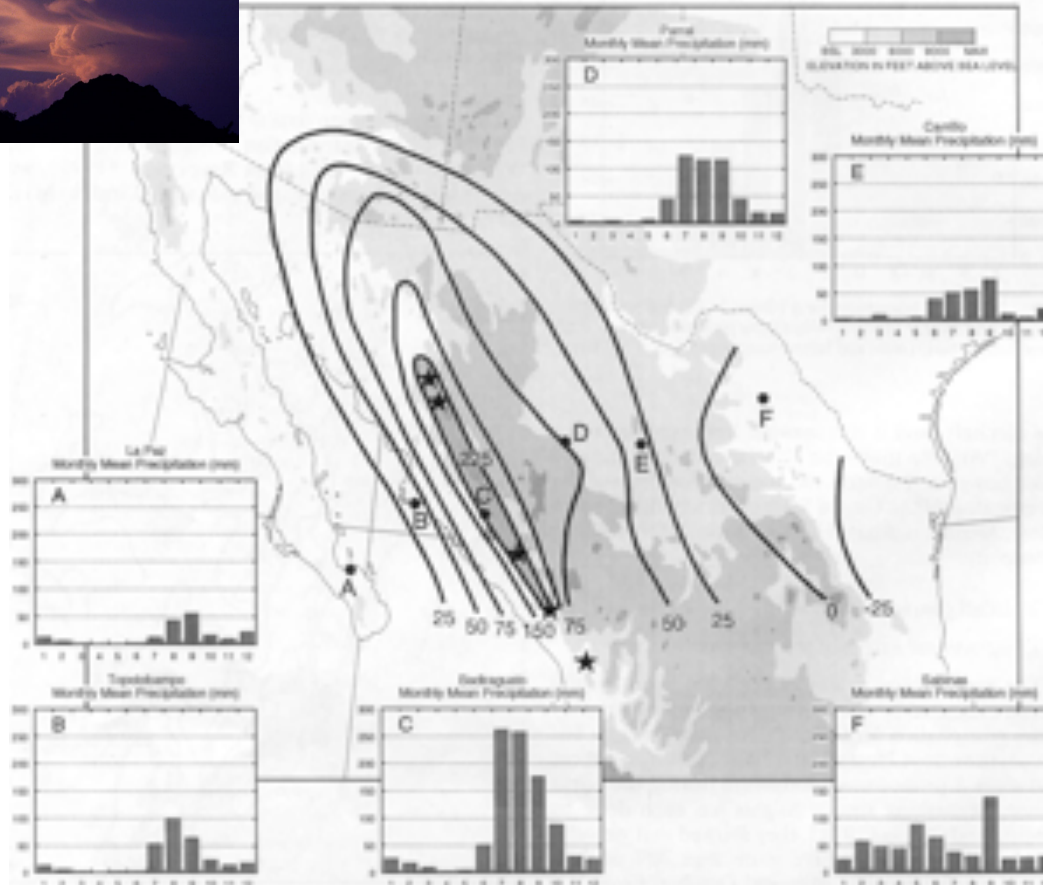
From NASA EOIOD

- Daily mean rainfall over West Africa shows a pronounced tendency to “jump” from an early season location close to the coast and a later season land region maximum
- Models have difficulty reproducing this jump

IRD DAILY RAINFALL DATABASE OVER WEST AFRICA 1992 MEAN 10W–10E



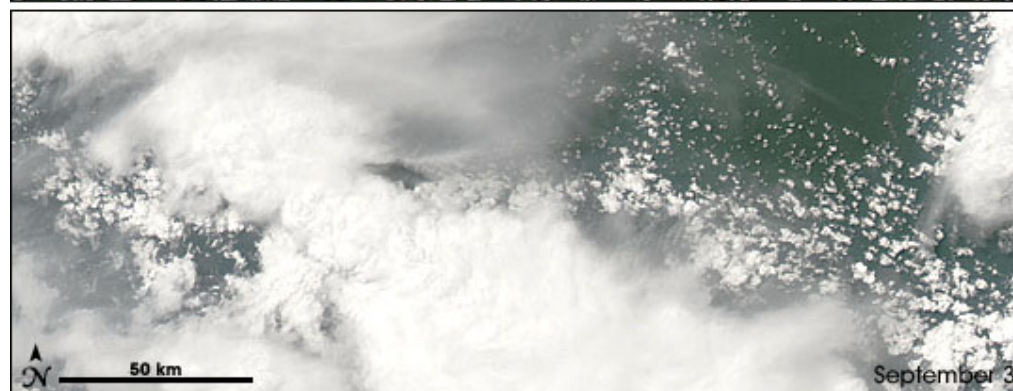
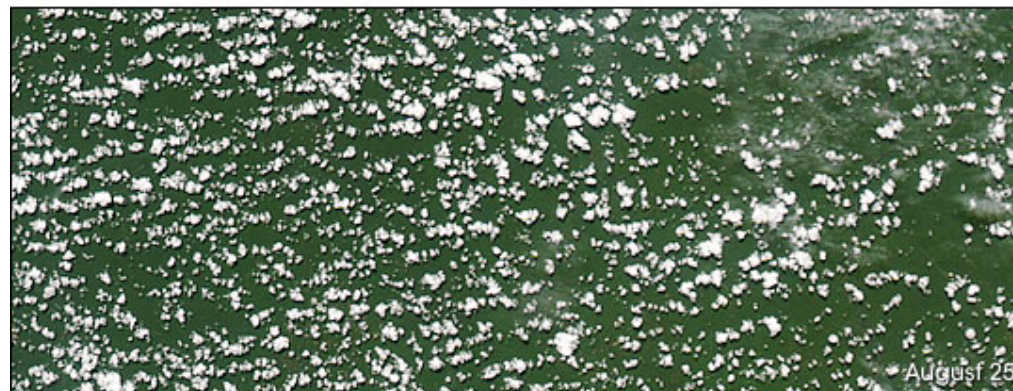
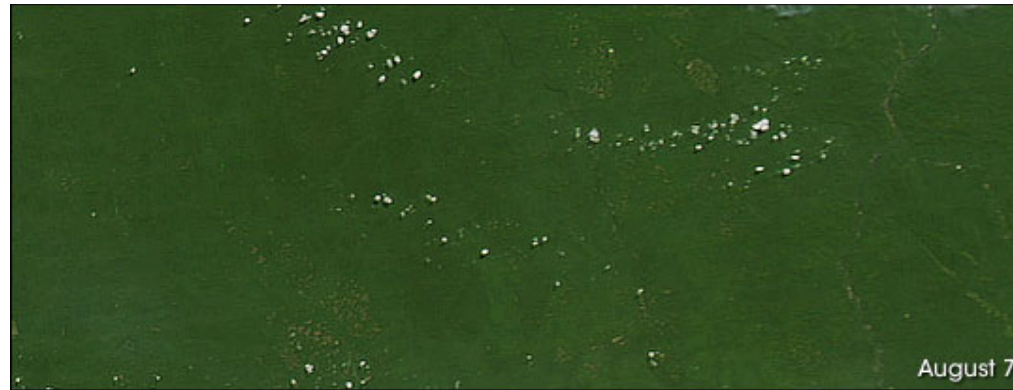
North American monsoon (NAM)



- Commences in southern Mexico in late May/early June and spreads northwestward along the western slope of the Sierra Madre Occidental
- The southwestern US (Arizona and New Mexico) is impacted by mid-to-late July
- Complex moisture source: Gulf of California/eastern Pacific (low levels) and the Gulf of Mexico (upper levels); potentially also the Great Plains

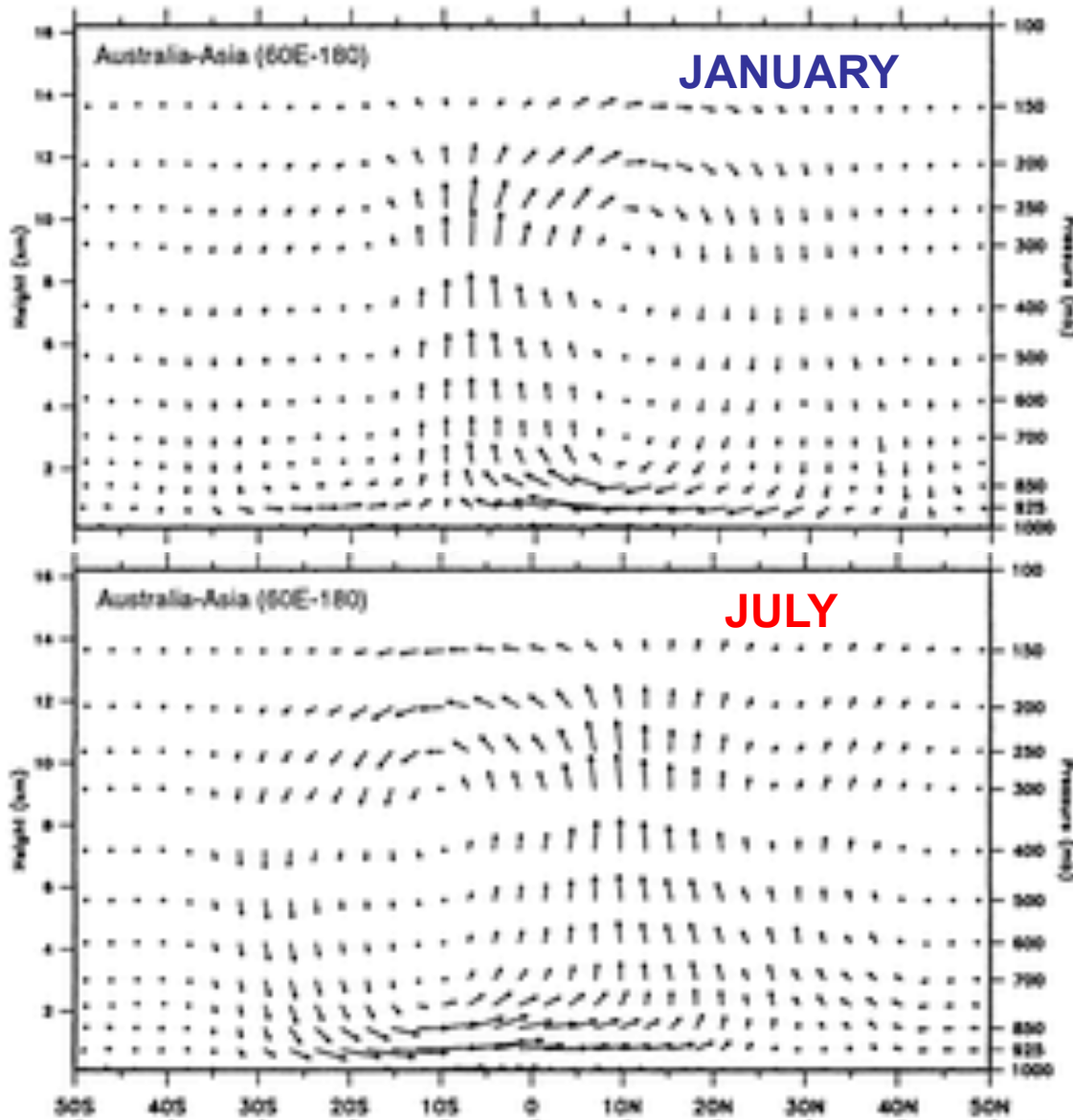
*Climatological NAM rainfall from Douglas et al., 1993.
Contours show July-June rainfall in mm.*

Developing South American wet monsoon



From NASA EOIOD

Monsoon vertical structure



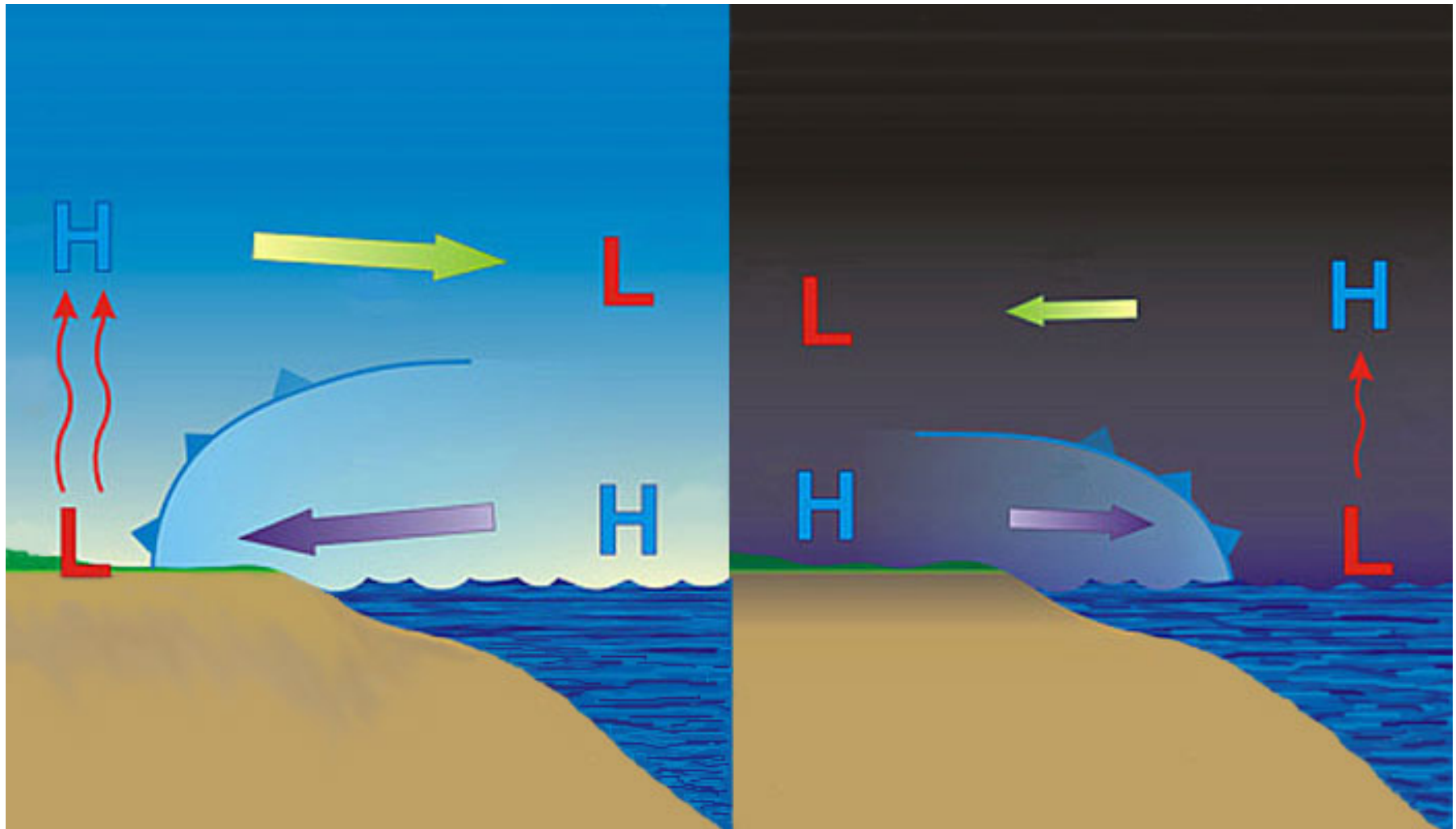
Trenberth et al. 2000

- Mean divergent v , ω averaged over 60°E-180°E
- January rising branch to the south of the equator; July rising branch to the north of the equator
- “Local Hadley circulation”: in fact, in NH summer, the Hadley circulation defined as the zonally-averaged overturning circulation is largely accounted for by the South Asian monsoon

Simple view: monsoons as “land-sea breeze”*

Day or “Summer”

Night or “Winter”



*This view posited by Halley in 1686

Beyond the simple view [next time]

- The land-sea breeze view fails to account for:
 - Tendency for rapid monsoon onset even while large-scale forcing [top-of-atmosphere radiative heating] varies smoothly
 - Active/break cycles
 - Effect of rotation at large-scales
- An alternative view is of the monsoon as a seasonal displacement of Intertropical Convergence Zones (ITCZs) toward the subtropics
- A significant aspect is how monsoonal convection feeds back onto circulation

- Application of axisymmetric theory
- Deviations from axisymmetry

Goal: Develop theoretical physical frameworks to interpret important monsoon features

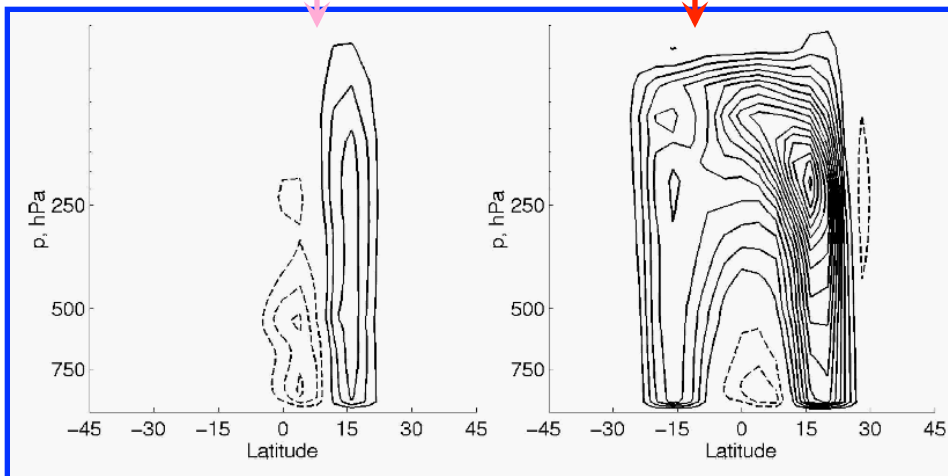
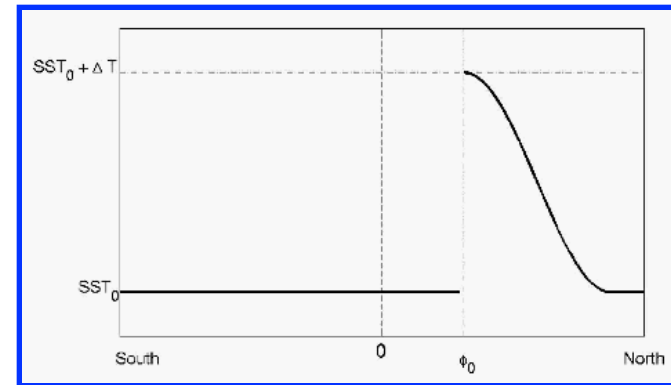
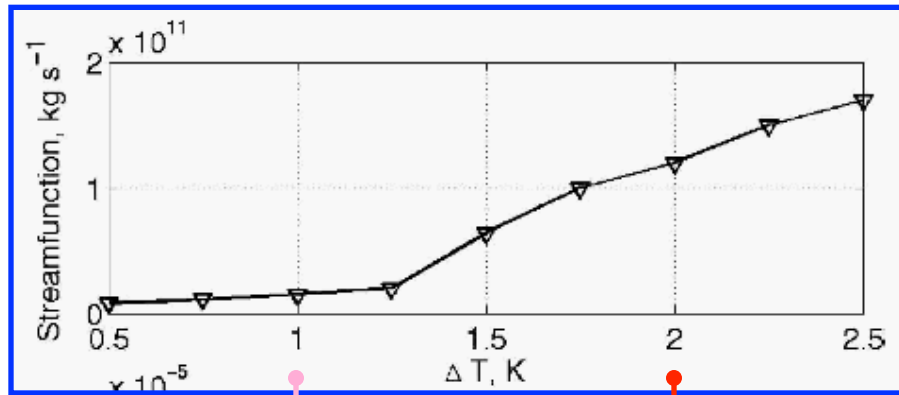
At the end of last lecture

- Description of the monsoon as a large-scale “land-sea breeze”
- The land-sea breeze view fails to account for:
 - Tendency for rapid monsoon onset even while large-scale forcing [top-of-atmosphere radiative heating] varies smoothly
 - Active/break cycles
 - Effect of rotation at large-scales
- An alternative view is of the monsoon as a seasonal displacement of Intertropical Convergence Zones (ITCZs) toward the subtropics
- A significant aspect is how monsoonal convection feeds back onto circulation

Application of nonlinear axisymmetric theory to monsoons

- That is, using a Held-Hou (1980) model, but with off-equatorial heating
- Key questions:
 - *The strength and extent of the monsoon?*
 - *Steady state circulation applicability to the transient monsoon dynamics?*
 - *Effects of interactive forcing and land surface?*

Aquaplanet simulations of Prive and Plumb 2007

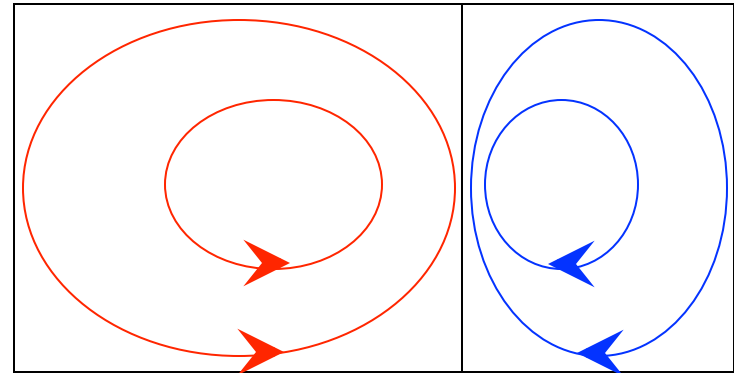


- Coarse resolution MIT GCM run in aquaplanet mode with moist convective parameterization and Newtonian relaxation radiation scheme with an imposed SST profile as above.
- Exhibits a threshold below which meridional circulation is insensitive to the SST “jump” difference; above, the circulation strength increases with increasing SST jump.
- The circulation in the below and above threshold regimes are distinct: the latter crosses the equator.

Angular momentum-conserving axisymmetric circulation

Consider the arrangement of streamlines for the 2D (latitude-height) flow shown on the right. Let's consider a flow for which angular momentum is conserved, i.e.,

$$\frac{dM}{dt} = 0 = \left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) M$$



Under steady state conditions, this implies: $v \frac{\partial M}{\partial y} + w \frac{\partial M}{\partial z} = 0$

Along the separatrix between the two “cells”, there is no meridional flow (except perhaps in a thin layer near the top and bottom boundaries), implying that $w \frac{\partial M}{\partial z} = 0$. For the circulation shown, $w > 0$ along the separatrix throughout the free troposphere; thus the angular momentum constraint requires that:

$$\frac{\partial M}{\partial z} = 0$$

For $M = \Omega R_e^2 \cos^2 \lambda + u R_e \cos \lambda$ this implies: $\frac{\partial u}{\partial z} = 0$

Monsoon rising branch location (I)

Let's now consider the steady meridional momentum equation in the inviscid, thermal wind balance limit:

$$fu + \frac{\partial \Phi}{\partial y} \approx 0$$

Taking the pressure derivative gives:

$$\frac{\partial u}{\partial p} + \frac{1}{f} \frac{\partial}{\partial y} \frac{\partial \Phi}{\partial p} = \frac{\partial u}{\partial p} + \frac{1}{f} \frac{\partial}{\partial y} \left(-\frac{1}{\rho} \right) = \frac{\partial u}{\partial p} - \frac{1}{f} \frac{\partial \alpha}{\partial y}$$

As in previous lectures, applying Maxwell's equations allows us to write:

$$\frac{\partial \alpha}{\partial y} = \left(\frac{\partial T}{\partial p} \right)_{s^*} \frac{\partial s^*}{\partial y} \quad \text{s}^* \text{ is saturation (moist) entropy}$$

From the vanishing of the vertical gradient of u along the separatrix, we thus have:

$$\left(\frac{\partial T}{\partial p} \right)_{s^*} \frac{\partial s^*}{\partial y} = 0$$

This condition requires that the meridional derivative of s^* vanish at the separatrix.

Monsoon rising branch location (II)

Assuming a moist adiabatic lapse rate, s^* is approximately constant in the vertical; we can thus set $s^* = s_b$, so

$$\left(\frac{\partial T}{\partial p}\right)_{s_b} \frac{\partial s_b}{\partial y} = 0$$

Recalling the definition of moist static energy (MSE), $h = c_p T + \Phi + L_c q$ and the relationship between differential equivalent potential temperature and h :

$$c_p d \ln \theta_e \approx c_p \frac{dT}{T} - R_d \frac{dp}{p} + d \left(\frac{L_c q}{T_{LCL}} \right) \approx \frac{dh}{T}$$

Thus:

$$\left(\frac{\partial T}{\partial p}\right)_{s_b} \frac{1}{T_b} \frac{\partial h_b}{\partial y} = 0$$

The above relationship means that boundary layer MSE is an extremum at the axisymmetric monsoon circulation (rising branch) boundary. Stronger westerlies aloft on the poleward edge of the boundary imply MSE decreases poleward of the boundary, so MSE is maximized at the boundary.

Continental solution from Prive and Plumb 2007

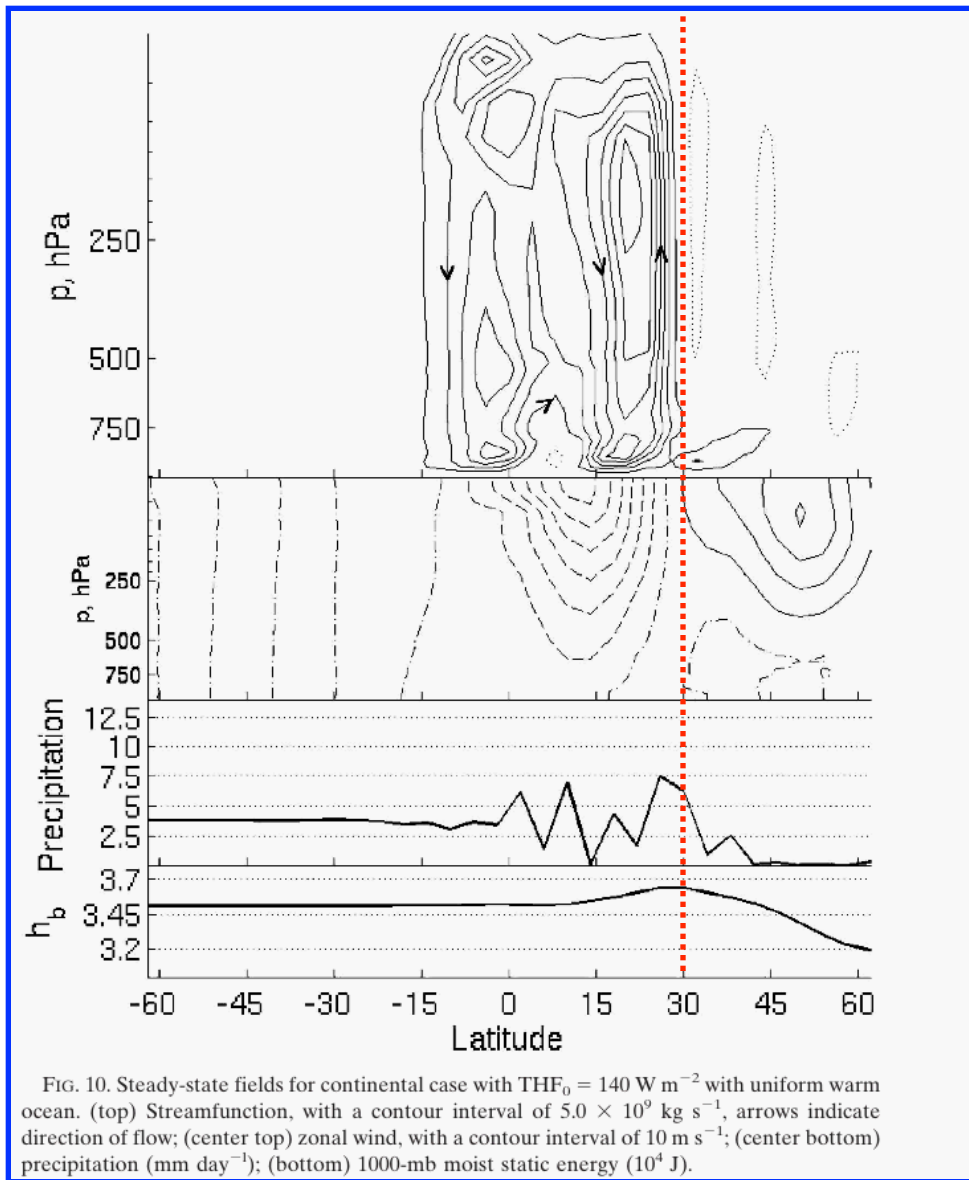
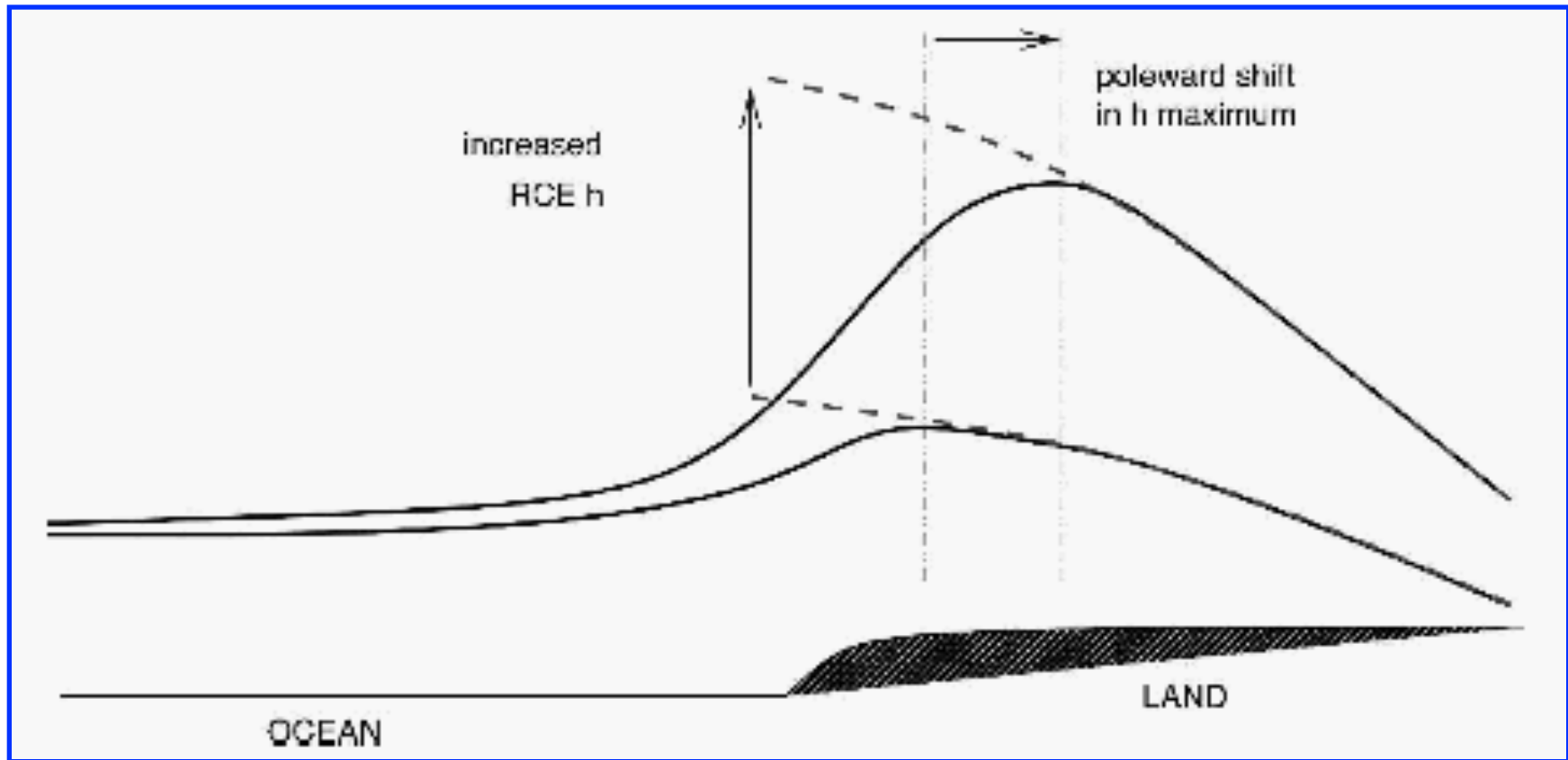


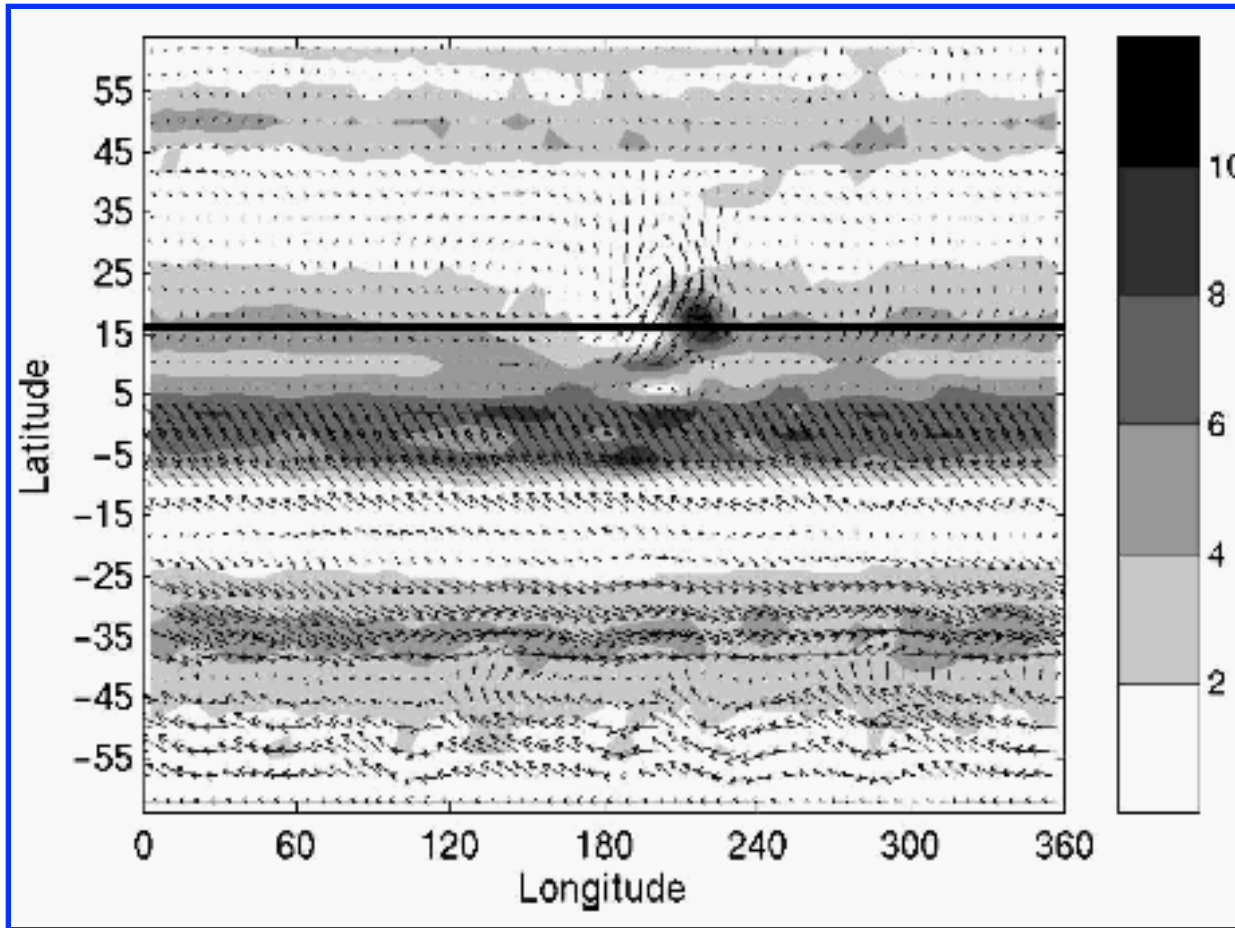
FIG. 10. Steady-state fields for continental case with $\text{THF}_0 = 140 \text{ W m}^{-2}$ with uniform warm ocean. (top) Streamfunction, with a contour interval of $5.0 \times 10^9 \text{ kg s}^{-1}$, arrows indicate direction of flow; (center top) zonal wind, with a contour interval of 10 m s^{-1} ; (center bottom) precipitation (mm day^{-1}); (bottom) 1000-mb moist static energy (10^4 J).

- In this case: Land region North of 16°N with a specified surface heat flux and bucket hydrology
- Strong monsoonal cell south of the h_b maximum ($\sim 30^\circ\text{N}$)
- Easterlies south of maximum and westerlies north, implying an upper level anticyclone
- Precipitation is maximized just to the south of the h_b maximum

Schematic illustration of monsoon shift with increasing forcing



Effects of transients

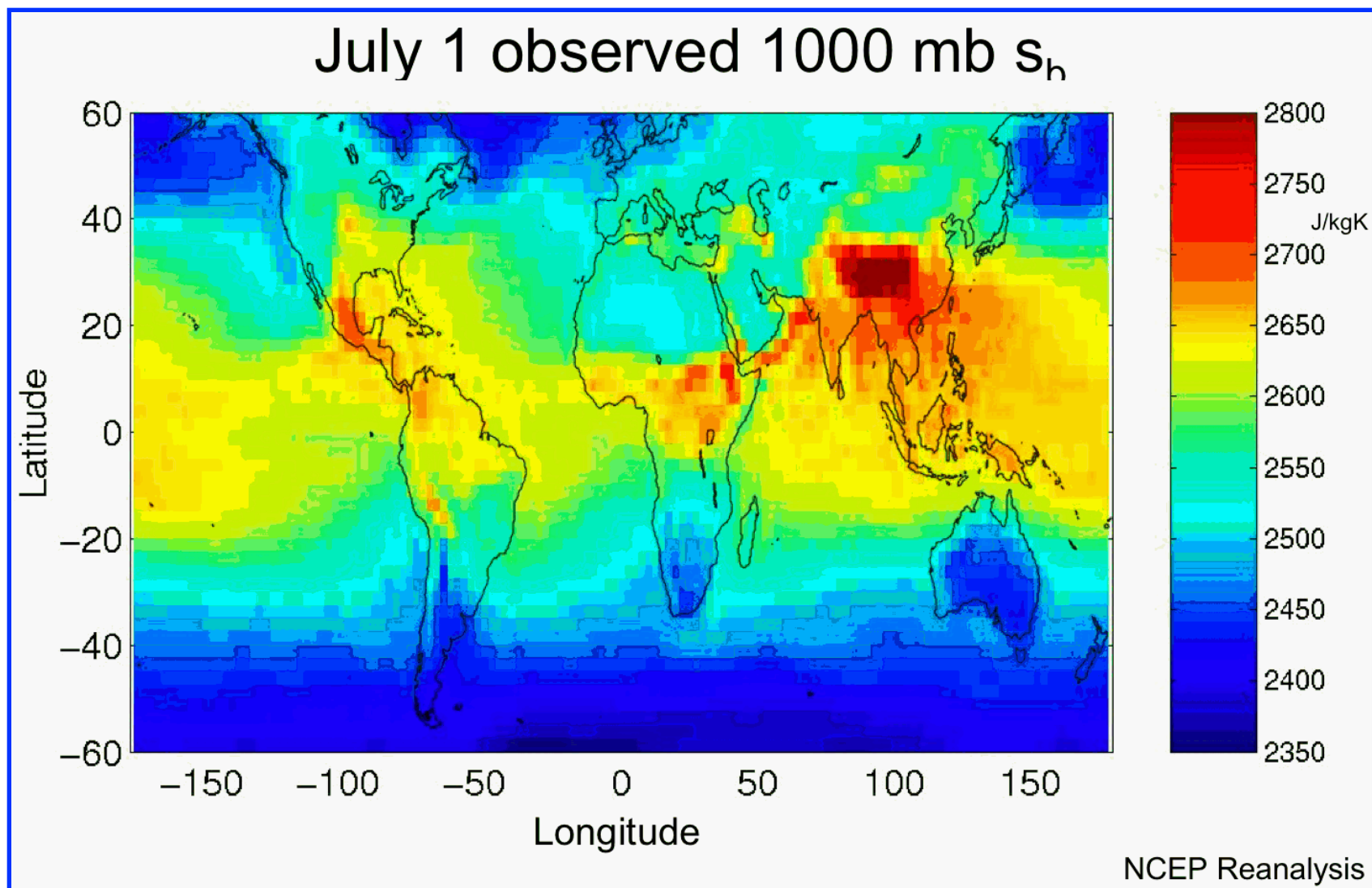


- Stronger heating of the continent produces a low-level easterly coastal jet.
- Baroclinic instability of this jet creates westward propagating eddy disturbances
- The net effect of these eddies is a weakening of the monsoon circulation

Asymmetric cases

- For example, what is the effect of introducing asymmetric continents?
- Using an idealized continent restricted to 180 degrees longitude, Prive and Plumb 2007 found that the meridional circulation does not closely follow the axisymmetric theory
 - Meridional circulation is relatively weak
 - Compensatory descent occurs not in the descending branch of the circulation but in a region northwest of the monsoon
- However, subcloud MSE remains a good indicator of deep convection over the continent
 - Continental convection occurs as long as MSE is larger than over the adjacent ocean
 - Ascent and precipitation occur equatorward of the MSE maximum

Distribution of ABL moist entropy



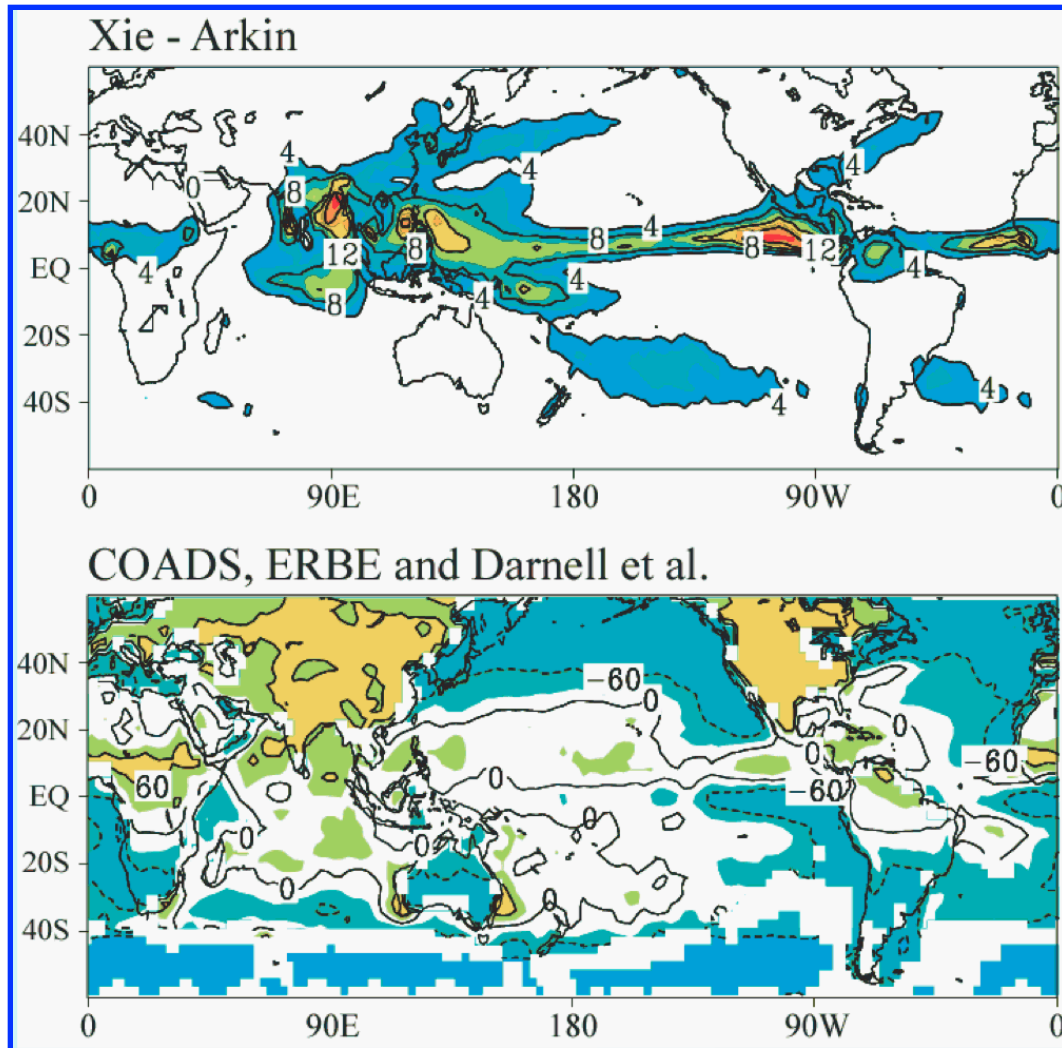
From Emanuel 2005

So, a key issue for the monsoon is the distribution of subcloud/ABL MSE...

Important Controls [recalling convective QE lecture]:

- Surface heat fluxes
- Radiative cooling
- Entrainment at the top of the subcloud layer
- Convective downdrafts
- Advection by large-scale flow

Limits on the poleward advance of the monsoon



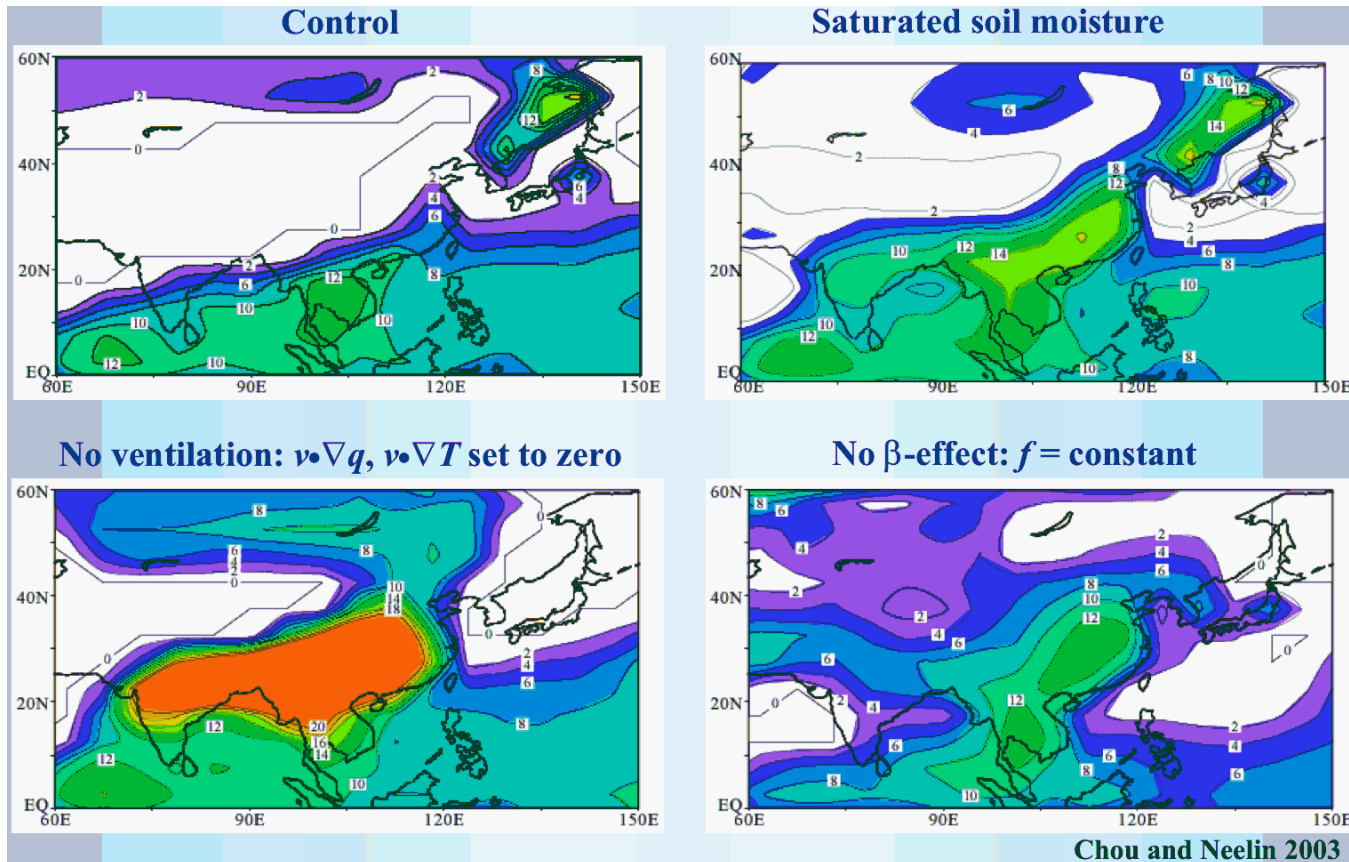
- Observed July precipitation (top) and net atmospheric column heating (bottom)
- For NH continents, net column energy flux is positive well north of continental precipitating regimes
 - ⇒ So why doesn't precipitation extend farther north (poleward)?

Courtesy J.D. Neelin

Possible limiting mechanisms

- *Soil moisture*
 - The land surface has a finite moisture capacity, putting the land at a competitive disadvantage relative to the ocean
- *Ventilation*
 - Advective import of low MSE air
- *Interactive Rodwell-Hoskins mechanism*
 - Convection generated by monsoonal precipitation sets up a stationary Rossby wave response to the west, which creates large-scale subsiding conditions

Asian monsoon simulations



- Results from an intermediate level complexity model for the tropical atmosphere, the Quasi-equilibrium Tropical Circulation Model [QTCM]
- Control (top left)+Sensitivity experiments:
 - (top right) Saturated surface
 - (bottom left) Suppressed moisture/temperature advection
 - (bottom right) Constant Coriolis parameter [to suppress Rossby waves]

Courtesy J.D. Neelin

Summary of mechanisms

Ventilation

- import of low moist static energy air from ocean where heat storage keeps cool
- » **balances heating** of midlatitude continent
- » limits poleward extension of summer monsoon convection
- » produces east-west asymmetry

Interactive Rodwell-Hoskins mechanism

- Rossby wave div/convergence pattern interacts with convection
- » eastern continent convection favored
- » western continent convection disfavored (eastern favored)

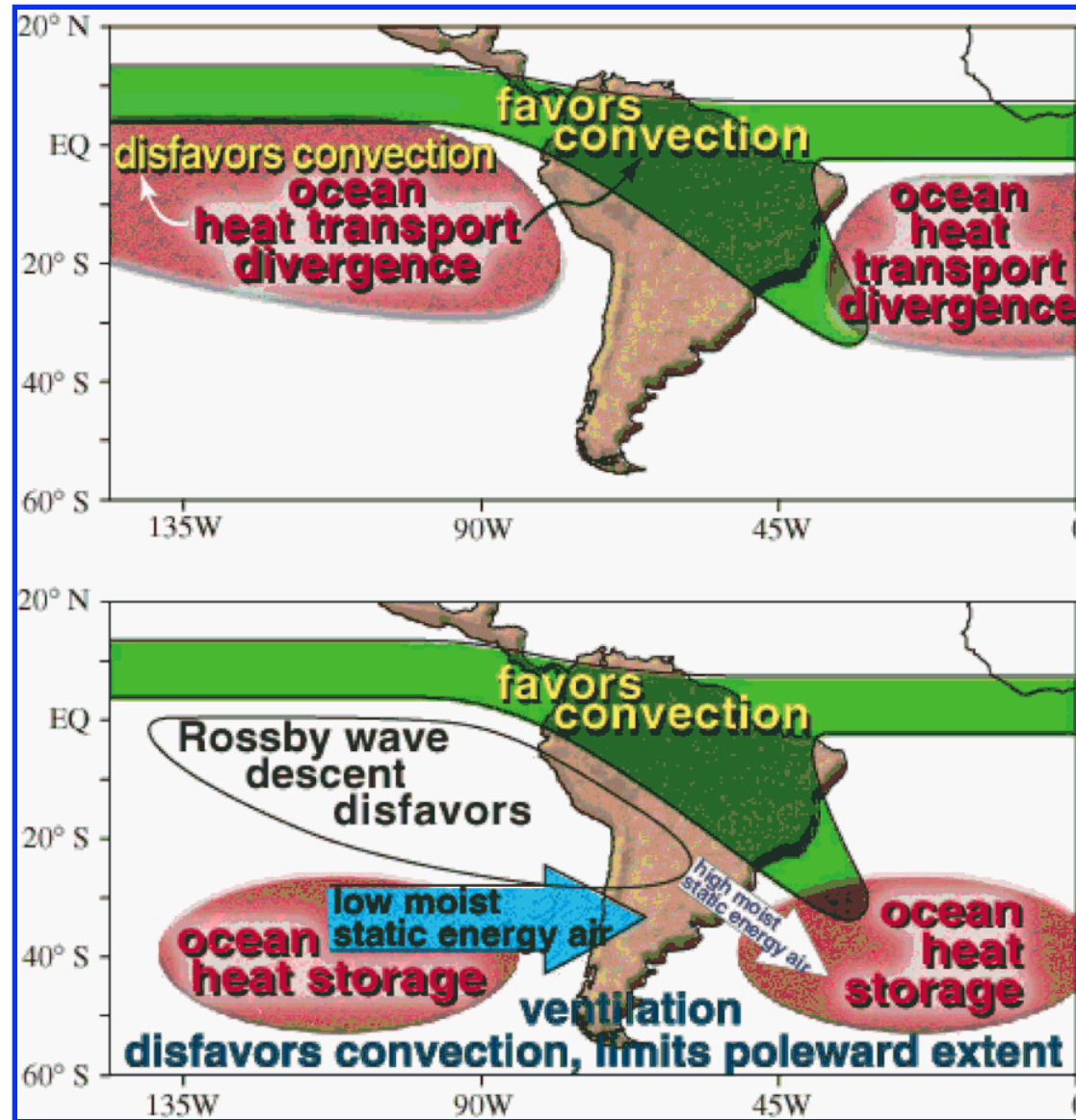
Soil moisture

- drying tendency in subtropical descent region
- » contributes to limiting poleward extent of convection
- » tropical continent convection disfavored

Ocean heat transport

- tropical ocean cooled by transport
- » tropical continent convection favored

Summary for South America



Courtesy J.D. Neelin