Some Large-Scale Aspects of the Coupled Ocean-Land-Atmosphere Monsoon System

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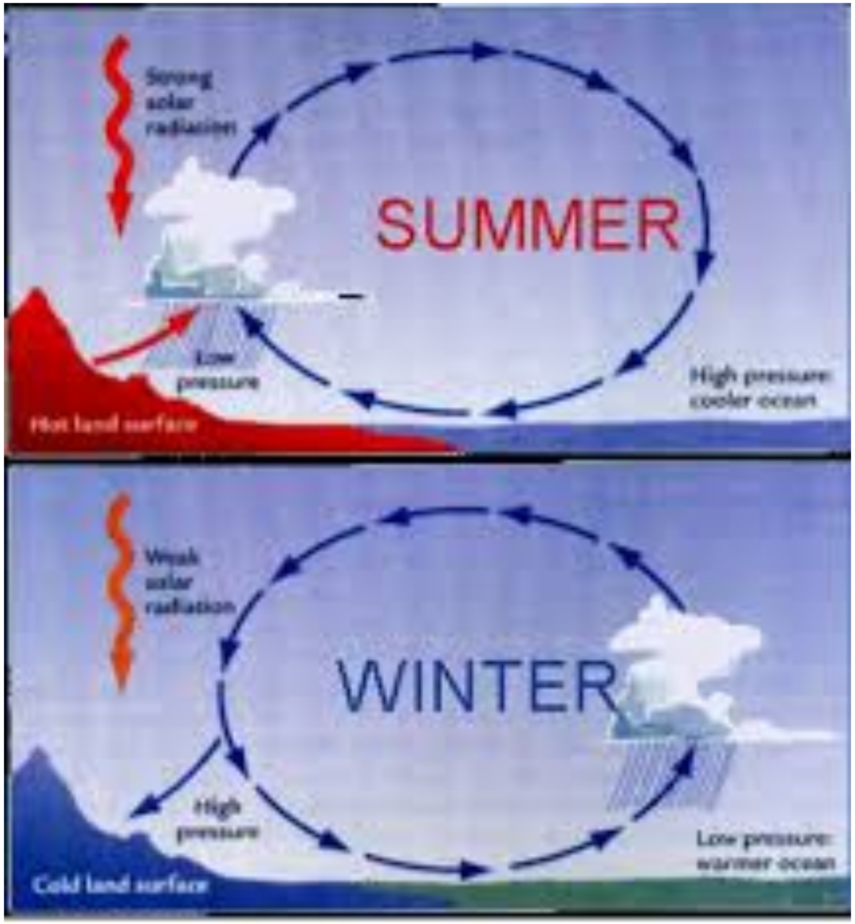
Overview

1. Early thoughts on the physics of the monsoon
2. Components: Land, ocean and atmosphere and how they interact
3. Temporal variability of the monsoon: annual, biennial, interannual and intraseasonal (and subseasonal)
4. Ocean-atmosphere interaction and the regulation of the monsoon
5. Domination of the Asian summer monsoon and elevated heating
6. Some conclusions and ways ahead

I do not have time to talk about biweekly variations of the monsoon and these are critical subjects and offer extended predictability. A discussion can be found at:
https://www.dropbox.com/sh/hpn9ldozhvvixt7/AADKWtfRhxoR52MtFfZ9EOyTa?dl=0

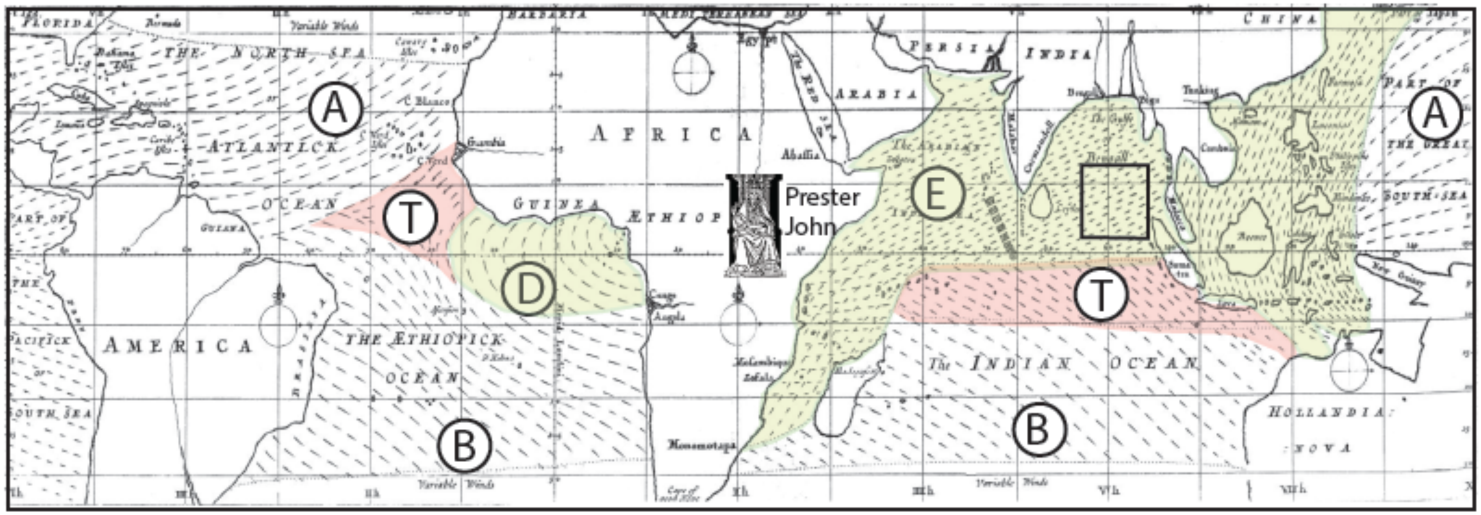


<u>Halley's theory of the monsoon:</u>
Differential buoyancy induced by land-sea temperature differences

Halley's great observation was that in summer, winds were on-shore. In winter, off-shore. He noted that this pattern occurred in certain parts of the world and not in others. His explanation:

"…action of the Sun's Beams upon air and water ..according to the Laws of Staticks, air which is less rarified or expanded by heat must have a motion towards those which are more rarified to bring it to an equilibrium …" (Halley 1686)

(a) Halley's Surface Wind Climatology (1686)

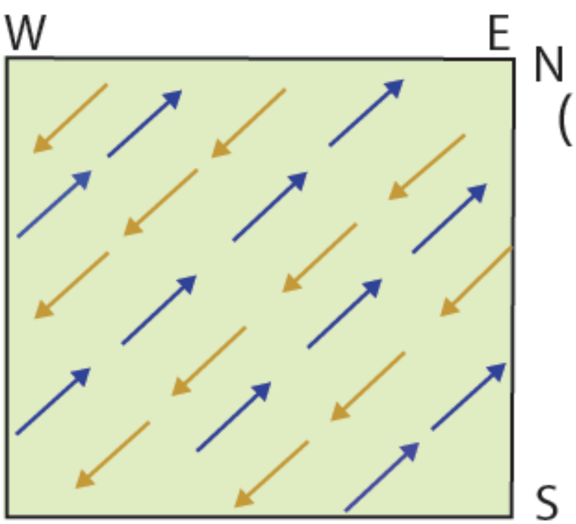


Halley

A: Northern hemisphere NE trades B: Southern hemisphere SE Trades

E: South/East Asia monsoon seasonally reversing winds

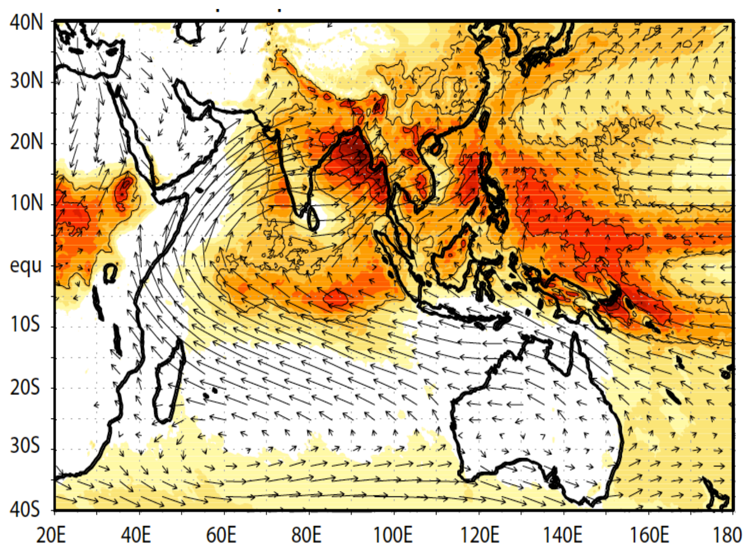
T: Monsoon trough/ITCZ seasonal migration



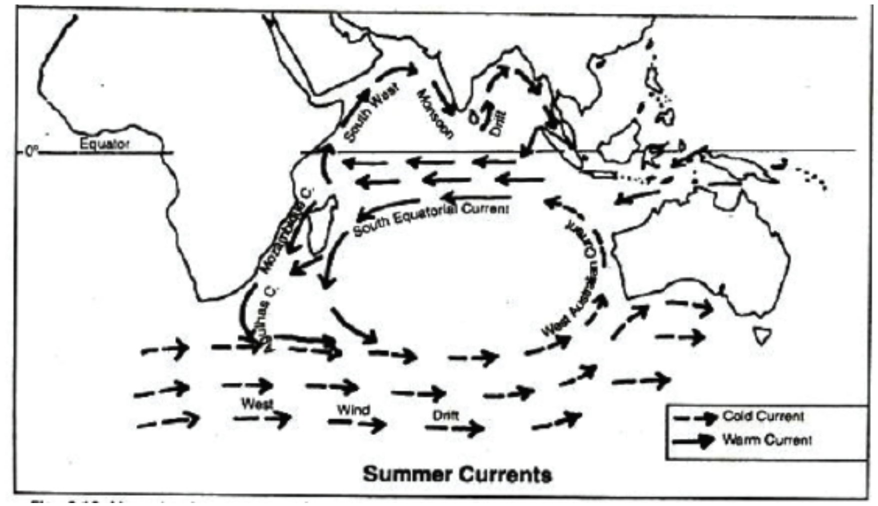
(b) Halley's depction of the monsoon annual cycle in the Indian Ocean

Alternating rows of vectors depicted the major summer and winter surface flow.

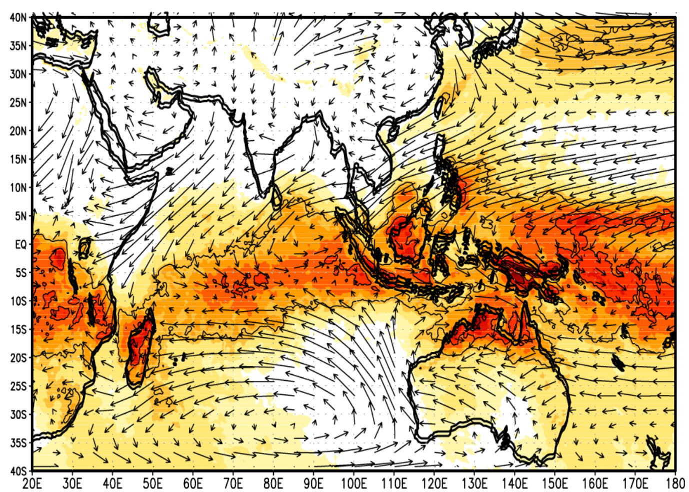
OCEAN AND ATMOPSPHERE: Precipitation, 925 hPa Winds and Ocean Currents



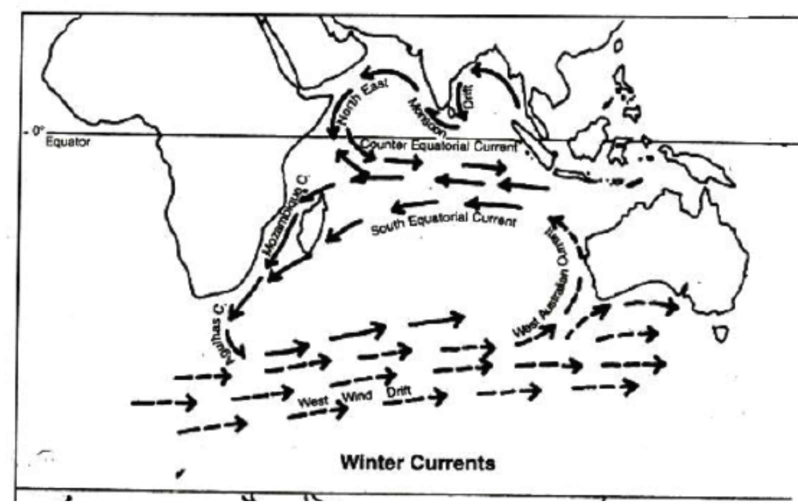
Summer ⟶ 15 ms-1



Summer

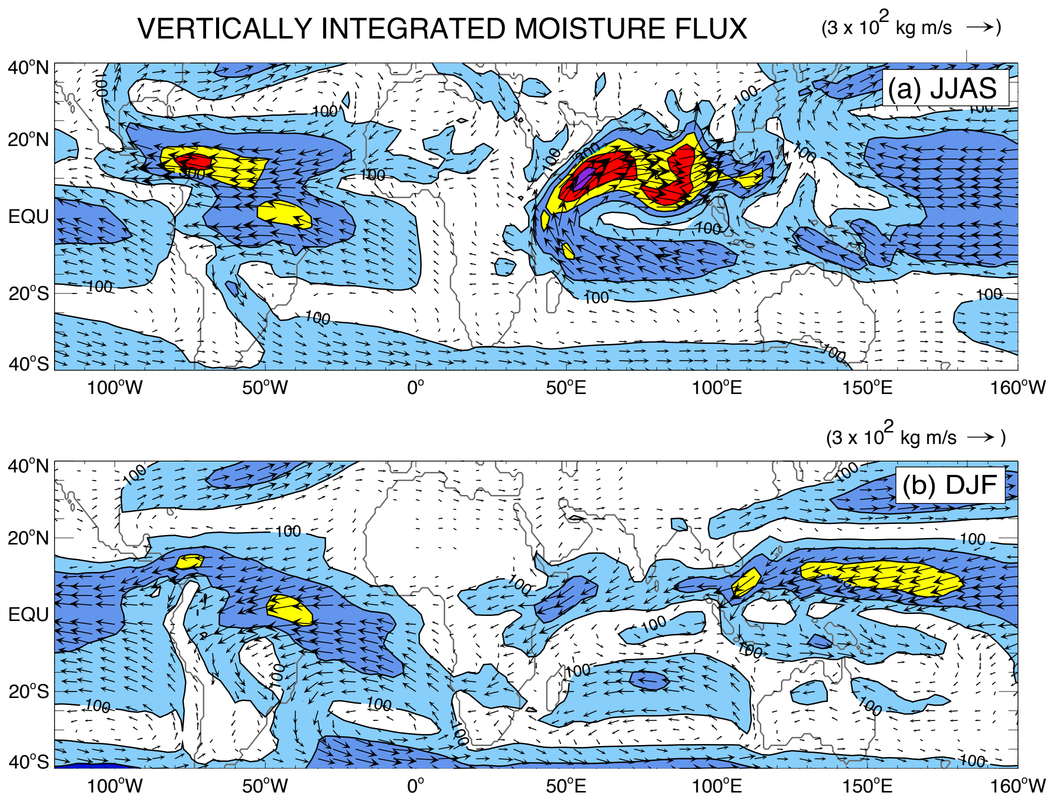


Winter

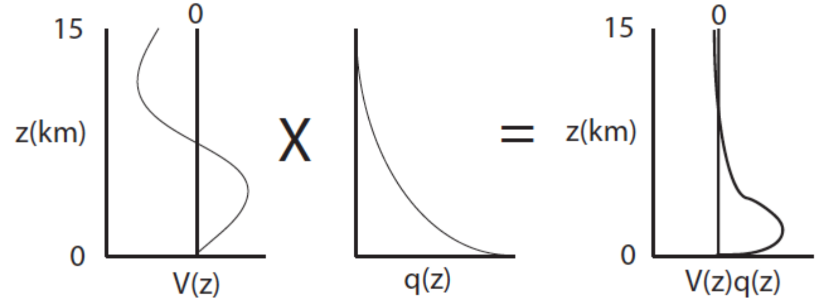


Winter

Asian Monsoon as a Vast Solar Collector: Moisture Transport



$$B_q = \int_0^\infty q(z)\tilde{V}\,dz$$

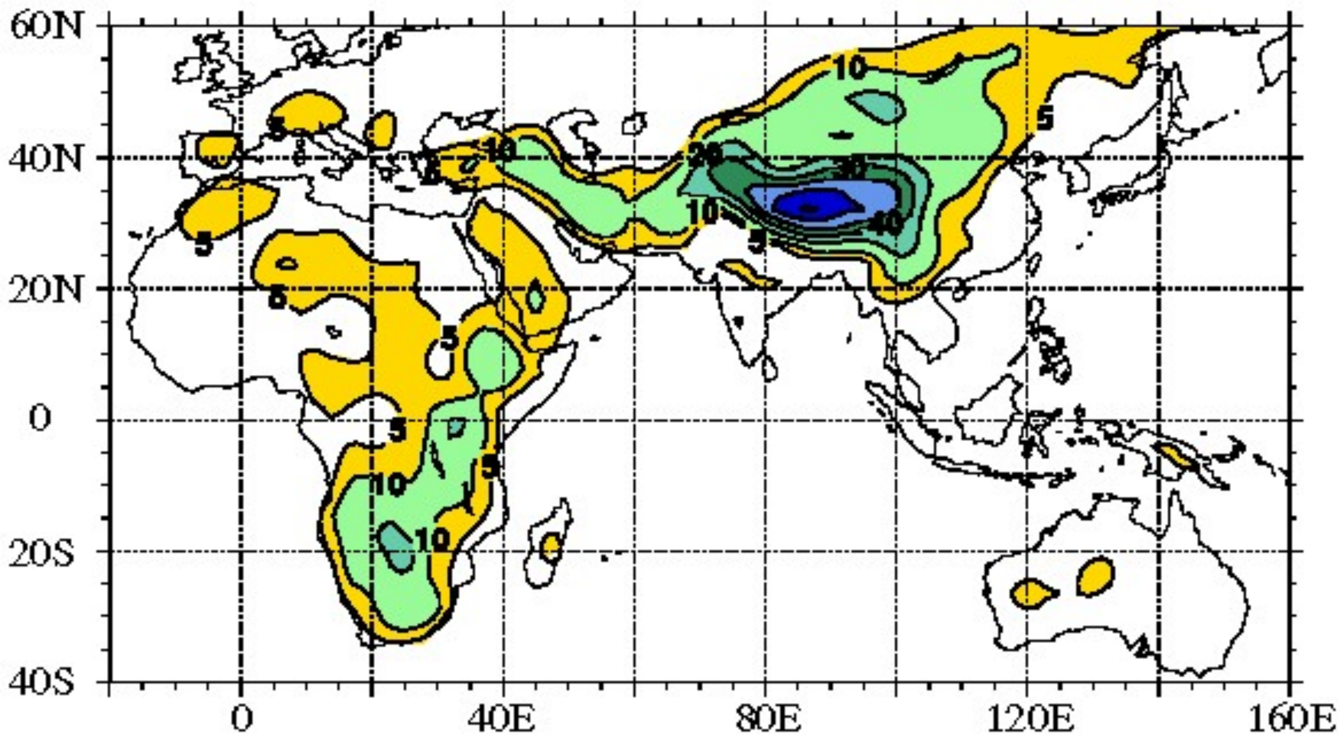


B_q is dominated by low level moisture and wind field

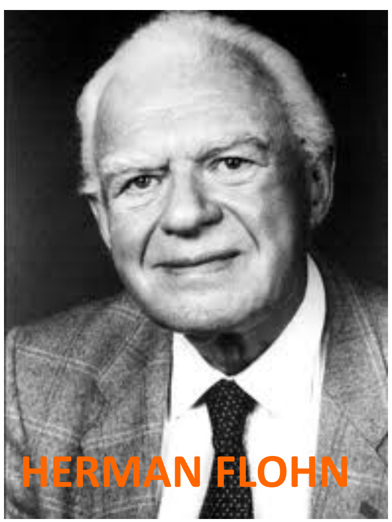
- Surface evaporation of flow over ocean by Halley's monsoon winds causes convergence of moisture.
- Major question why is moisture flux in North Indian Ocean so extraordinarily large compared to other regions?

Fasullo and Webster 2002

A Unique feature of South Asia is the Himalayan-Tibetan Plateau (HTP)



In essence, this is Halley plus where differential buoyancy is exaggerated by elevation.

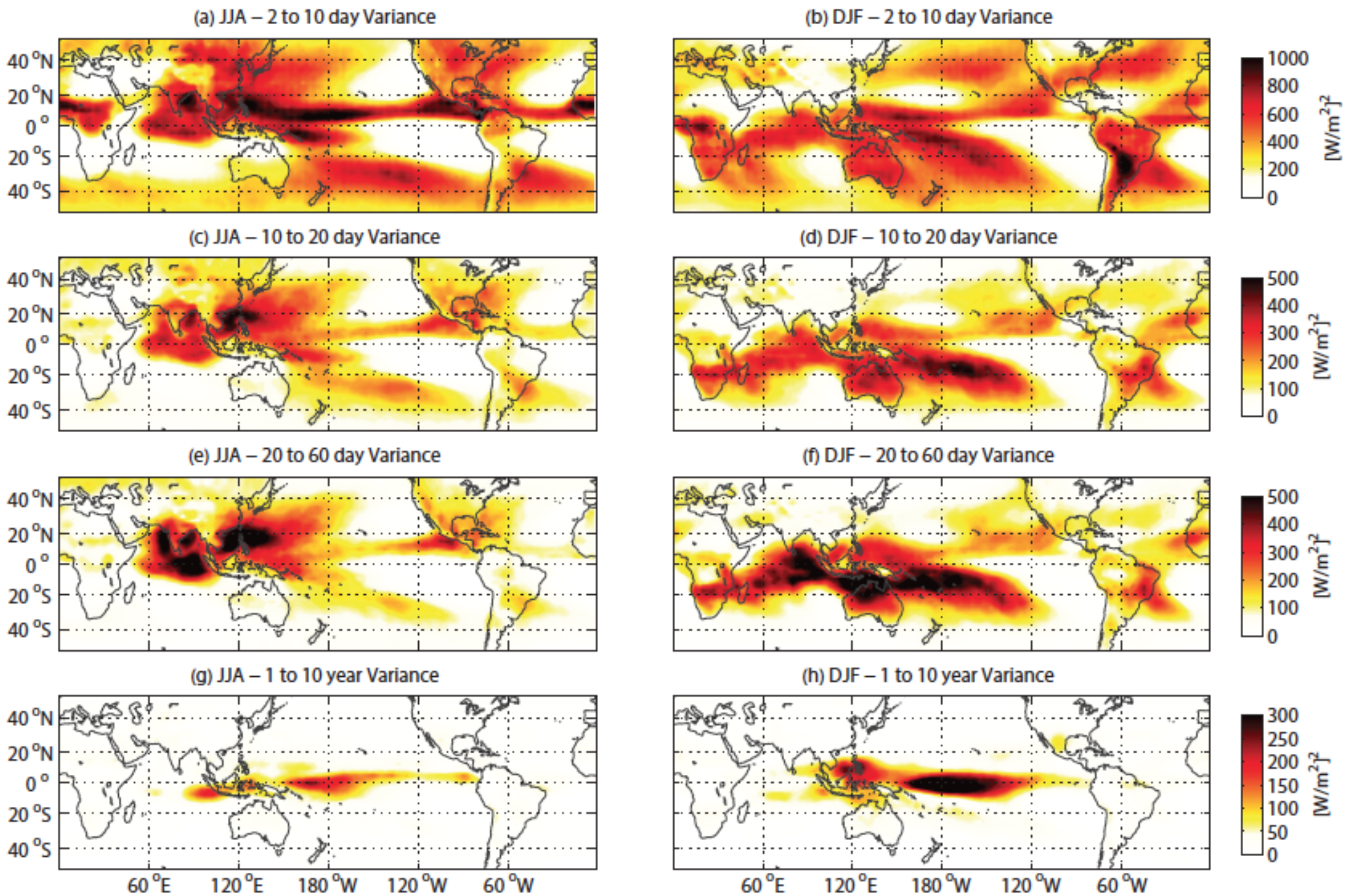


In a series of articles in the 1950s-70s, Prof. Herman Flohn argues that the anomalous strength of the Asian monsoon was the result the elevated heating of the HTP

(see recent review Wu, et al 2015, National Science Review)

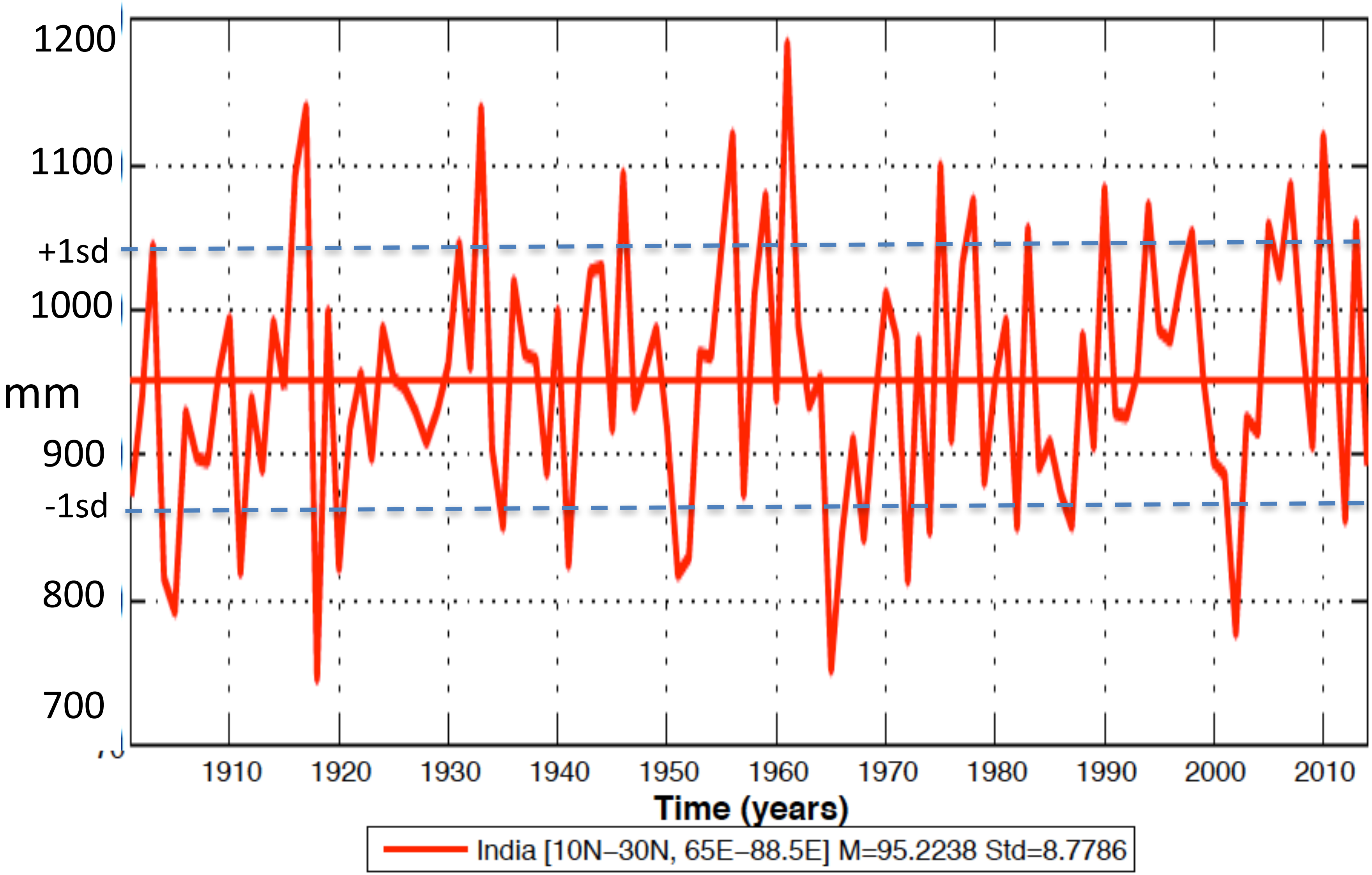
Variability of the Monsoon

Time Scales and Patterns of OLR Variability in the Tropics (Ortega et al. 2016)



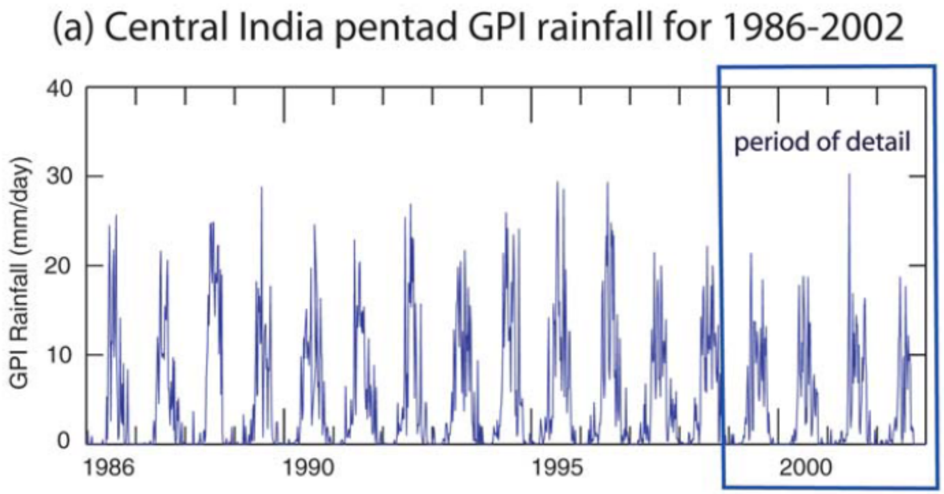
Note overlapping patterns of high variance. There appears to be strong relationships between the various variance bands.

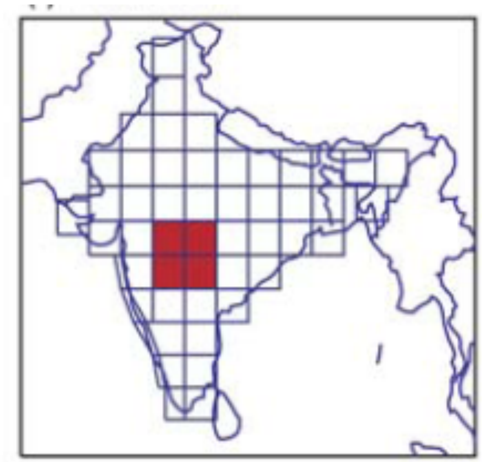
Interannual Variability of the Indian Monsoon

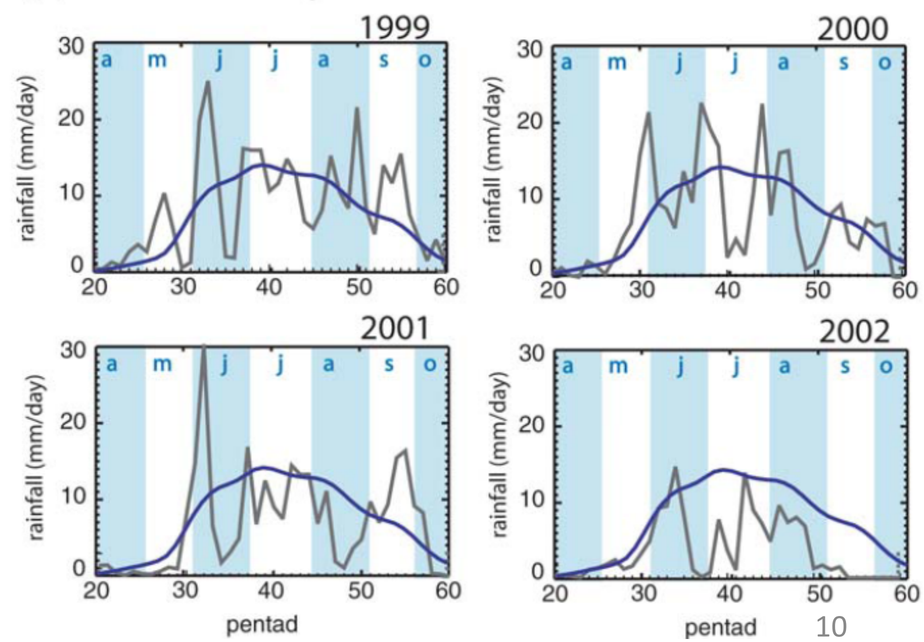


Note small Indian monsoon sd of 87 mm or < 10% of mean: Very small

Intraseasonal Variability of the Indian Monsoon (MISO)

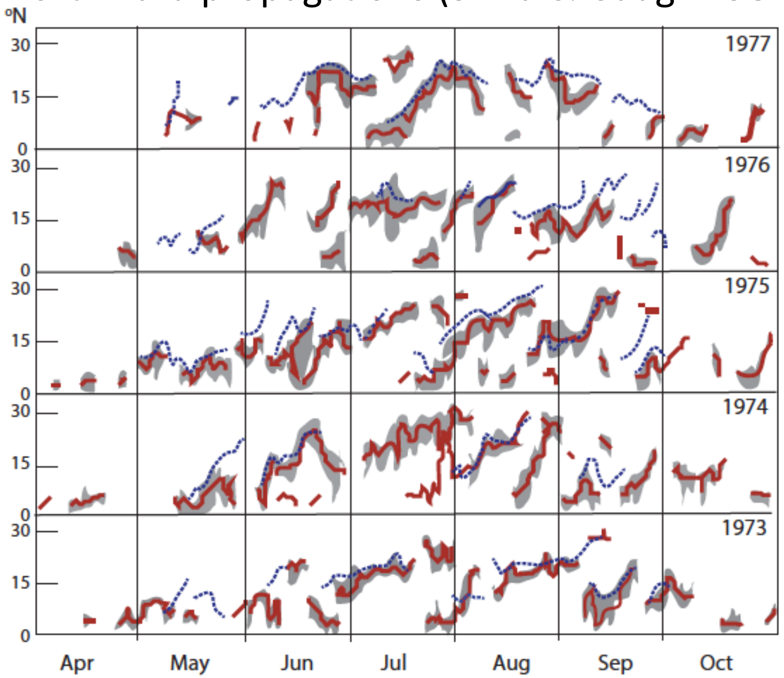


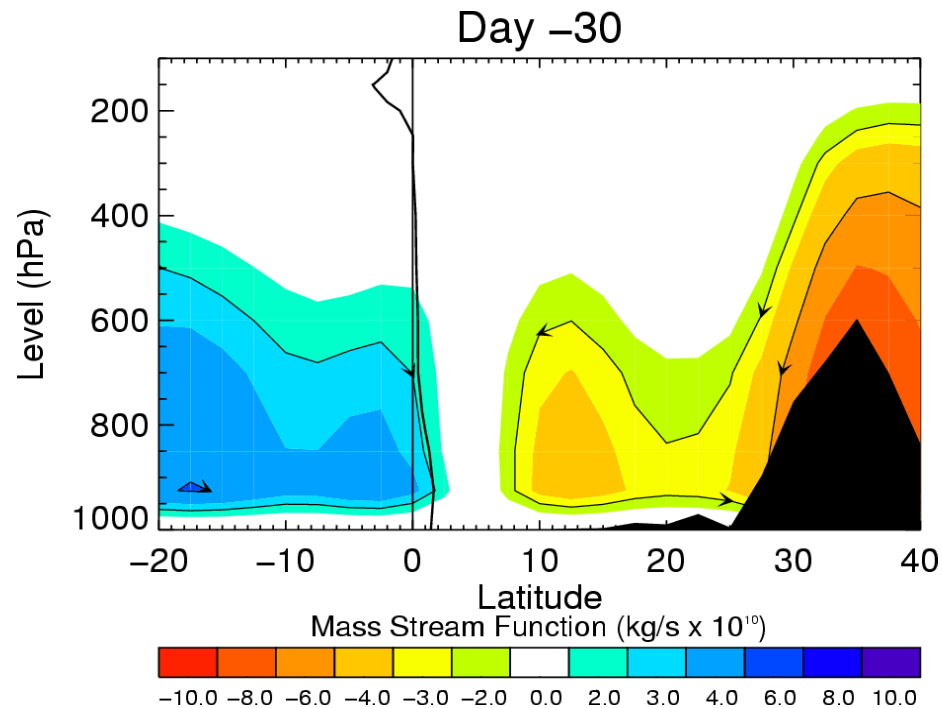




- Each summer, the rainfall is divided into periods of mini-droughts (“breaks” in the monsoon) and pluvial period (“active” monsoon).
- The timing of these oscillations is crucial for agriculture
- Alas, this is not an operational product in India although forecasting schemes do exist (e.g., Webster and Hoyos 2004)

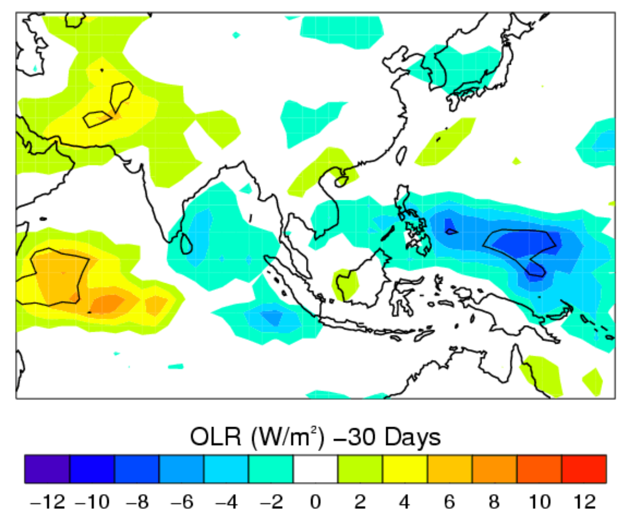
Northward propagations (Sikka & Gadgil 1981)



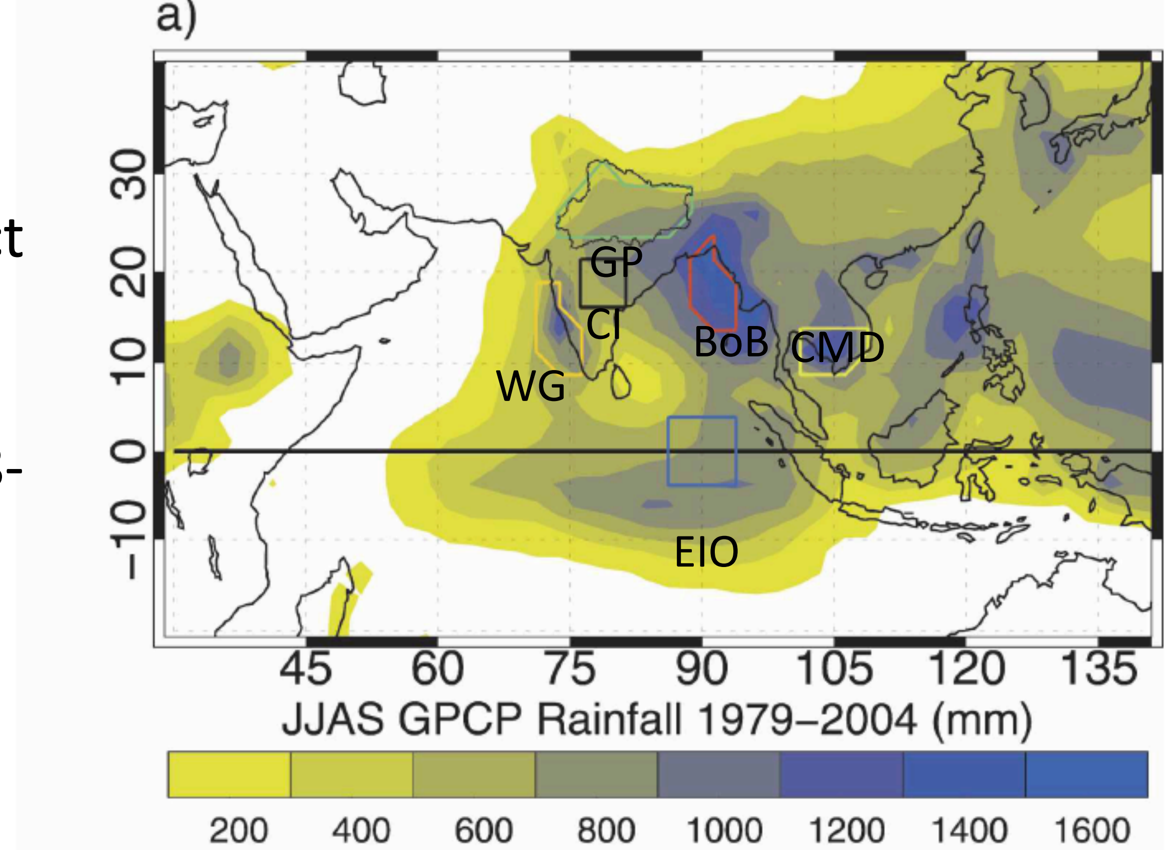


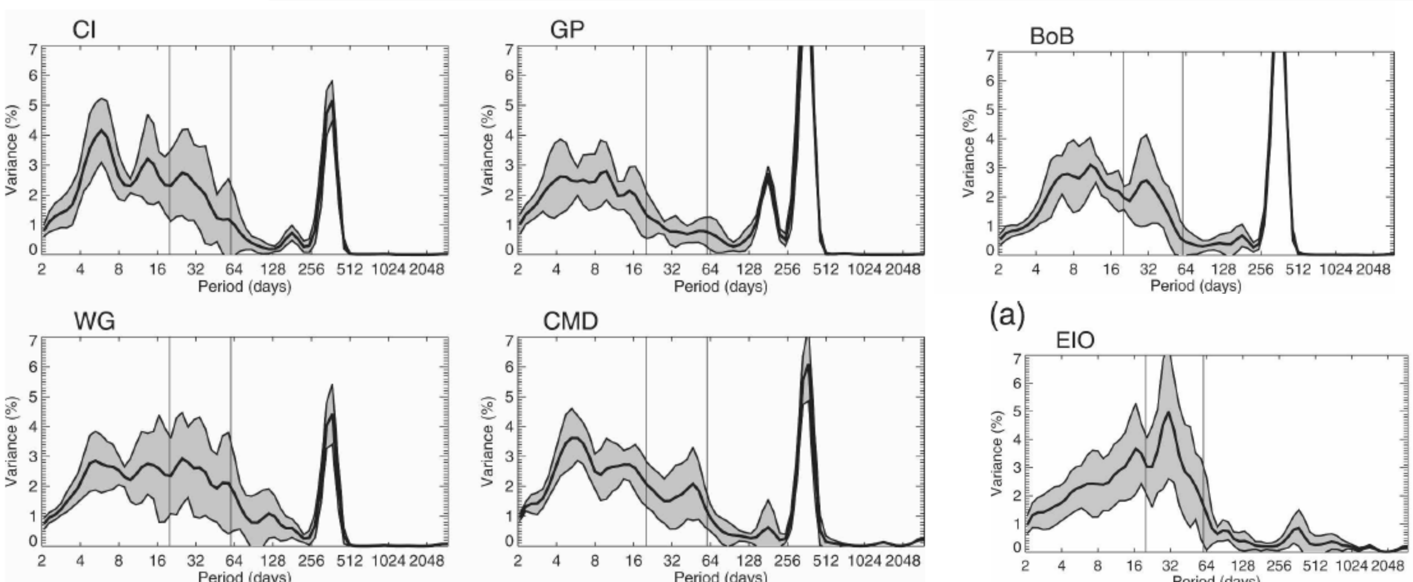
- Intraseasonal oscillations are principally northwardly propagating bands that extend well beyond the Asian region.

- They also have a distinctive ocean signal as we shall see later.



Rainfall in the monsoon has distinct periodicities with broad sub-seasonal bands (20-40 days, 8-14 days)



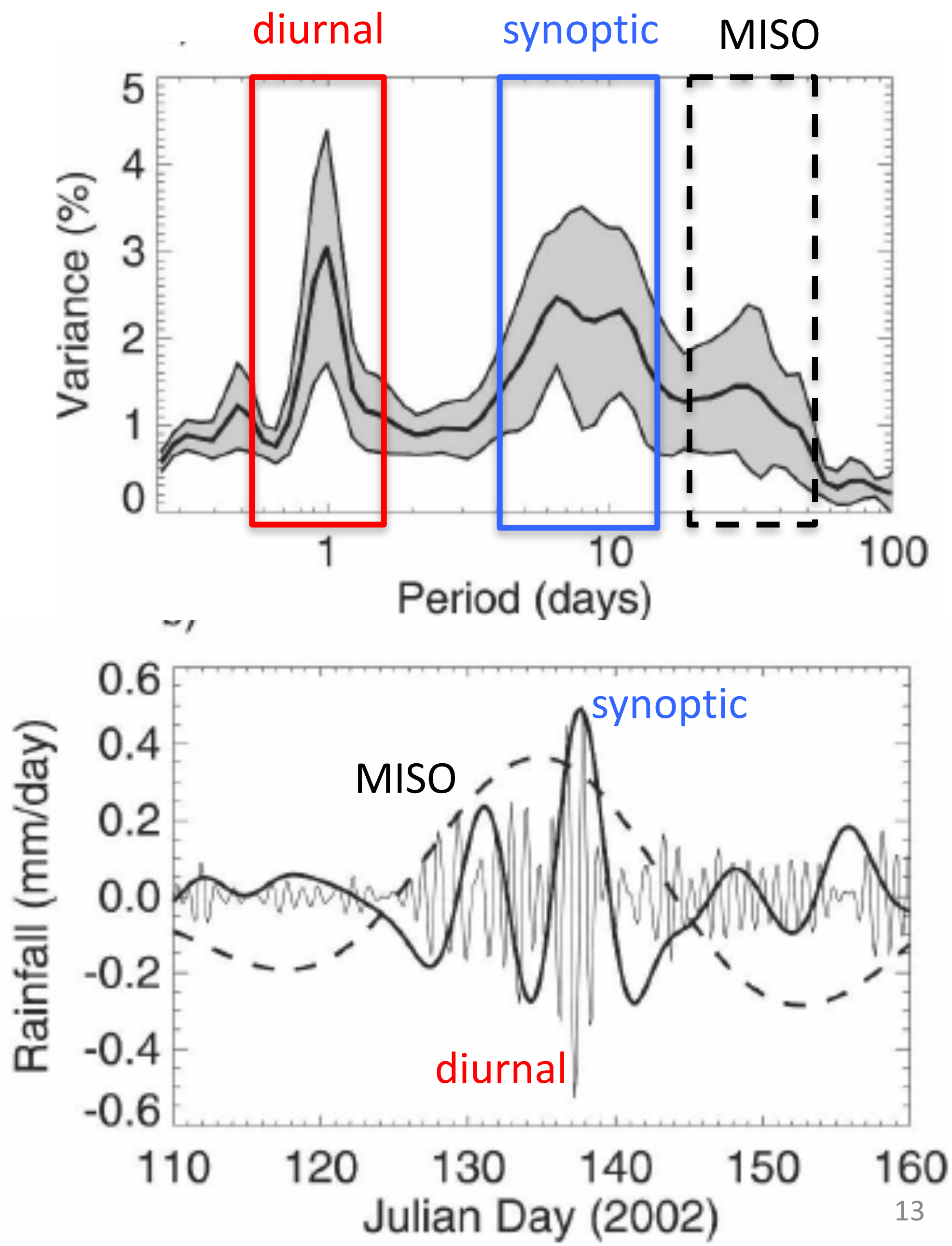


Modal Inter-dependence

Three major time scales of precipitation in monsoon system (upper panel):

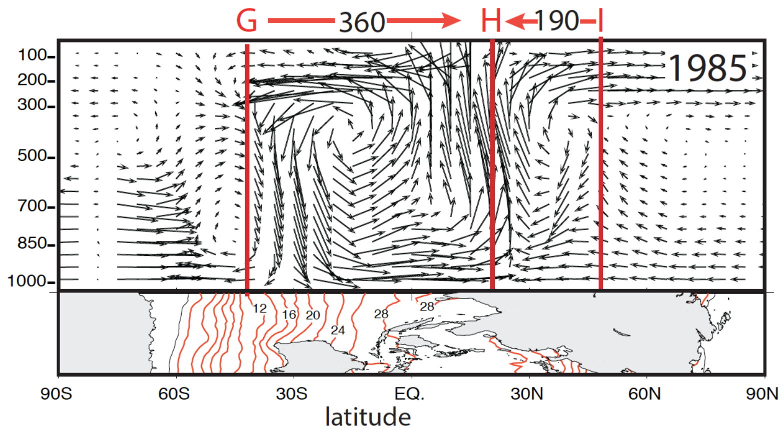
- Diurnal
- Synoptic (4-14 days) or quasi-biweekly
- Intraseasonal Oscillation (20-40 days).

These three phenomena are interrelated with their maximum convective phases occurring at the same time (lower panel).

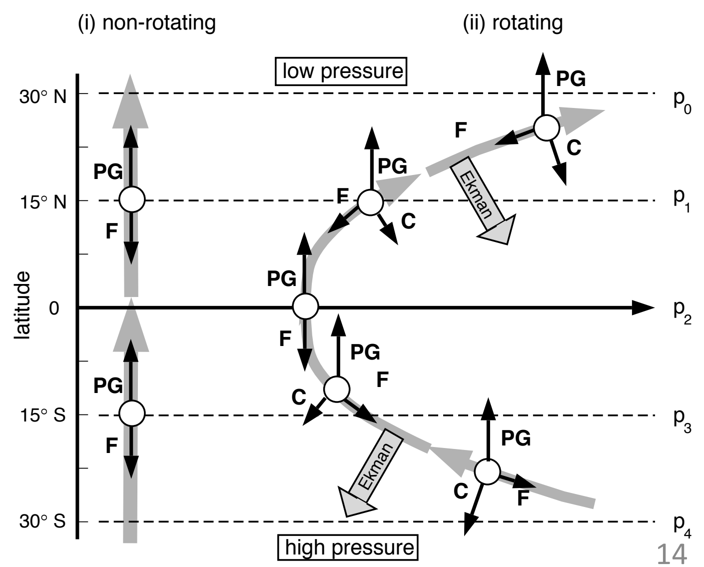


Cooperative Ocean-Atmosphere Dynamics and the Regulation of the Monsoon

Positive feedback:
Warm summer hemisphere SSTs and heating over land produce cross-equatorial pressure gradient that transports moisture from the winter to the summer hemisphere. Latent heat release exacerbates the latent heat over the heated land. Increased subsidence allows SST to rise Pressure gradient increases and etc.

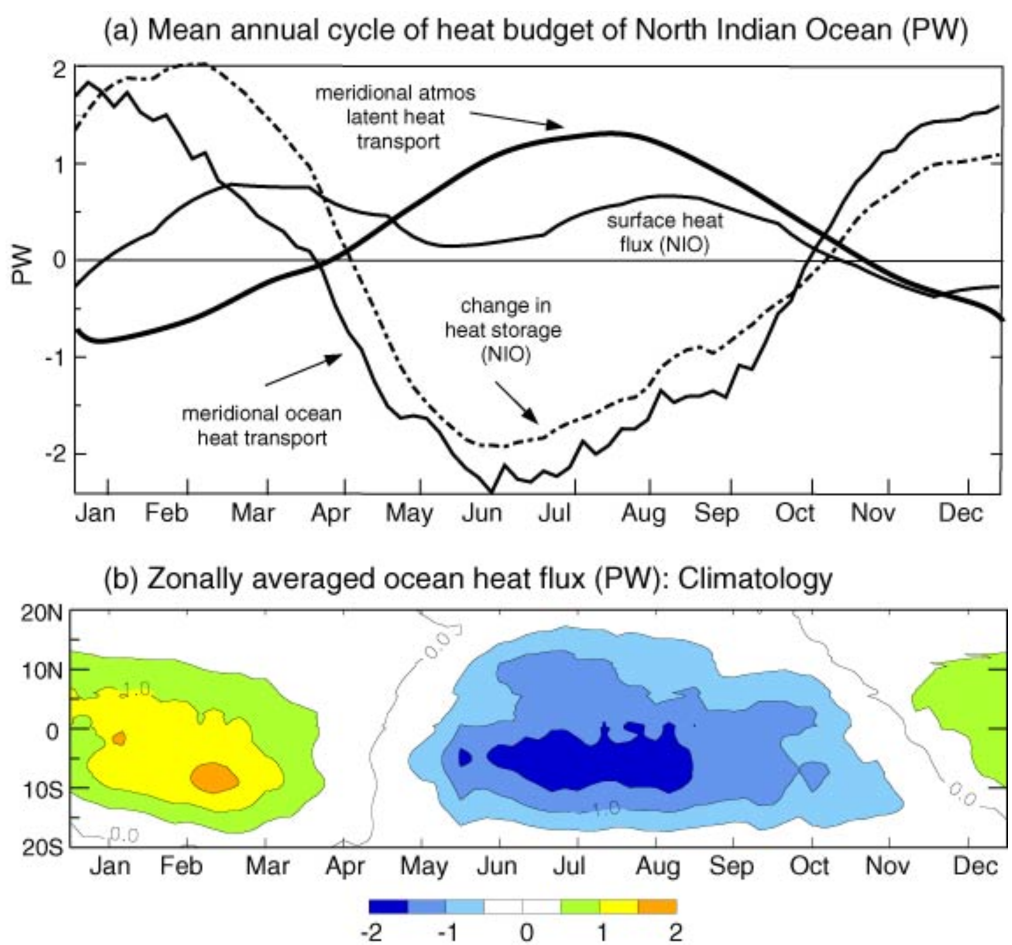


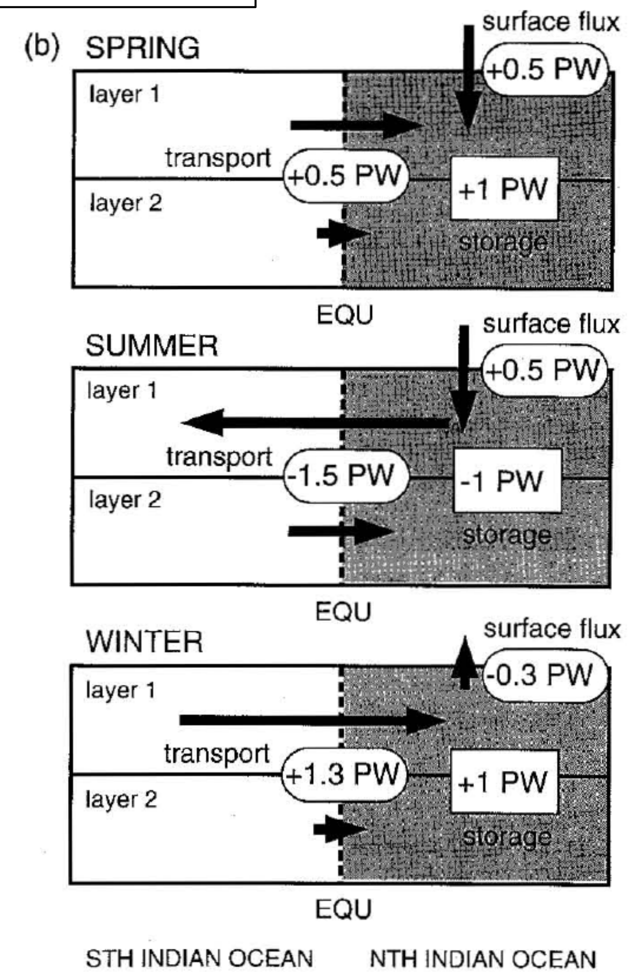
Negative feedback:
Near surface winds produce Ekman transport from the summer to the winter hemisphere, reducing the SST gradient and reduces the intensity of the monsoon.



In combination, these processes regulate the intensity of the monsoon on intraseasonal and interannual time scales, keeping its amplitude within rather narrow bounds

Negative & Positive Feedbacks: Interannual time scales



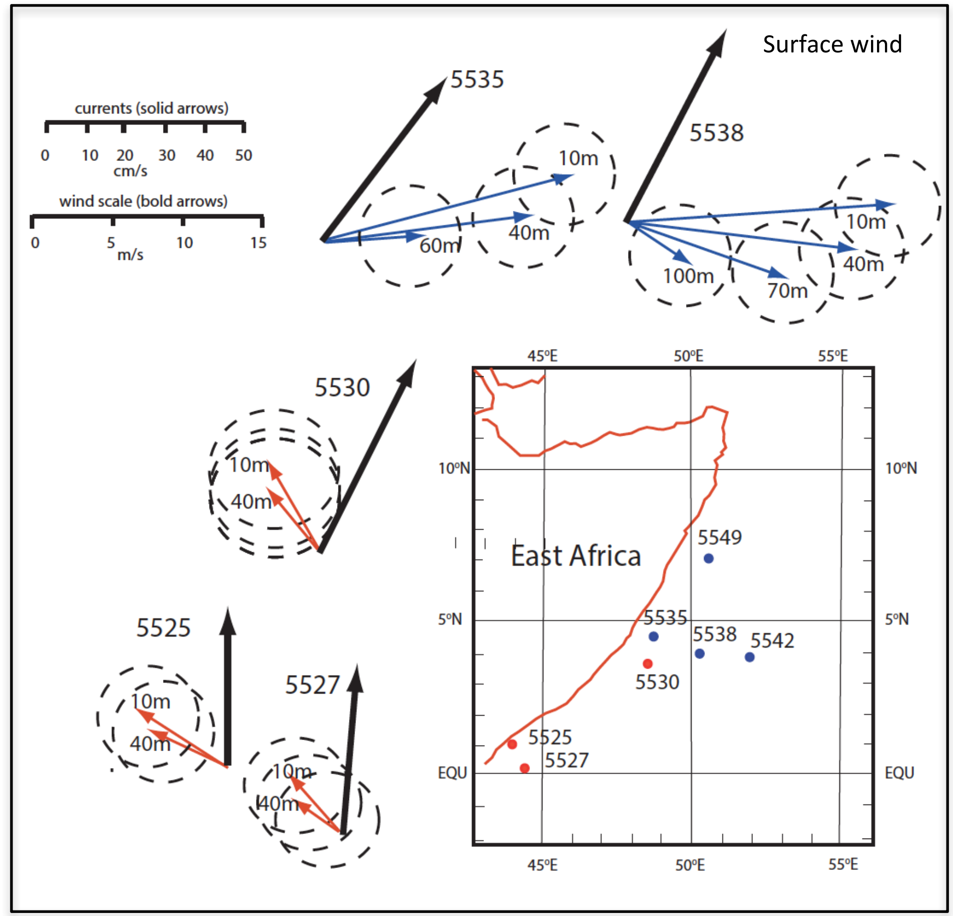


- Note that surface wind strength and counter Ekman transport depend on strength of the monsoon.
- Note meridional atmospheric heat transport depends on strength of the monsoon.
- Meridional ocean heat transport almost counters meridional latent heat flux

Loschnigg & W, 2000, Chirokova and W 2010.

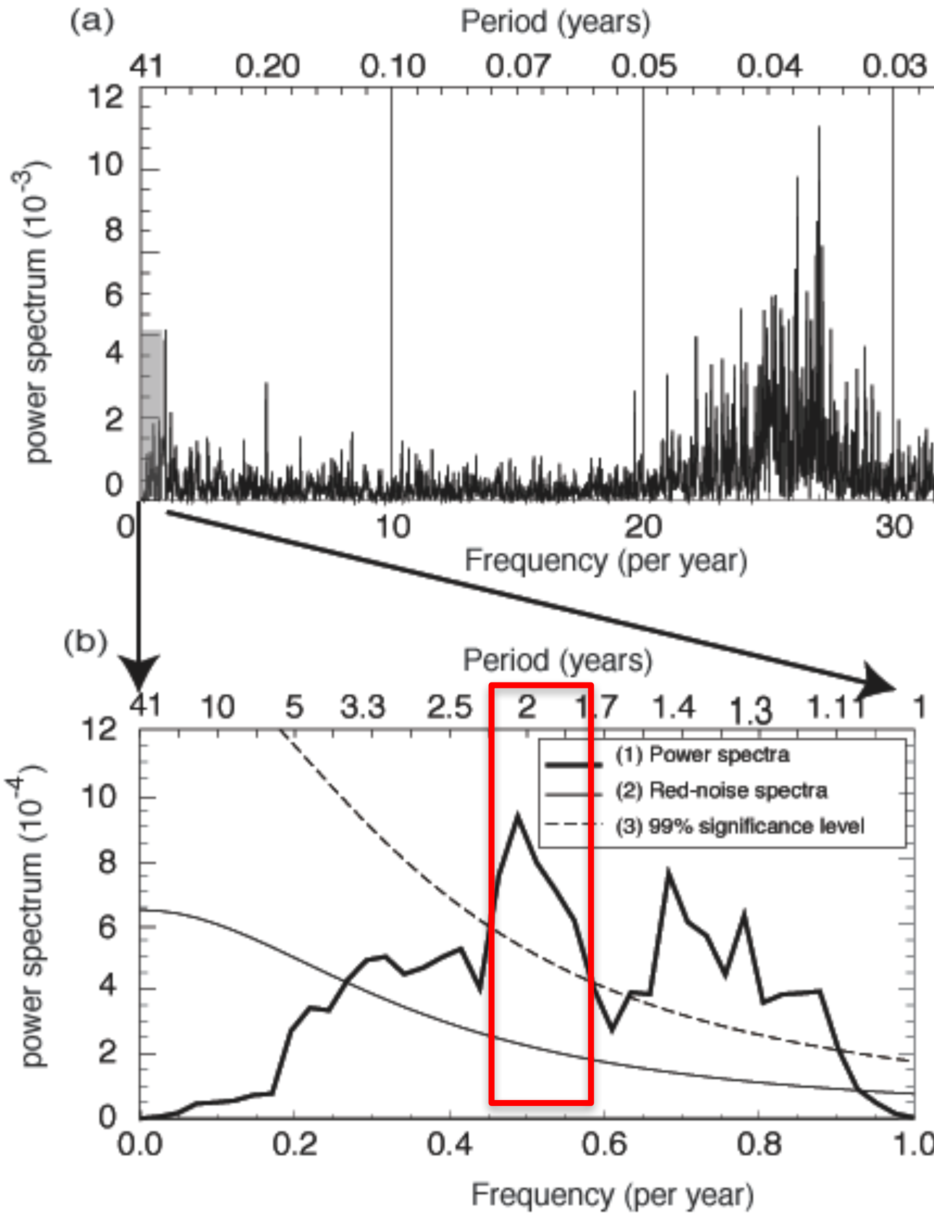
Oceanic Cross-equatorial Ekman Transports

- It may seem counter-intuitive that wind-driven Ekman transports are responsible for the counter oceanic heat flux.
- Ekman drift goes as τ^x/f so there should be a singularity at the equator.
- Miyama et al. (2003) have shown this not to be the case and that singularity is removable!
- Also, the spin up/down time scale goes as $1/f$ so that a SH profile will be advected across the equator. This is shown in the figure on right.



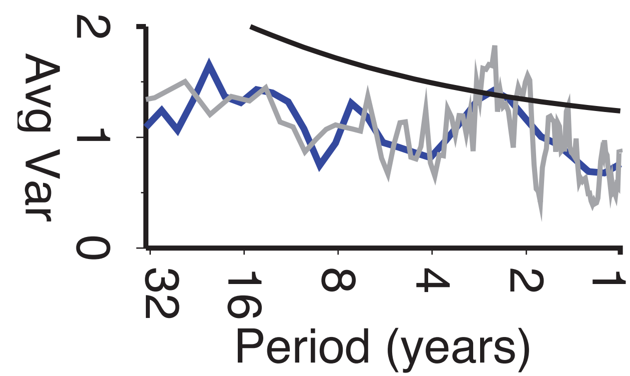
Boundary layer current profiles across the equator using data collected by Swallow & Bruce (1966). Blue vectors have NH signature. Red vectors SH.

Spectra of the cross-equatorial flux of heat



- Cross-equatorial ocean flux of heat has a strong biennial peak
- This peak (both found in observations and models) is a sign of the variability of the monsoon within rather narrow bounds

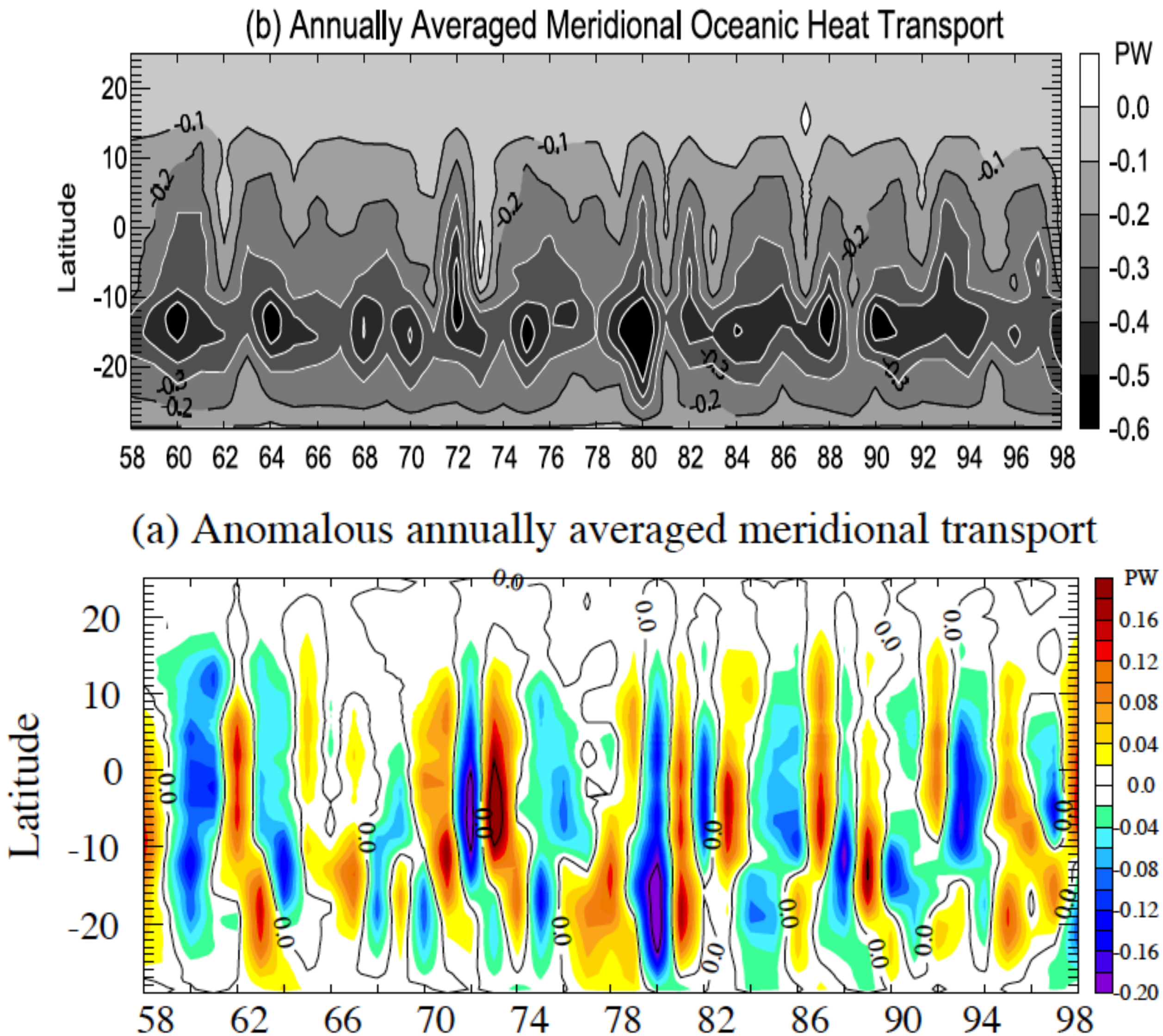
Monsoon rainfall spectra



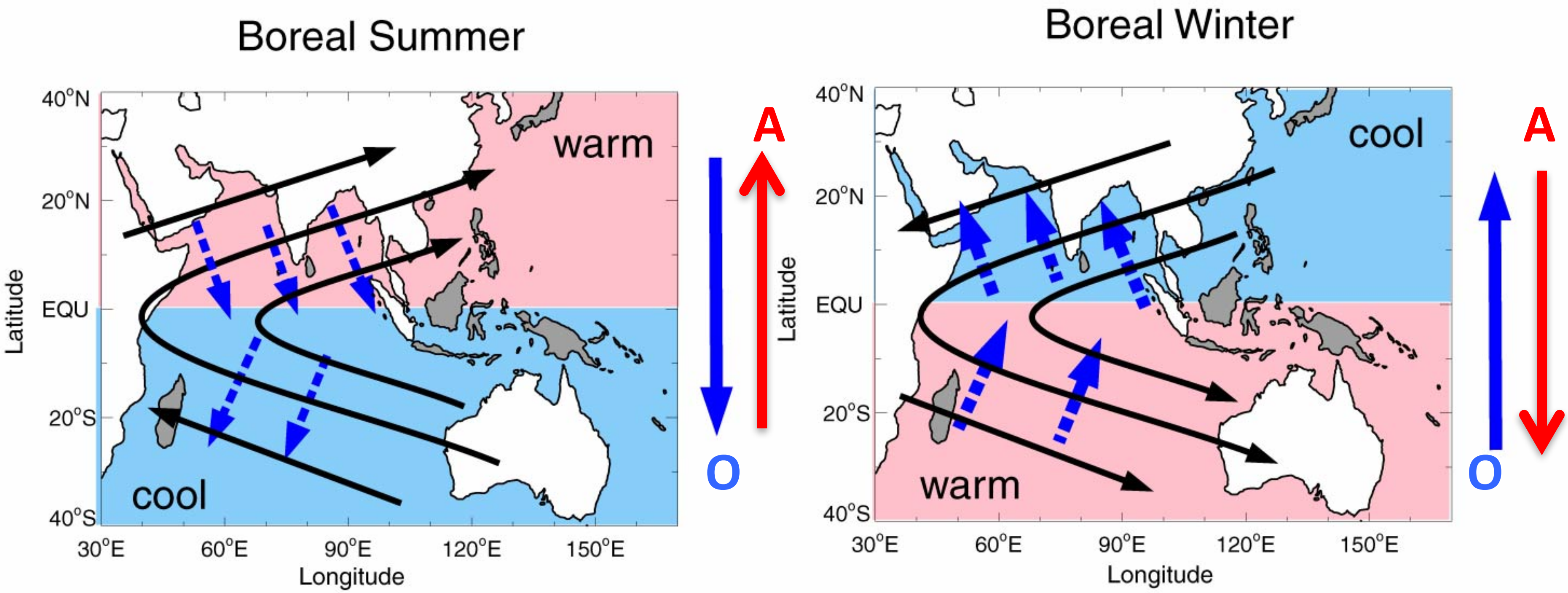
Loschnigg and Webster (2002)
Chirokova and Webster (2010)

Annually Averaged and Anomalous Oceanic Heat Transports fn(latitude)

- Total annually averaged heat flux as a function of latitude. Long term average is negative with values of 0 to -0.6 PW
- Subtracting out long-term annual average heat flux.
- Note that anomalies are about 20-30% of annual average, show strong bienniality and that the signals are coherent between 20°N and 20°S



Regulation of the monsoon annual cycle



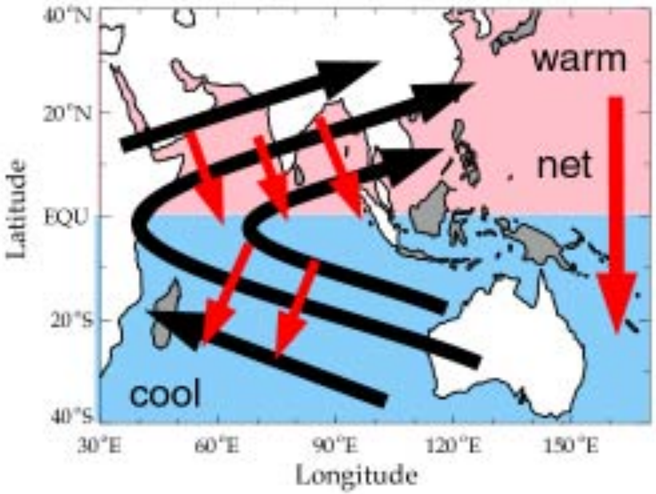
Southward ocean heat transport of 1.5 PW
(cools NIO while warming SIO)

Northward ocean heat transport of 1.5 PW
(cools SIO while warming NIO)

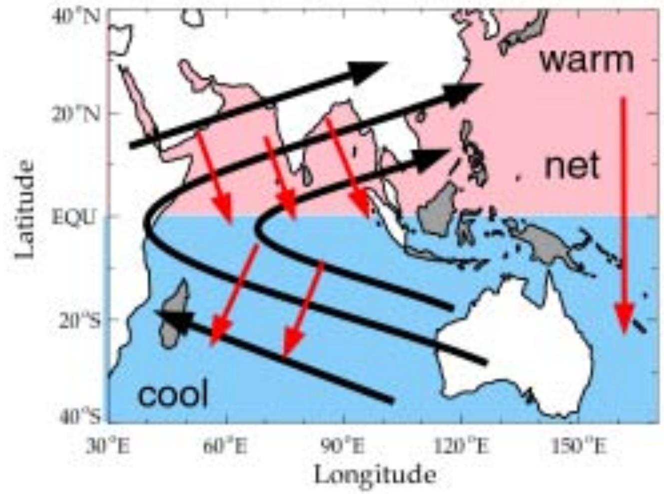
Overall impact of wind-driven Ekman ocean heat transport is to cool the summer hemisphere and warm the winter hemisphere thus reducing the cross-equatorial SST gradient and minimizing seasonal extremes in the monsoon

MODULATION OF INTERANNUAL VARIABILITY IN THE MONSOON

STRONG MONSOON



WEAK MONSOON



Strong monsoon:
- strong winds
- strong Ekman transport
- large southward transport
- cool North Indian Ocean

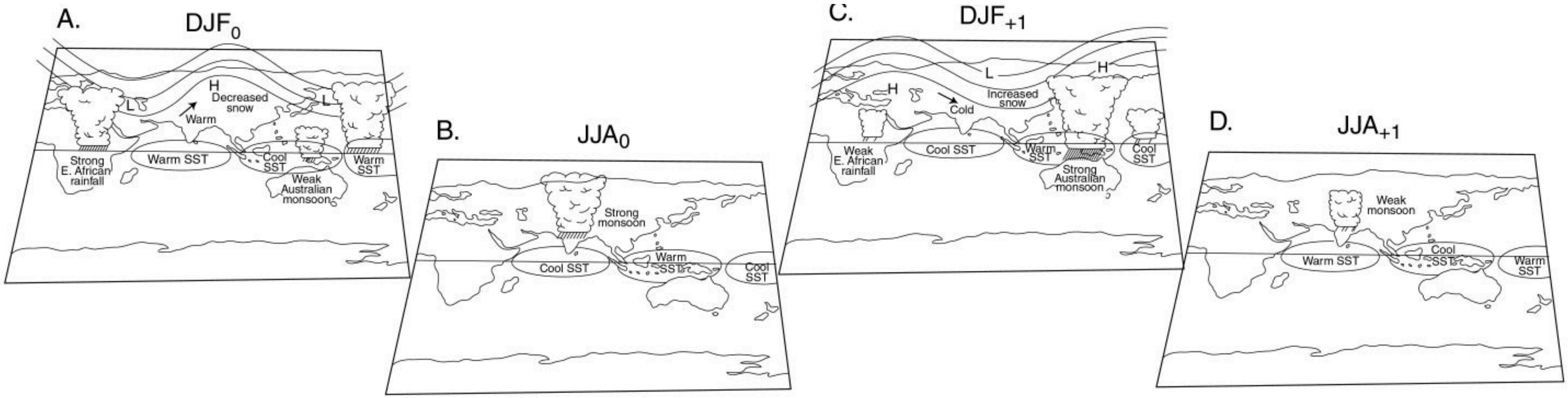
Weak monsoon:
- weak winds
- weak Ekman transport
- weak southward transport
- warm Northern Indian Ocean

Tendency to produce anomaous monsoon of opposite sign the following year.

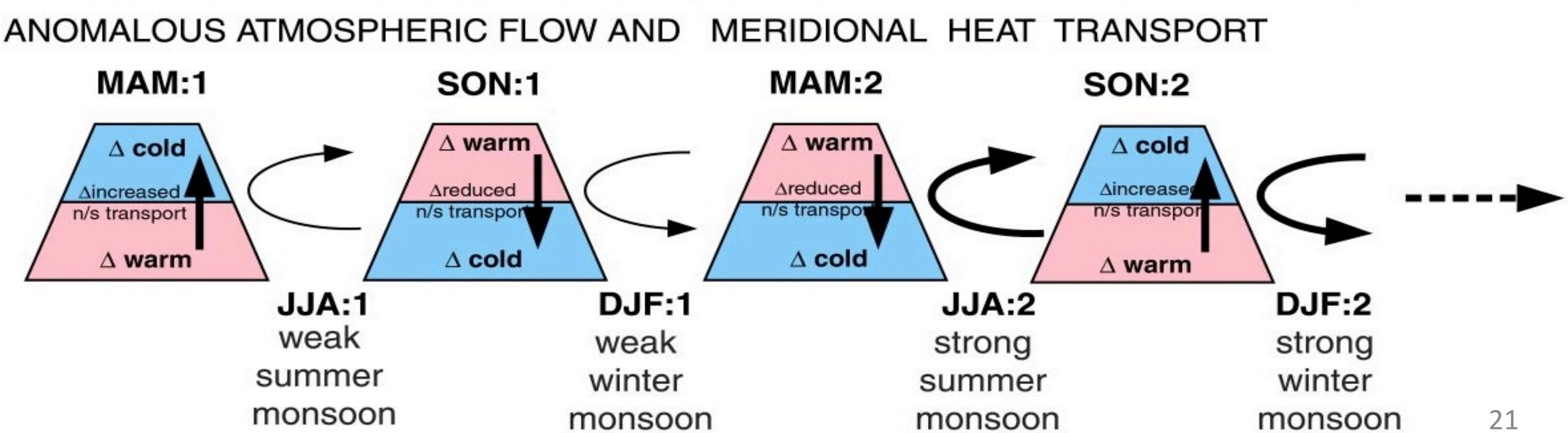
Bienniality produced into monsoon system

Biennial Regulation of the South Asian Monsoon

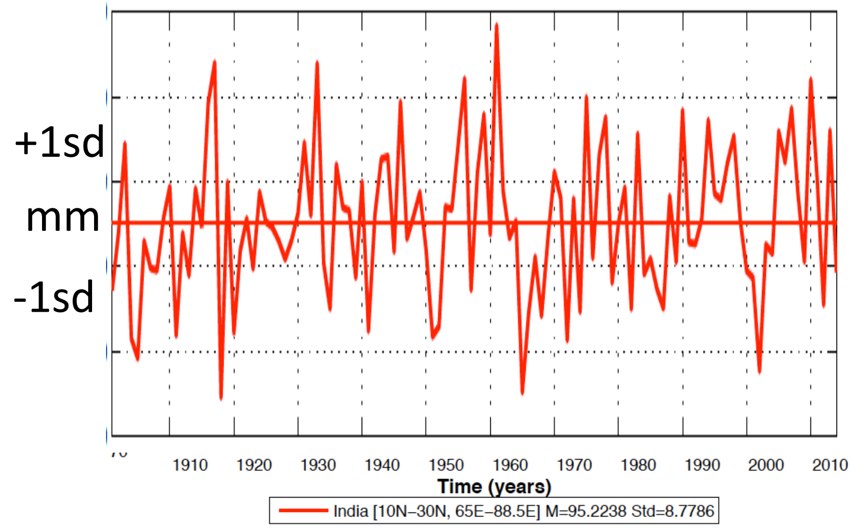
(a) Biennial regulation with local mixing (Meehl 1994, 1997)



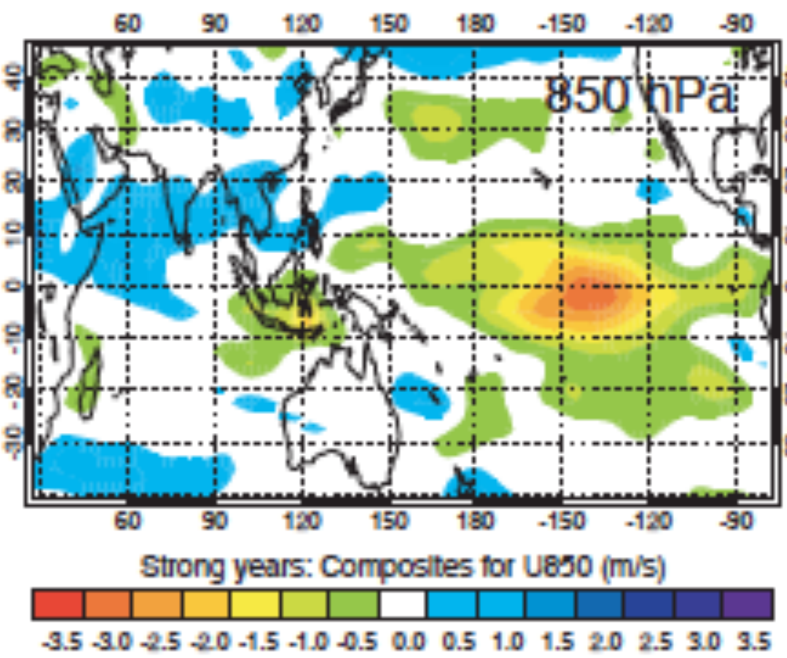
(b) Biennial regulation with ocean transport (Webster et al 2002)



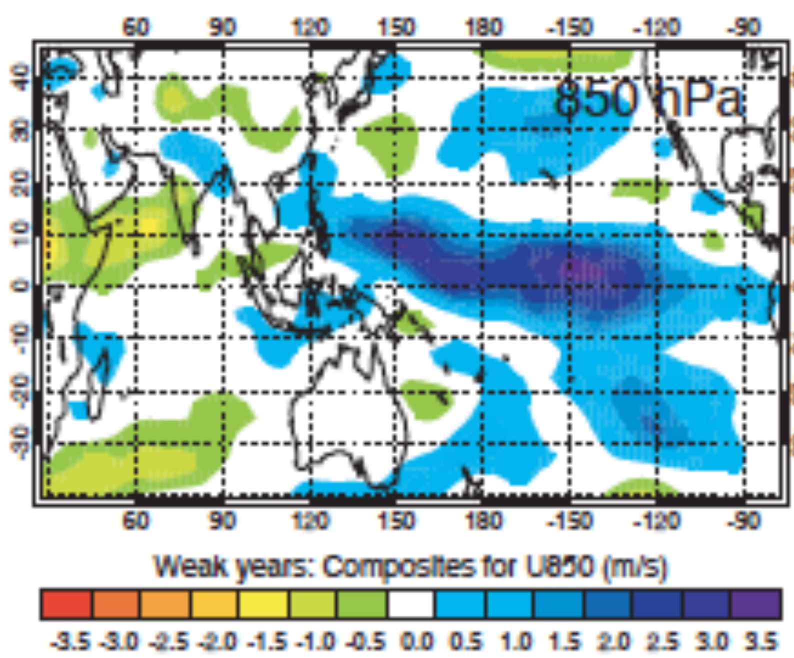
Anomalous lower tropospheric wind fields associate with strong/weak monsoons defined by +/-1 sd precipitation



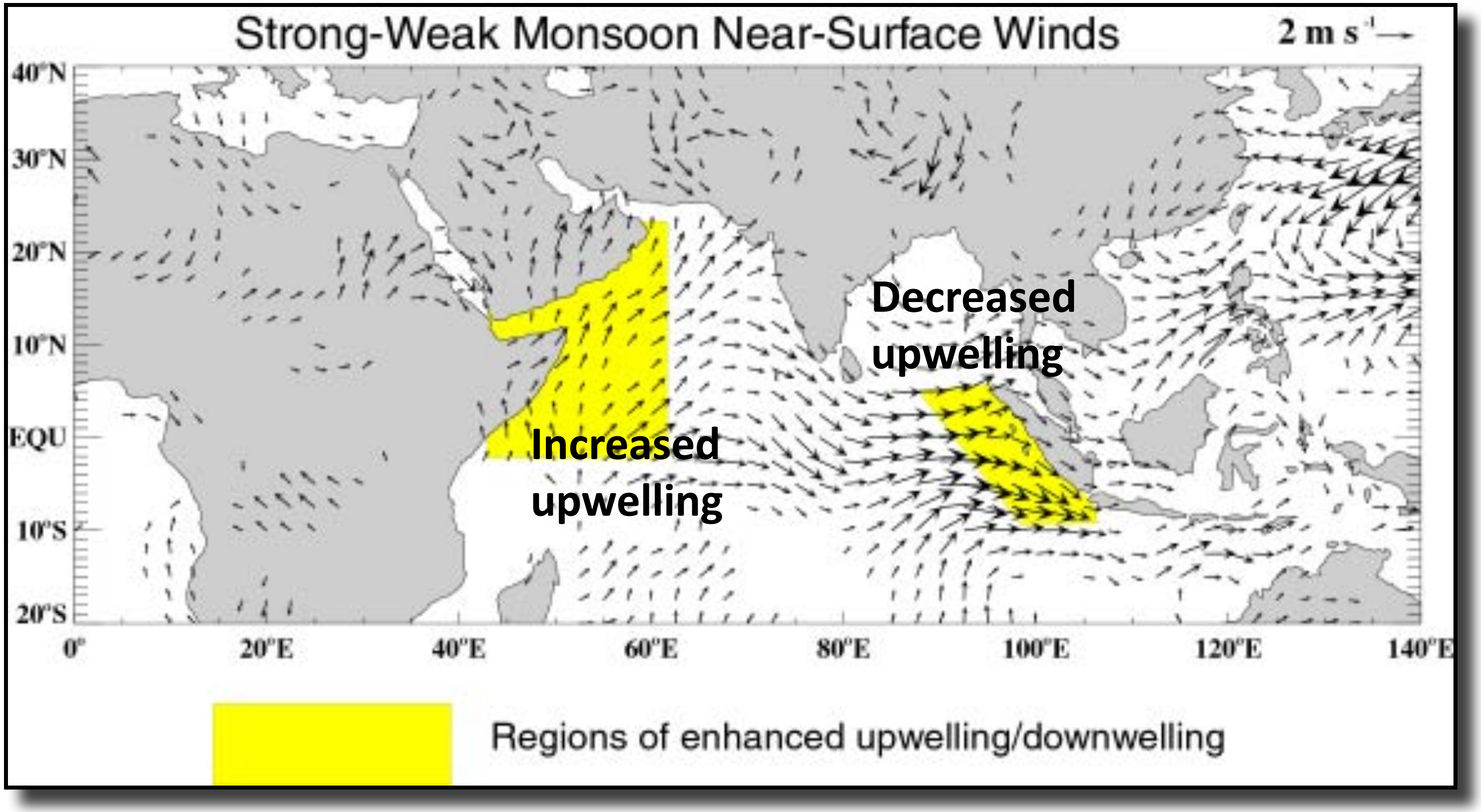
(i) Strong 850 hPa U-field



(ii) Weak 850 hPa U-field



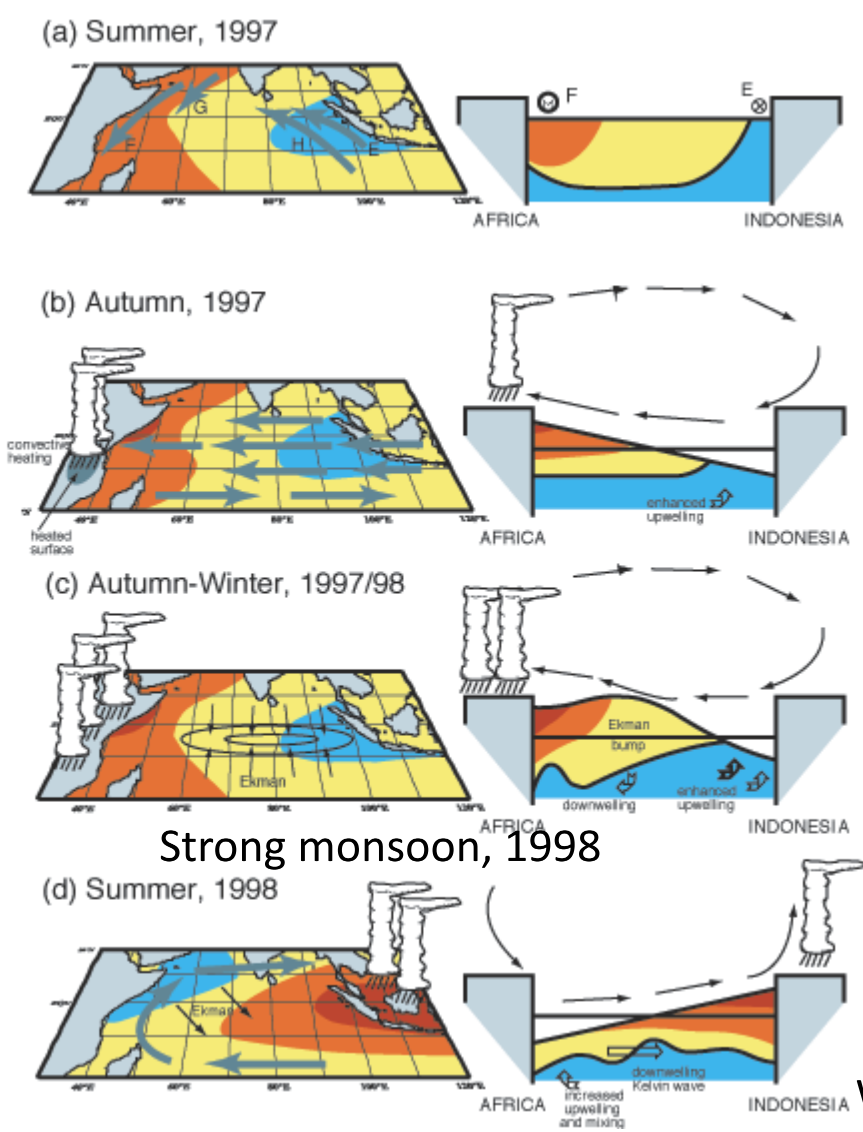
Anomalous Near-surface Winds and Up/Downwelling



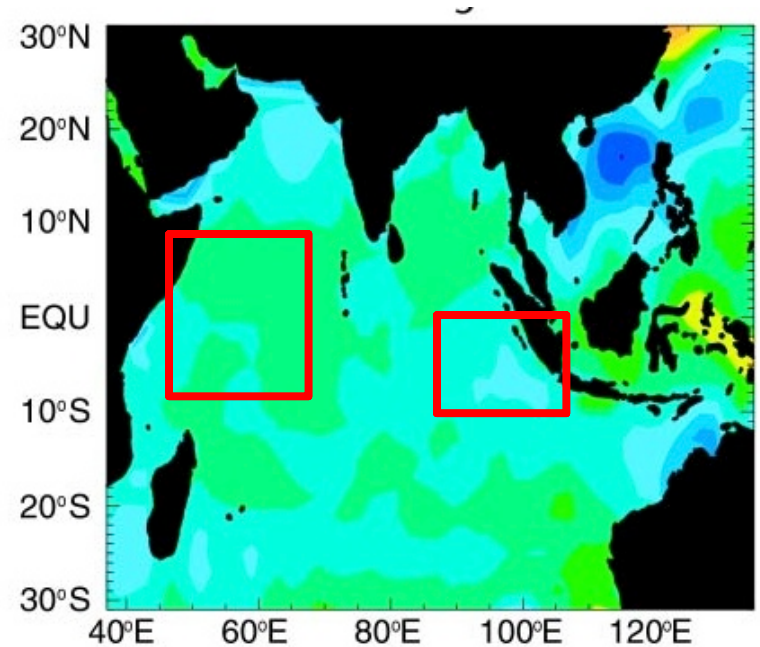
- When the monsoon is strong, enhanced upwelling (cooling) in west, downwelling (warming) in east.
- Setting up dipole structure (Indian Ocean Dipole) and explains its biennial time scale and its phase-locking with annual cycle..

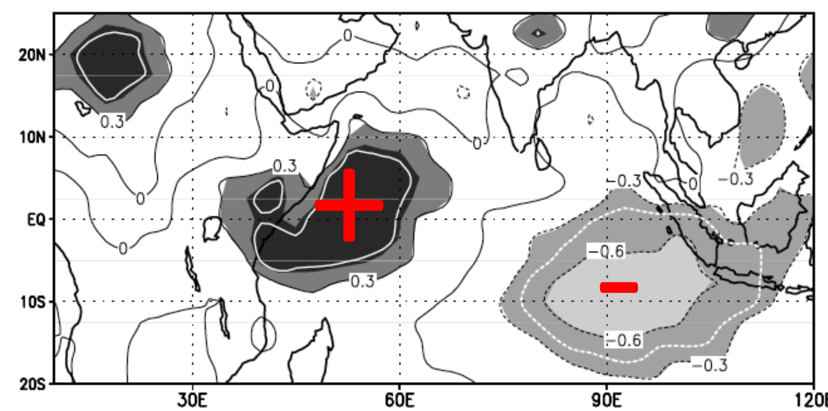
Generation of the Indian Ocean Dipole (differential upwelling + feedbacks)

Weak monsoon, 1997



Strong monsoon, 1998

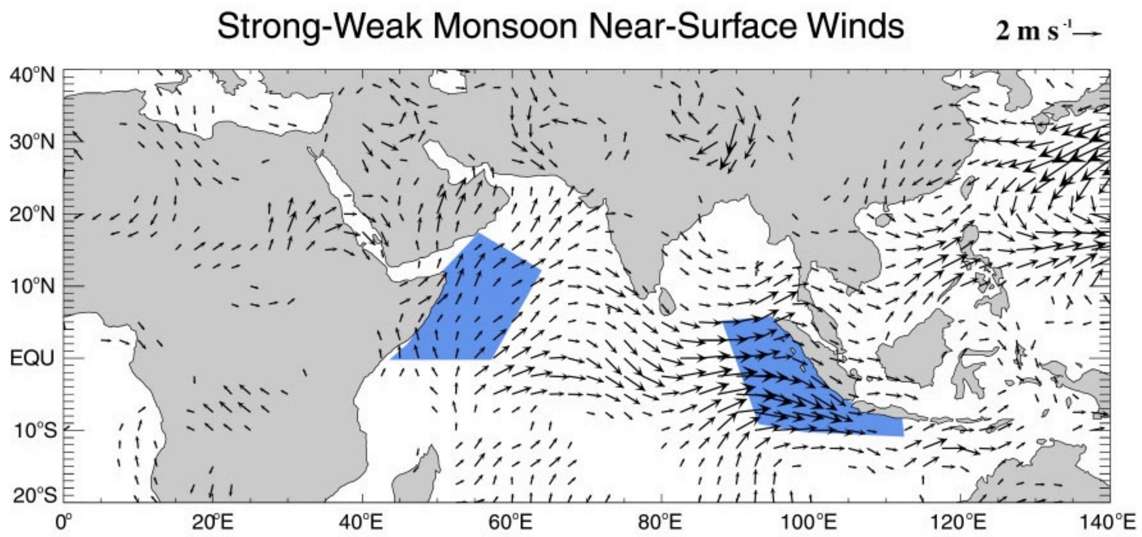




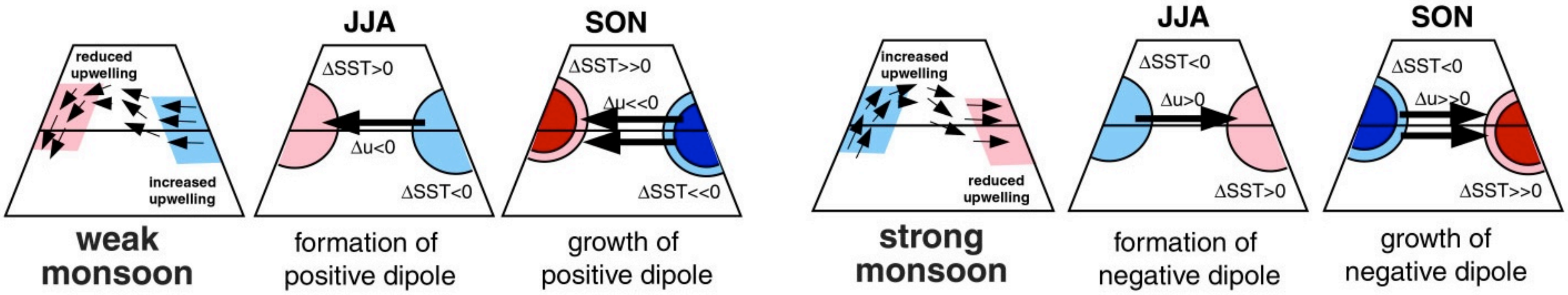
Pfrecipitation anomaly (Saji et al,1999)

Webster et al. (1999) Saji et al (1999)

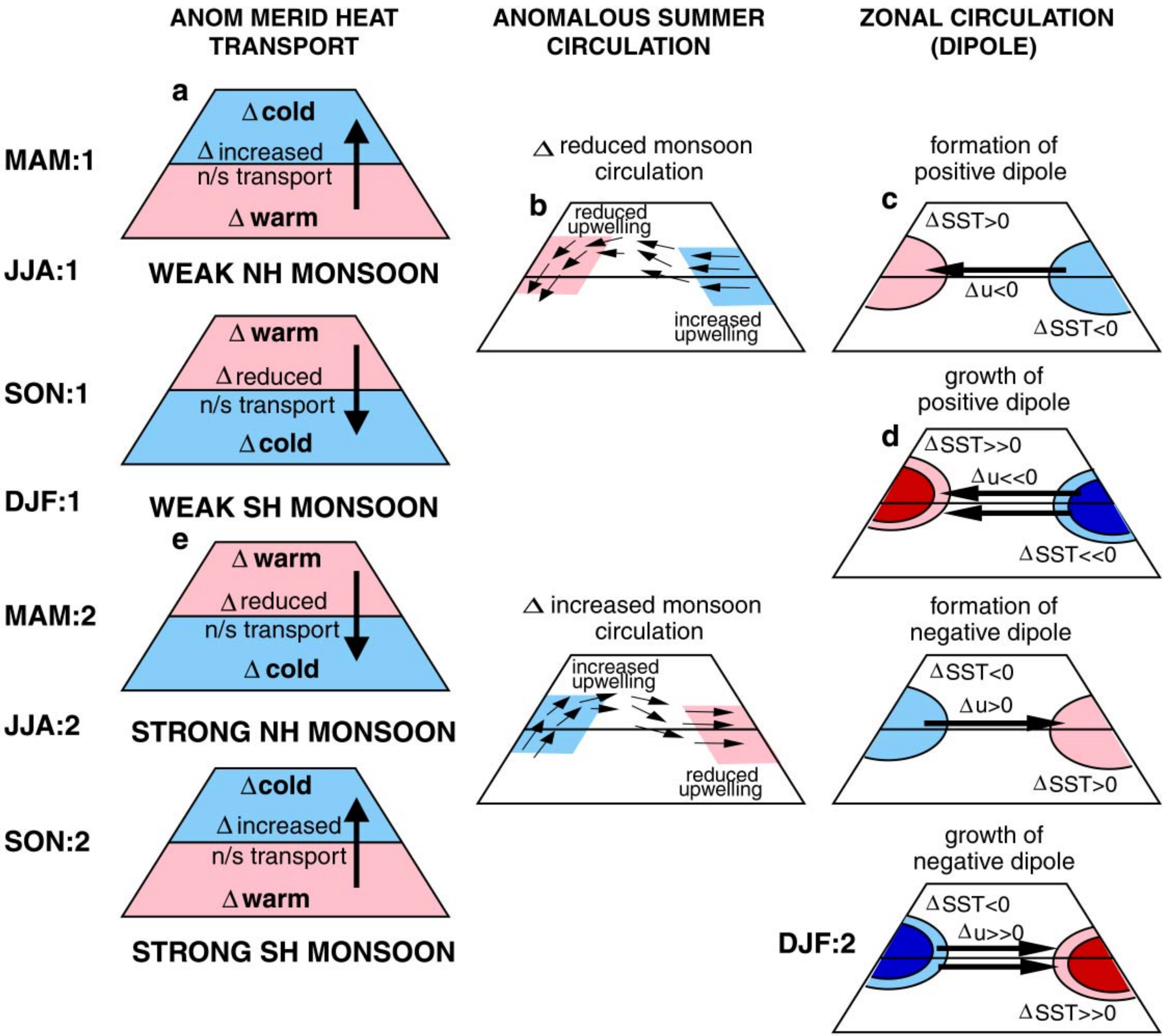
Dipole is set up by enhanced/decreased monsoon strength.



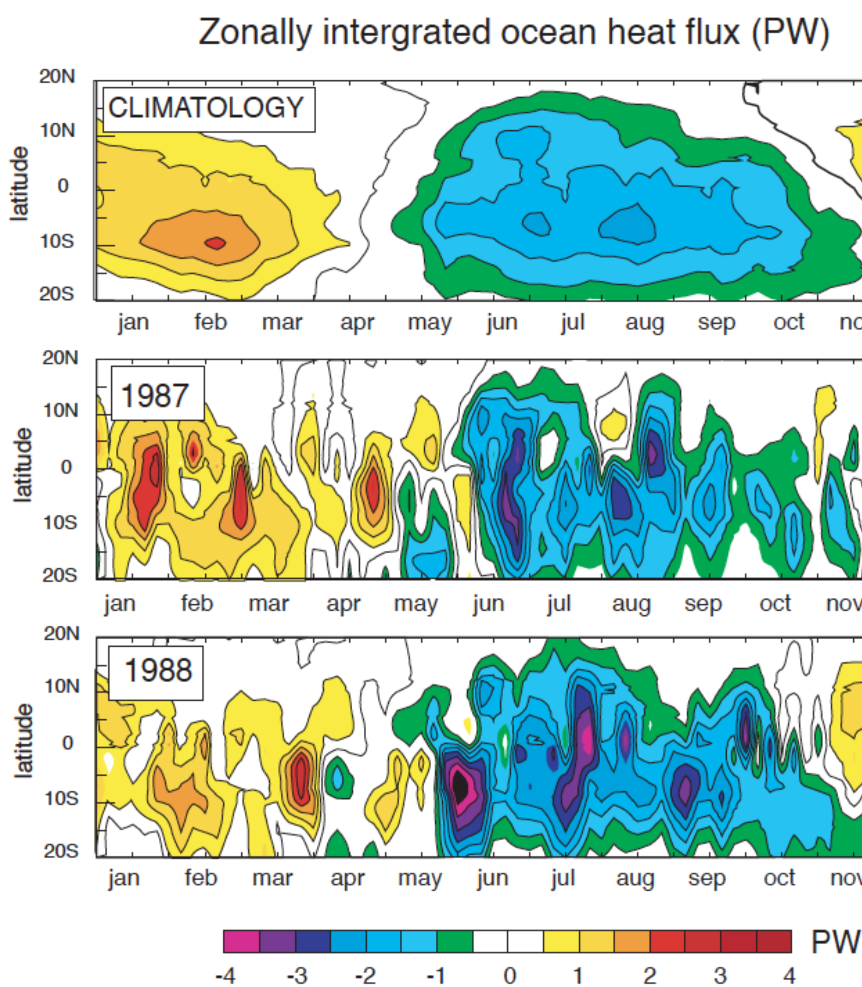
- We can now relate the formation of the IOZM with the anomalous summer monsoon:



COMPOSITE MONSOON REGULATION SYSTEM



Zonally Averaged Climatological and Intraseasonal Meridional Heat Flux in Indian Ocean



Each “pulse” corresponds to the meridional propagation of a monsoon intraseasonal event. Intraseasonal variability very important in heat balance of the monsoon system

Conclusions so far:

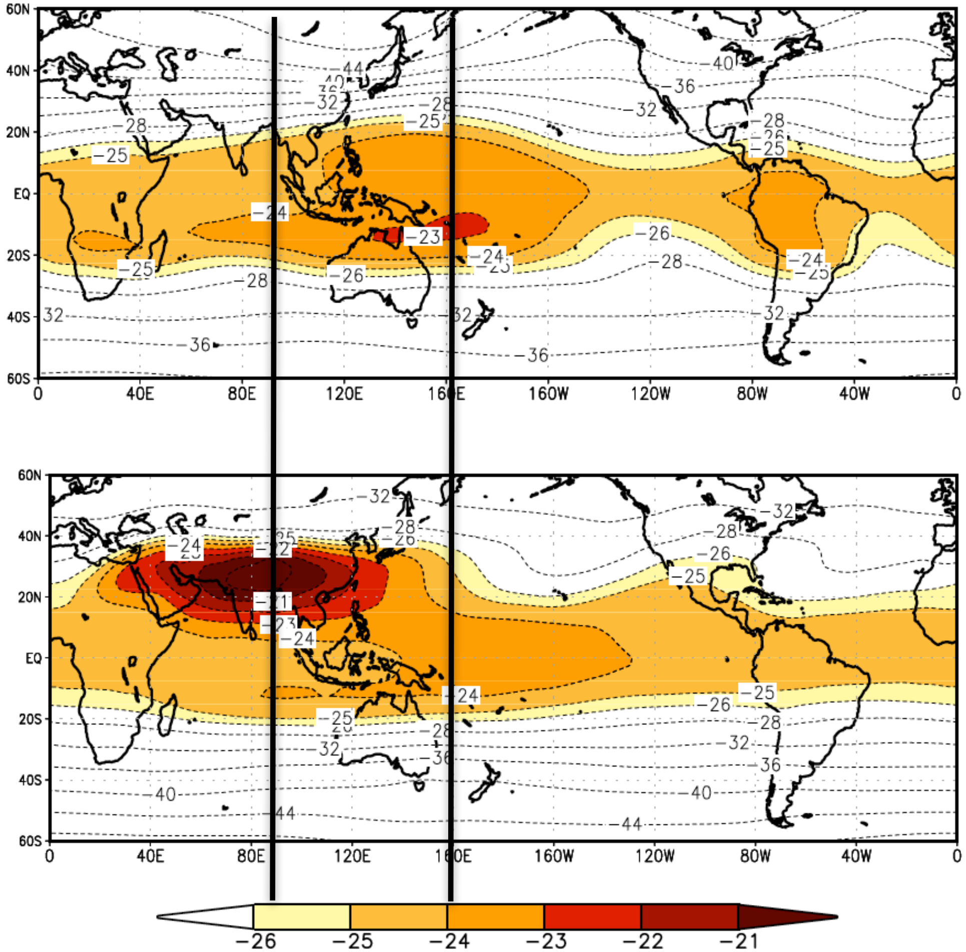
- Monsoon is a coupled ocean/atmosphere system
- Halley-like driven winds produce strong moisture convergence and latent heat release driving stronger winds
- Can conjure up mechanisms for regulation of the monsoon system with coupled o/a dynamics.

Thus, if we want to predict the behavior of the monsoon on all time scales, we need a coupled ocean-atmosphere model.

- Also we need a model that handles orography properly….. As the Himalayan-Tibetan Plateau (HTP) features mightily in mosoon dynamics.

The Himalaya-Tibet summer "hot tower"

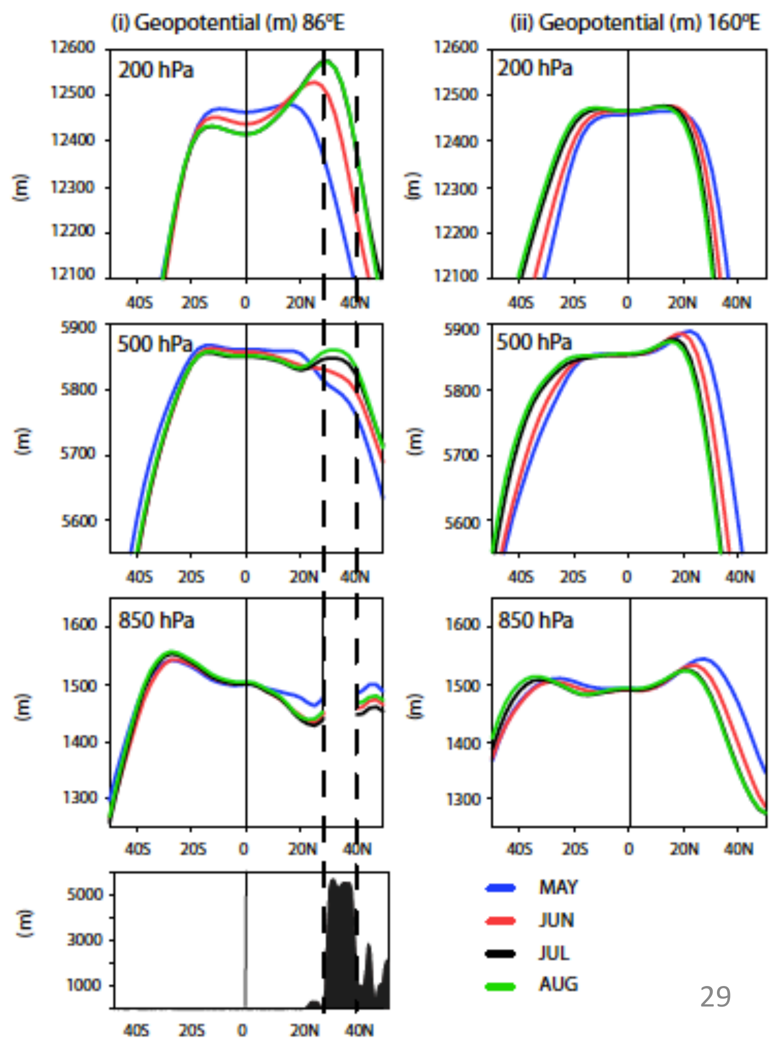
(a) Mean upper-tropospheric temperature



(b) Cross-sections of geopotential

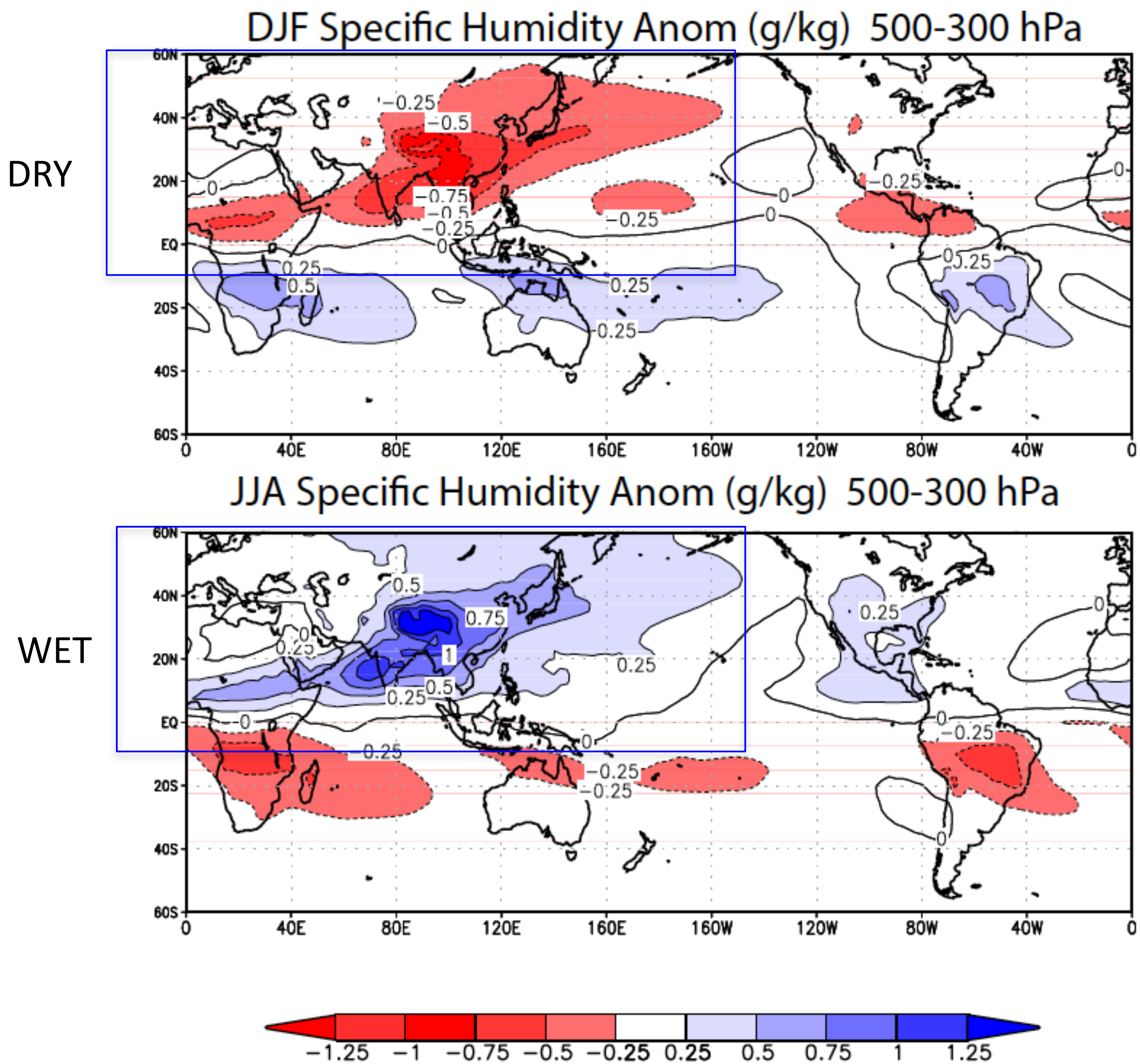
86E

160E

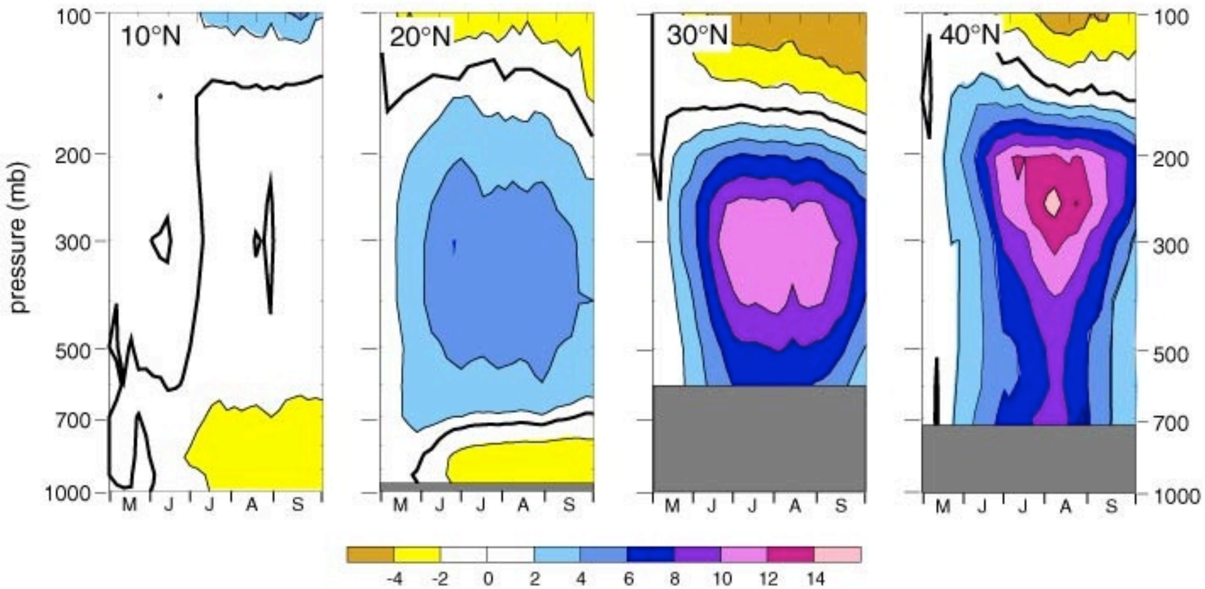


ΔT criterion appears to be met!

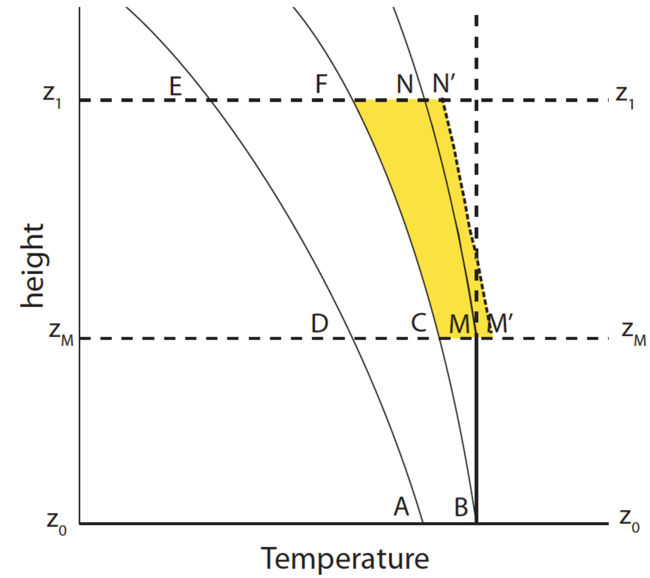
The Himalaya-Tibet summer “water tower”



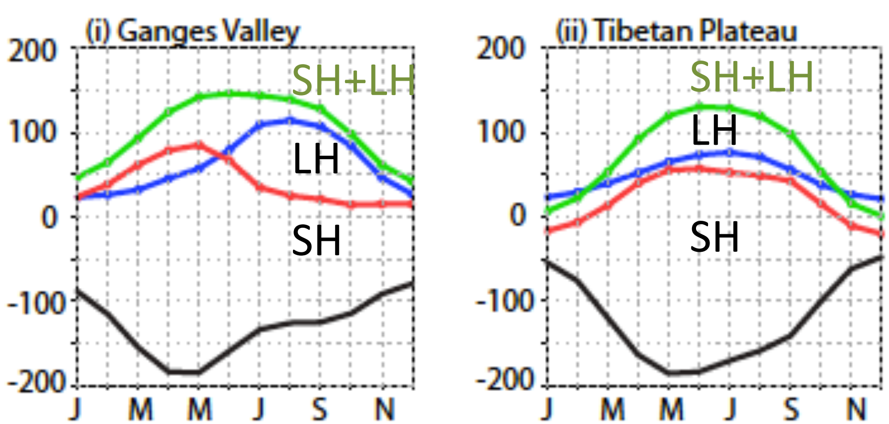
(a) Tropospheric temperature change relative to May 1

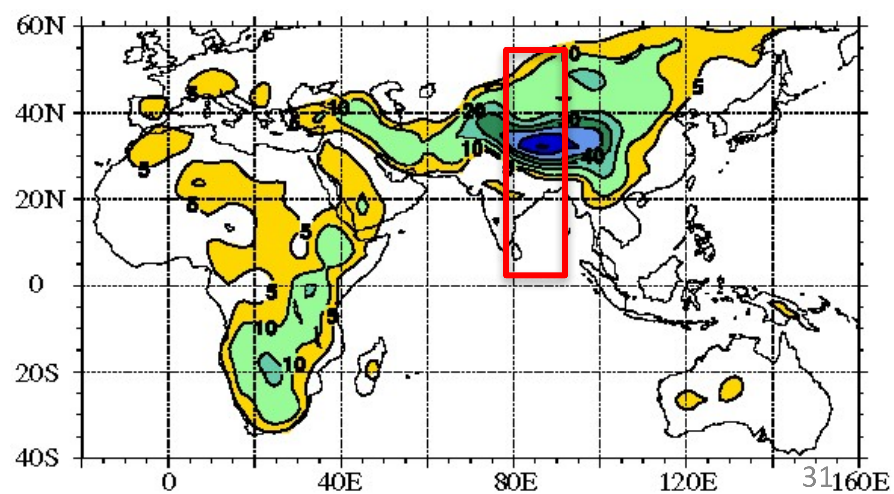


(c) Vertical aerology above HTP elevated heat flux

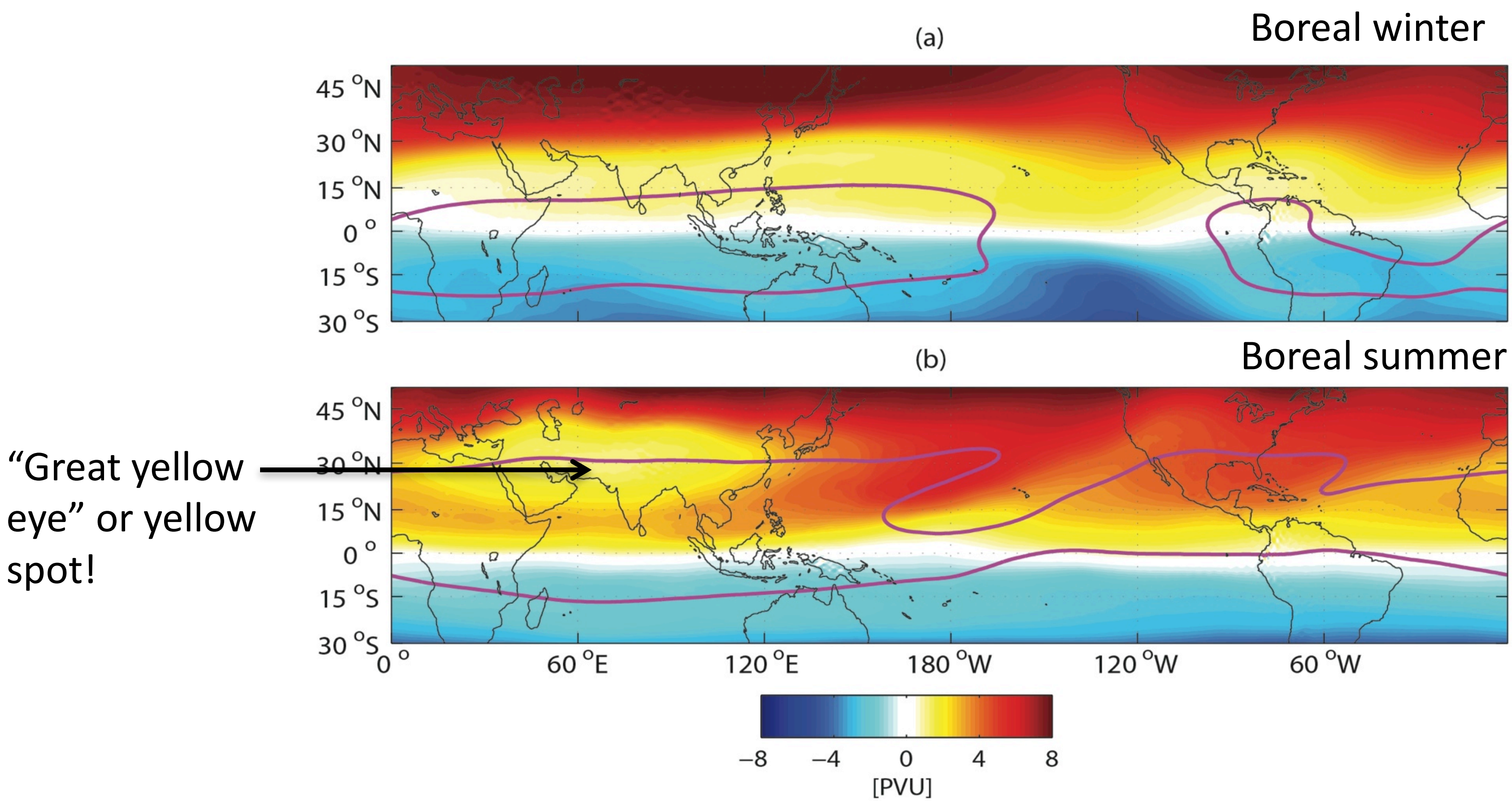


(b) Estimates of the annual cycle of heat fluxes for the Ganges Valley and the HTP



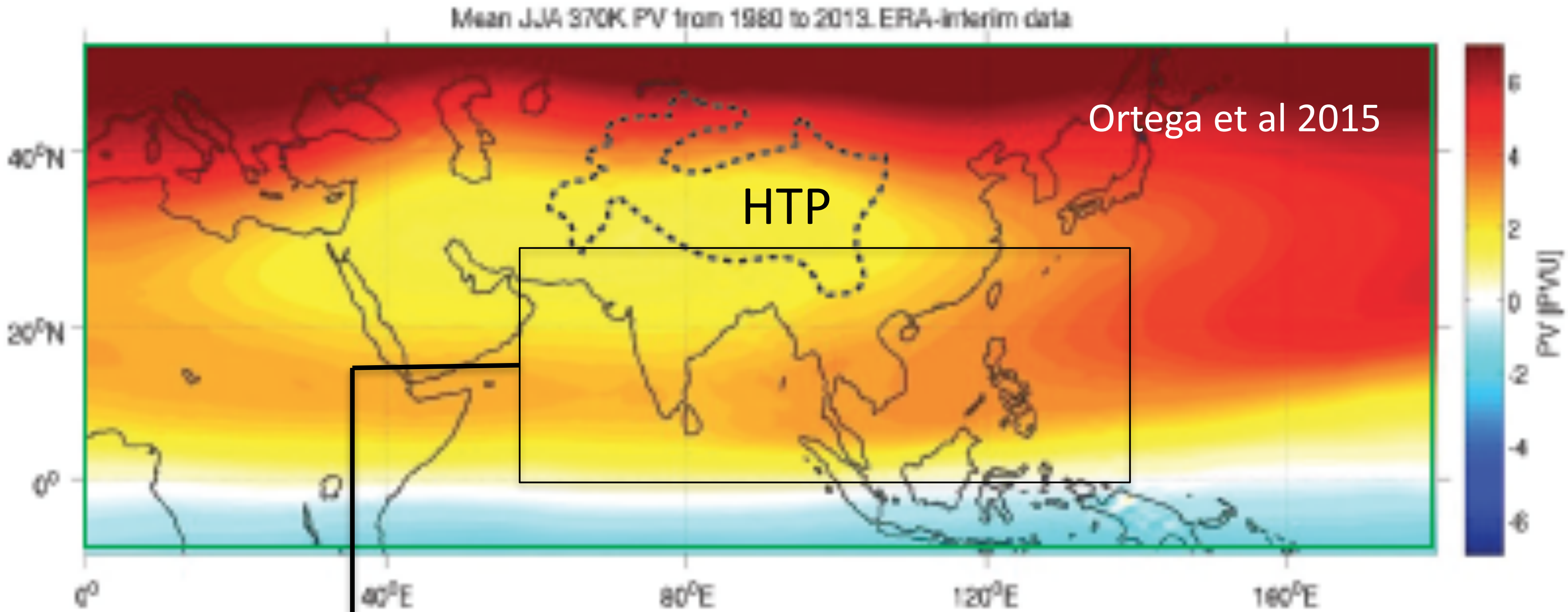


Upper-tropospheric potential vorticity field

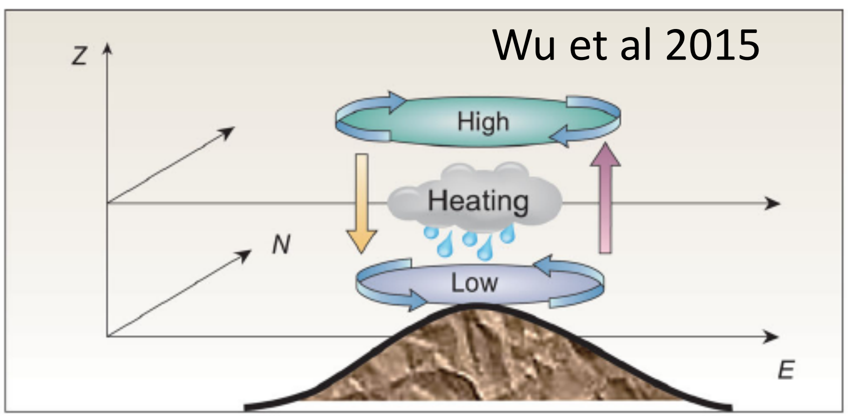


- During the boreal summer, the PV on fields are dominated by an anticyclone center over south Asia on the scale of 10,000 km and a corresponding Pacific trough. A weak counterpart exists over the Rockies. No counterpart exists in the austral summer.

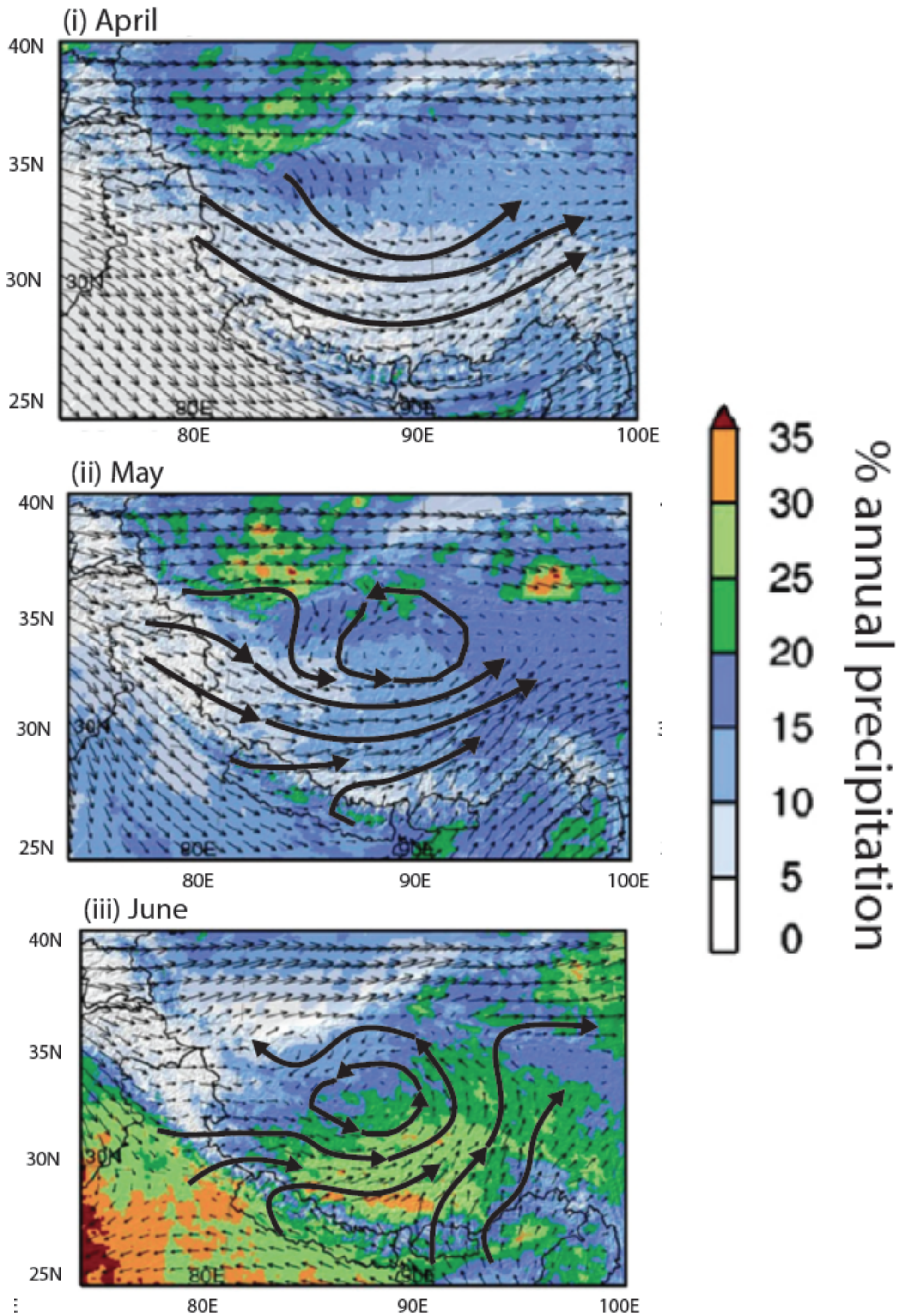
Ortega et al (2015)



- System is unstable (Hsu & Plumb 1998) as there is change of sign of IPV gradient (Charney & Stern 1962). Spawns instabilities that rotate anticyclonically around Asia

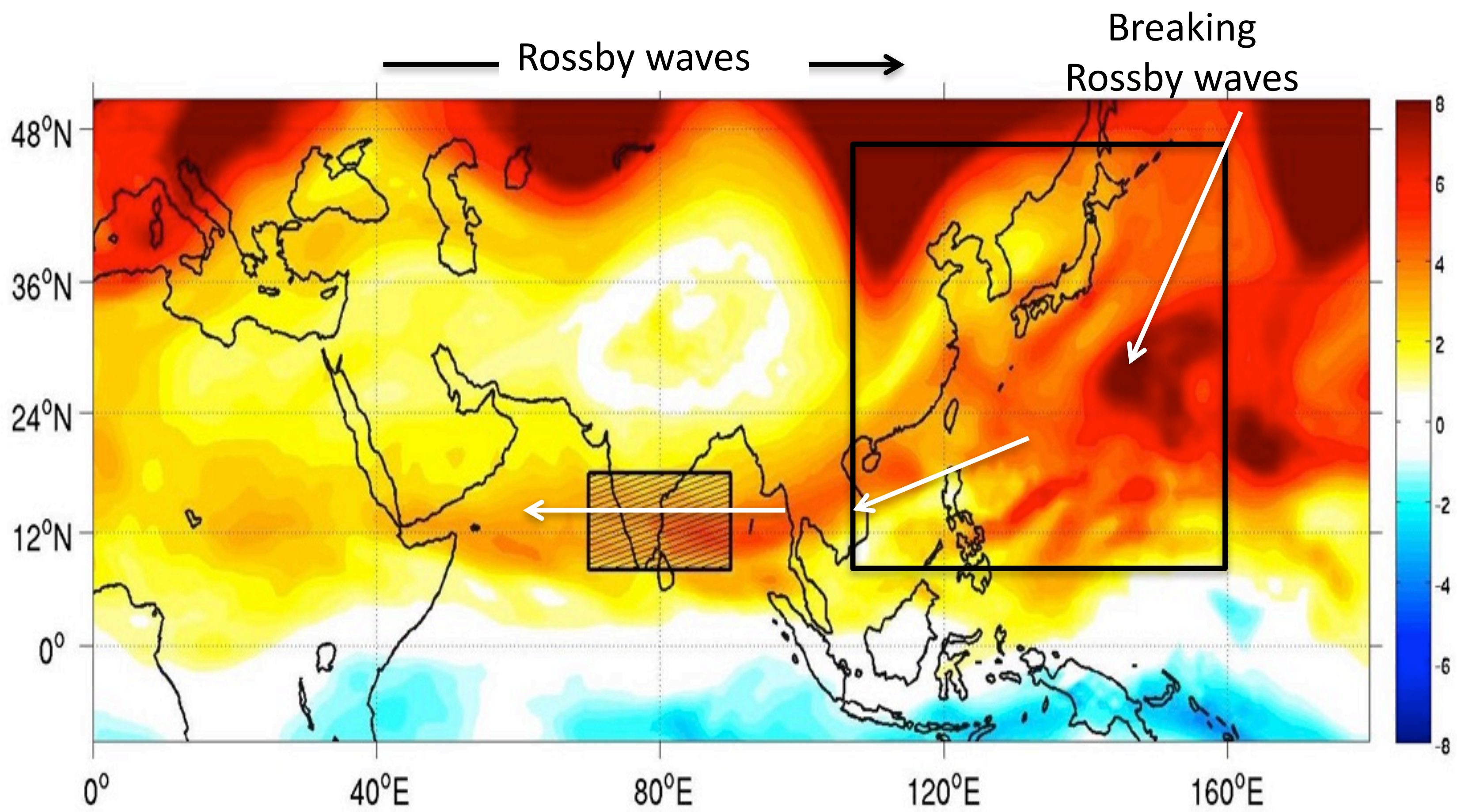


HTP Analyses Using High Altitude Reanalysis (Maussion et al. 2010)



- Mean April, May and June surface winds and % of annual precipitation falling during each months.
- Note the early formation of the surface trough on the surface of the HTP *well prior to the onset of the monsoon over India*
- A closed cyclonic circulation forms in May when 10-20% of the annual precipitation occurs.
- In June the cyclonic circulation is stronger and up to 25-35 % of the total rainfall occurs. Precip in the foothills is now occurring.
- Analysis fits well with the hypothesis of Prof. Hermann Flohn.

Quasi-biweekly oscillation around the monsoon gyre



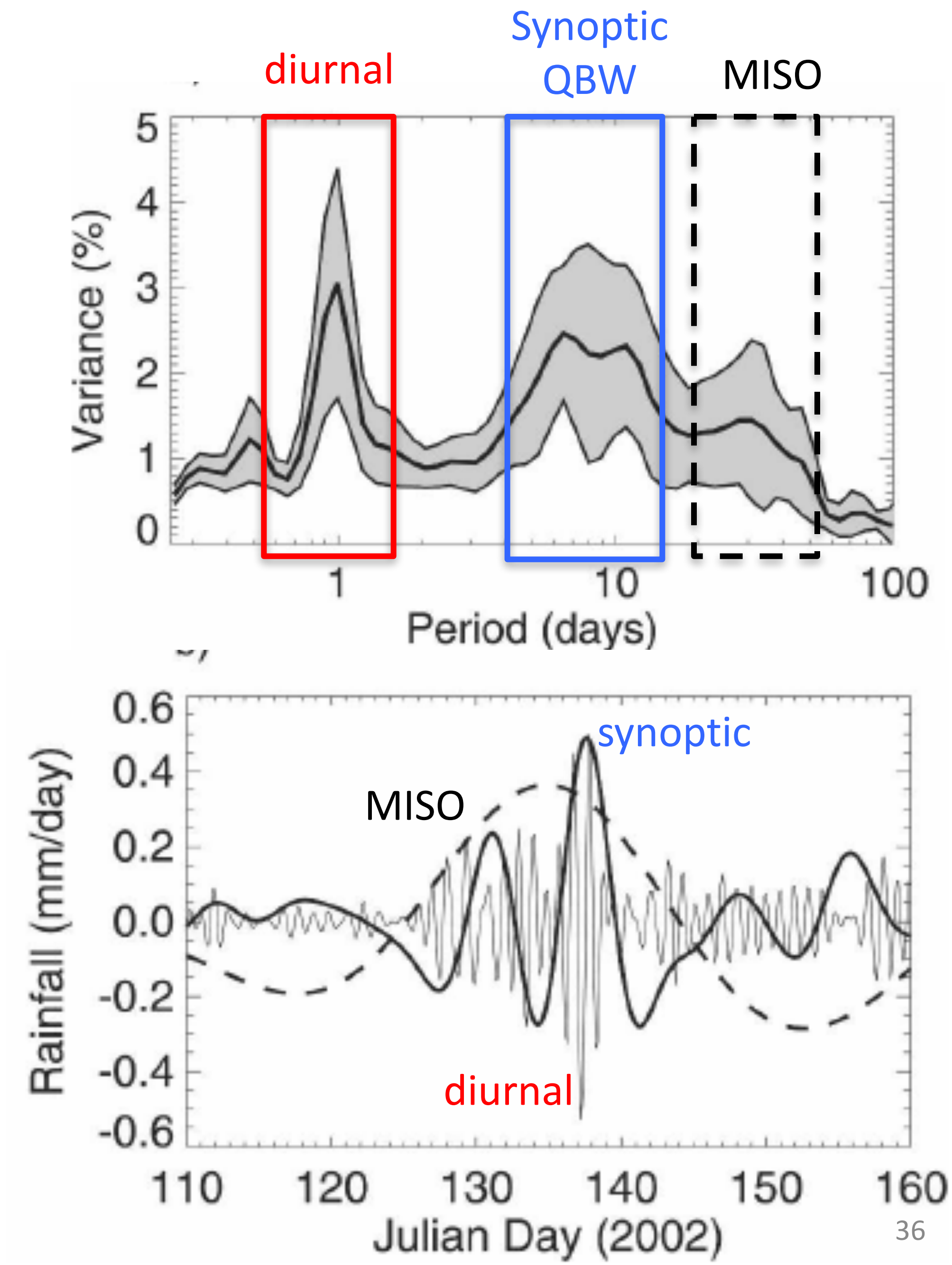
Ortega et al. (2015)

Reminder of the importance of bi-weekly variability in monsoon

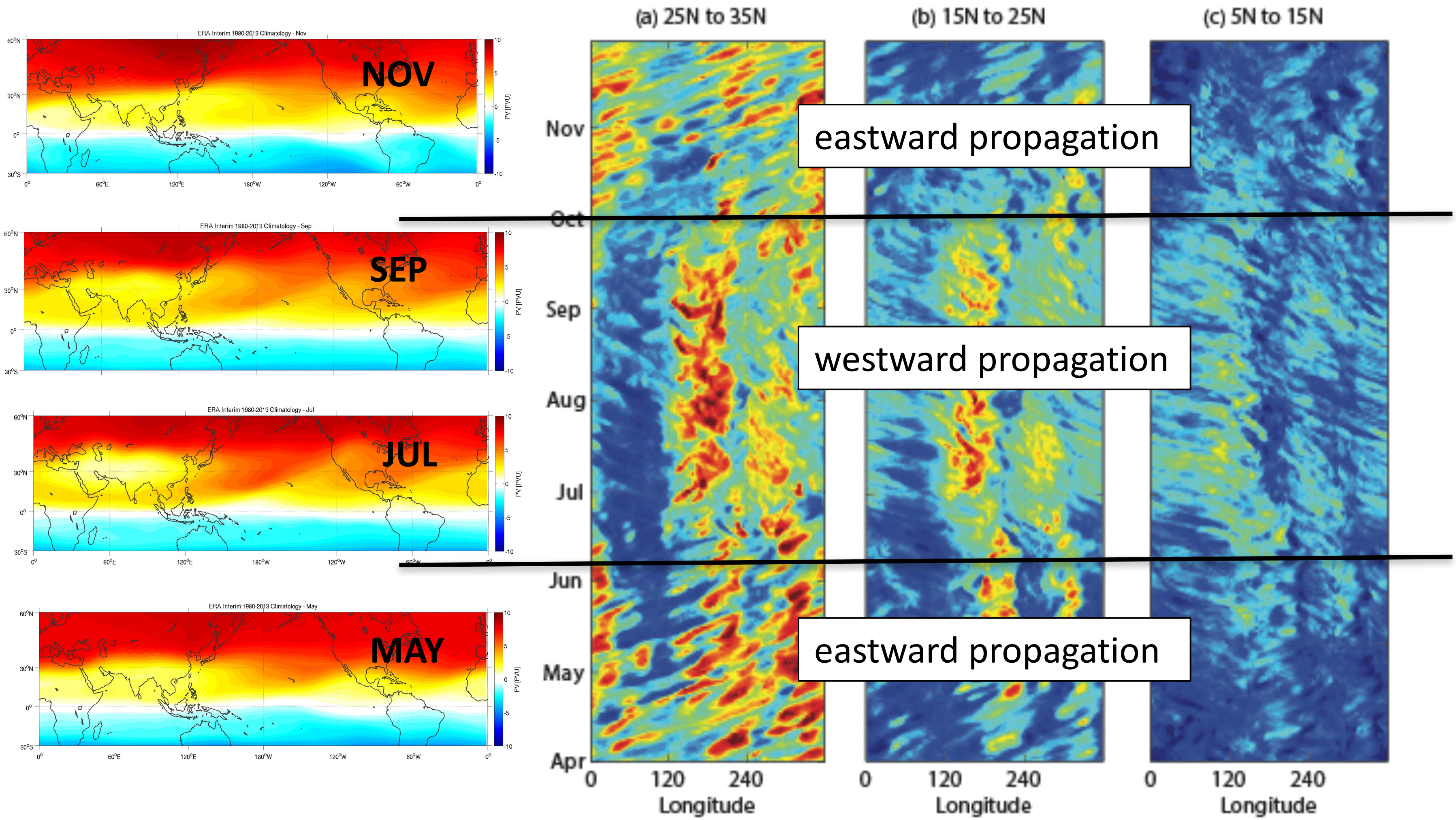
Three major time scales of precipitation in monsoon system (upper panel):

- Diurnal
- Synoptic (4-14 days) or quasi-biweekly
- Intraseasonal Oscillation (20-40 days).

These three phenomena are interrelated with their maximum convective phases occurring at the same time (lower panel).



GLOBAL DISTURBANCES and INSTABILITY OF MONSOON ANTICYCLONE



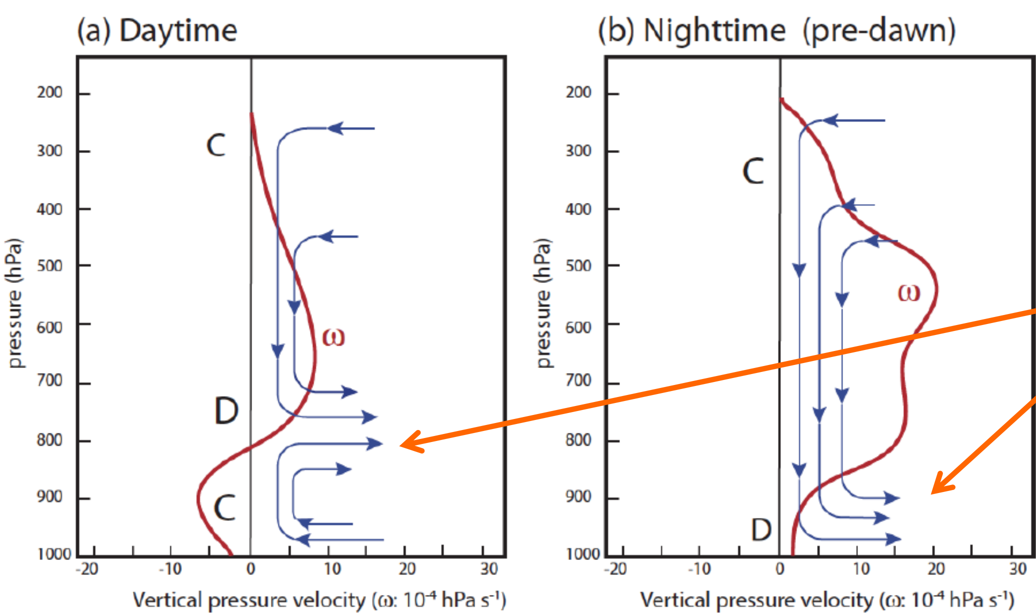
- Upper troposphere dominated by westward propagation in period where IPV gradient reverses.
- Are these oscillations relevant to precipitation events in tropics

Summary: The transient monsoon

- Elevated heating of the HTP creates planetary scale anticyclonic gyre expanding over 180^{o} longitude
- Gyre is dynamically unstable and breaking waves are advected anticyclonically around the gyre, originating in the extratropics and extending deeply into the tropics.
- These upper tropospheric disturbances appear to be associated with westward propagating rainfall events that impact South Asia.
- They also appear to generate westward propagating waves that exist on a global scale in sharp contrast to the boreal winter when propagation is to the east.

Another important "land" effect: Deserts

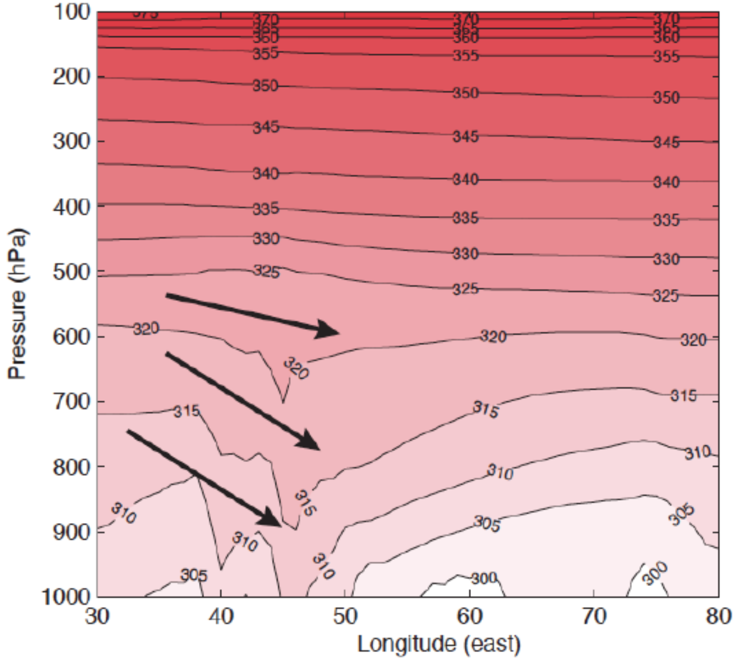
- Rodwell and Hoskins (1996) noted the importance of deserts in determining the intensity monsoons.
- Early results (Smith, 1986, Johnson 2002, Blake et al 1983) from the MONEX "Empty Quarter" Experiment in 1979 showed strong adiabatic descent emerging from desert region where there existed strong cooling to space. Balanced by adiabatic warming.

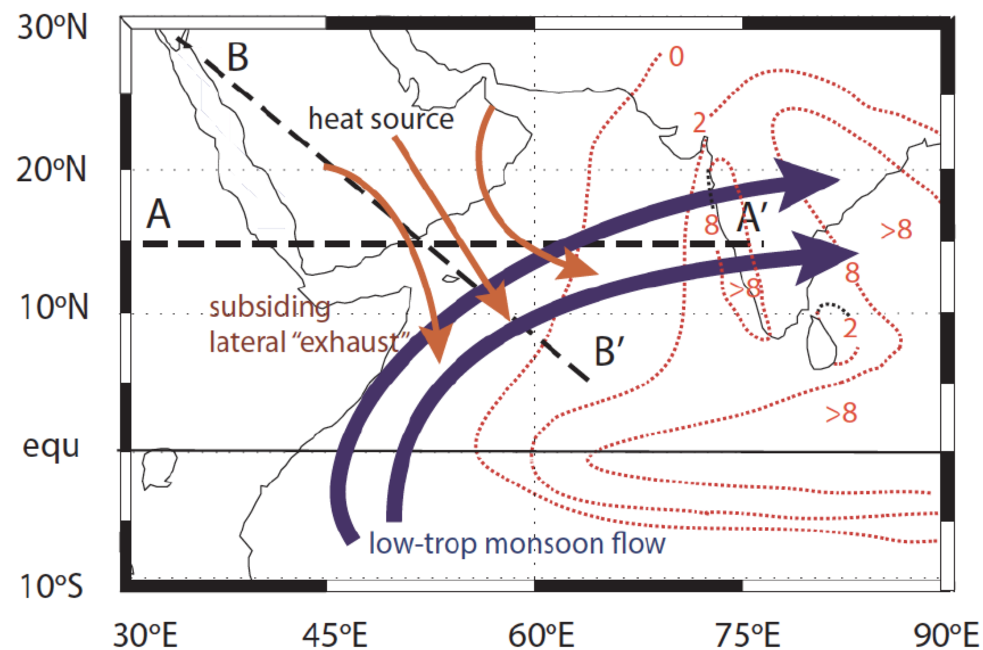


- Very strong diurnal variation
- Surface low forms during daytime.
- Lateral "exhaust" of downwelling air expands laterally over the Arabian Sea both day and night.

Lateral exhaust extends eastwards along isentropes extending over the Arabian Sea. This extension creates an inversion that (i) renders the flow across the equator inertially stable (Toma and Webster 2010) and also reduces convection.

(i) Isentropes along 15°N (JJA: section A-A′)





- Note the restriction of isohyets (mm/day: red dotted contours) to the central and western Indian Ocean.
- Clearly, to understand monsoon dynamics, there is a need to understand the physics of neighboring deserts and their influence, as well as their own dynamics.

Summary:

I have attempted to:

- Describe the components of the South Asian summer monsoon:
  - Land (elevated and desert), ocean and atmosphere.
- Emphasized the coupled nature of the components and how they interact to produce the characteristic temporal scales
- Hinted at the mechanisms that produce higher frequency variability
- Attempted to underline the necessity of understanding the coupled phenomena in order to predict it.
- I am of the opinion that if one is contemplating field expeditions or numerical experimentation that we are now well-set to ask the right questions. And, perhaps, be able to say something worthwhile about the monsoon in a changing climate.

Because of time limitations, I have given short-change to the physics of sub-seasonal monsoon variability. Much has been learned and our predictability potential is gaining strength. There is much more at:
https://www.dropbox.com/sh/hpn9ldozhvvixt7/AADKWtfRhxoR52MtFfZ9EOyTa?dl=0


Thank you