Atmosphere–Ocean Interactions

11. Monsoon Systems

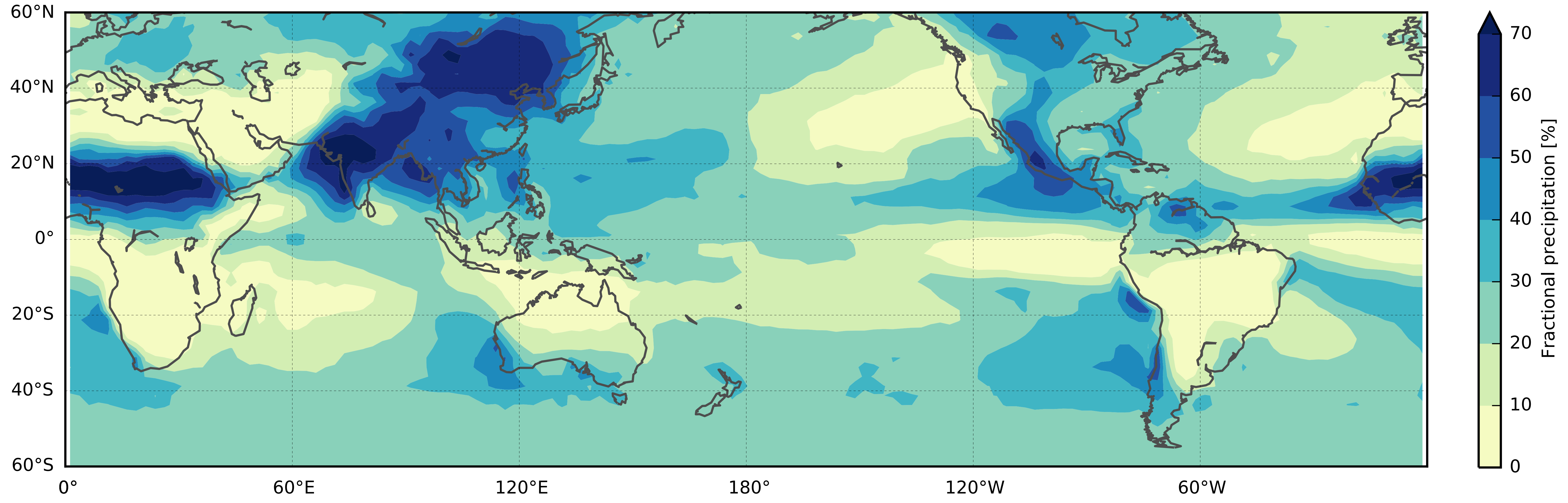
- What are monsoons?
- The global monsoon
- A focused examination of the South Asian monsoon
- Simulating monsoons

Monsoons

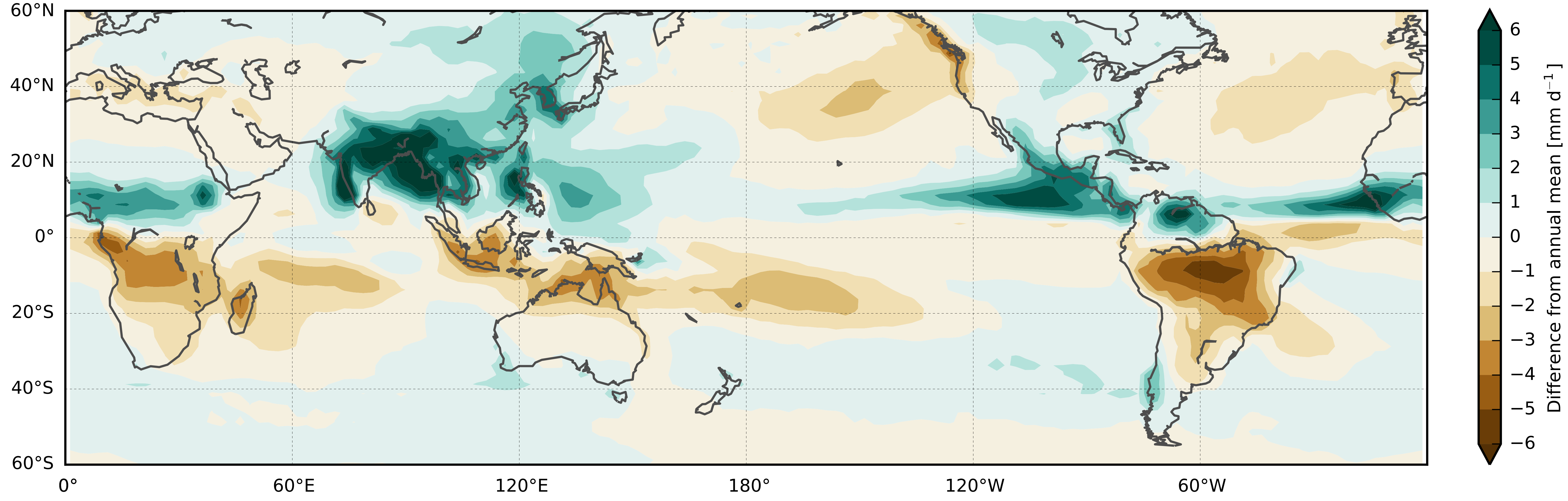
1. The term monsoon comes from an Arabic word for seasonal variations in the winds, though it is more often used to refer to seasonal variations in precipitation
2. Monsoons arise from seasonal reversals in atmospheric heating and temperature gradients between land and ocean
3. Monsoon climate regimes affect approximately half of the world's population
4. Understanding monsoons is important for agricultural planning and flood and drought mitigation
5. Monsoons vary on a variety of time scales: biweekly, intraseasonally (30–60 days), interannually (e.g., ENSO), and interdecadally. These variations are tightly linked to atmosphere–ocean interactions.

The Global Monsoon

Fraction of annual precipitation that falls during JJA



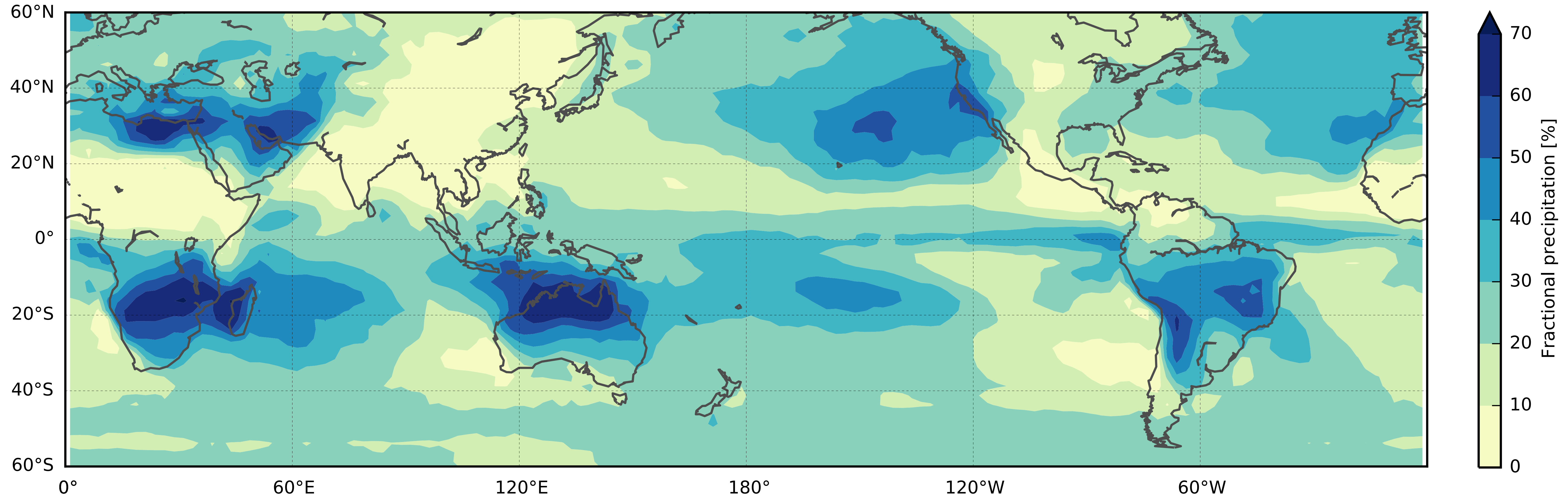
JJA precipitation rate minus annual mean precipitation rate



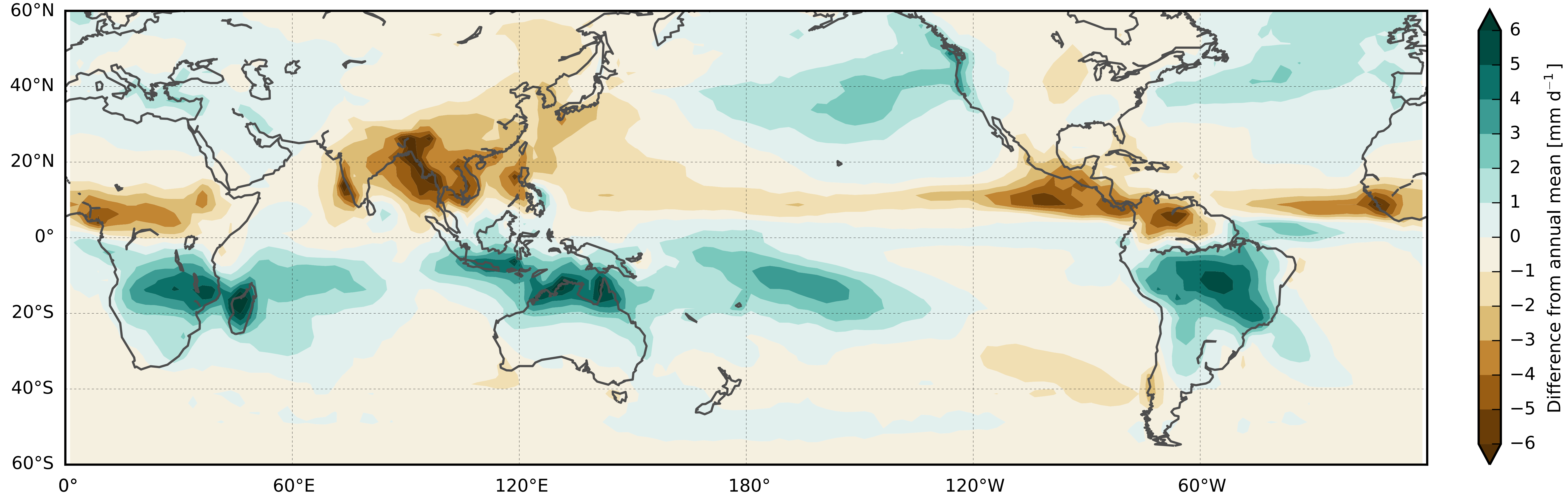
Data source: GPCP

The Global Monsoon

Fraction of annual precipitation that falls during DJF



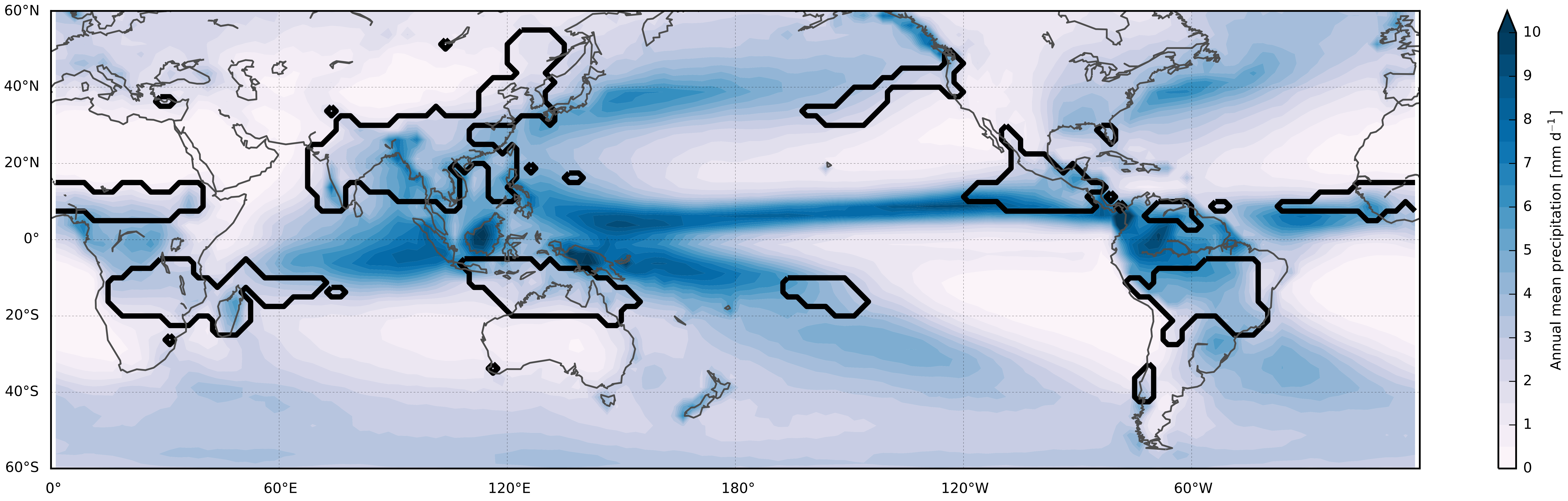
DJF precipitation rate minus annual mean precipitation rate



Data source: GPCP

The Global Monsoon

One definition: at least 40% of precipitation during local summer **and** summer mean more than 2 mm/d above annual mean



The monsoon regions are not the regions with largest annual mean precipitation — they are on the edges of the regions with largest annual mean precipitation

Data source: GPCP

The Global Monsoon

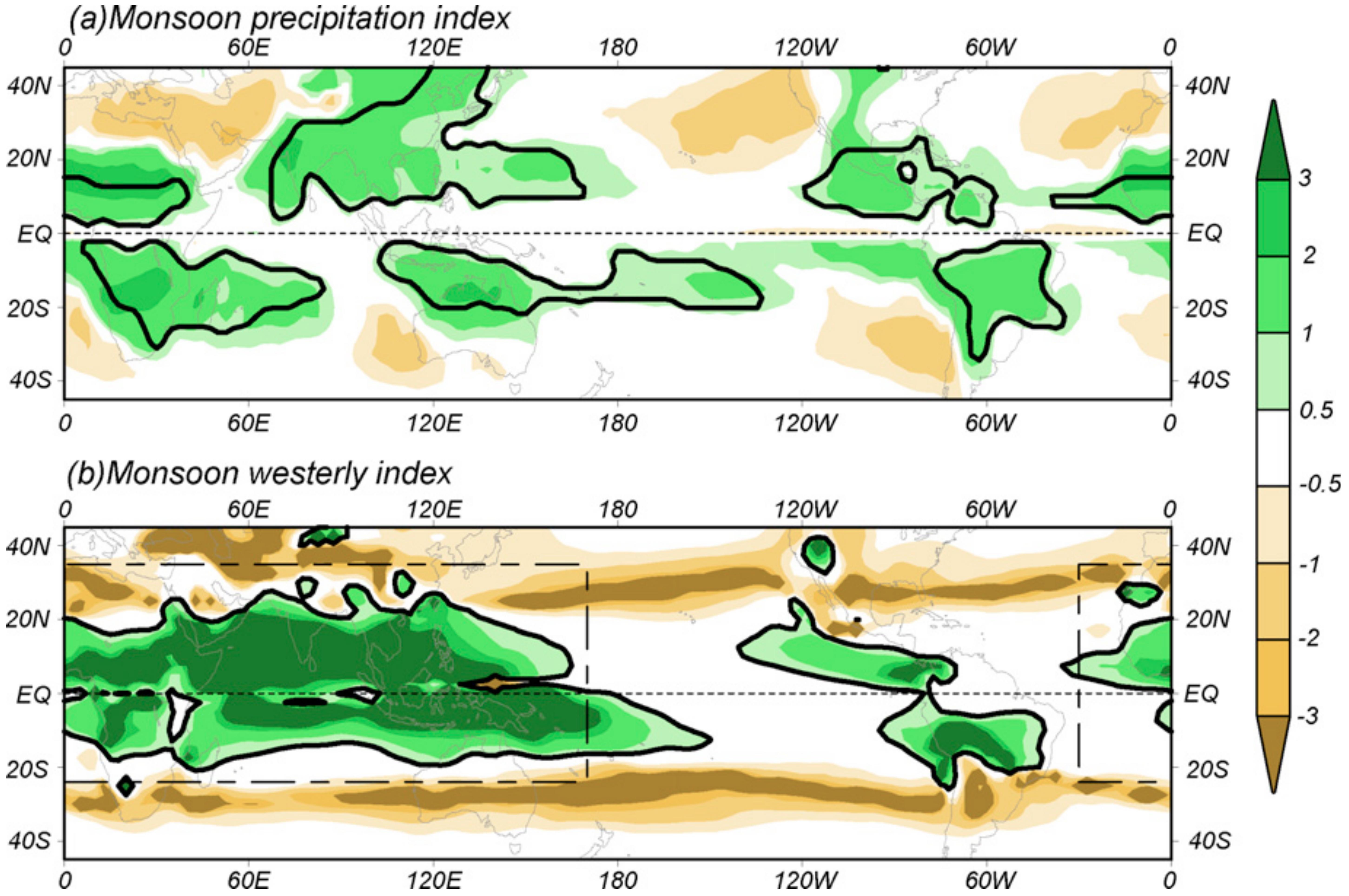
There are many different ways to define the global monsoon domain based on precipitation and/or circulation changes

$$\text{MPI} = \frac{\text{annual range of precipitation}}{\text{annual mean precipitation}} > 0.5$$

(provided annual mean precipitation > 300 mm)

$$\text{MWI} = \frac{\text{annual range of zonal wind}}{\text{annual mean zonal wind}} > 0.5$$

(in the lower troposphere at 850 hPa)

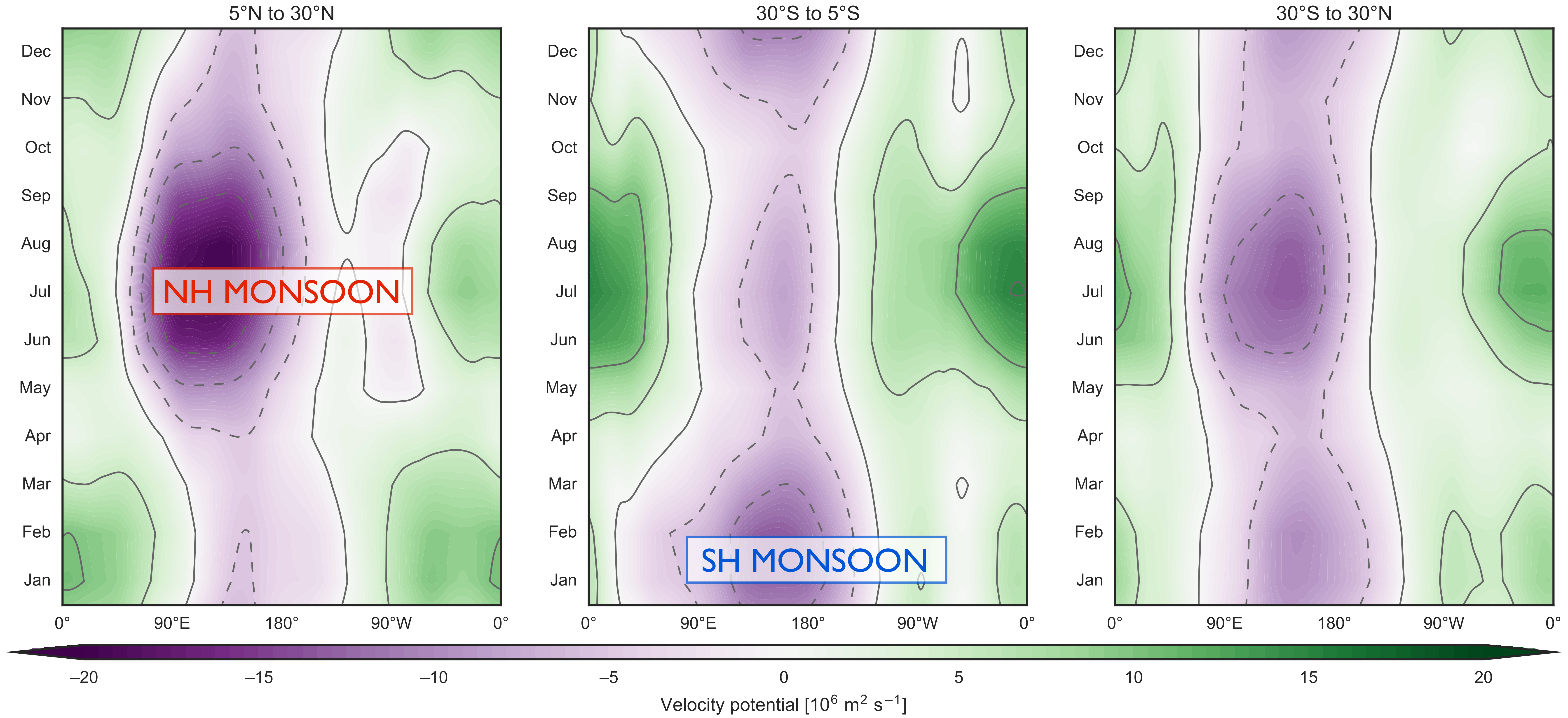


Wang & Ding, *Dyn. Atmos. Oceans* 2008

The Global Monsoon

Monsoon climates are characterized by a seasonal reversal in the wind fields. This reversal is global in scope

1. Regional monsoons are coordinated primarily by land–sea thermal contrasts related to the annual cycle of solar heating
2. Tied to the Hadley and Walker circulations (the ‘lateral’ and ‘transverse’ monsoons)
3. Monsoon circulations can be clearly identified in the annual cycle of velocity potential in the upper troposphere, which indicates large-scale convergence and divergence

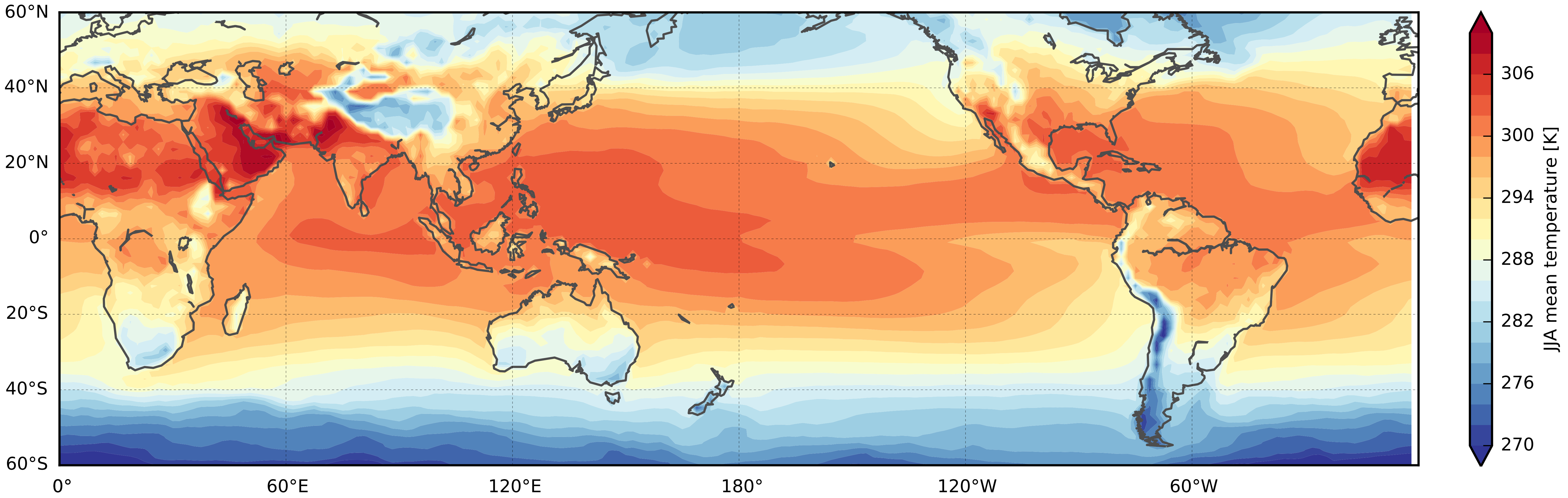


Data source: JRA-55

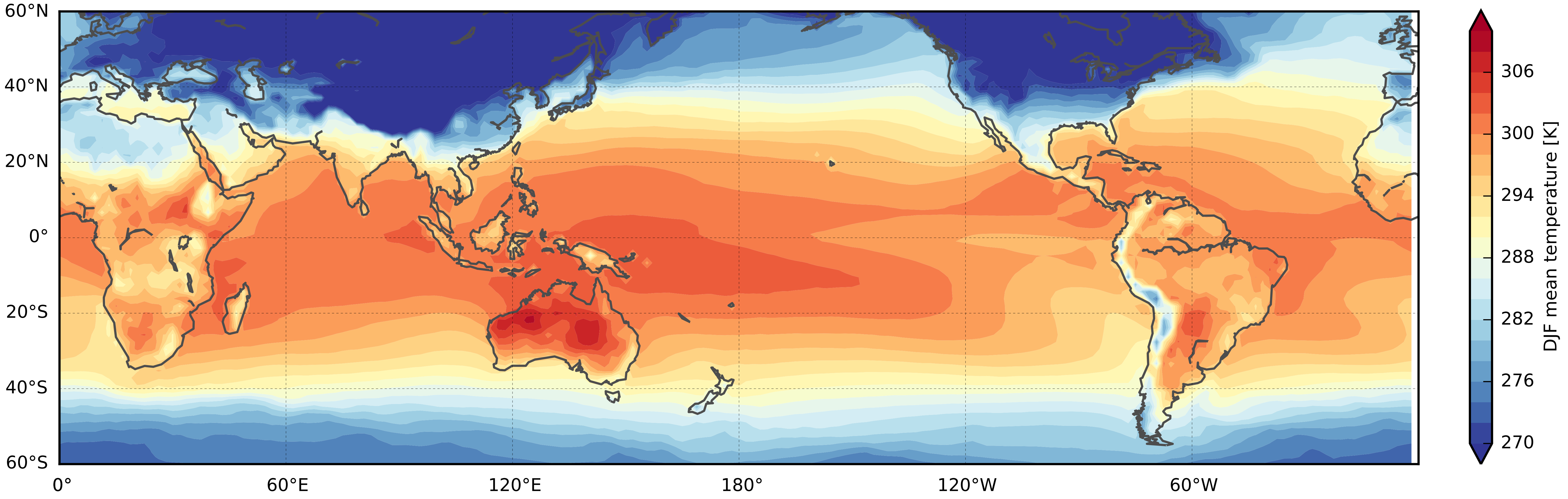
The Global Monsoon

The seasonal cycle of solar radiation and differences in heat capacity lead to strong land–sea contrasts in surface temperature

JJA surface temperature



DJF surface temperature

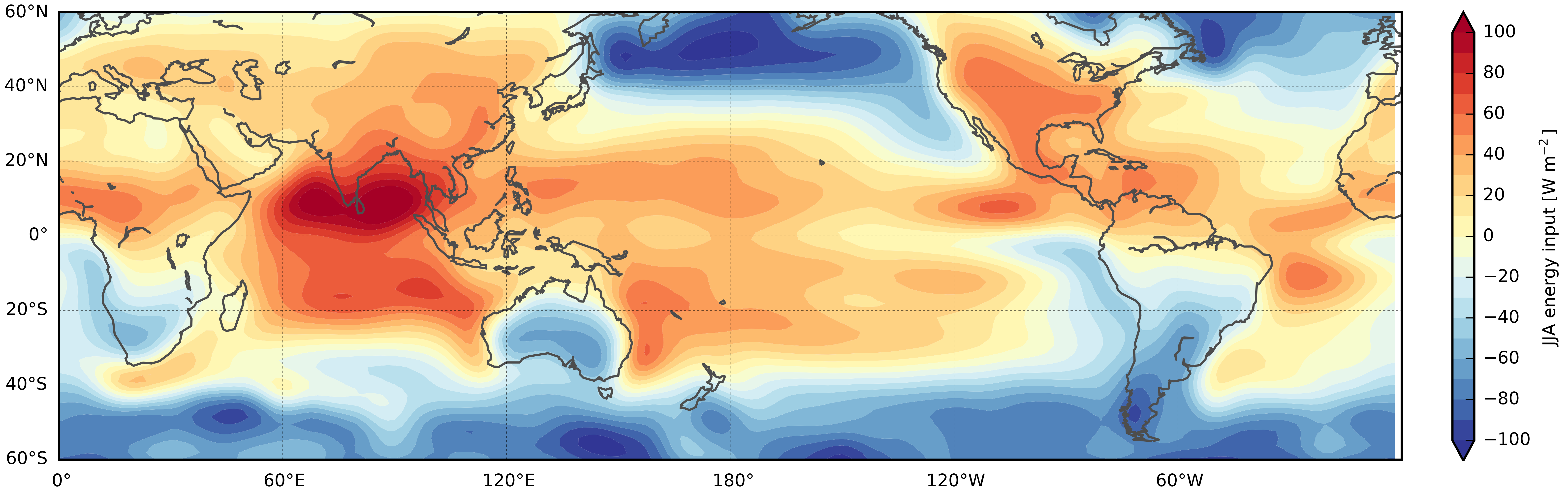


Data source: CFSR

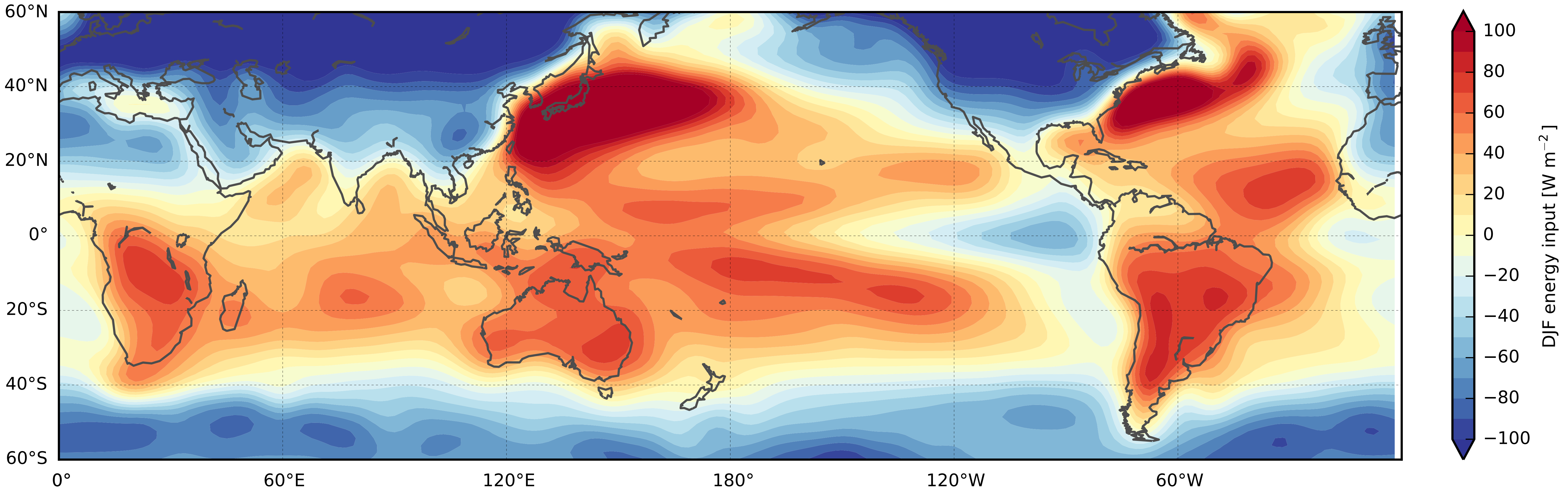
The Global Monsoon

The thermal contrast may be more effectively understood in terms of the atmospheric moist energy budget

JJA



DJF



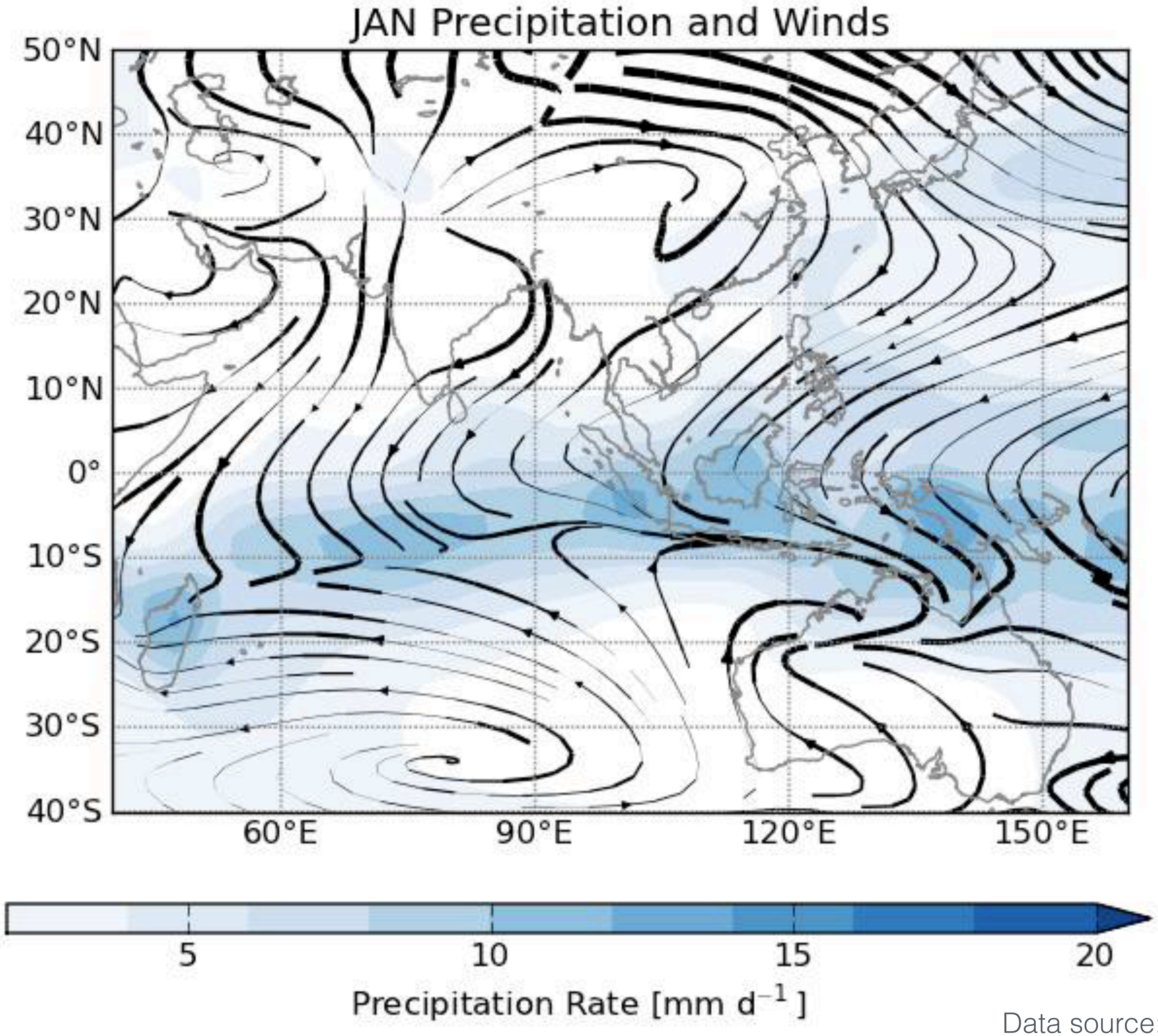
The surface heating is only part of the story — it is the atmospheric heating that drives convergence!

Data source: CFSR

The Global Monsoon

Asian–Australian Monsoon

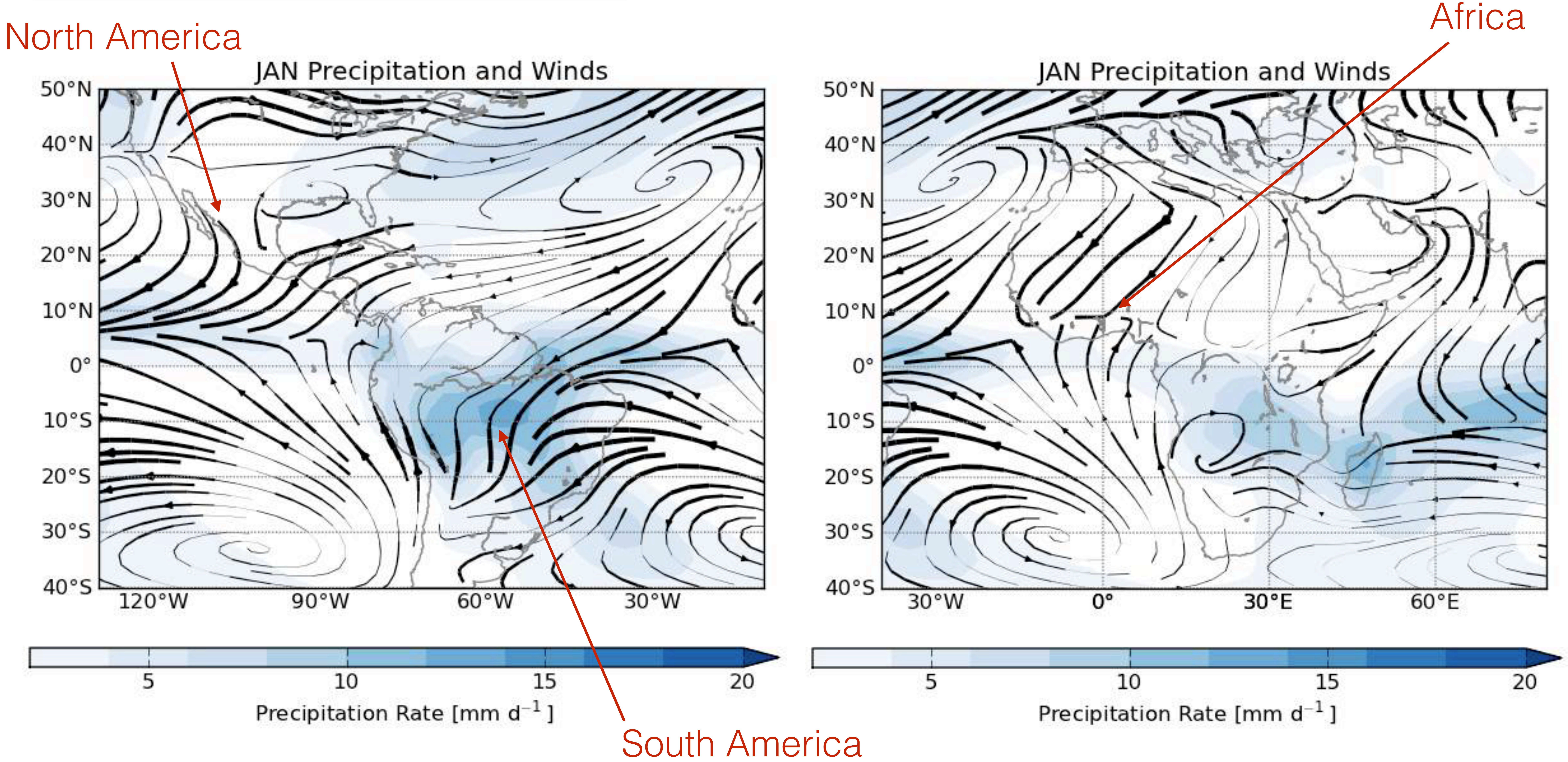
Associated with the north–south seasonal migration of solar and atmospheric heating



Data source: CFSR

The Global Monsoon

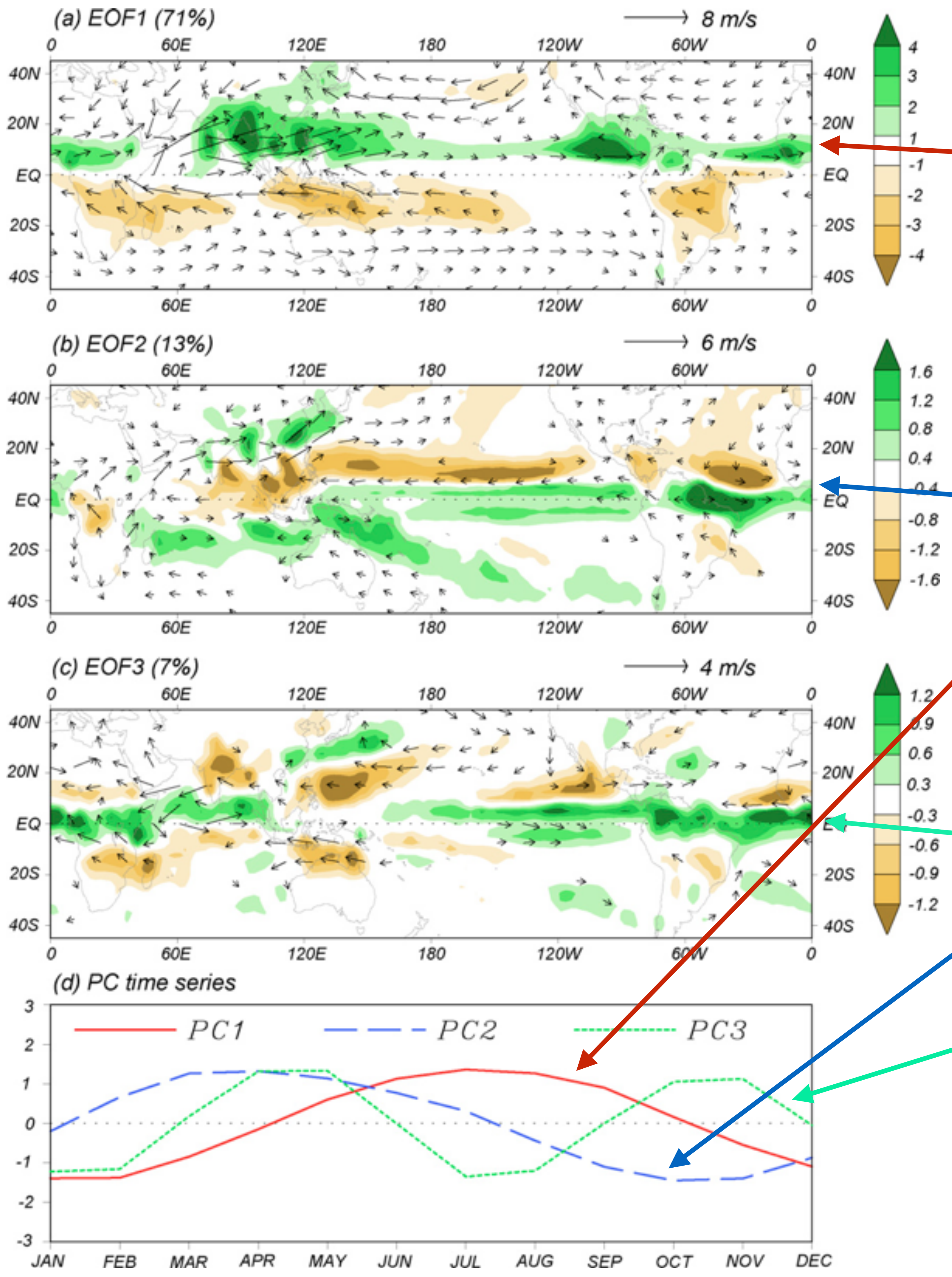
Other regional monsoons



Data source: CFSR

The Global Monsoon

EOF analysis: annual cycle of precipitation and winds



solstice mode: annual cycle with maximum in July and minimum in January

First two modes explain 84% of total variance

equinox mode: annual cycle with maximum in April and minimum in October

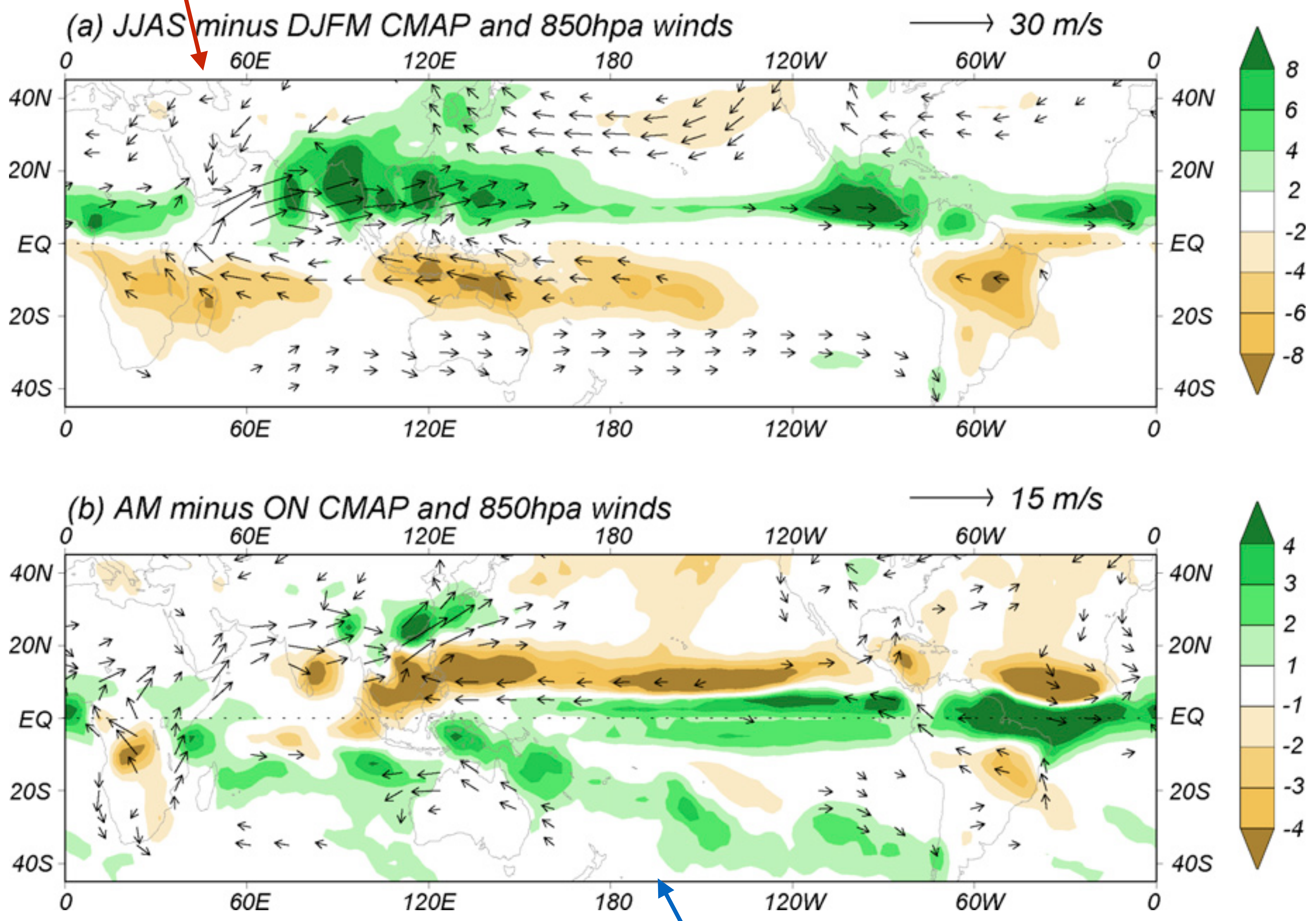
semi-annual mode: maxima in April and October

Wang & Ding, *Dyn. Atmos. Oceans* 2008

The Global Monsoon

EOF analysis: annual cycle of precipitation and winds

solstice mode: regional monsoons driven by land–ocean thermal contrast

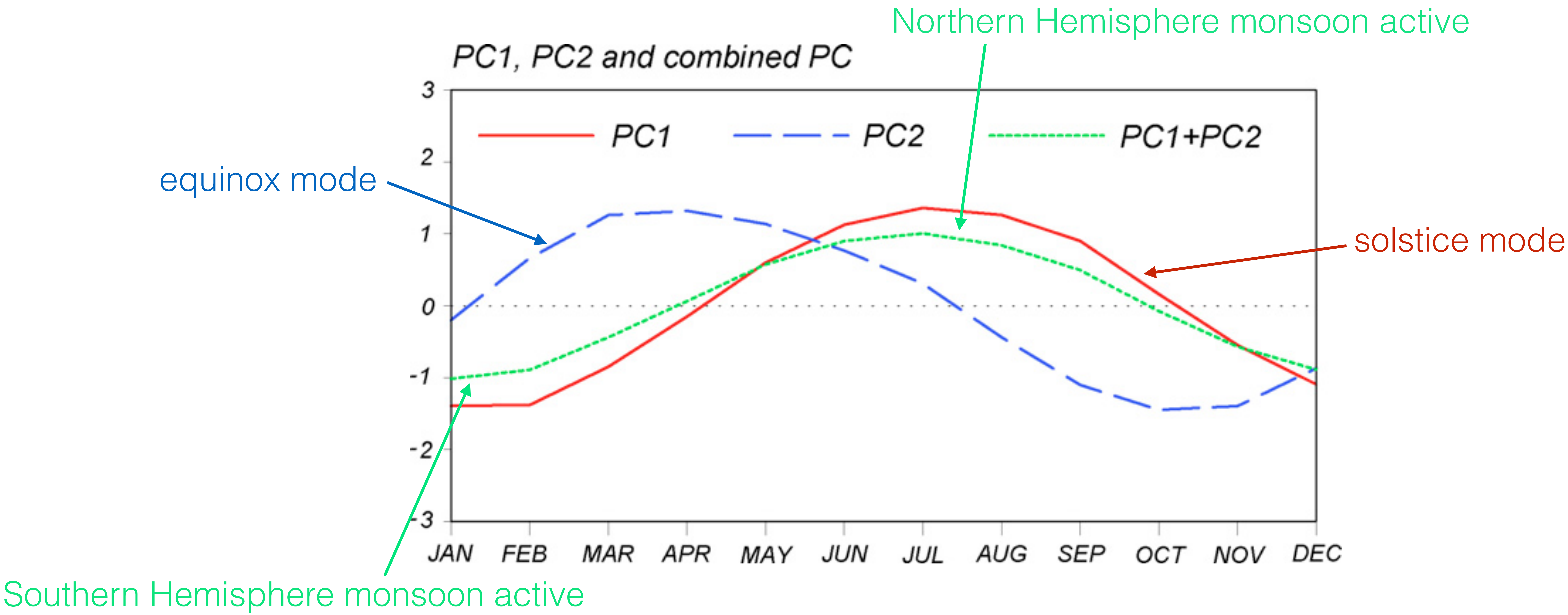


equinox mode: ocean temperatures change more slowly

Wang & Ding, *Dyn. Atmos. Oceans* 2008

The Global Monsoon

The combination of the principal components gives a representation of the annual cycle in the global land–ocean monsoon system



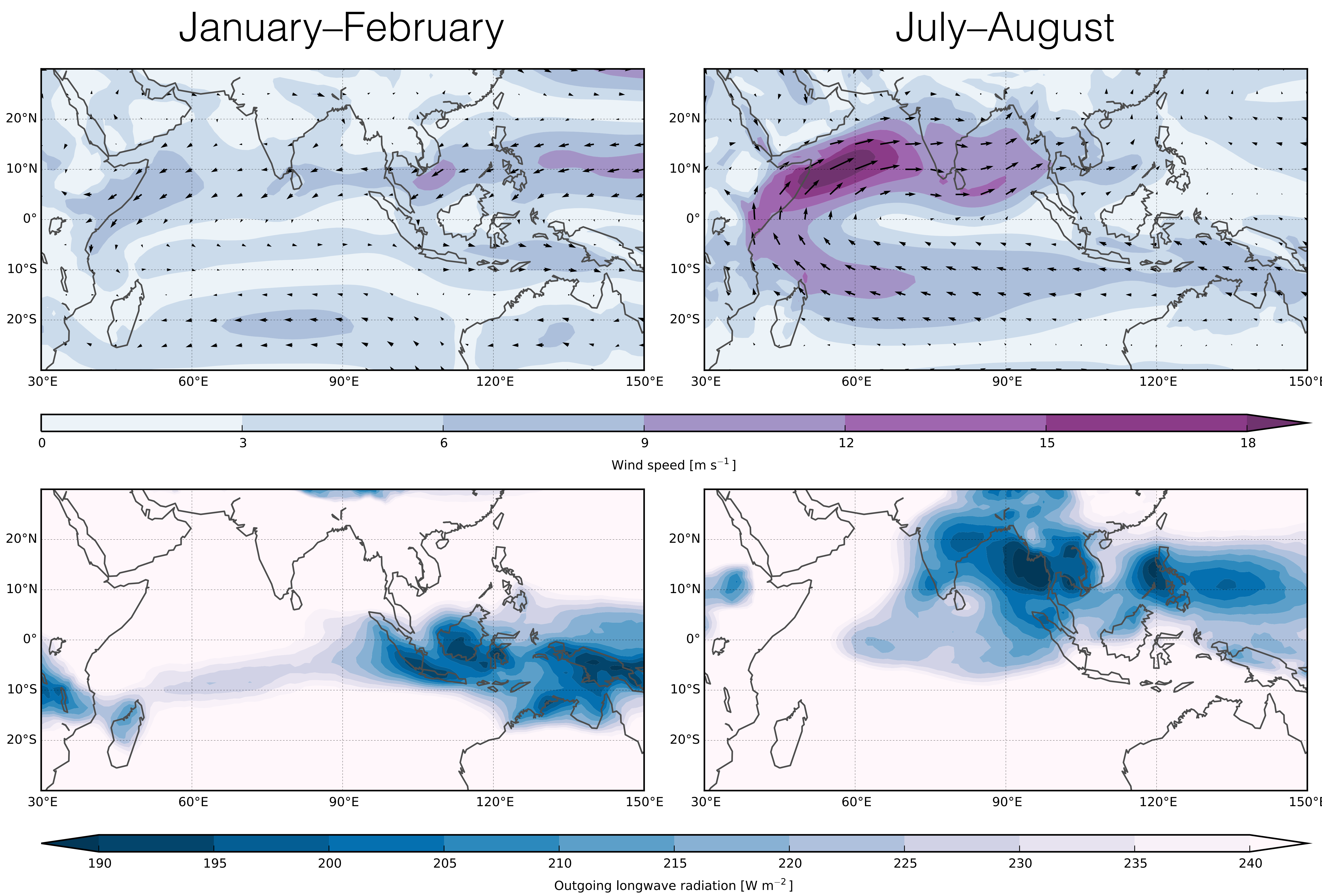
Wang & Ding, *Dyn. Atmos. Oceans* 2008

Australalasian Monsoon

Data source: CFSR

Australasian Monsoon

The annual cycle of OLR shows strong variations in atmospheric heating by deep convection, which are tightly related to variations in low-level winds

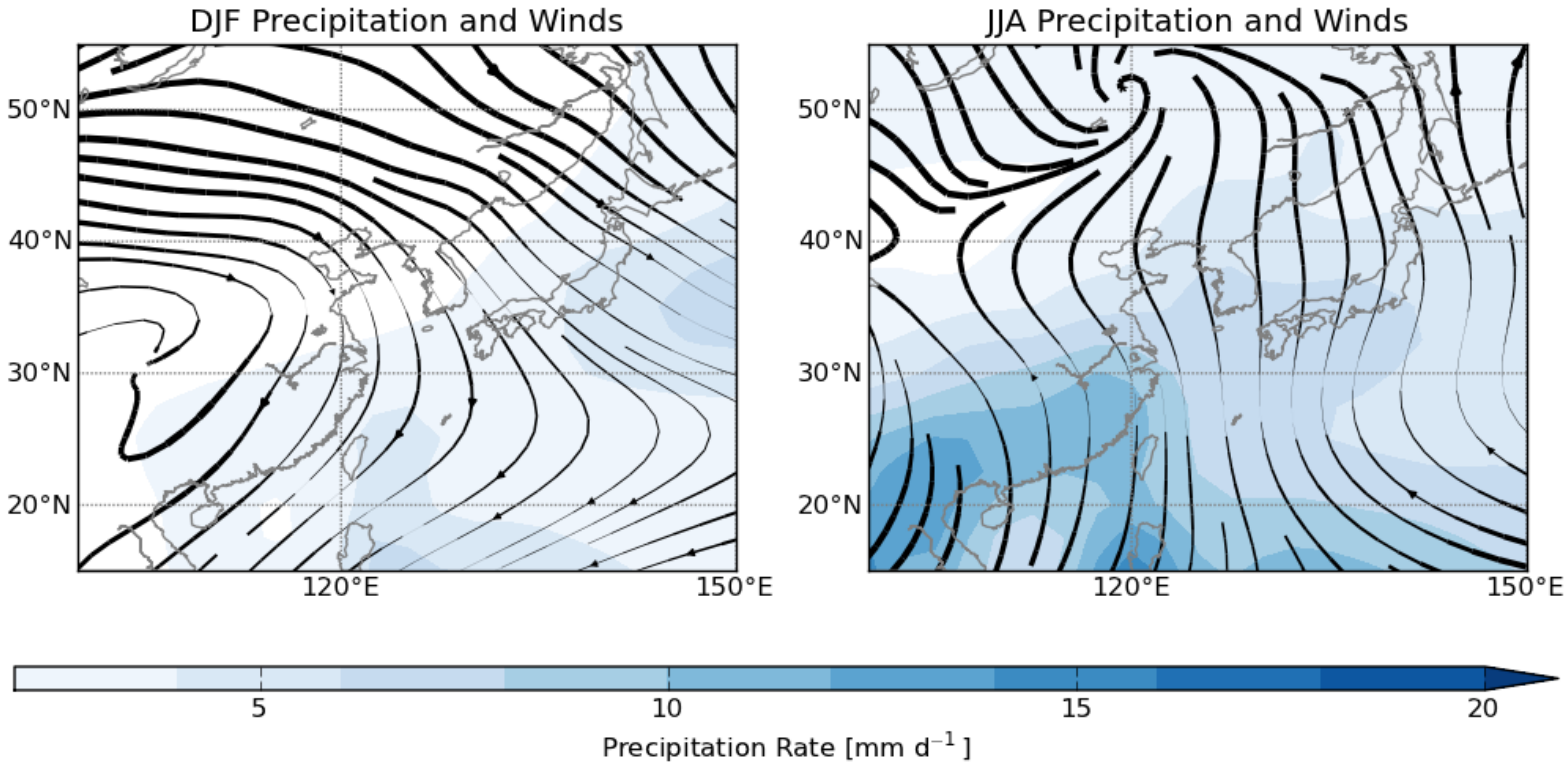


Data source: JRA-55 and CERES Syn1Deg

Australasian Monsoon

East Asian monsoon

- carries moist air from South Asia and the North Pacific to East Asia
- affects approximately one third of global population (China, Korea, Japan)
- driven by temperature differences between Asia and the Pacific Ocean
- a series of stationary states, separated by jumps that occur in mid-May (South China), mid-June (Yangtze River Valley), and mid-July (North China).

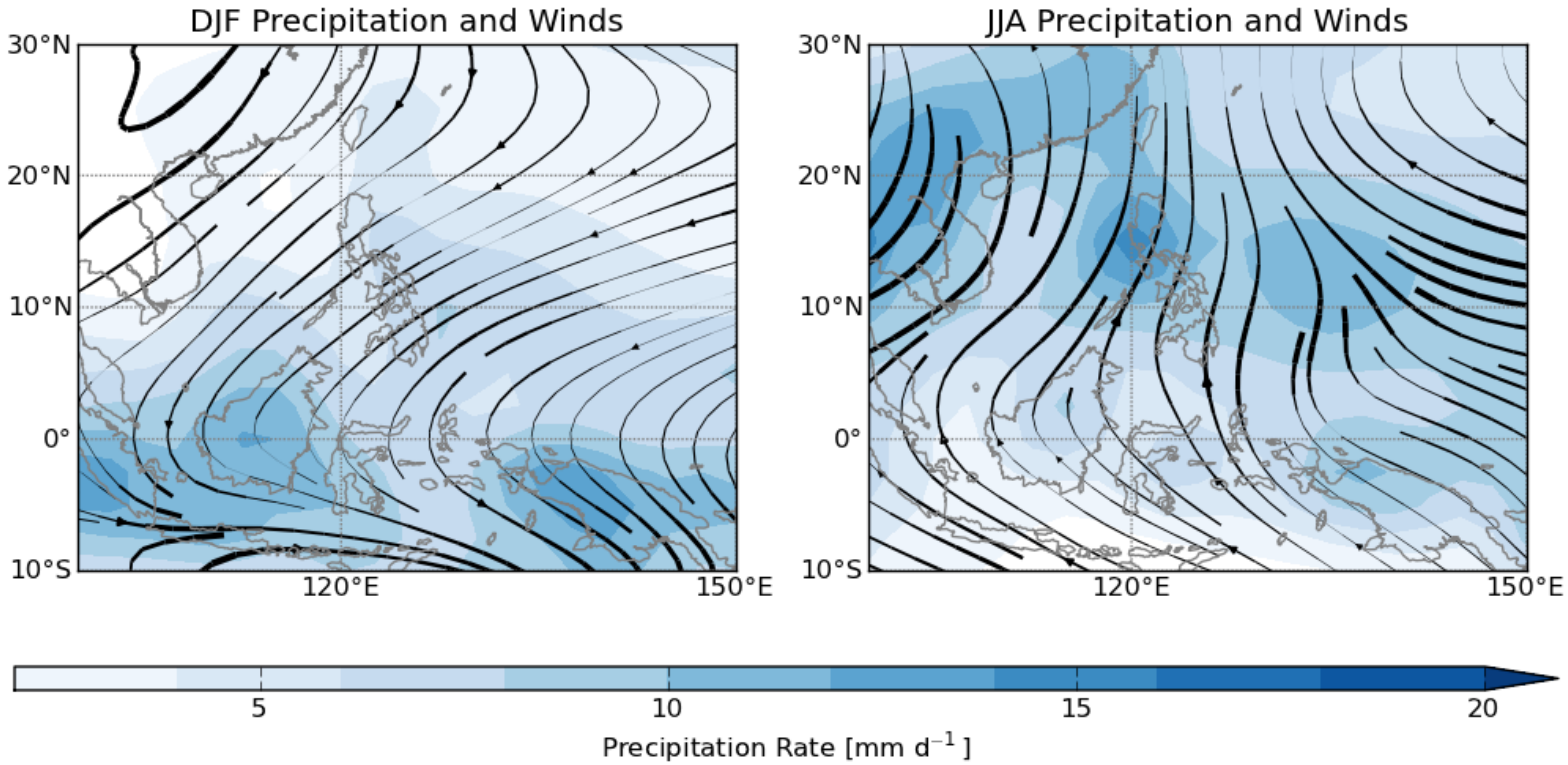


Data source: CFSR

Australasian Monsoon

Western North Pacific monsoon

- an oceanic component of the Asian monsoon system
- monsoon onset is in mid-summer, much later than over South and East Asia
- meridional SST and pressure gradients are relatively small, but convection is as active as in the South Asian monsoon
- important for tropical cyclone tracks in the Pacific

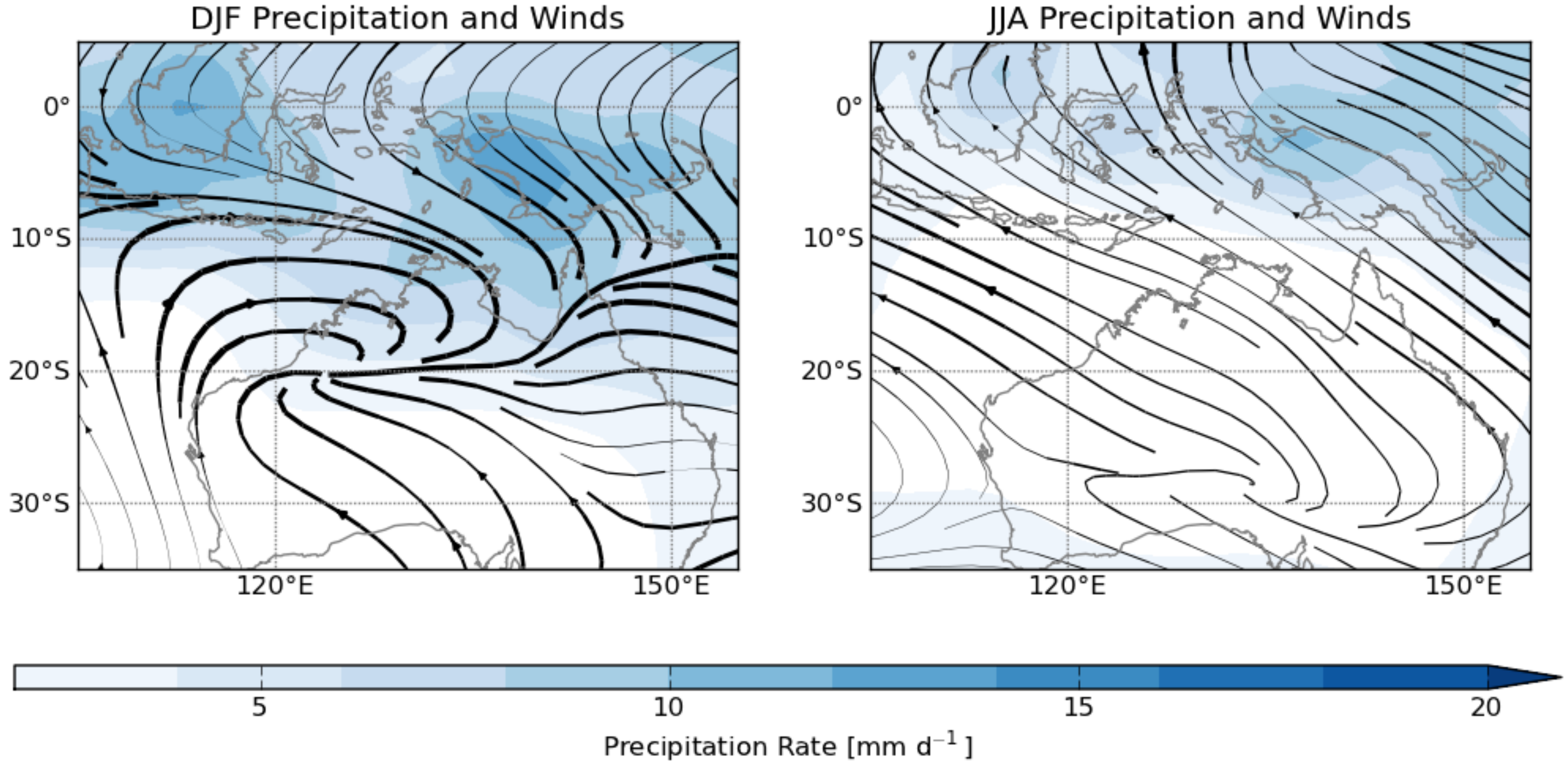


Data source: CFSR

Australasian Monsoon

Indonesian–Australian monsoon

- the southern hemisphere component of the Asian monsoon system
- effects mainly confined to area north of 20°S
- dry during May–October, wet during December–February
- strength of monsoon dependent on strength of cross-equatorial flow, with interannual variability in tandem with the South Asian monsoon

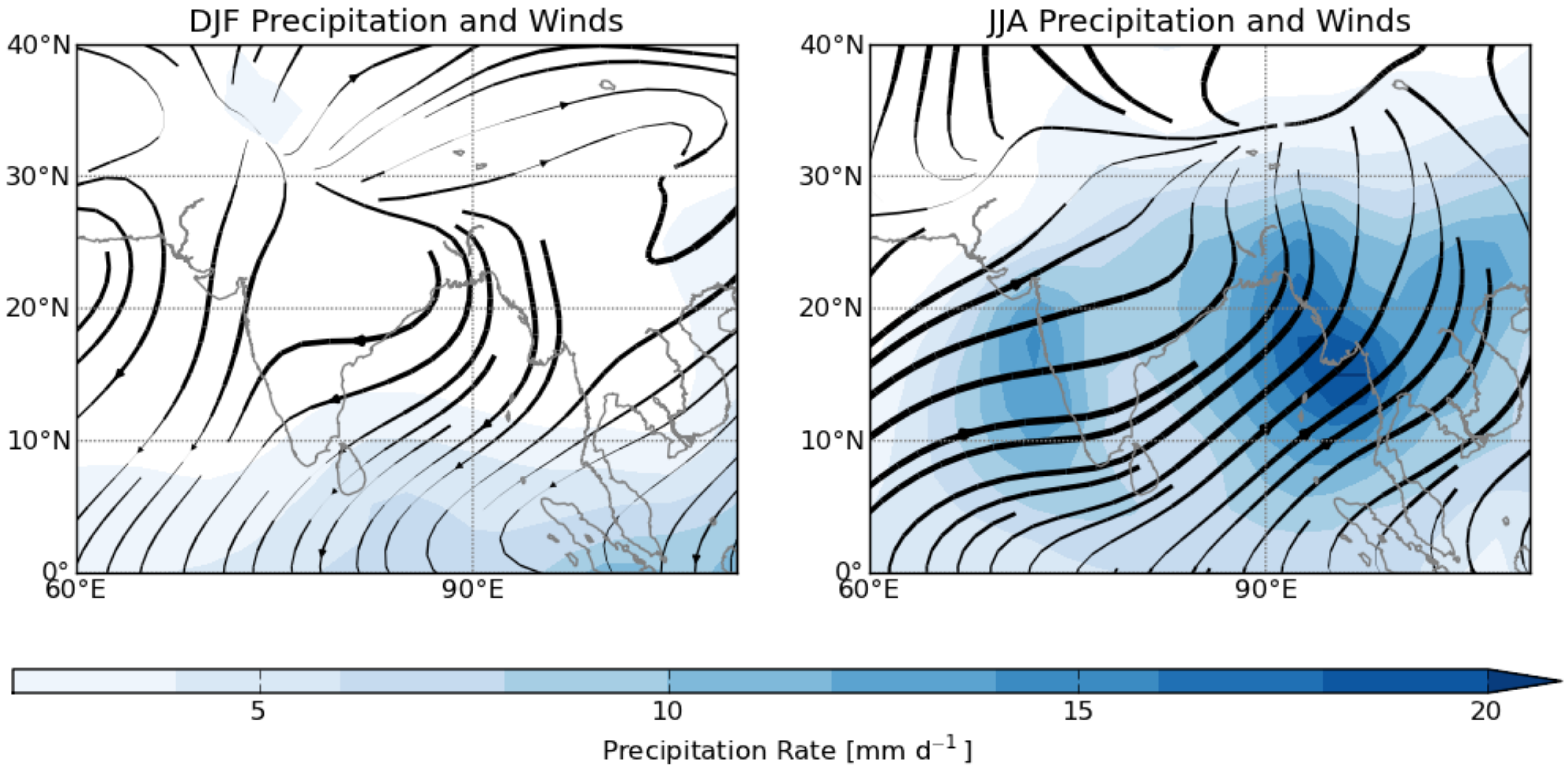


Data source: CFSR

Australasian Monsoon

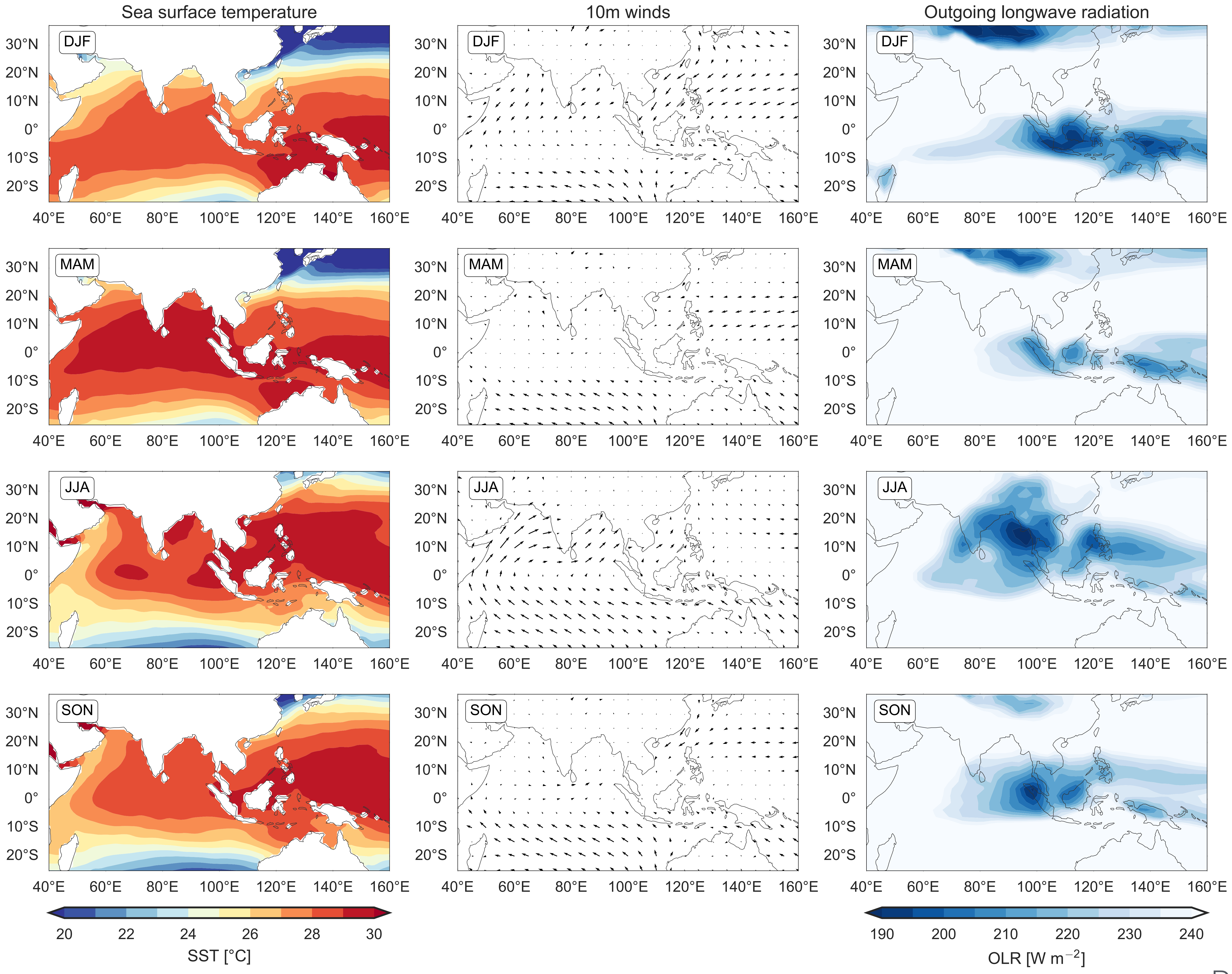
South Asian monsoon

- largest and most powerful of the regional monsoons
- accounts for about 80% of the rainfall in India
- orography plays important roles:
  (1) shapes the monsoon circulation and isolates moist tropical air from dry extratropical air
  (2) mechanical heating and uplift enhance the mid-tropospheric heat source



Data source: CFSR

The Coupled Annual Cycle



AUSTRALIAN MONSOON

WARMEST SSTs

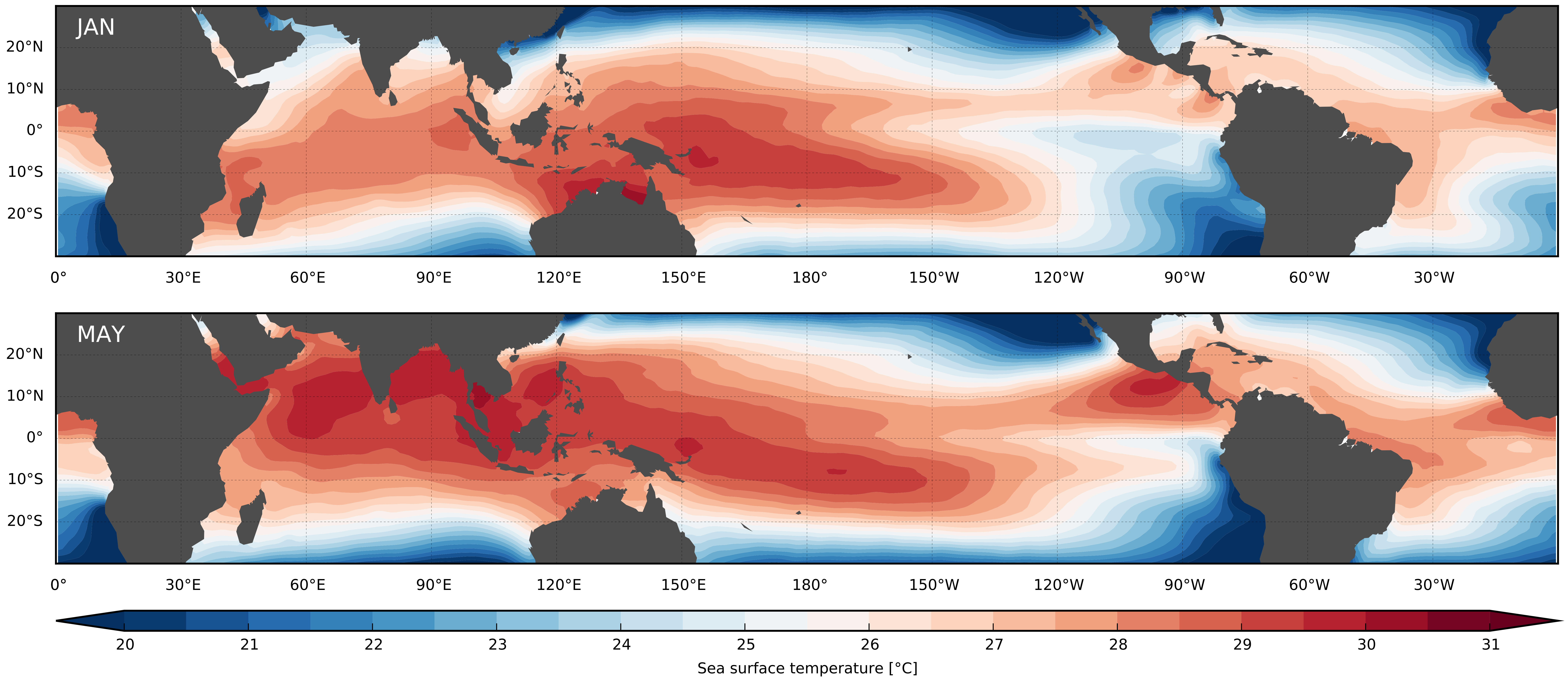
UPWELLING IN WEST IO

ASIAN MONSOON

Data source: COBE, JRA-55, HIRS OLR

The Coupled Monsoon

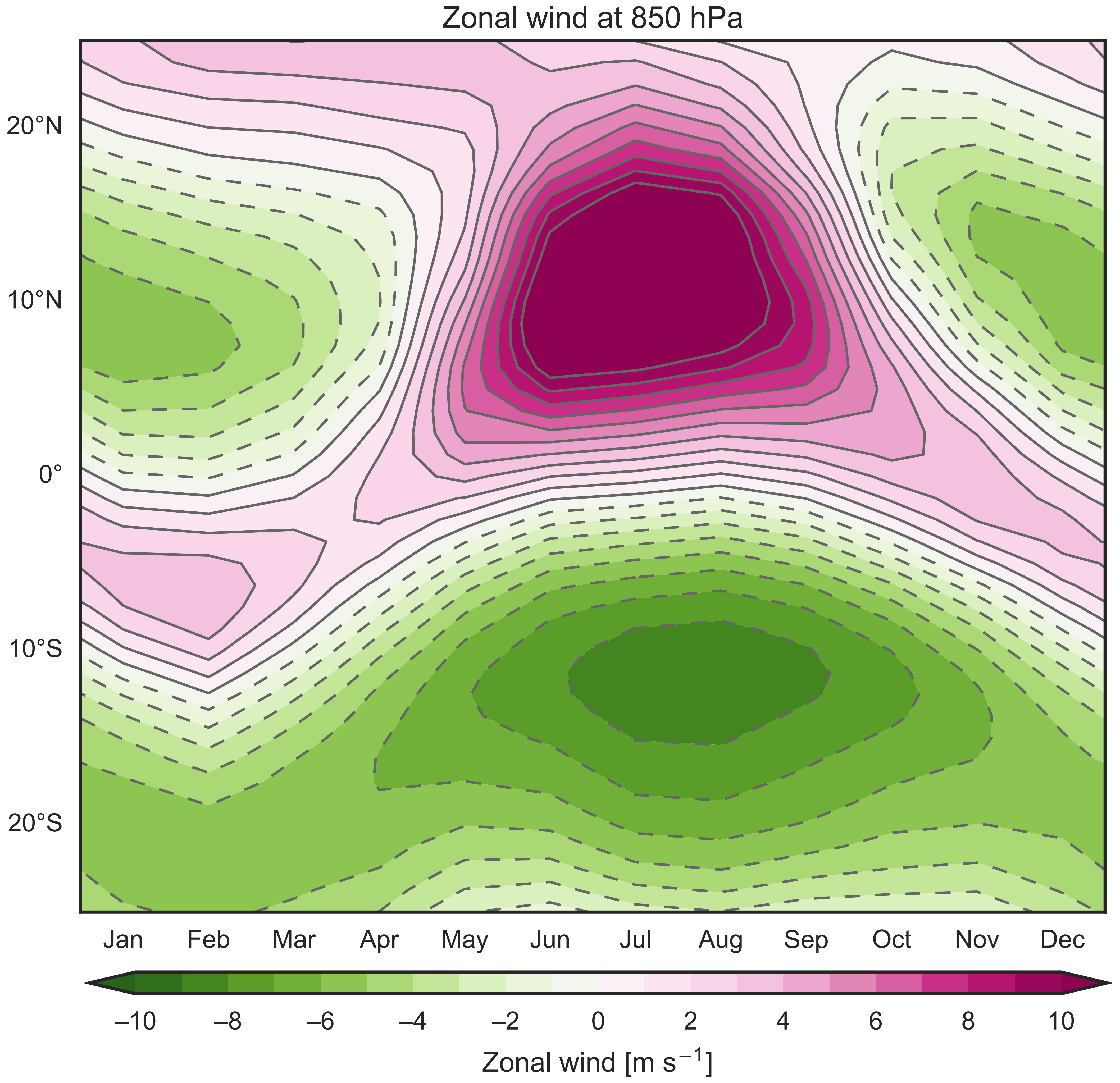
The South Asian monsoon rainy season follows a northwestward shift of the location of the warm pool into the Bay of Bengal

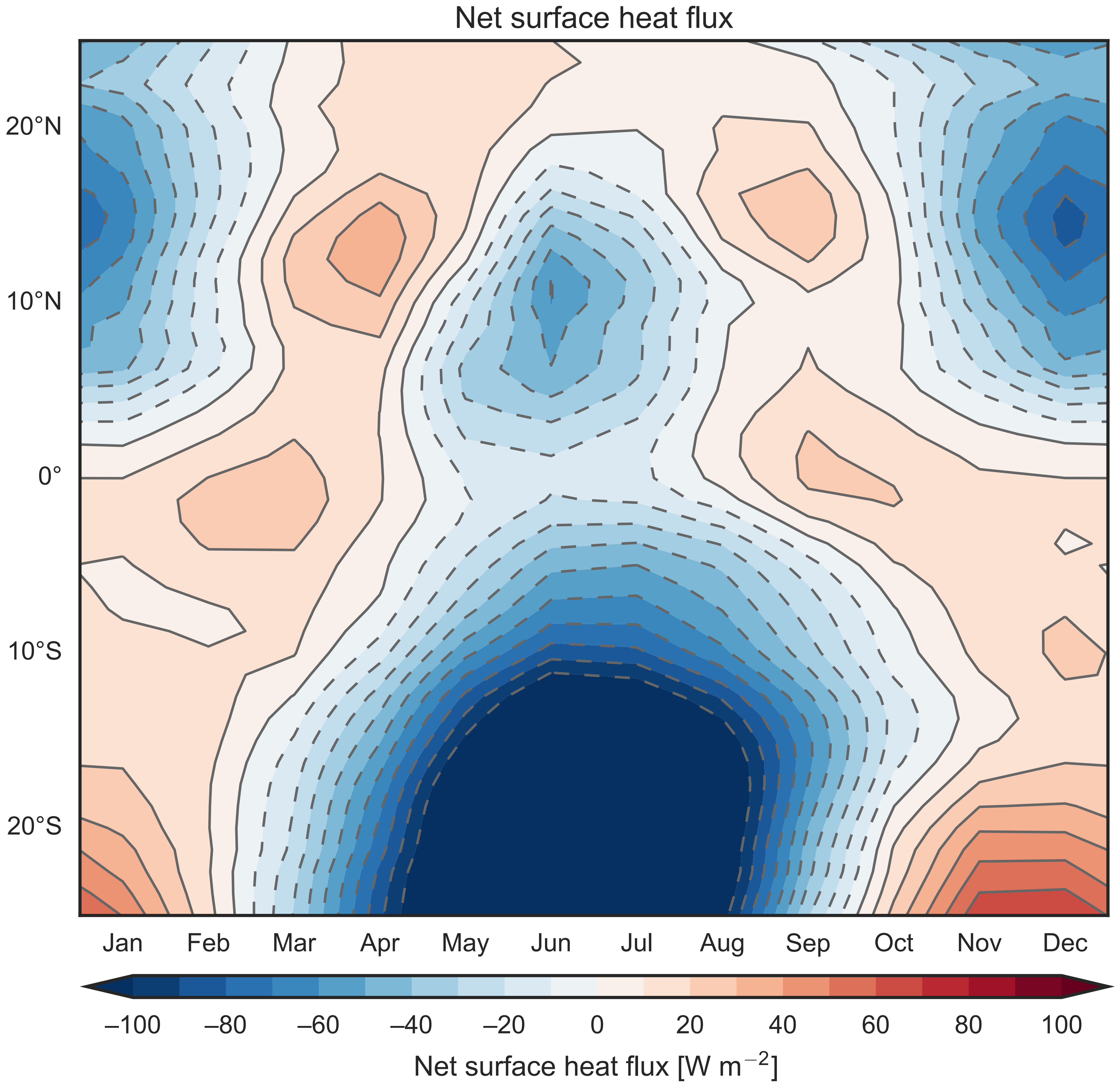


Data source: COBE

The Coupled Monsoon

Weak winds and low cloud cover during boreal spring associated with strong heat flux into the North Indian Ocean

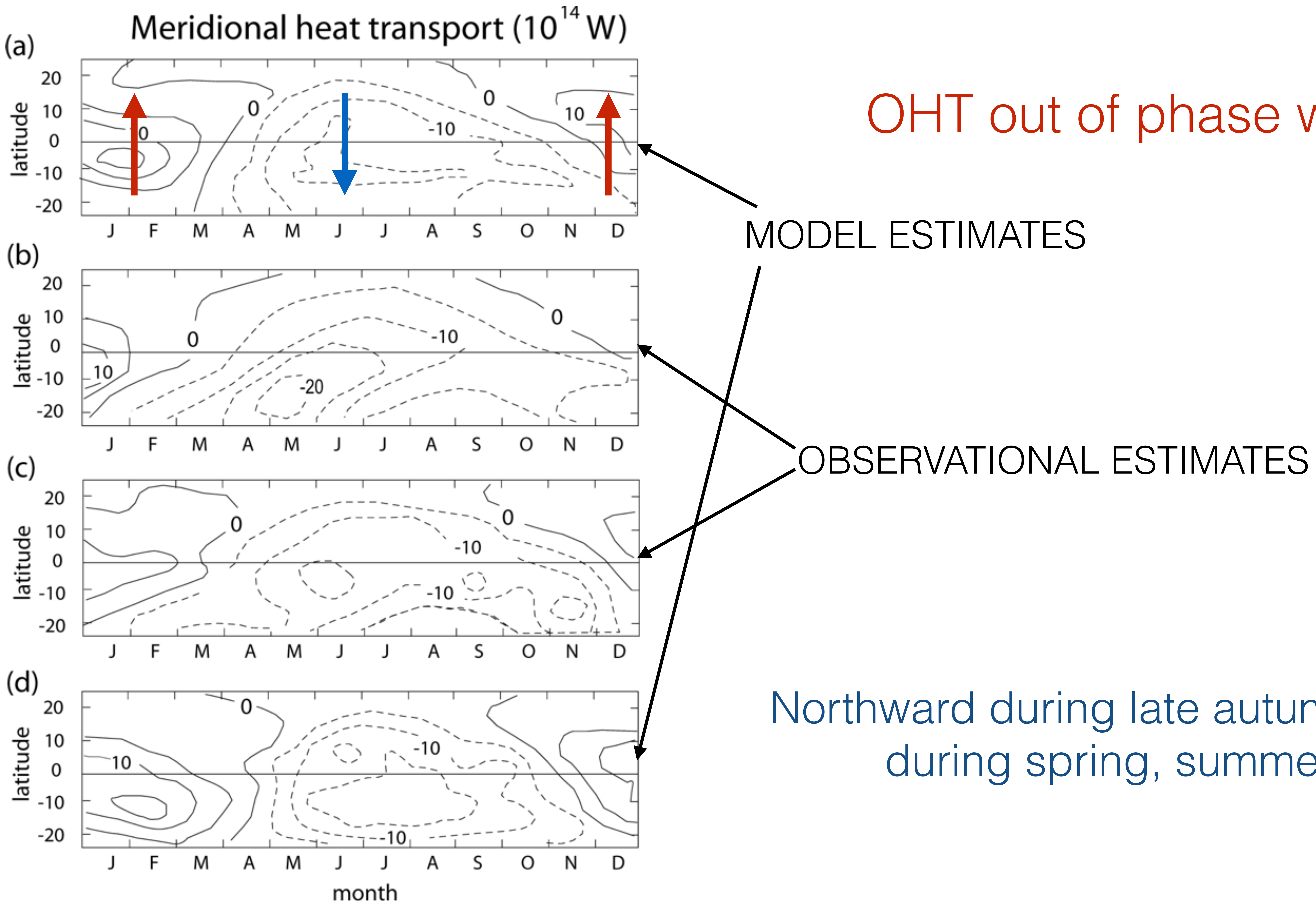




Data source: JRA-55

The Coupled Monsoon

In addition to surface heat fluxes into the Indian Ocean, ocean heat transport contributes to springtime warming



OHT out of phase with solar heating

Northward during late autumn and winter, southward during spring, summer and early autumn

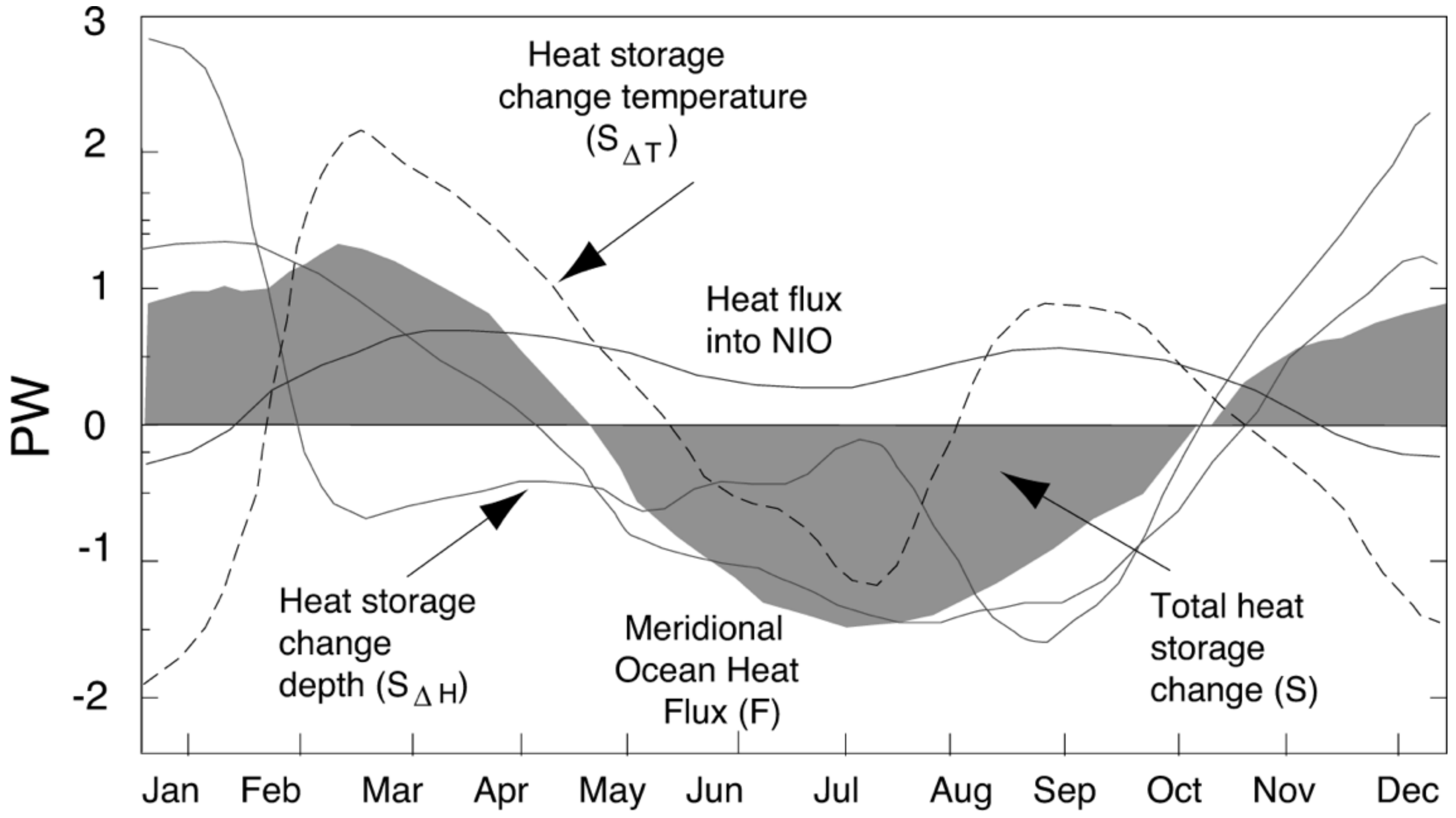
Webster, 2006

The Coupled Monsoon

Changes in ocean heat storage can be broken down into two terms: changes in temperature for a layer of constant depth, and changes in depth for a layer of constant temperature

$$S_{\Delta T}(t) = \rho_w C_w \int\int H(t)\frac{\partial T(t)}{\partial t}dxdy$$

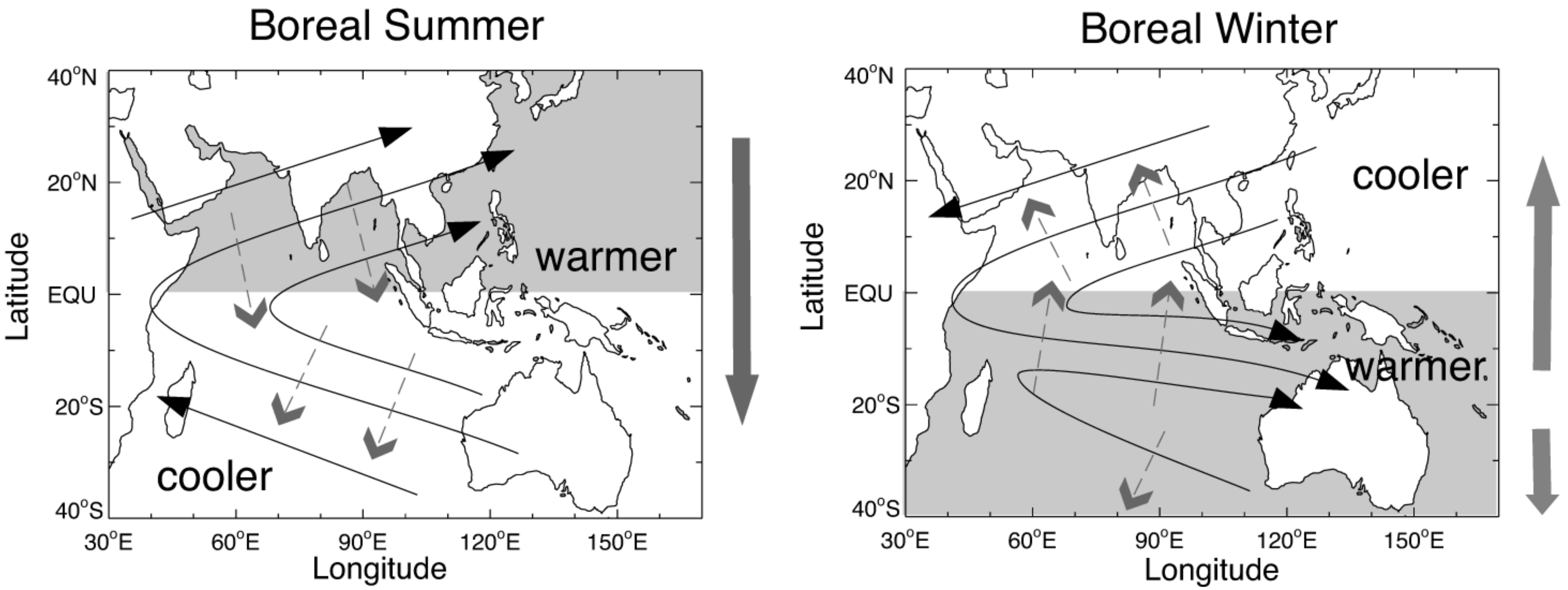
$$S_{\Delta H}(t) = \rho_w C_w \int\int T(t)\frac{\partial H(t)}{\partial t}dxdy$$



Webster, 2006

The Coupled Monsoon

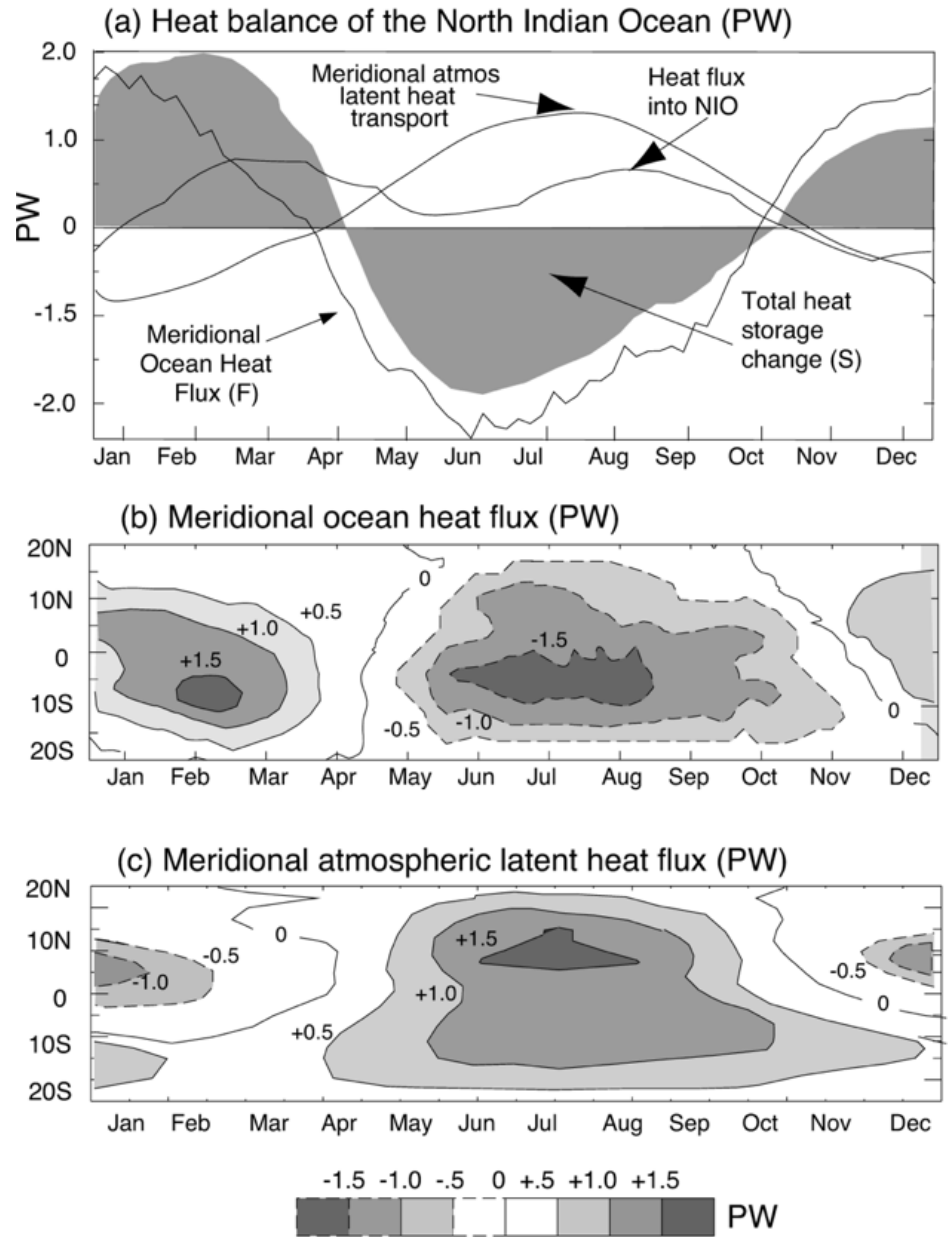
- ocean transport is driven by atmospheric circulation
- atmospheric circulation is driven by the surface fluxes associated with the buoyancy gradient (land–sea and hemispheric thermal contrasts)
- the monsoon seasonal cycle is modulated by a negative atmosphere–ocean feedback associated with Ekman transport



Webster, 2006

The Coupled Monsoon

Energy transports due to cross-equatorial winds in the lower atmosphere and Ekman currents in the upper ocean compensate



The ocean moves energy from the summer hemisphere to the winter hemisphere

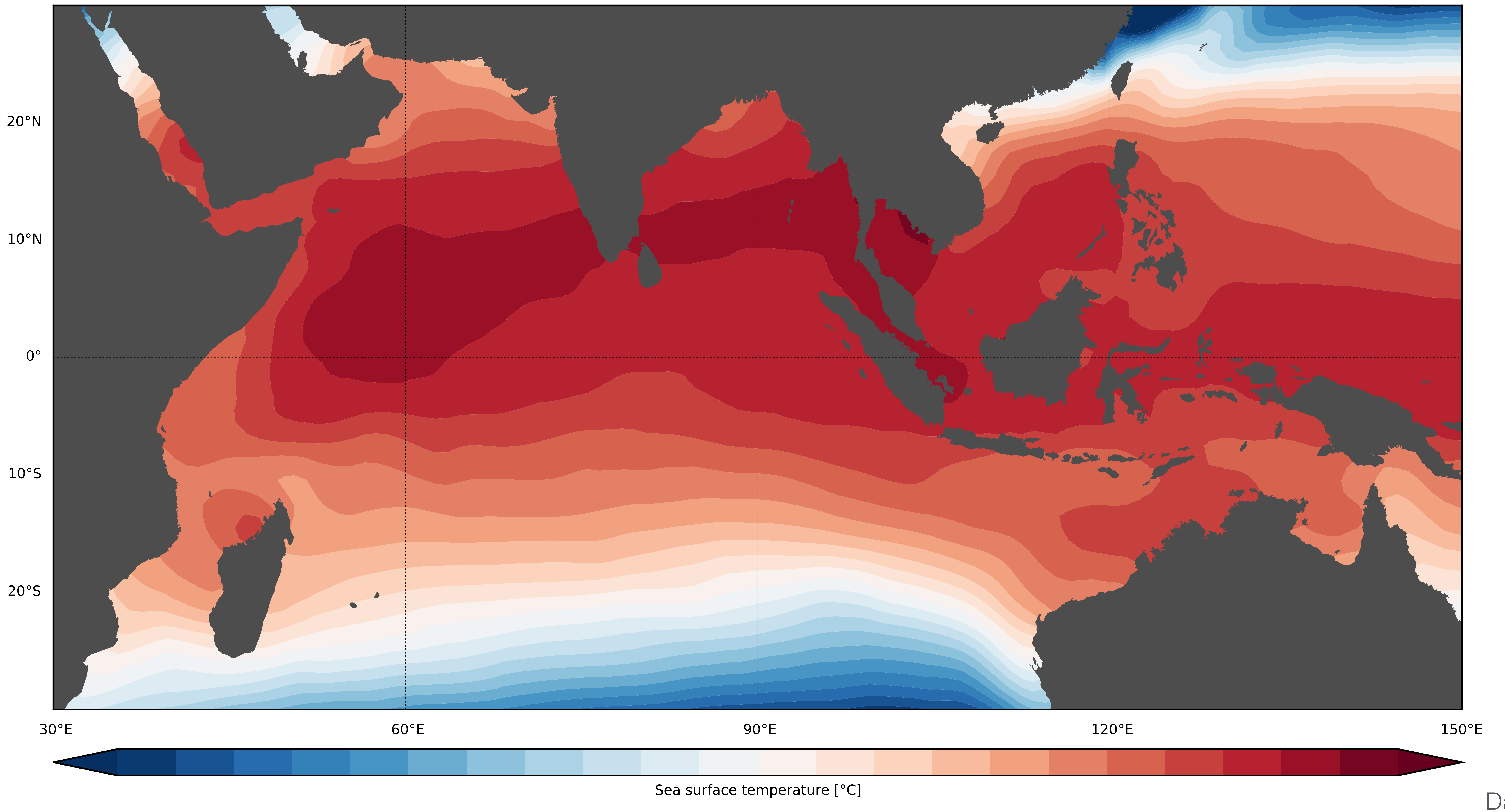
The atmosphere moves energy from the winter hemisphere to the summer hemisphere

Webster, 2006

Monsoon Onset

Sea surface temperatures in the Bay of Bengal warm rapidly in the weeks leading up to monsoon onset (typically mid-May to mid-June)

4 weeks before onset



Data source: COBE

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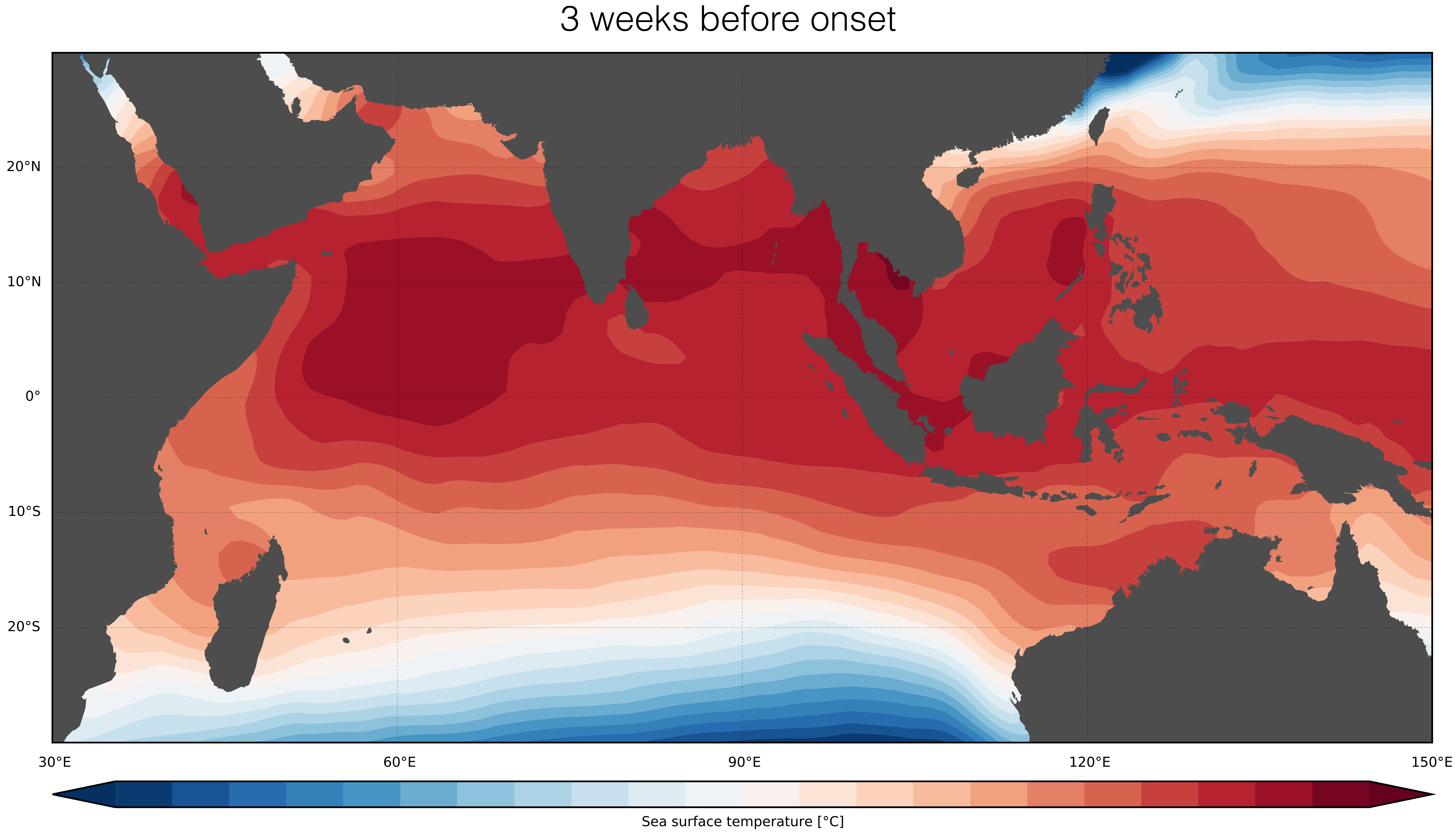
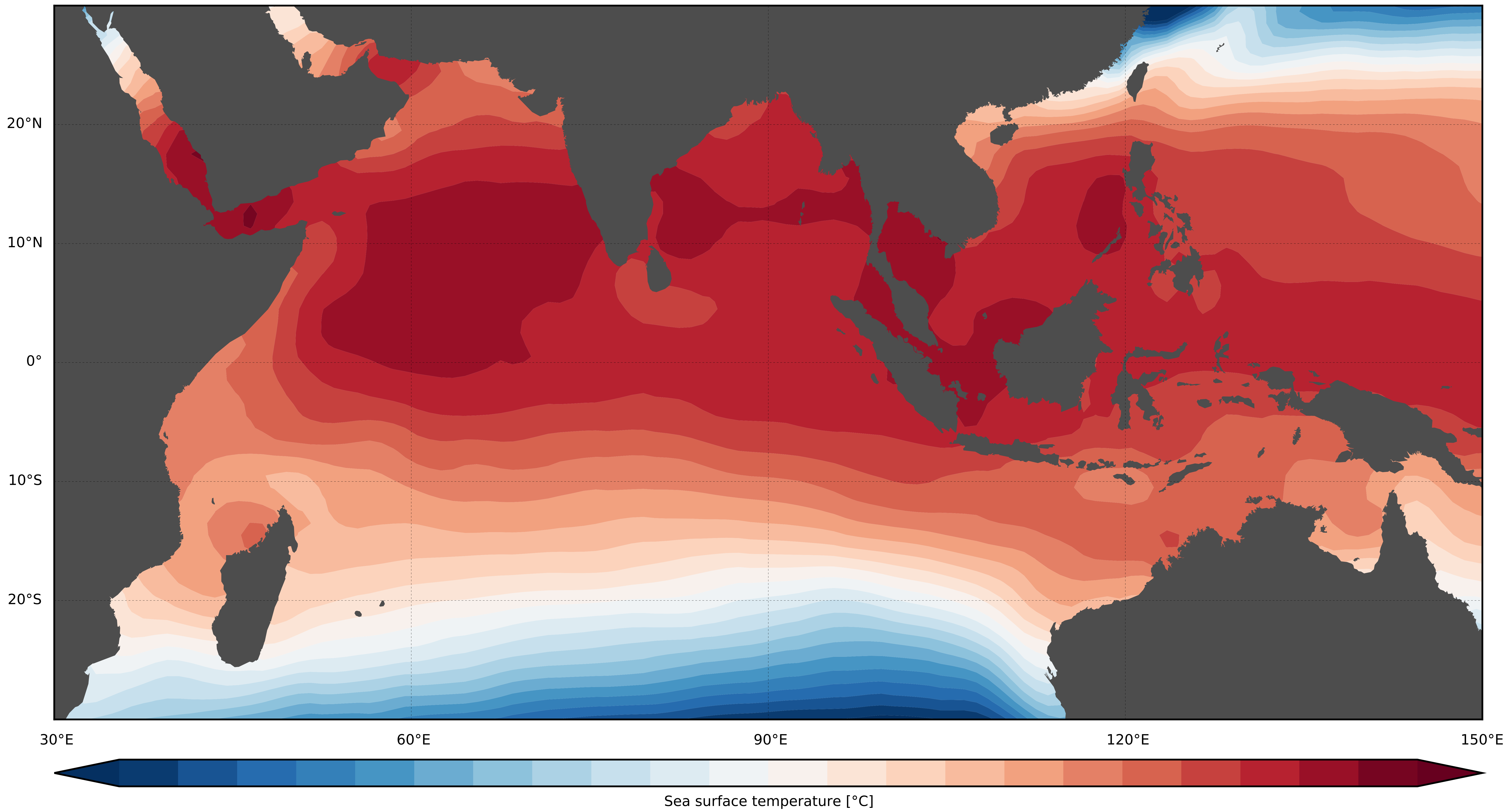


Data source: COBE

Monsoon Onset

Sea surface temperatures in the Bay of Bengal warm rapidly in the weeks leading up to monsoon onset (typically mid-May to mid-June)

2 weeks before onset

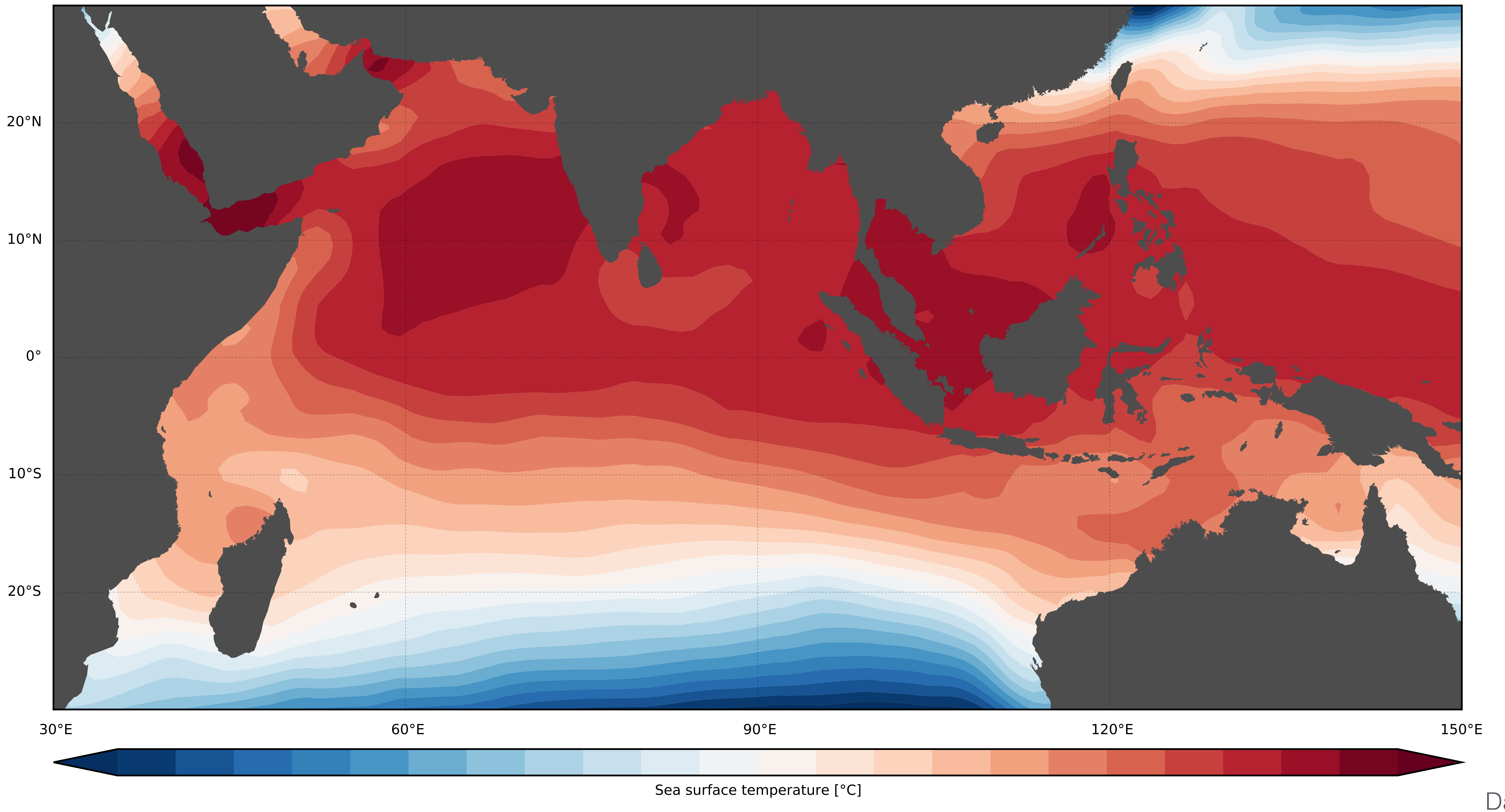


Data source: COBE

Monsoon Onset

Sea surface temperatures in the Bay of Bengal warm rapidly in the weeks leading up to monsoon onset (typically mid-May to mid-June)

1 weeks before onset



Data source: COBE

Monsoon Onset

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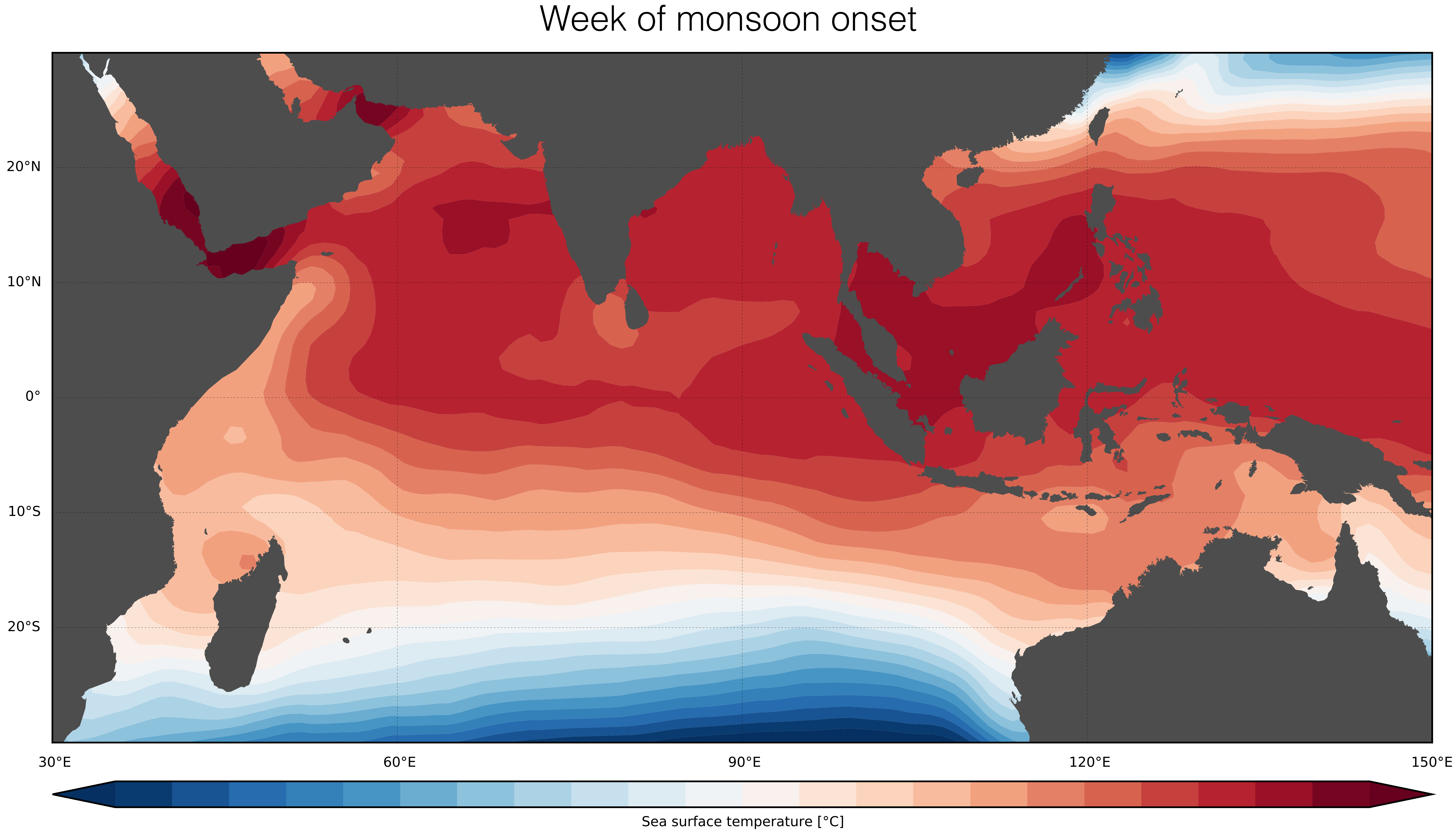
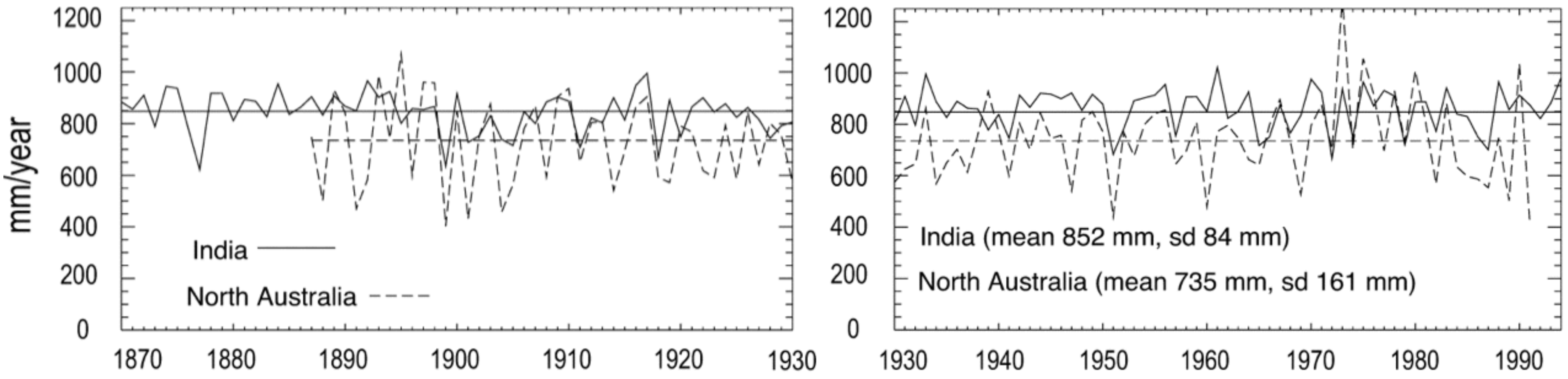


Data source: COBE

Rainfall Variability

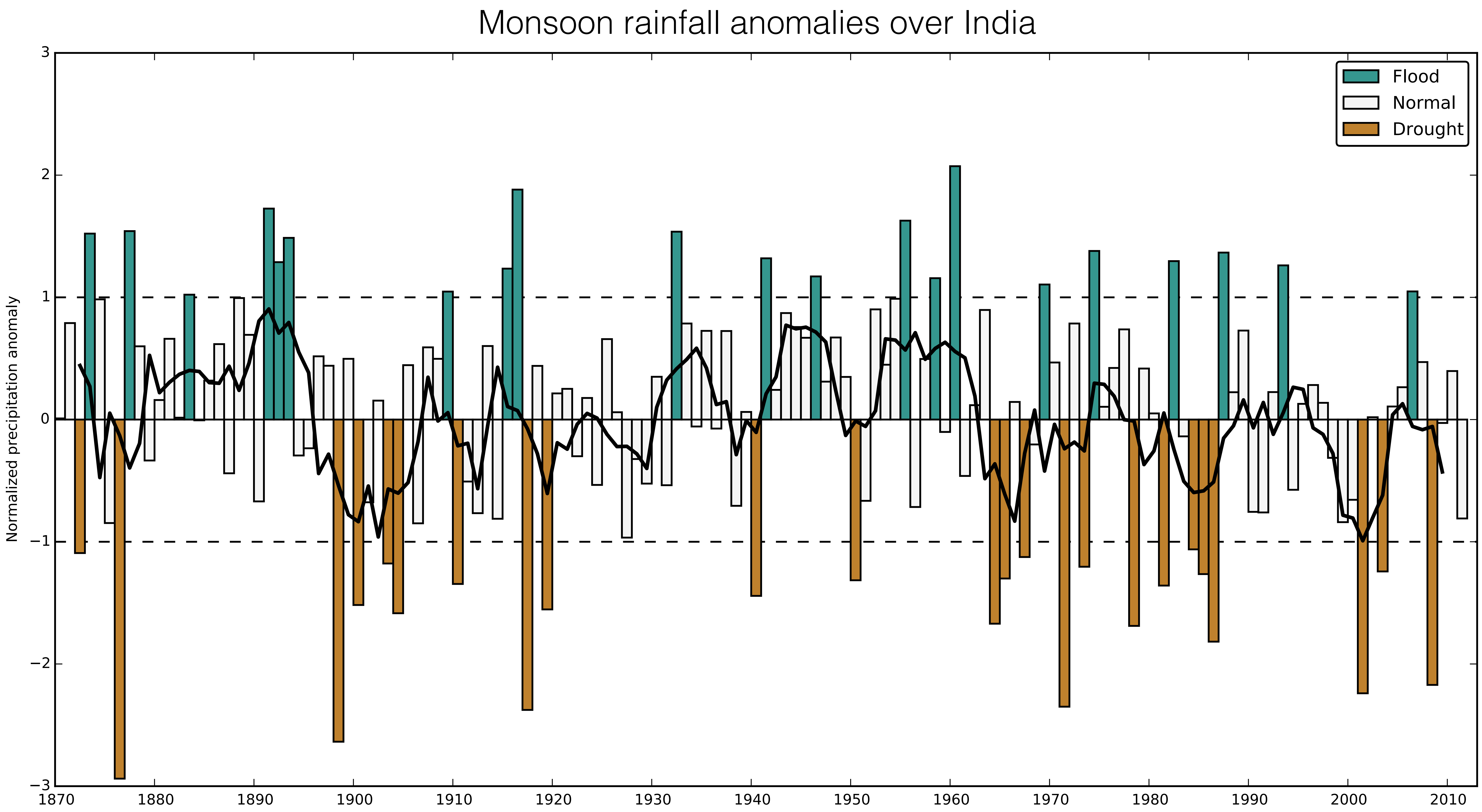


Strong interannual variability in rainfall associated with both the South Asian and Indonesian–Australian monsoons — why?

Webster, 2006

Rainfall Variability

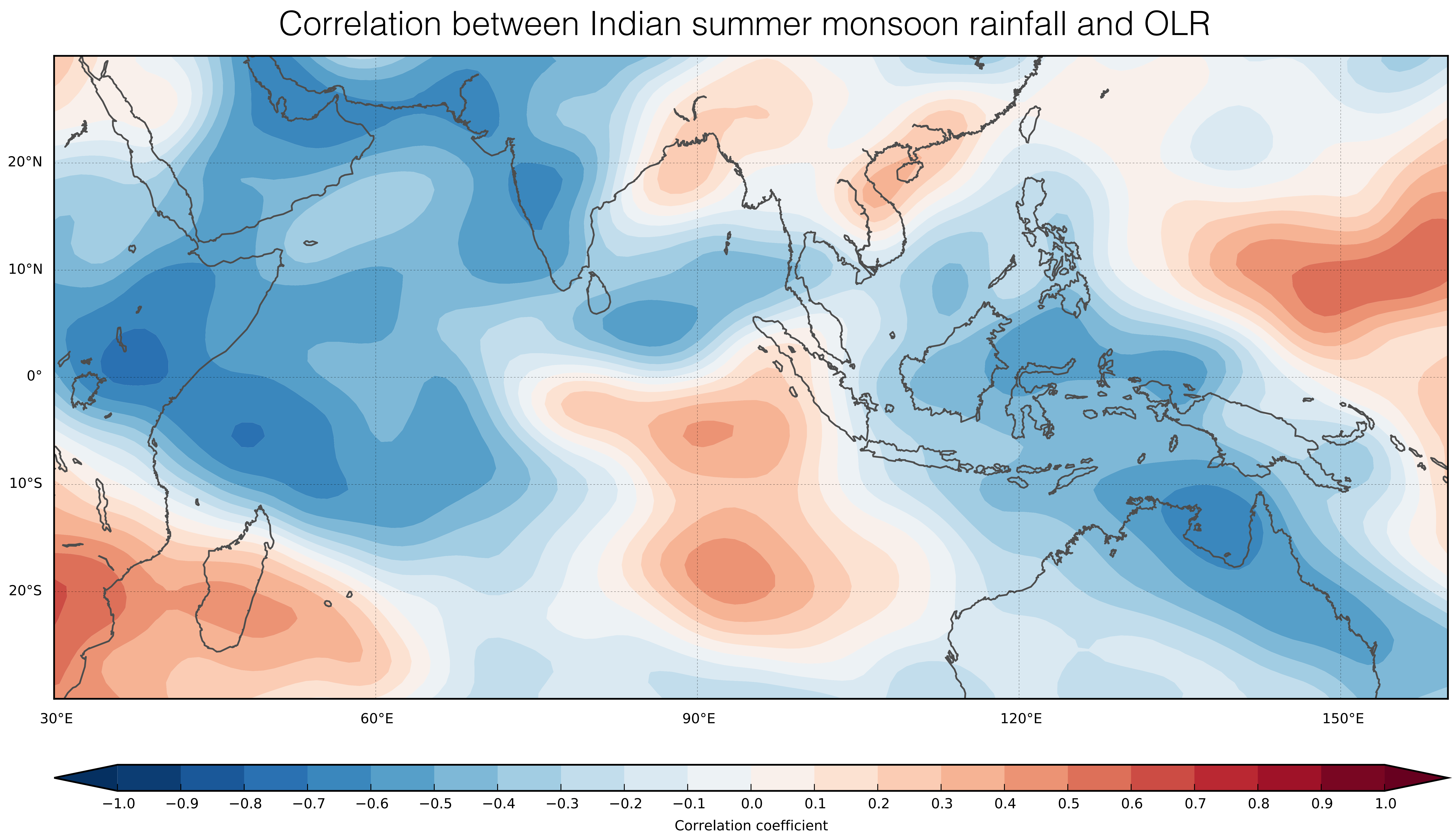
South Asian monsoon rainfall varies on multiple time scales, including interdecadal and interannual time scales



Data source: India Meteorological Department

Interannual Variability

Correlations between rainfall and OLR show shifts in the dominant locations of convection in flood and drought years

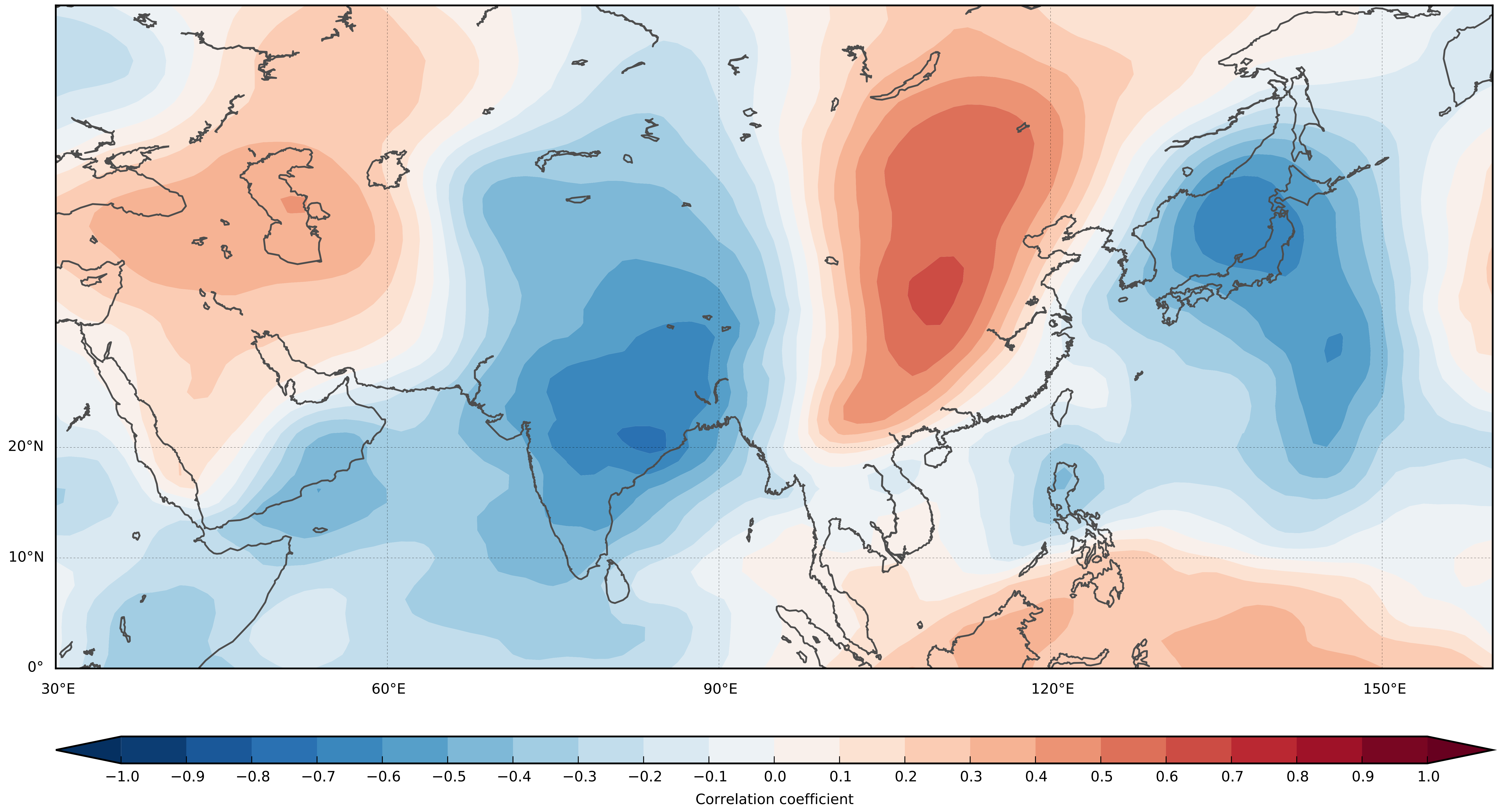


Data source: CERES Syn1Deg

Interannual Variability

Correlations between rainfall and upper tropospheric meridional wind show that SASM variability can have global impacts

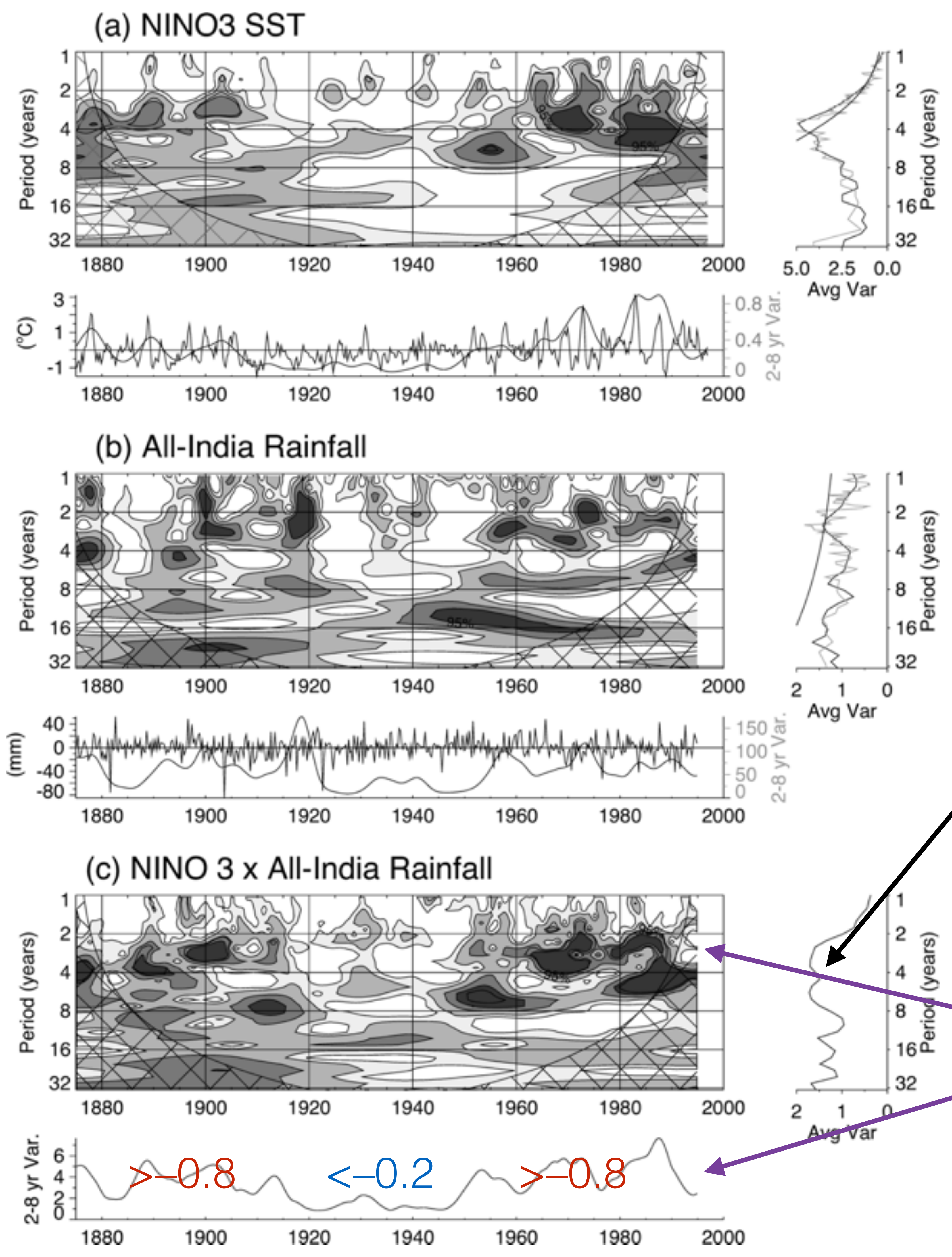
Correlation between Indian summer monsoon rainfall and 200 hPa *v* wind



Data source: JRA-55

Interannual Variability: ENSO

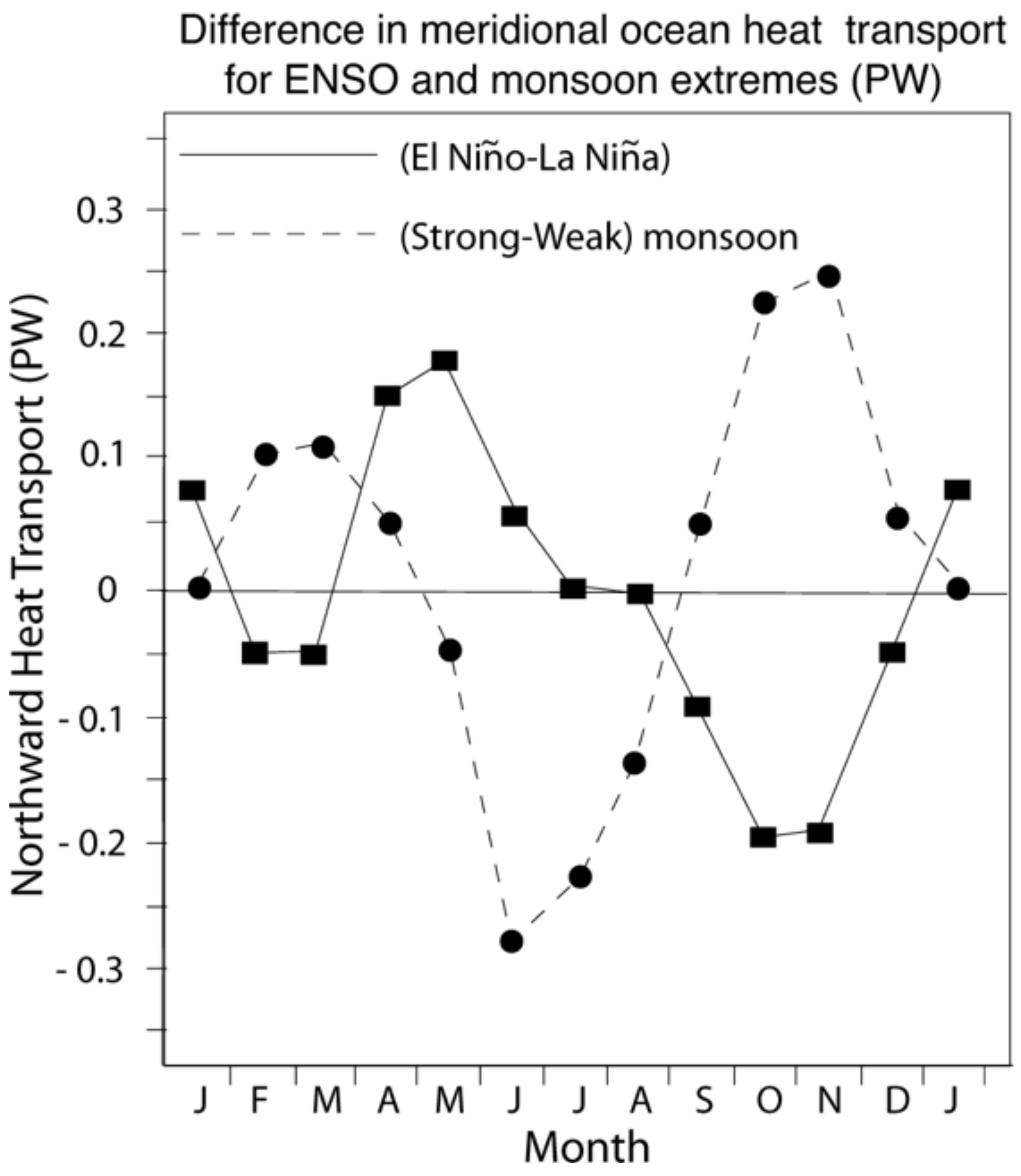
Interannual variability in the Asian monsoon was first tied to ENSO in the 1920s



El Niño — below average
La Niña — above average

Accounts for about 40% of interannual variance in monsoon precipitation

Relationship varies with time

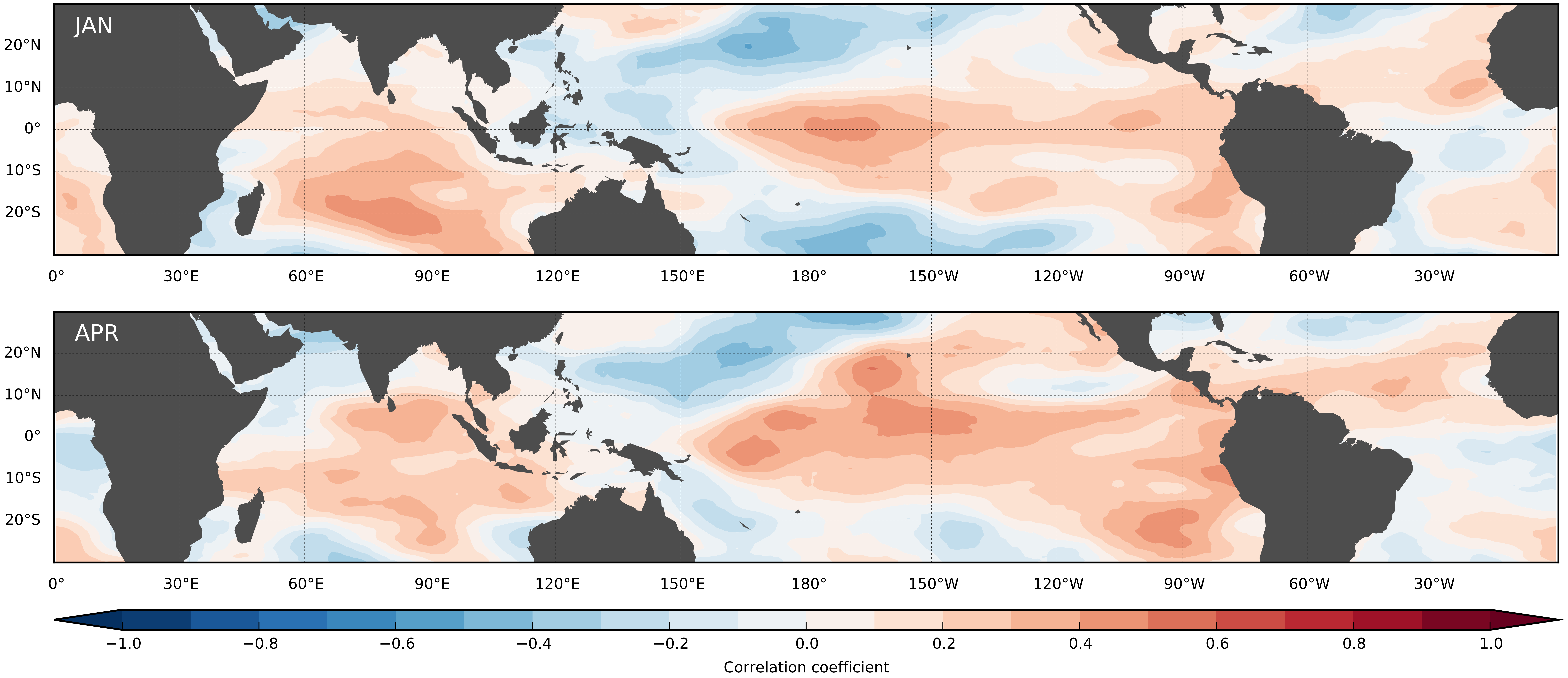


Webster, 2006

Interannual Variability: ENSO

Part of the ENSO effect is that monsoon onset occurs later in the year during El Niño years

Correlation between onset date and SST



Data source: COBE

Biennial Variability

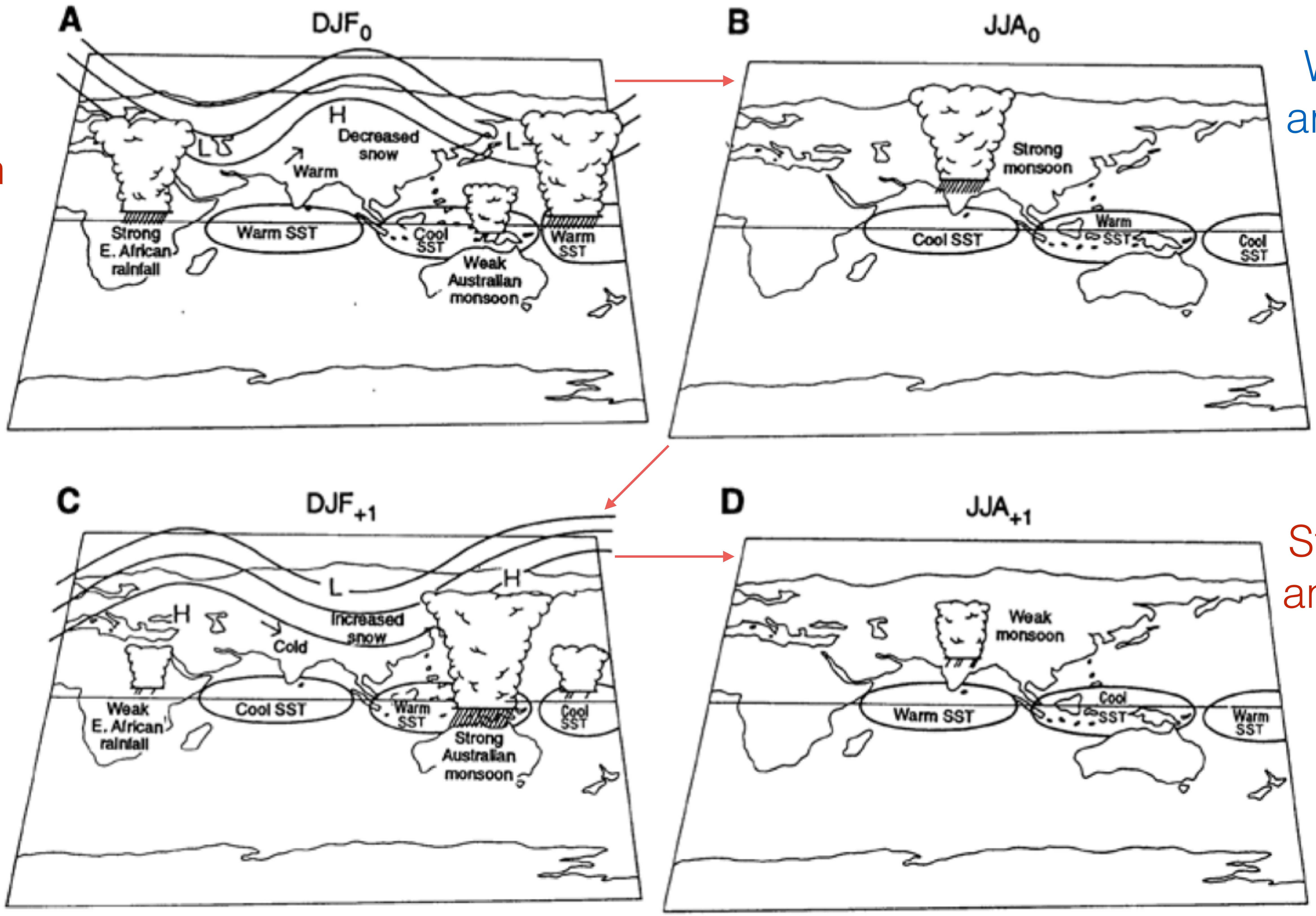
Tendency for weak monsoon to follow strong monsoon and vice versa (in both South Asia and Australia)

Warm SST in west precedes strong South Asian monsoon

Weaker surface heating and stronger OHT reduce SST in Indian Ocean

Warm SST in east causes strong Australian monsoon

Stronger surface heating and weaker OHT increase SST in Indian Ocean

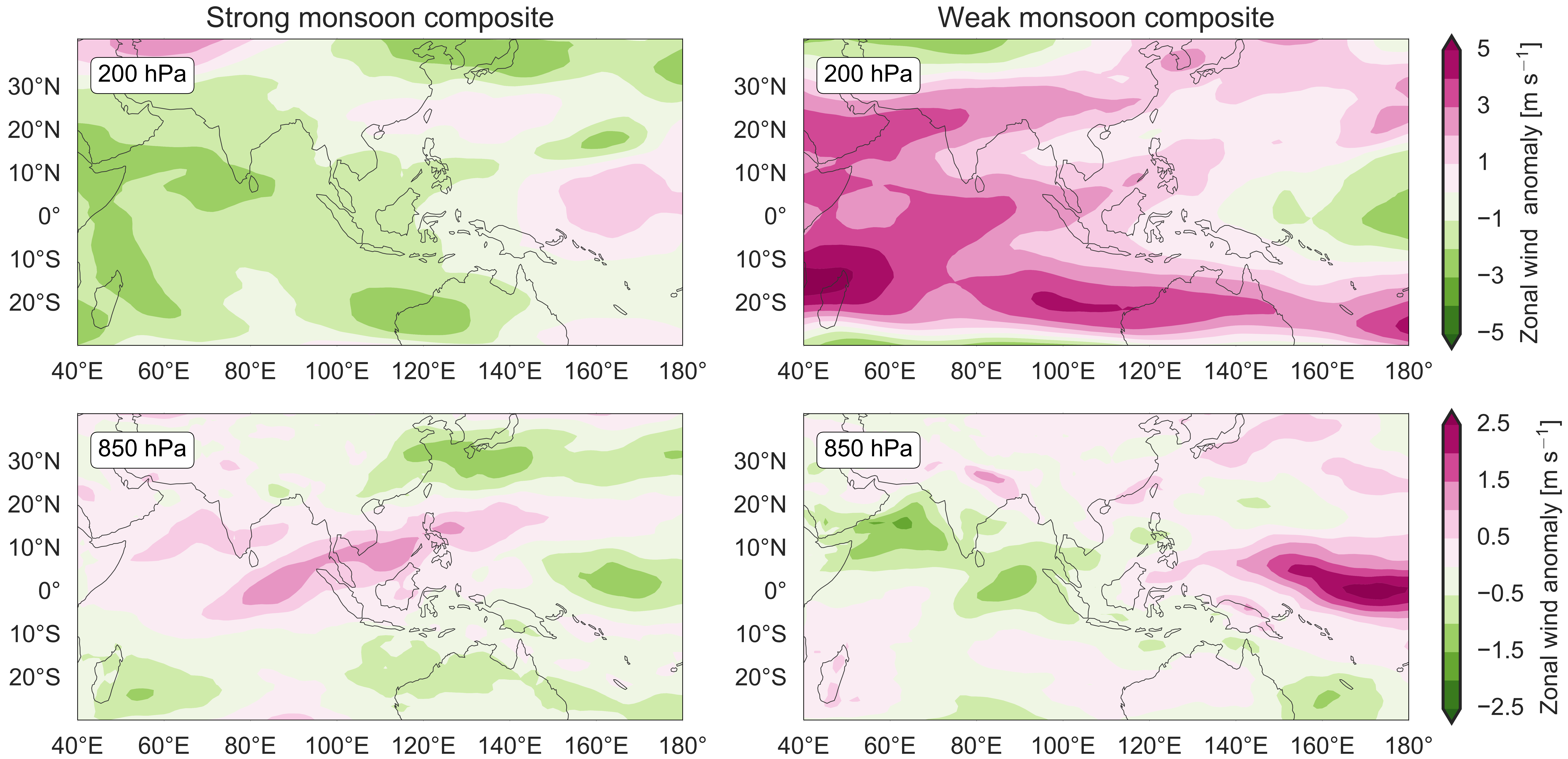


Cool SST in west leads to weak monsoon

Webster, 2006

Biennial Variability

Systematic large-scale differences in both upper and lower level winds between strong and weak South Asian monsoons



Data source: JRA-55

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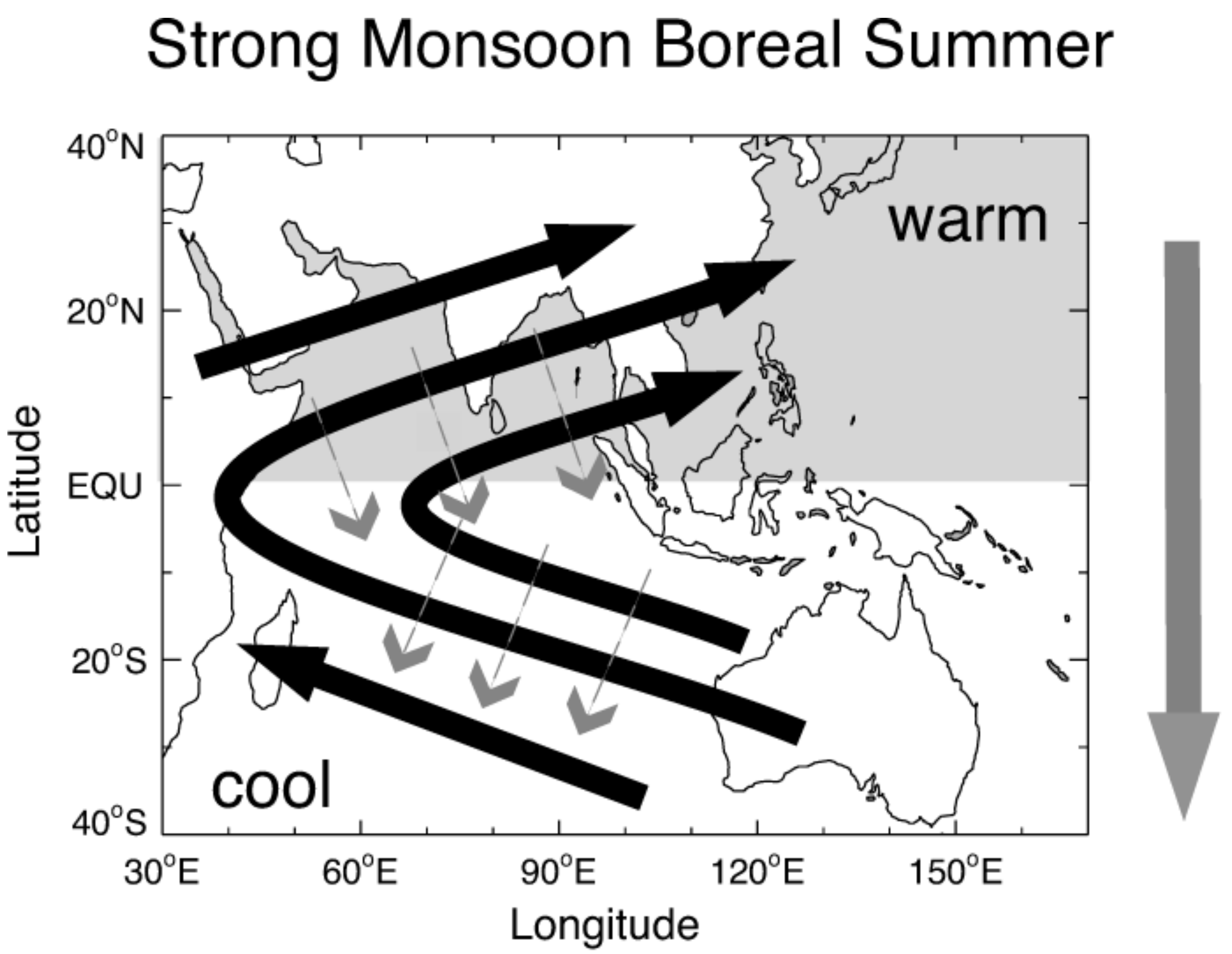
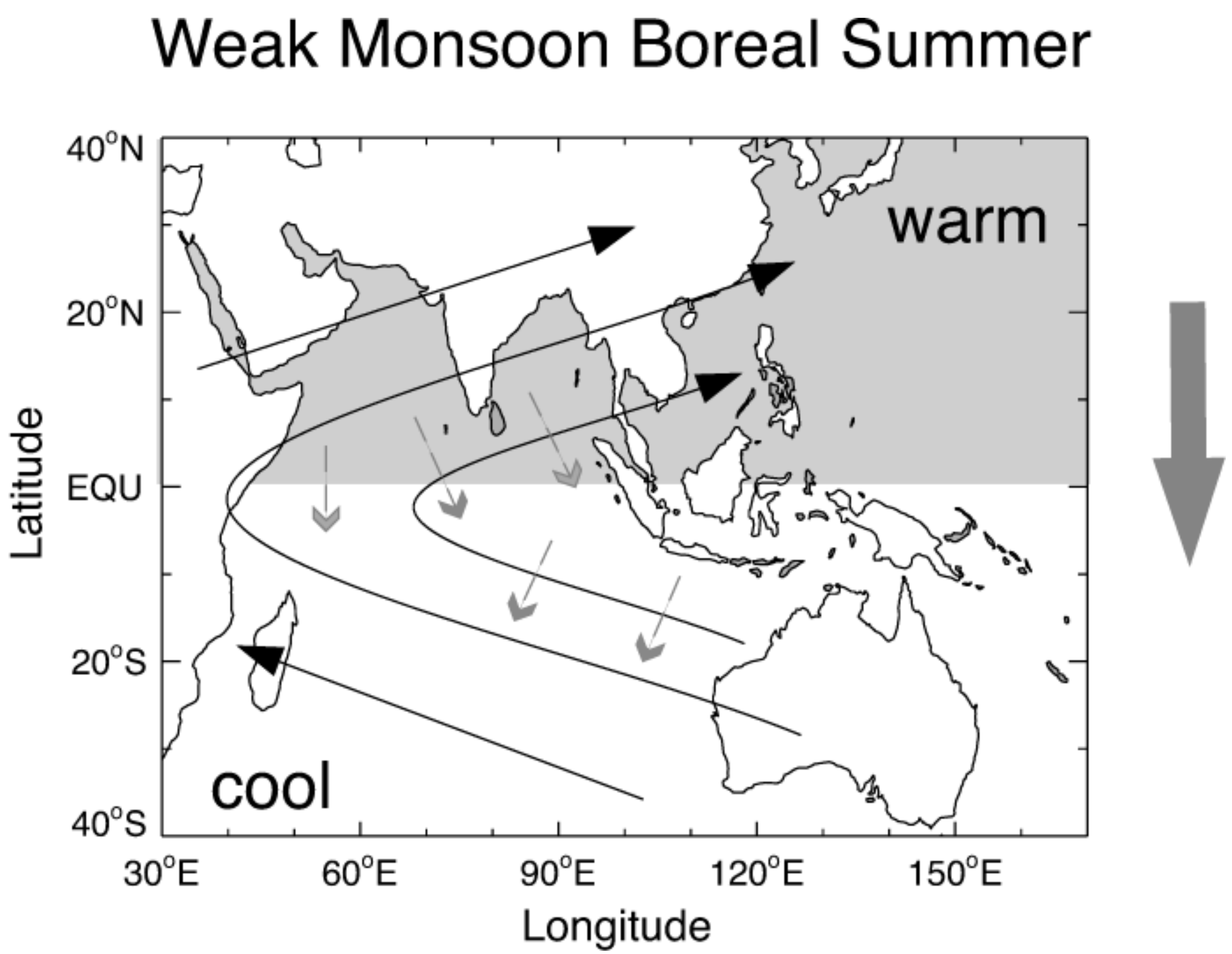


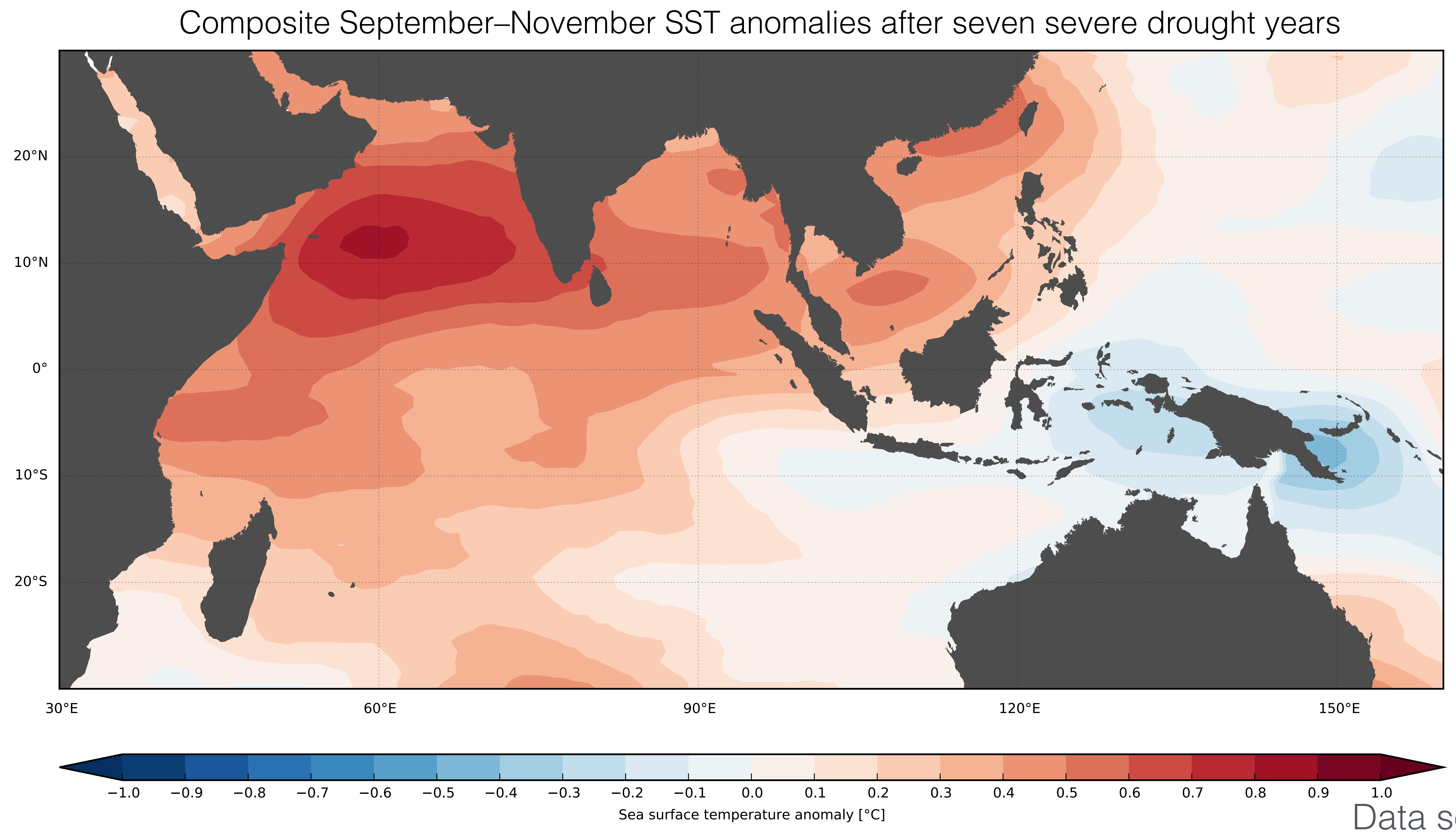


Variability of Ekman heat transport from the summer to the winter hemisphere

Webster, 2006

Biennial Variability

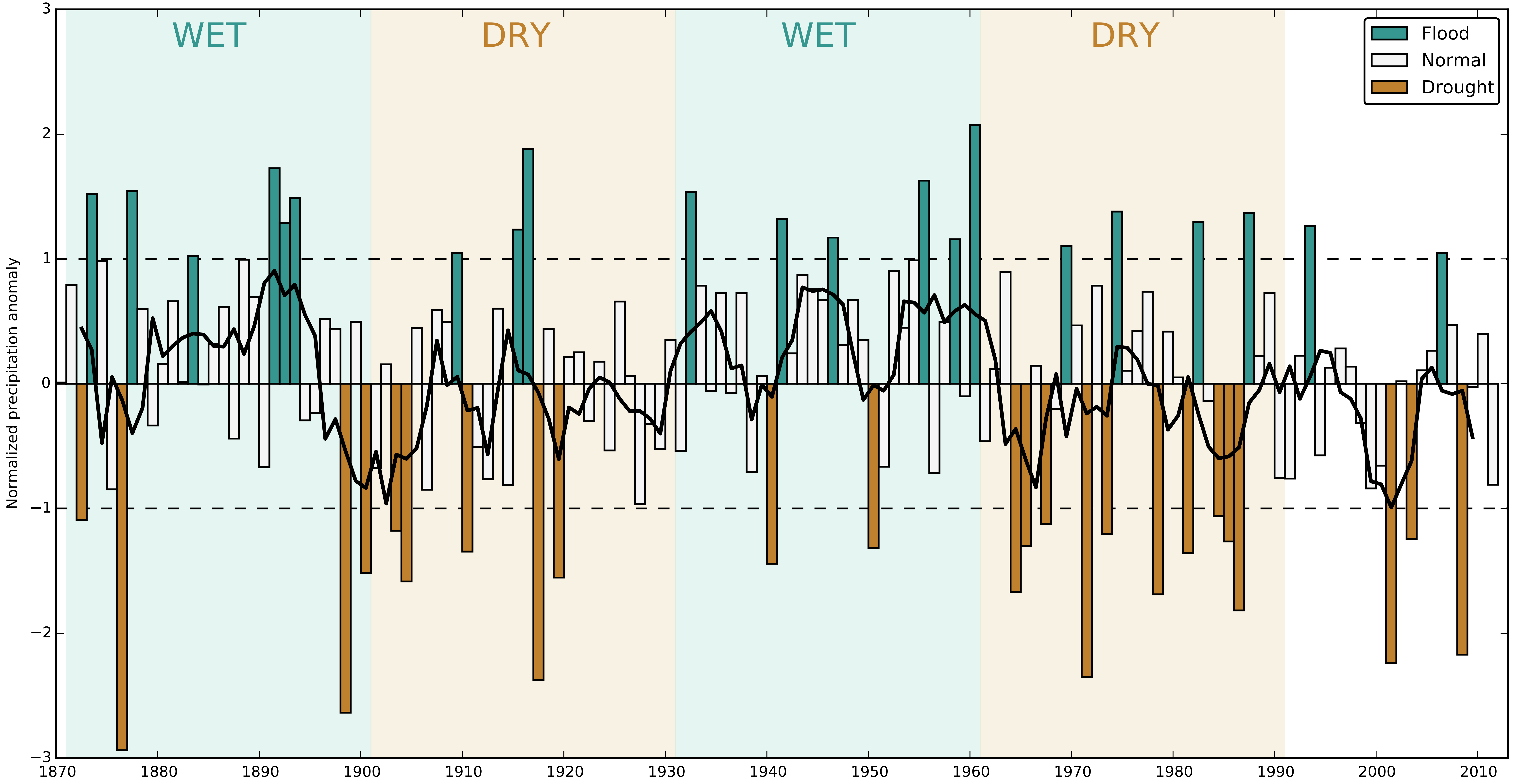
SST in the North Indian Ocean is anomalously warm following drought years



Data source: COBE

Interdecadal Variability and Trends

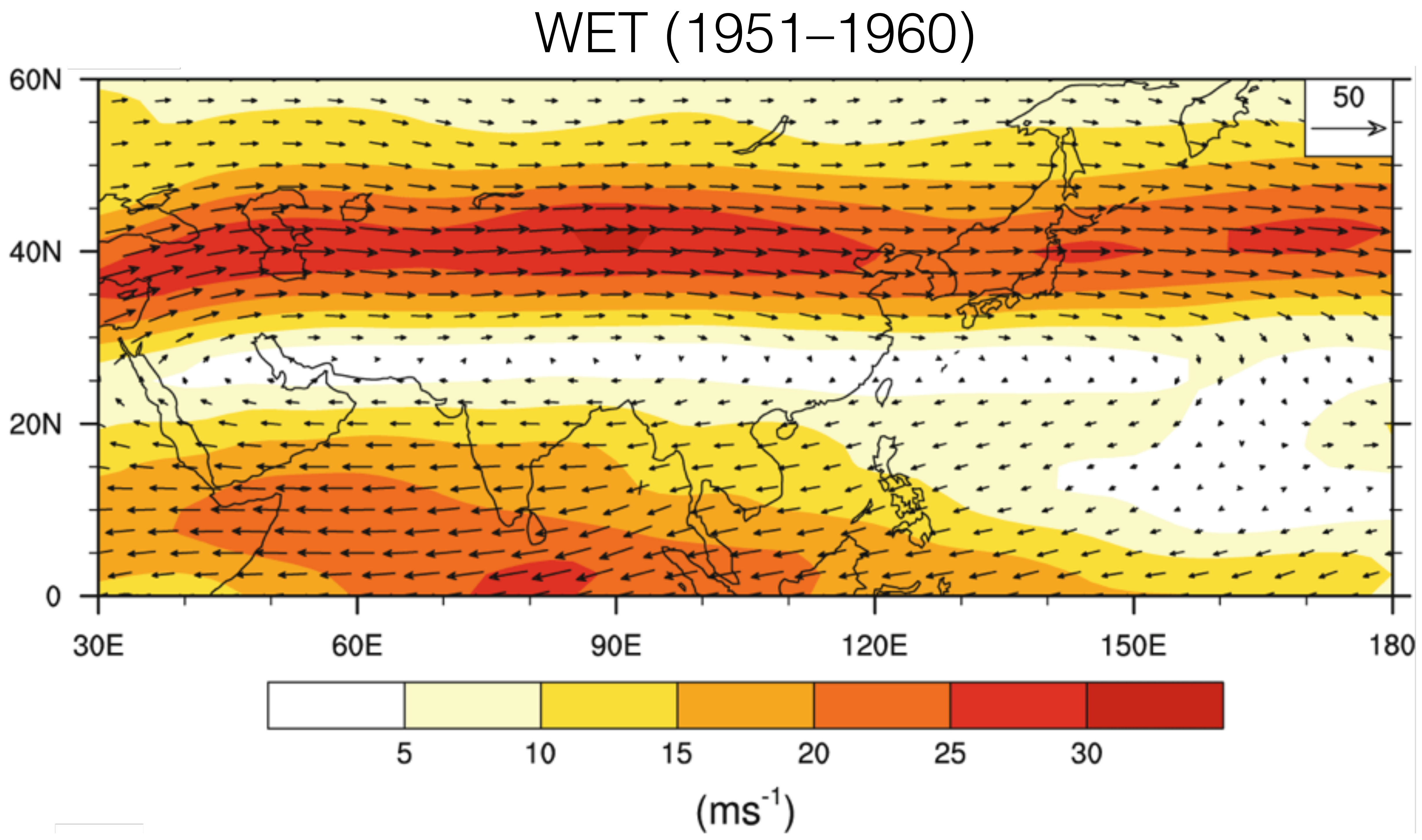
Rainfall variability over the past decades can be divided into 30-year wet and dry periods

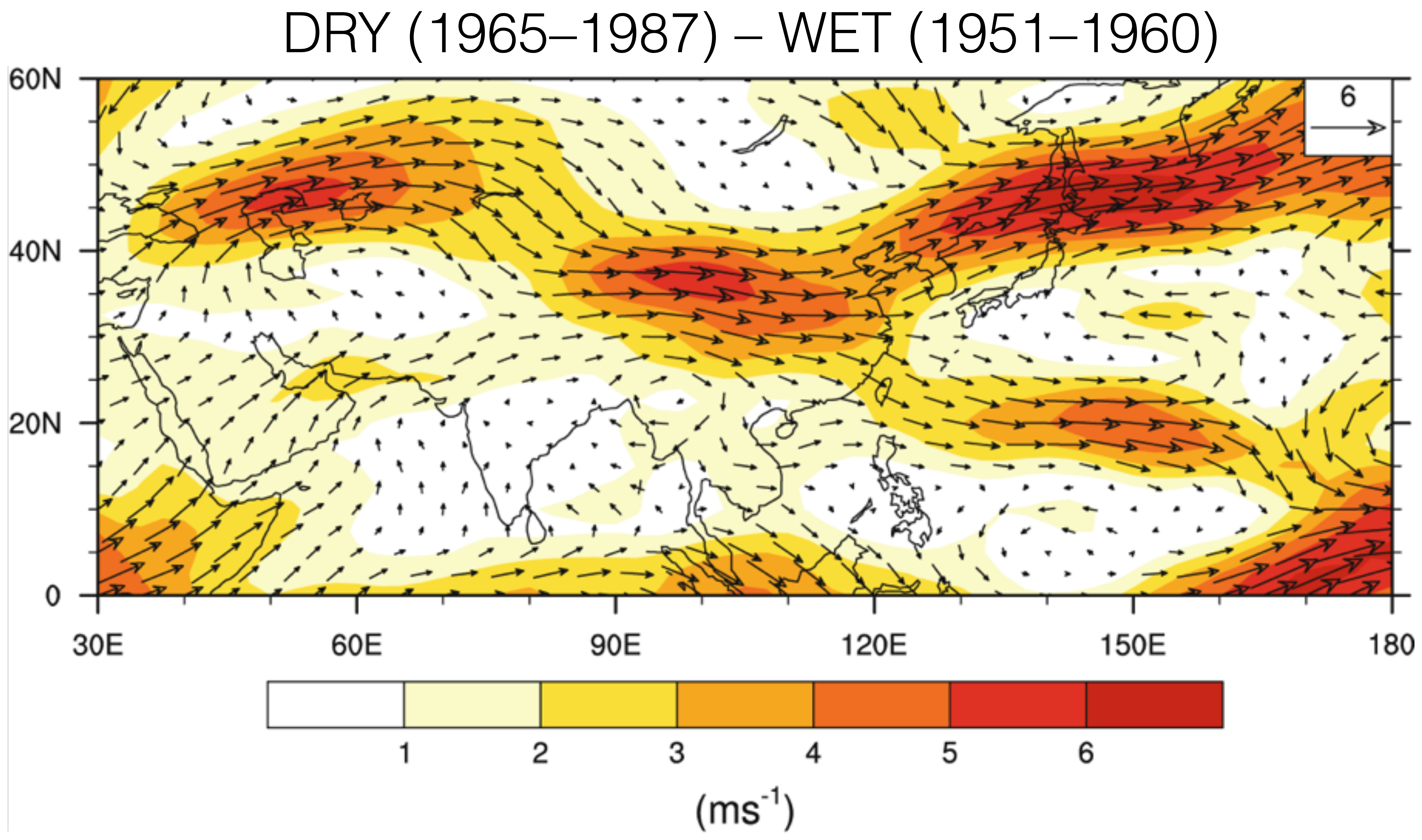


Data source: India Meteorological Department

Interdecadal Variability and Trends

- The reason for multidecadal oscillations between wet and dry periods remains elusive
- The changes are correlated with variability in the Atlantic (AMO) and Pacific (PDO)
- One hypothesis holds that the PDO and AMO force changes in the location and waviness of the jet that then impact the South Asian monsoon, but more study is needed





Joseph, 2014

Interdecadal Variability and Trends

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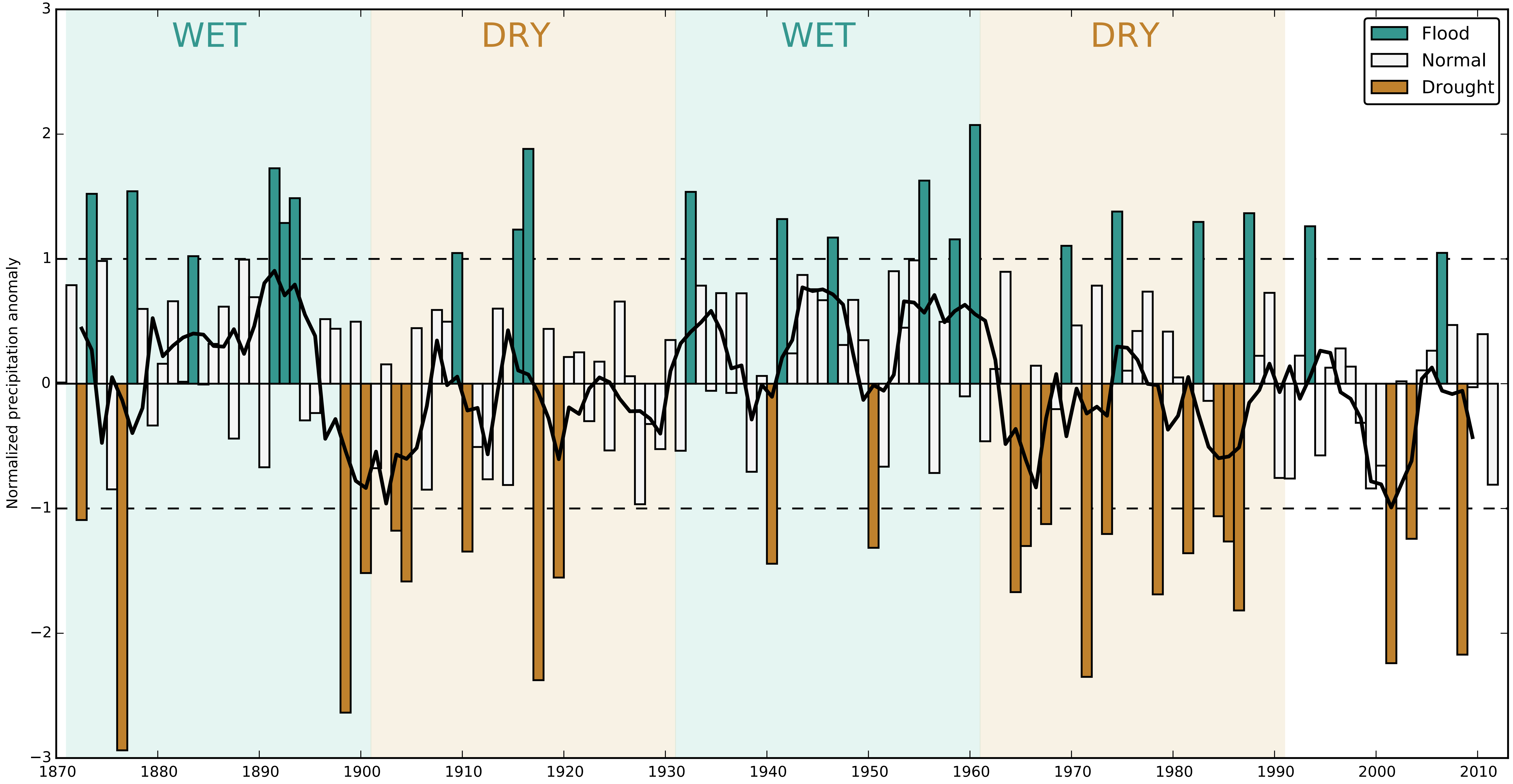
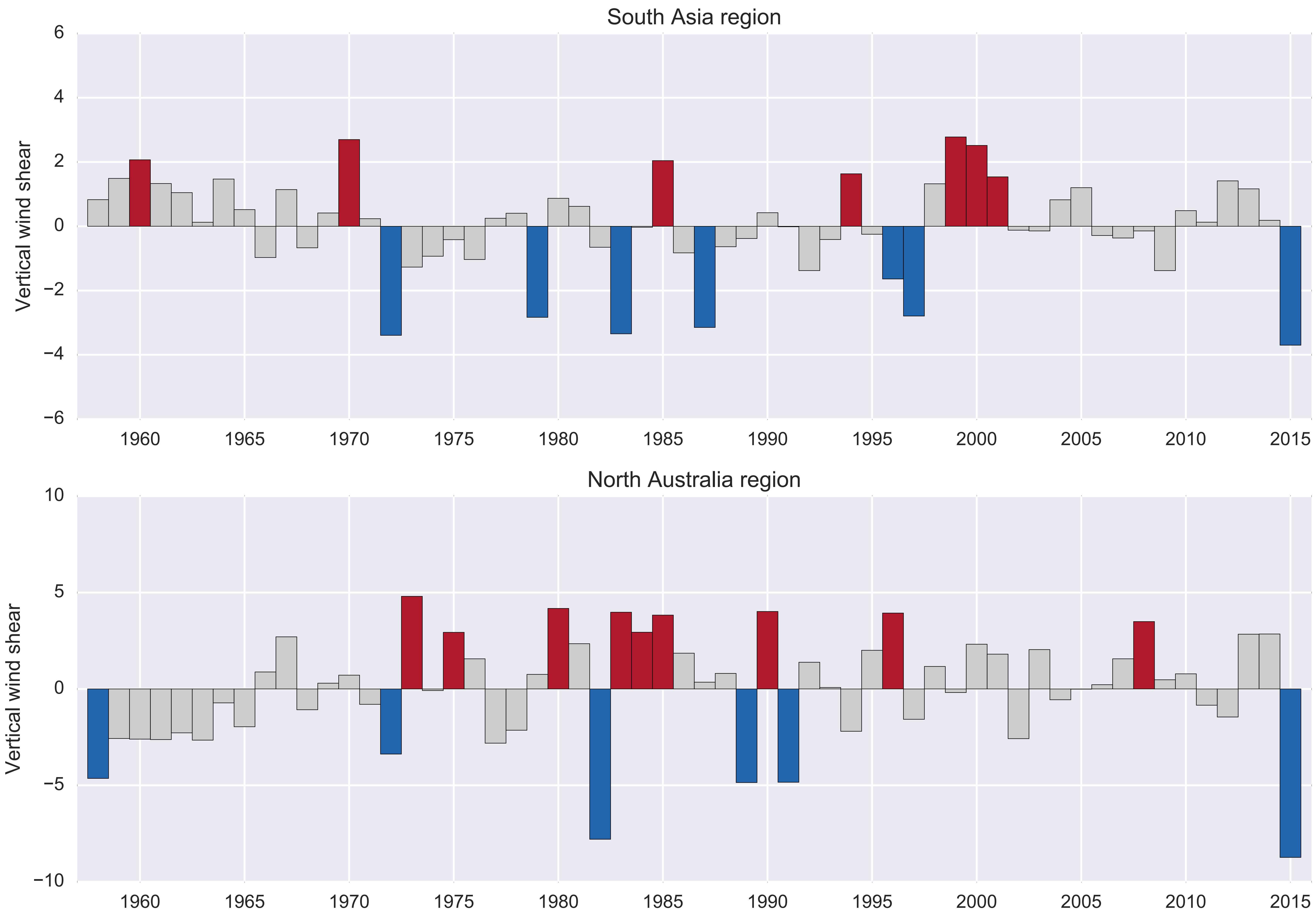


The most recent years should have been “wet”, but haven’t been — why?

Data source: India Meteorological Department

Interdecadal Variability and Trends

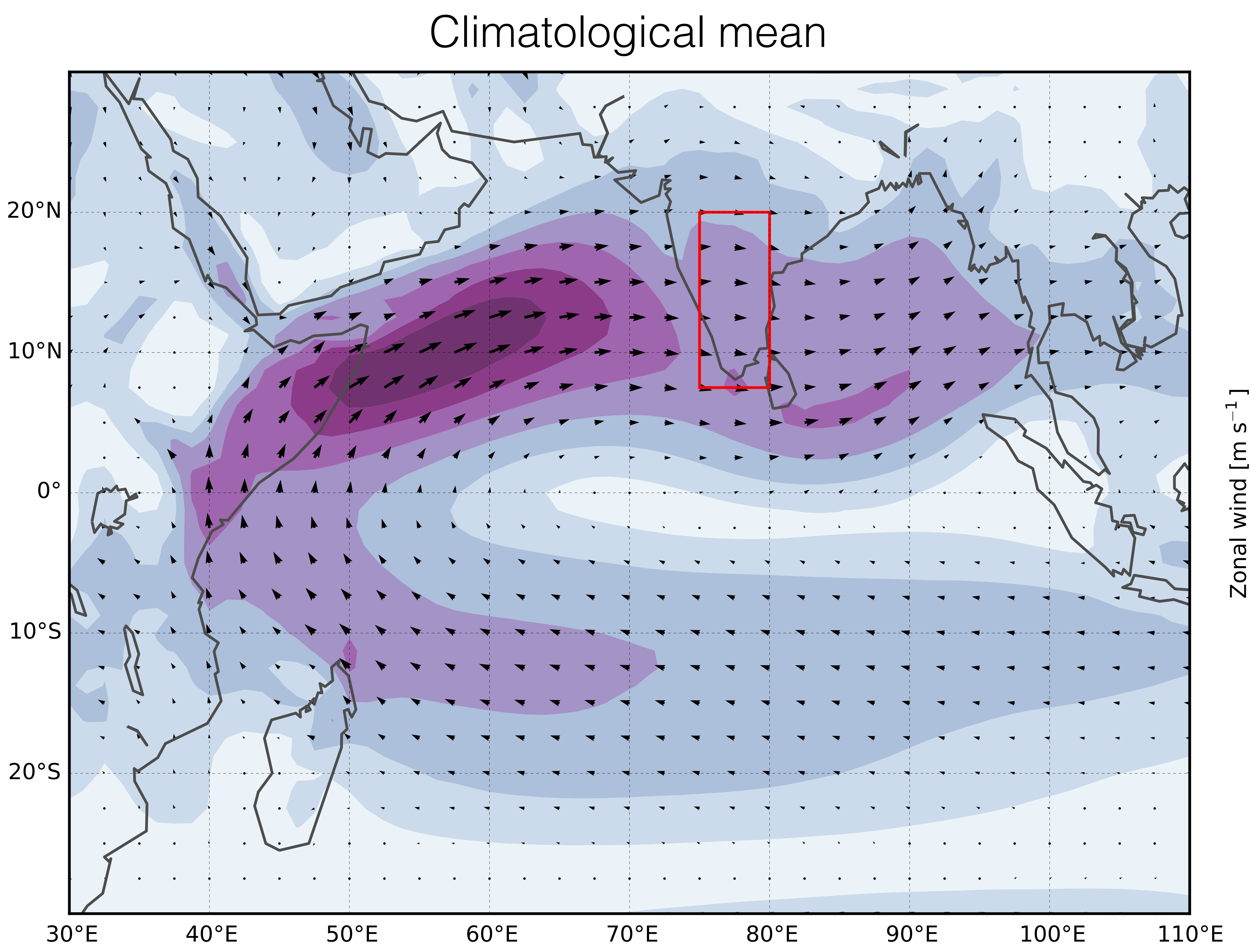
Both the South Asian and Australian monsoons show significant interdecadal variability

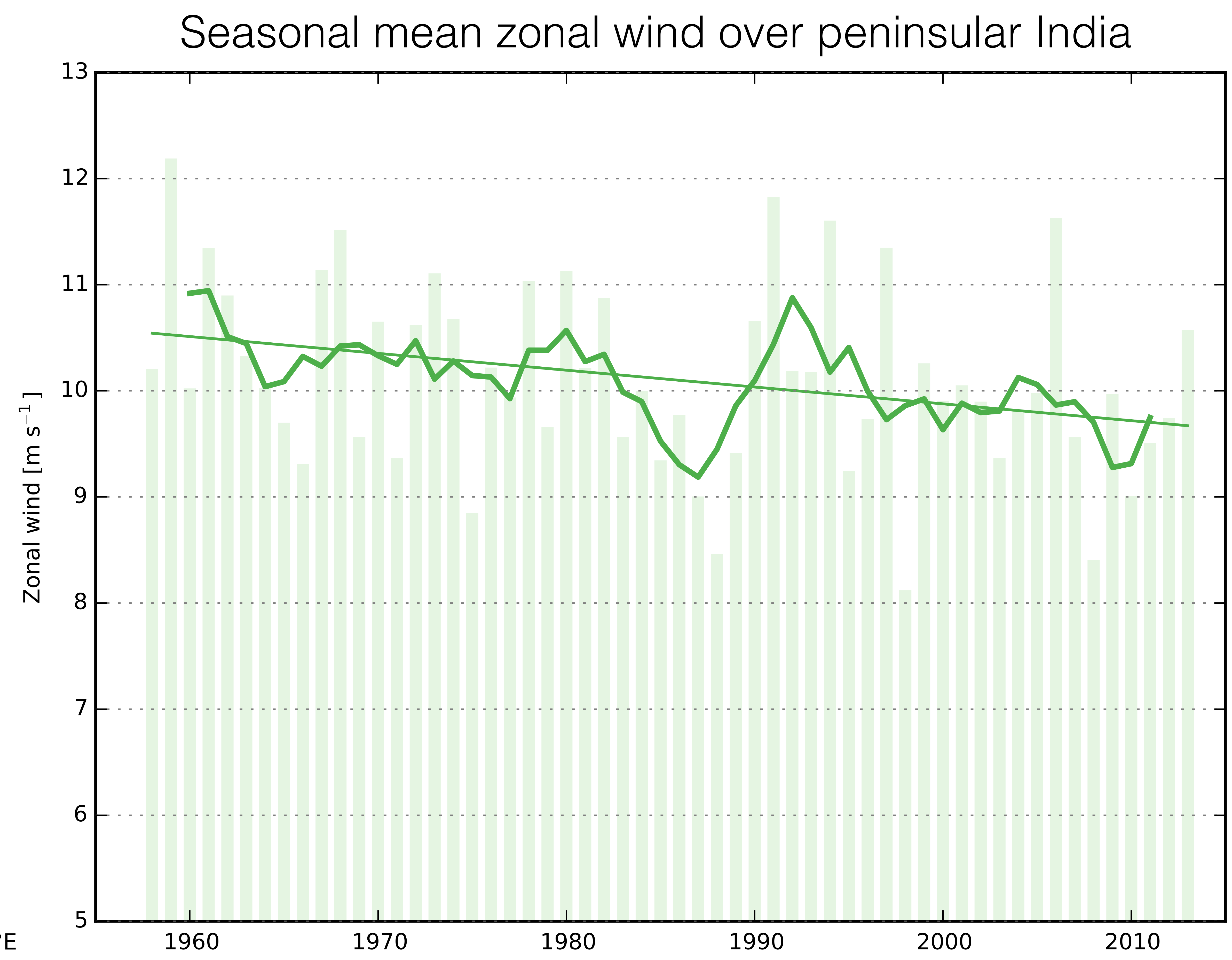


Data source: JRA-55

Interdecadal Variability and Trends

The low-level jet (and associated moisture convergence) have weakened in recent years

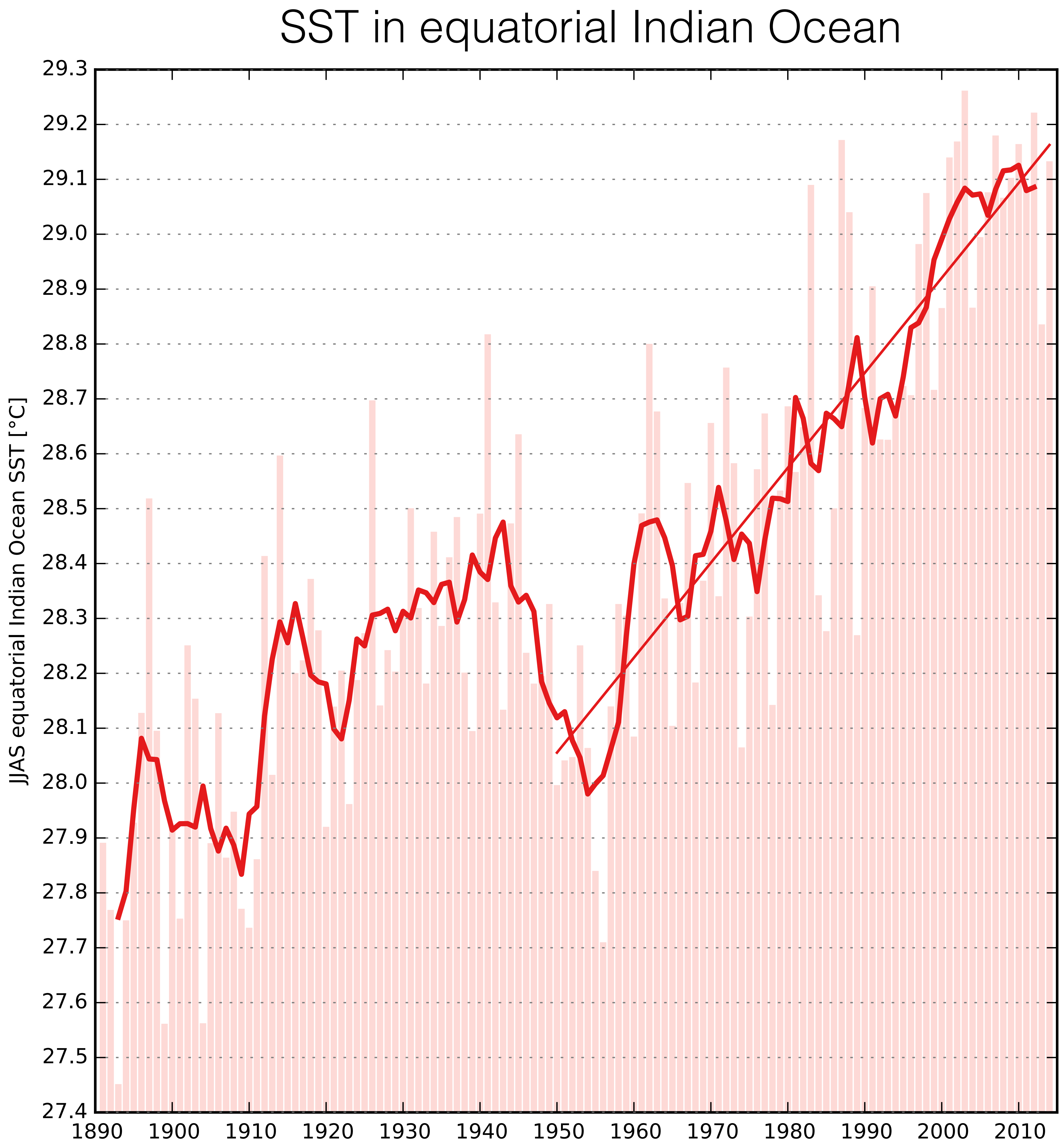


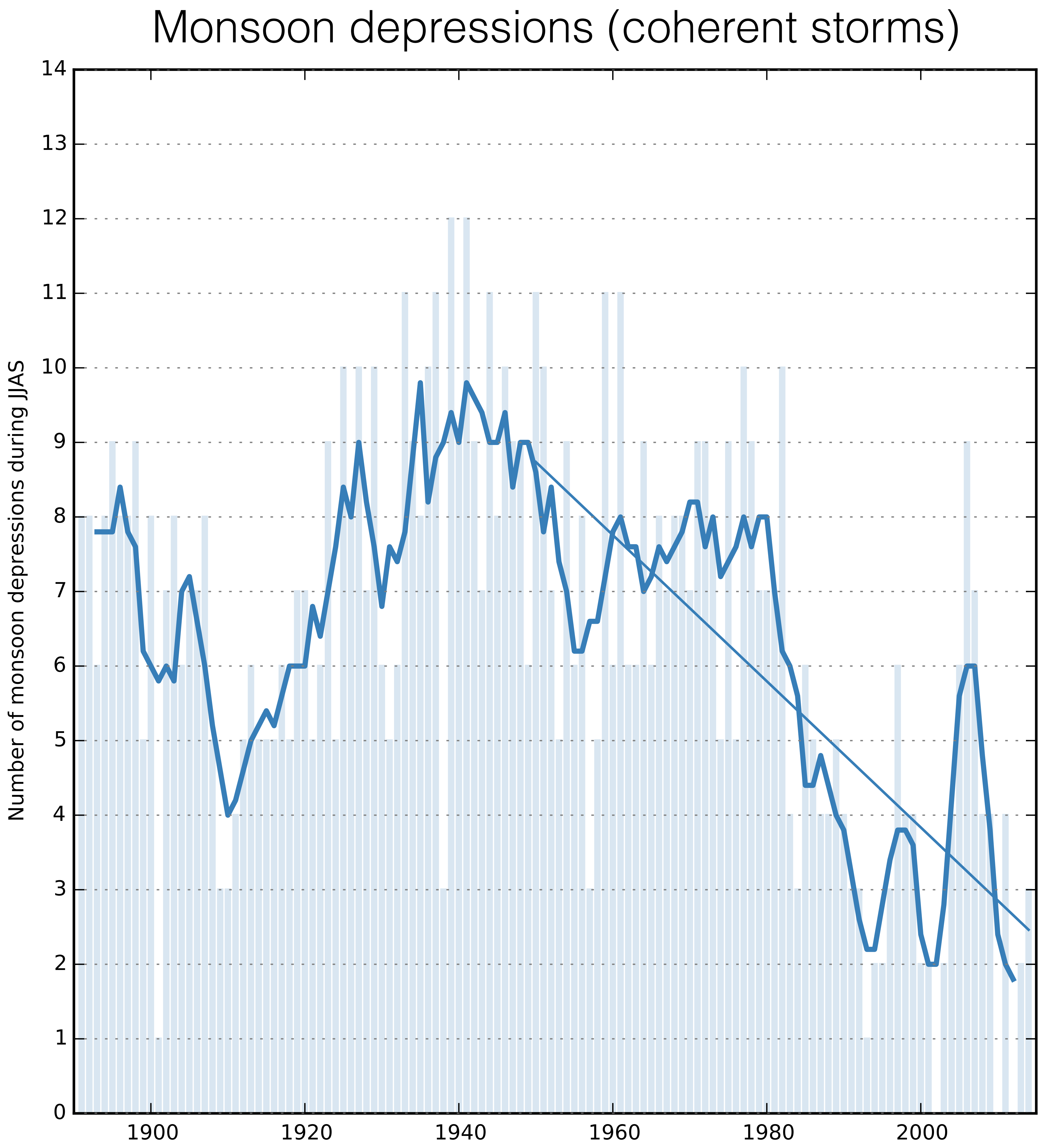


Data source: JRA-55

Interdecadal Variability and Trends

Suggestions that the number of storm systems in the monsoon has decreased, perhaps due to SST changes?

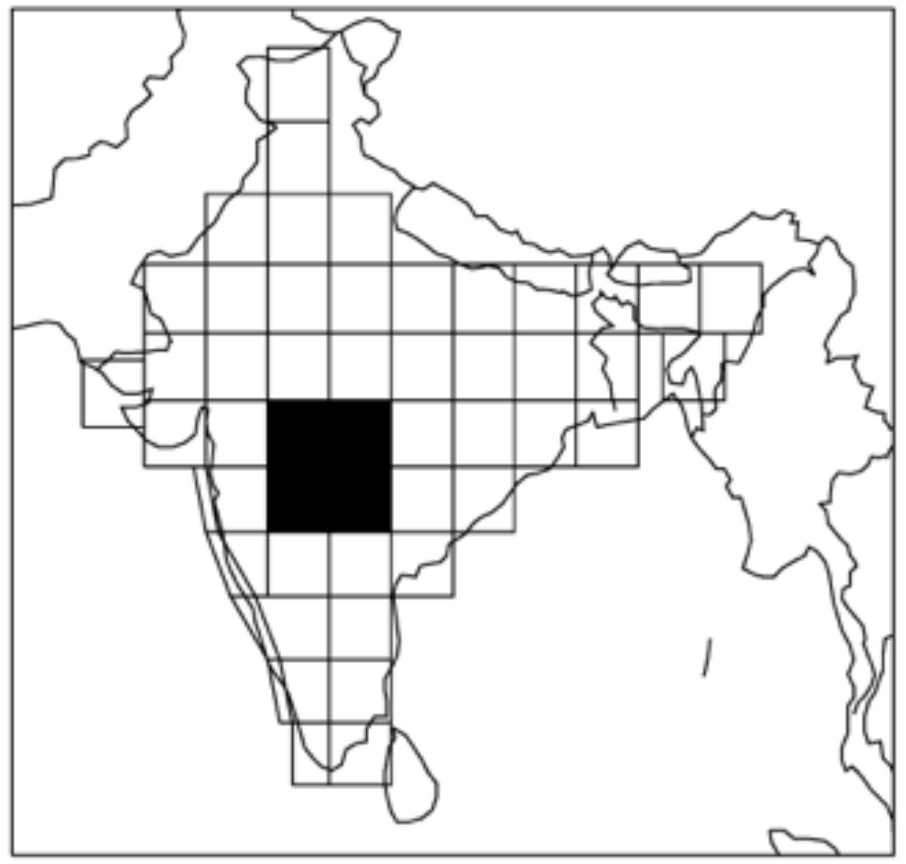


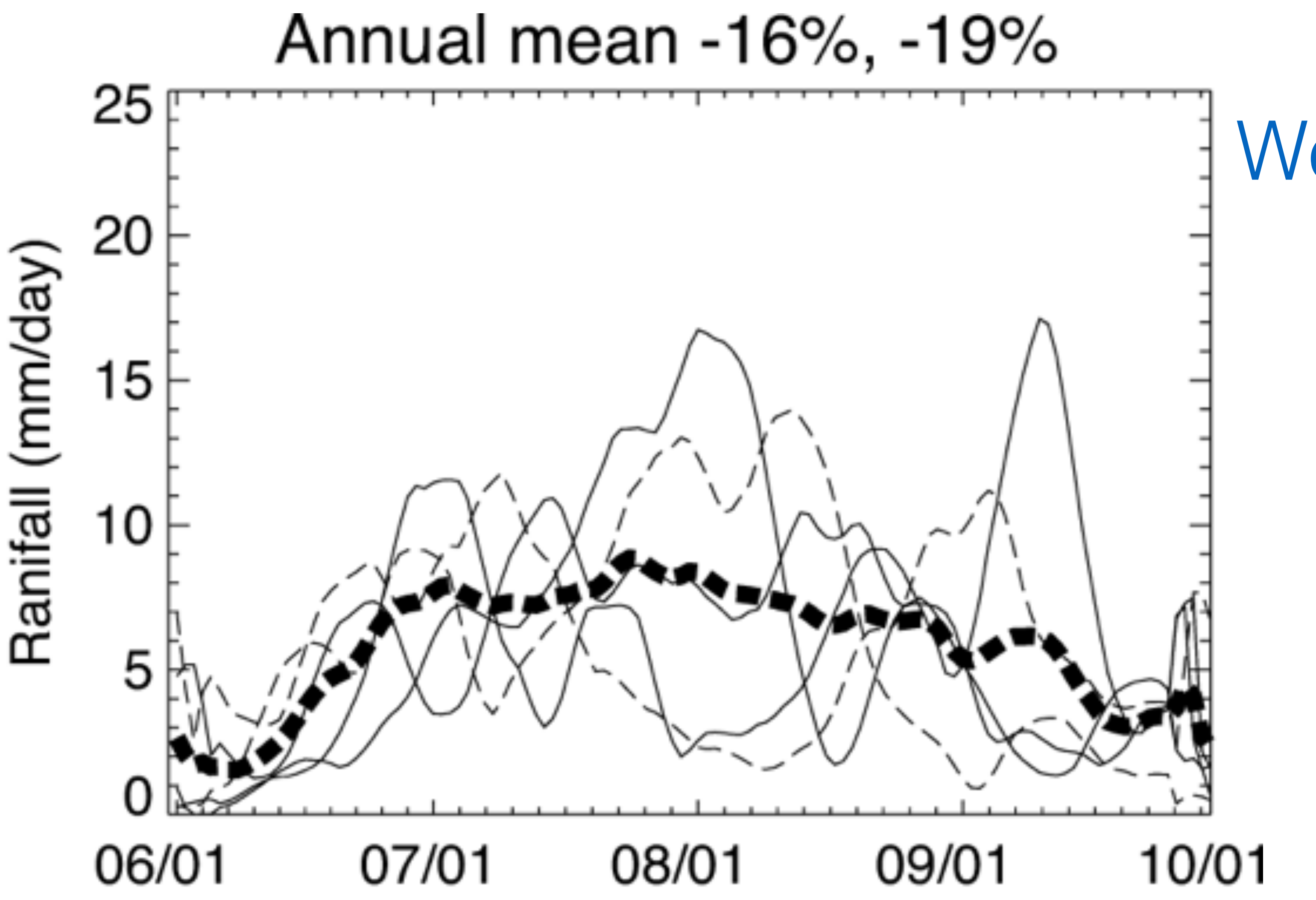


Data source: COBE SST and India Meteorological Department

Intraseasonal Variability

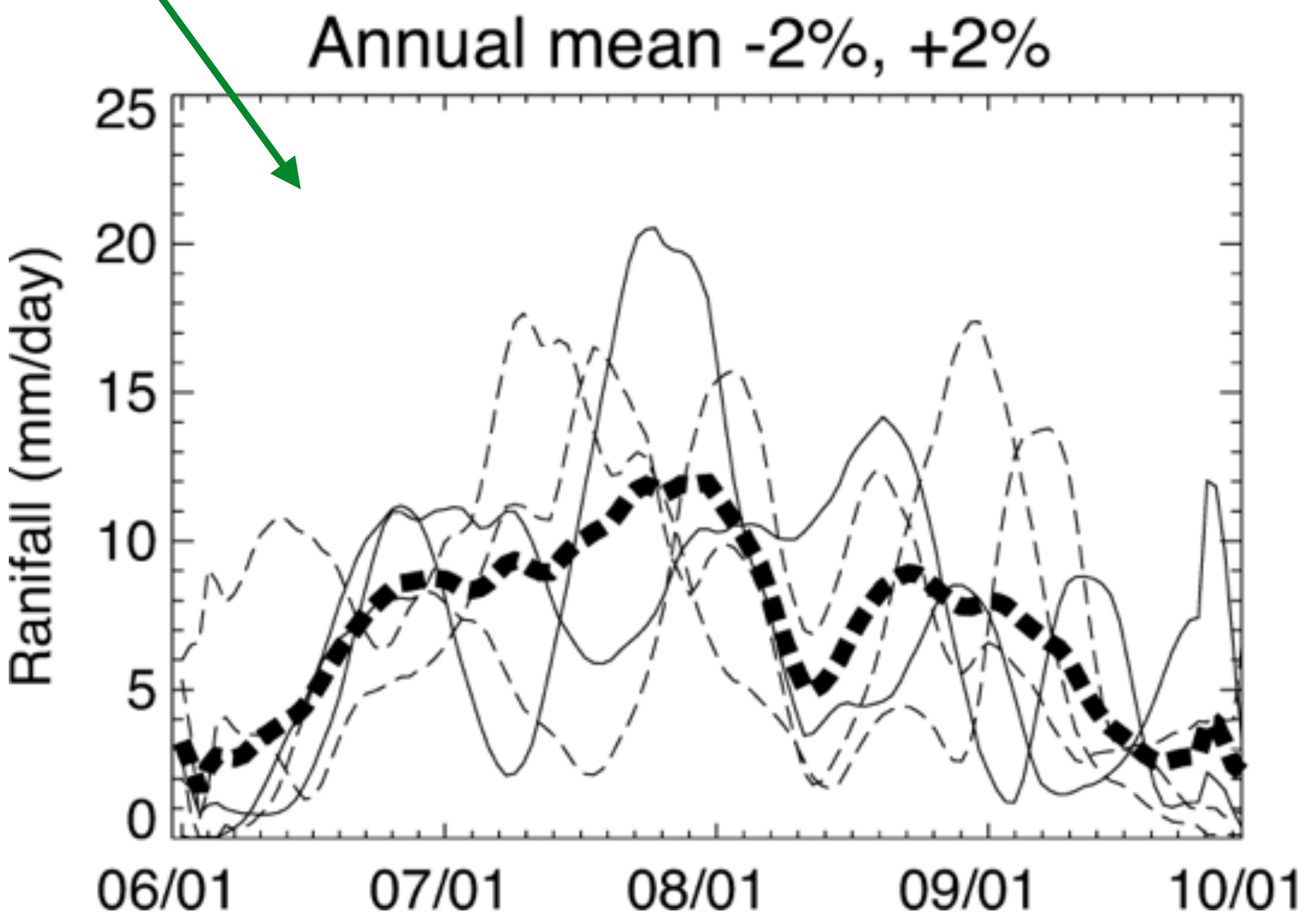
Intraseasonal variability superimposed on interannual variability

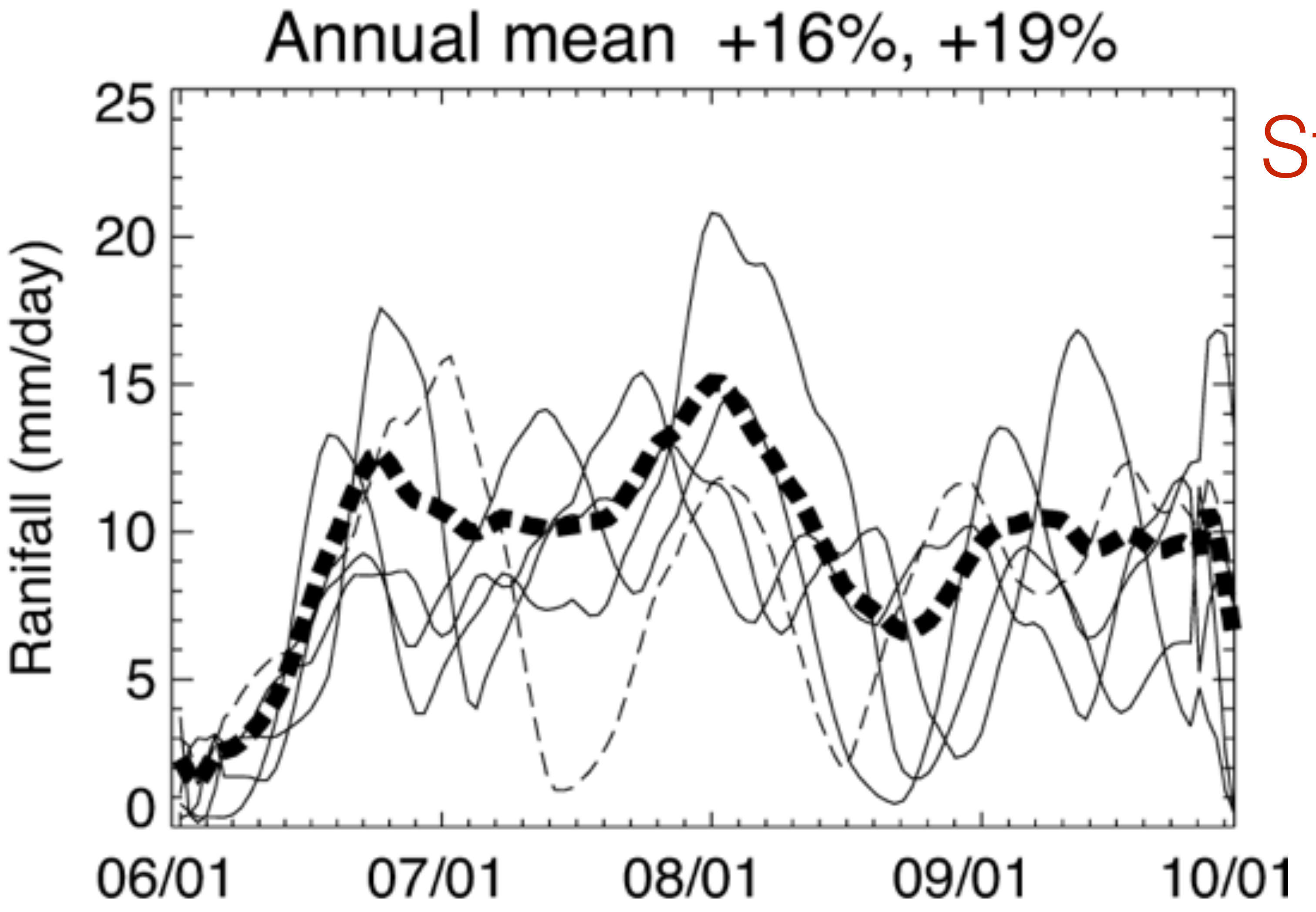




Weak monsoon years

“Typical” monsoon years





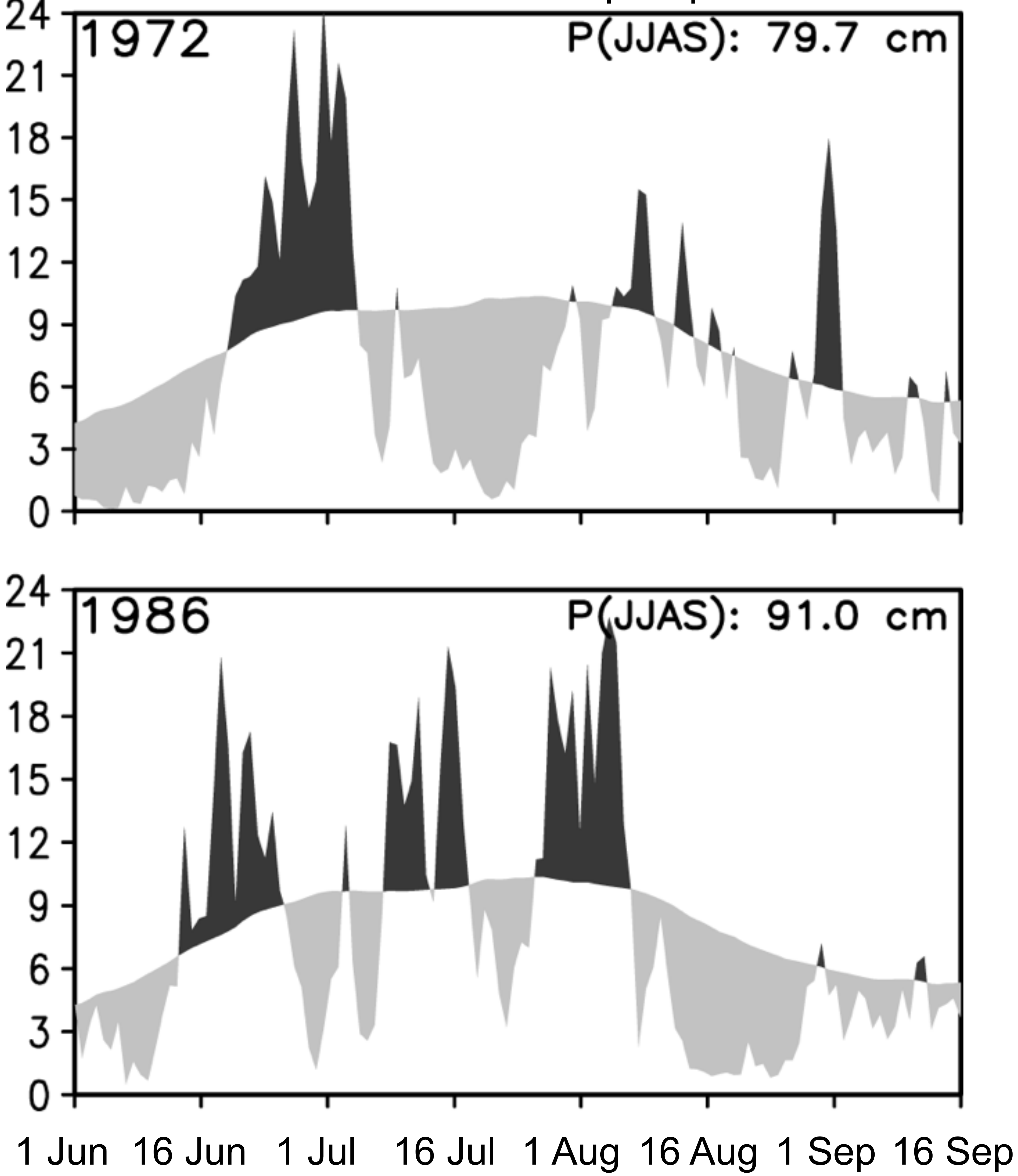
Strong monsoon years

Webster, 2006

Intraseasonal Variability

South Asian monsoon experiences active and break phases (intraseasonal oscillations) during the monsoon season

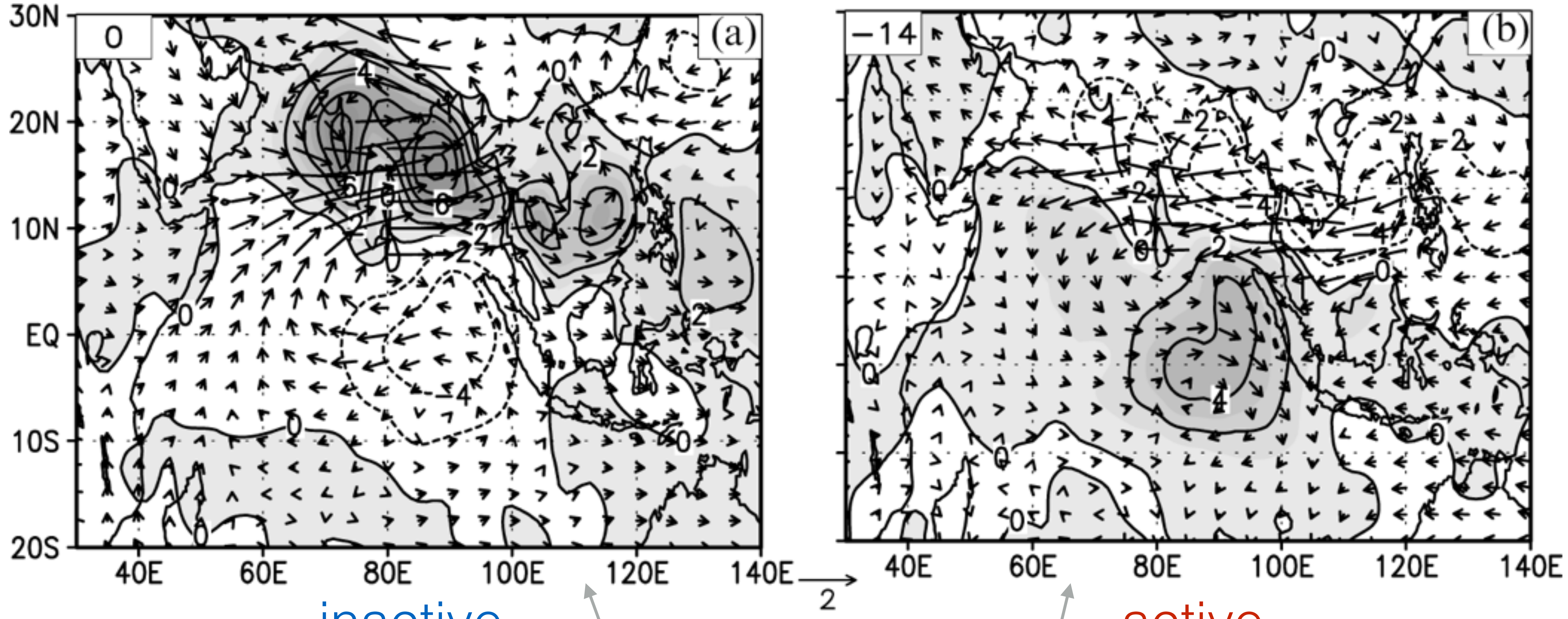
South Asian monsoon precipitation



monsoon

active

break



inactive

active

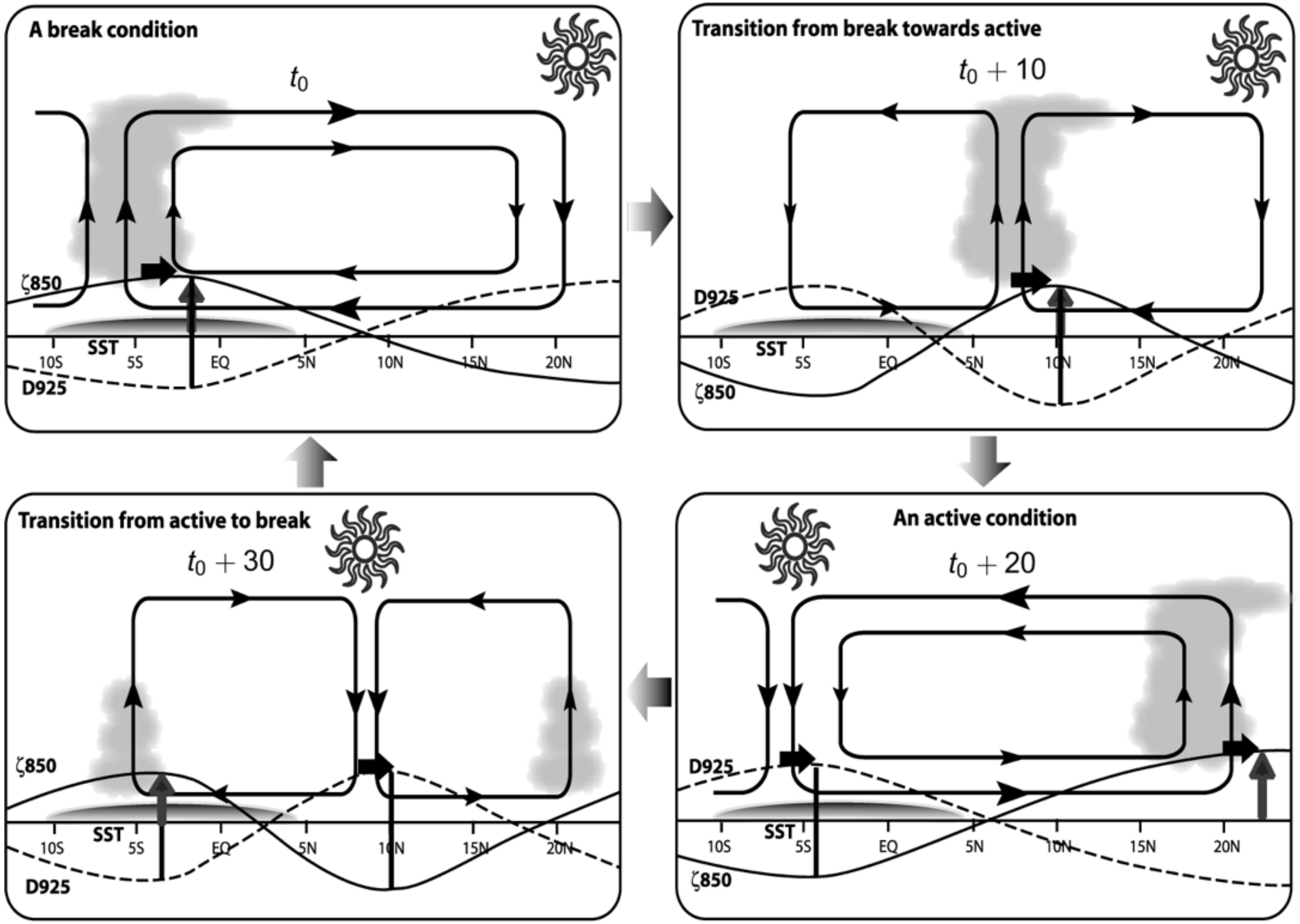
MJO

regressions of 10–90 day filtered precipitation and winds

Goswami, 2005

Intraseasonal Variability

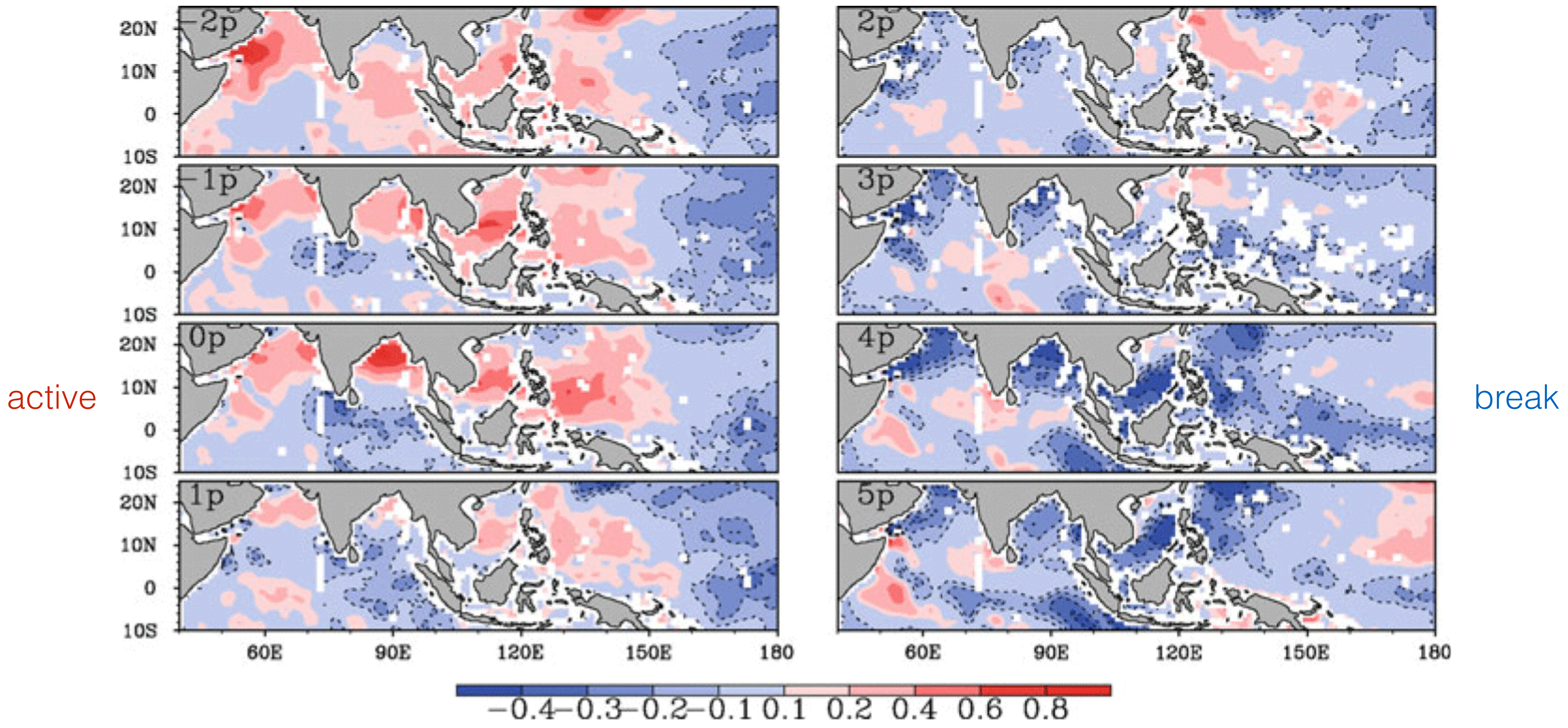
South Asian monsoon experiences active and break phases (intraseasonal oscillations) during the monsoon season



Goswami, 2005

Intraseasonal Variability

Intraseasonal oscillations in convection and winds affect SST via ocean surface heat fluxes and northward heat transport

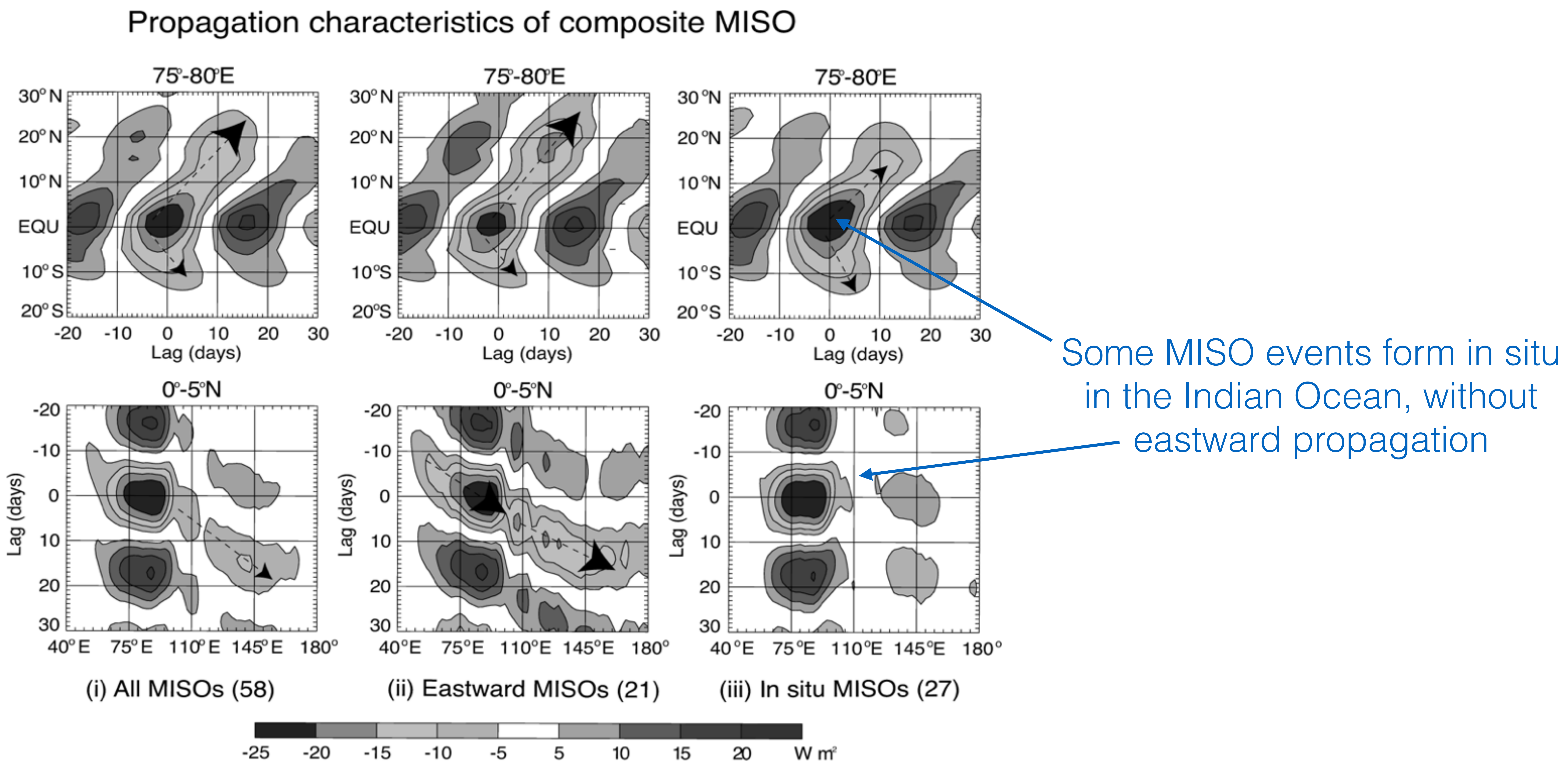


Composite SST anomalies

Joseph, 2014

Intraseasonal Variability

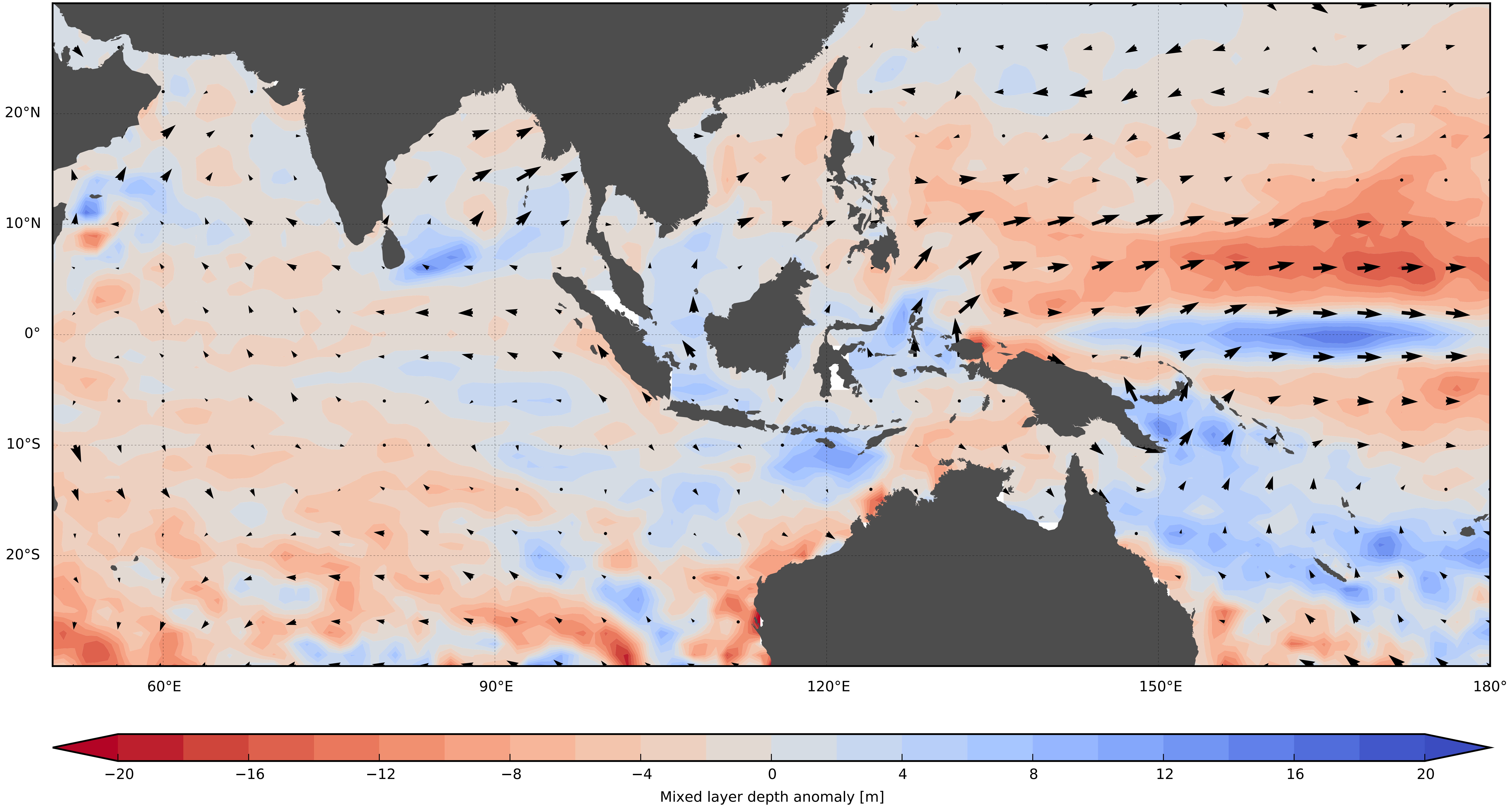
Monsoon intraseasonal oscillations (MISO) are sometimes (but not always) associated with MJO events



Webster, 2006

Intraseasonal Variability

El Niño wind anomalies reduce mixed layer depth in the tropical North Pacific; resulting warm SSTs affect MISO propagation

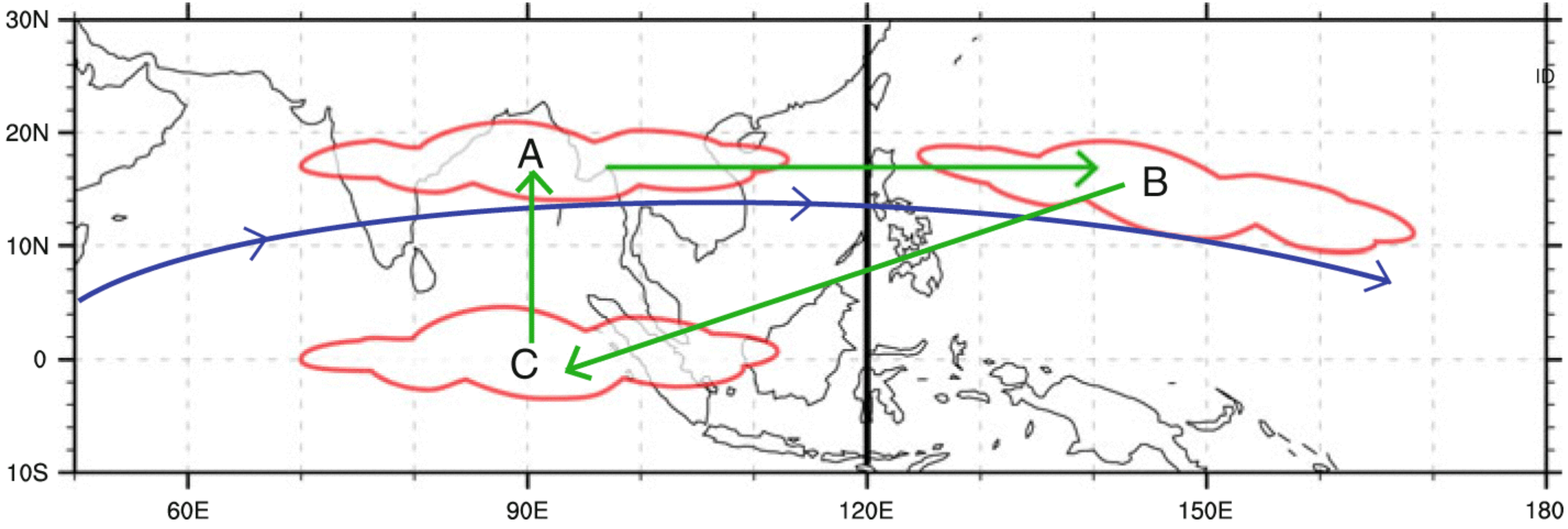


Data source: CFSR

Intraseasonal Variability

The time period between active and break phases depends on the ENSO phase

During La Niña, oscillates between A and C (break ~ 1 month)

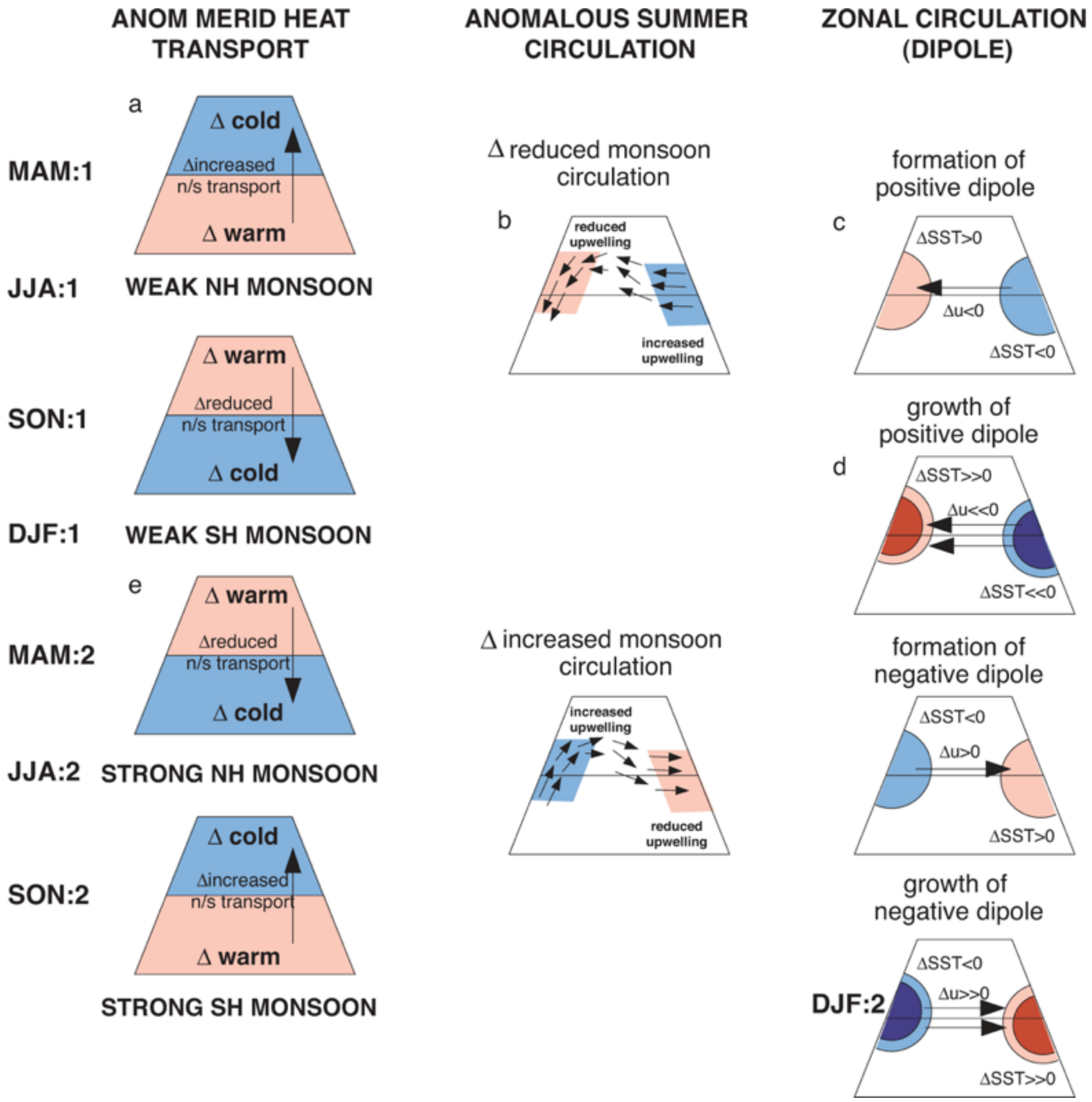


During El Niño, oscillates from A to B to C (break ~ 2 months)

Joseph, 2014

The Coupled Monsoon

Summary



1. Cold Indian Ocean » weak monsoon » less ocean heat transport » warm Indian Ocean » strong monsoon
2. Weak monsoon circulation reduces upwelling along the east coast of Africa and increases upwelling along the west coast of Sumatra (cold in the east; warm in the west) — strong monsoon has the opposite effect
3. Dipole and its influence on equatorial waves introduces slow dynamics to the system, enhancing and prolonging the SST patterns that regulate the monsoon

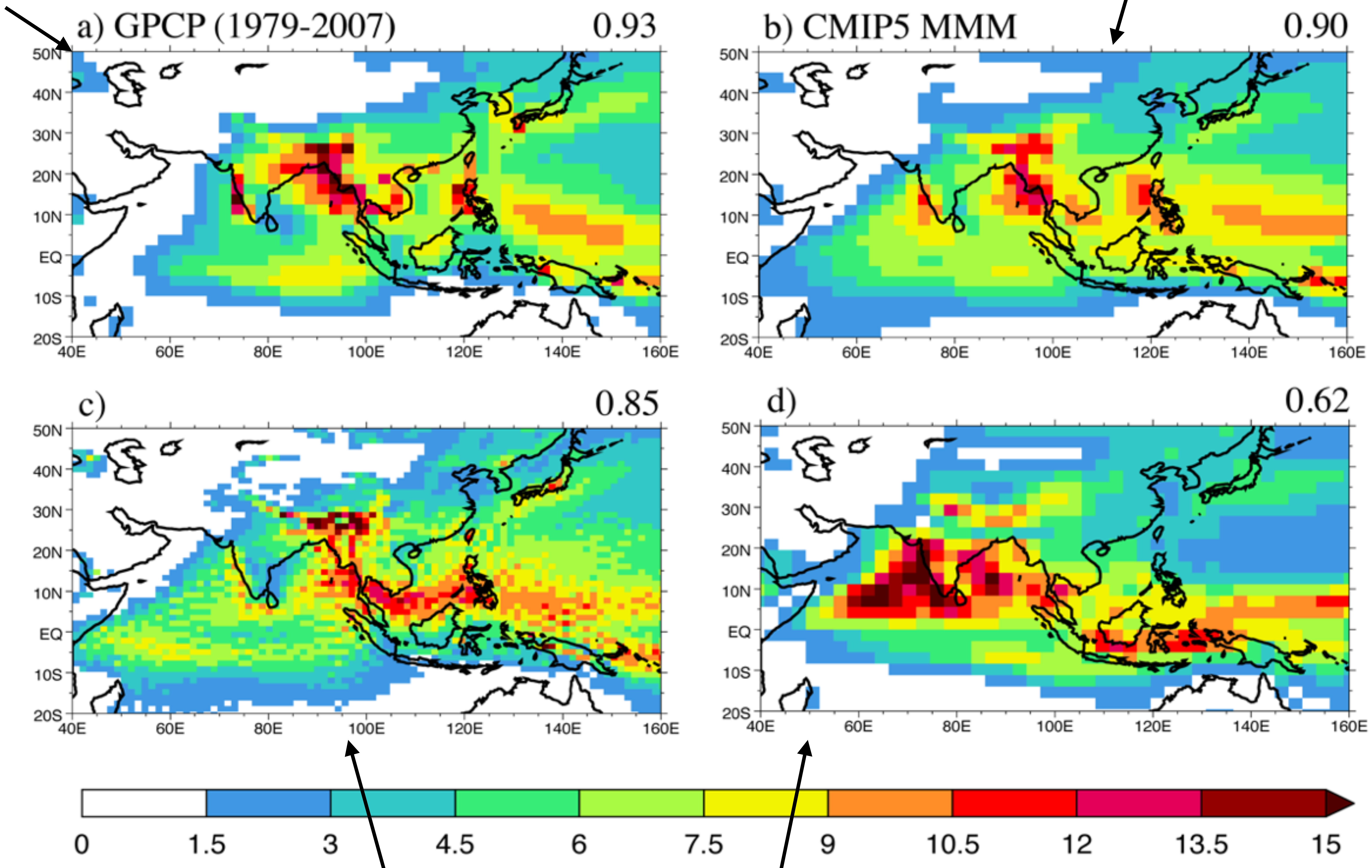
Webster, 2006

Simulating Monsoons

The Asian monsoon

multi-model mean outperforms all individual models

observations



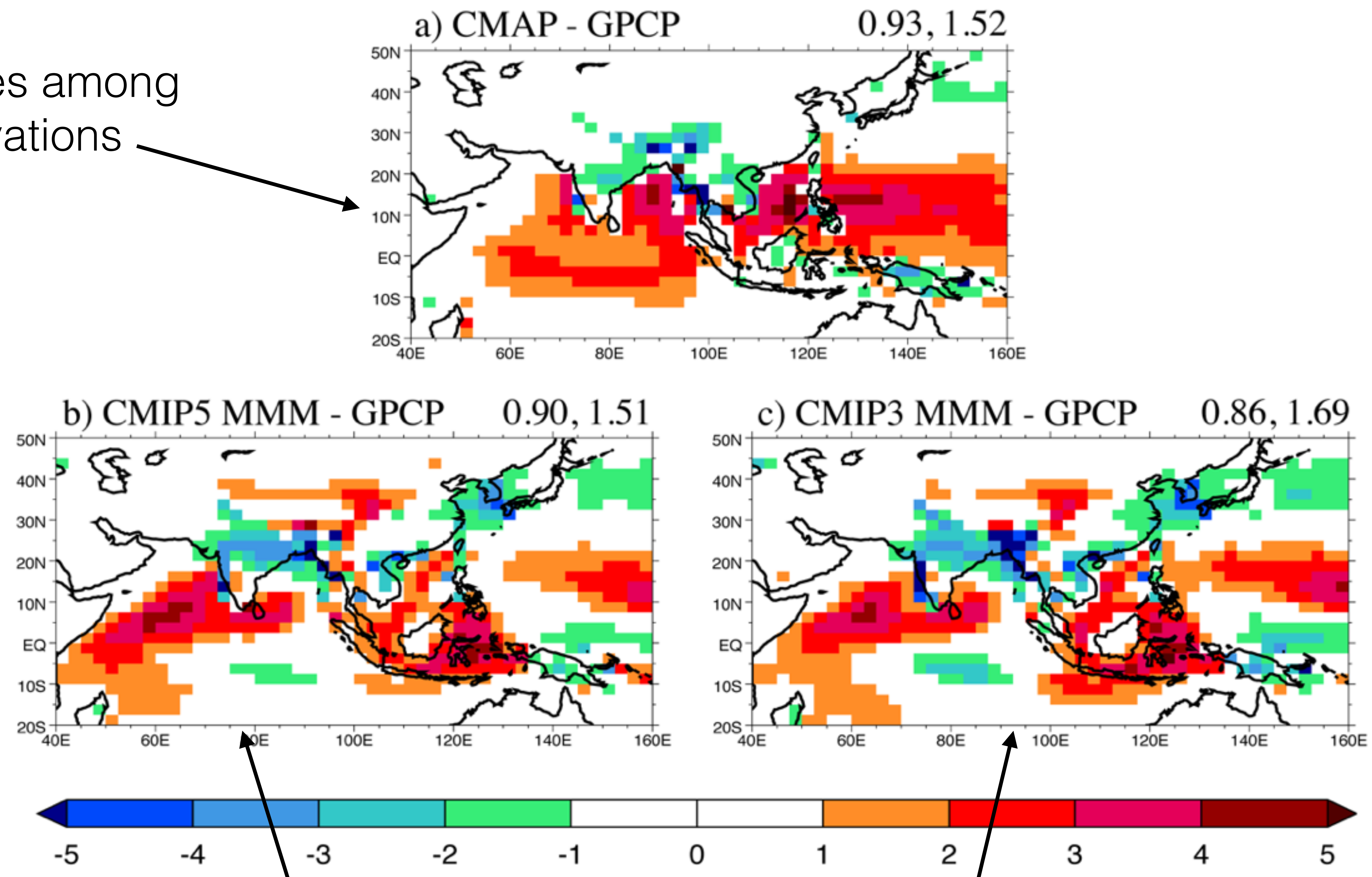
range of individual model performance

Sperber et al., *Clim. Dyn.* 2012

Simulating Monsoons

The Asian monsoon

differences among observations



spatial distribution of errors in CMIP5 models similar to that in CMIP3 models

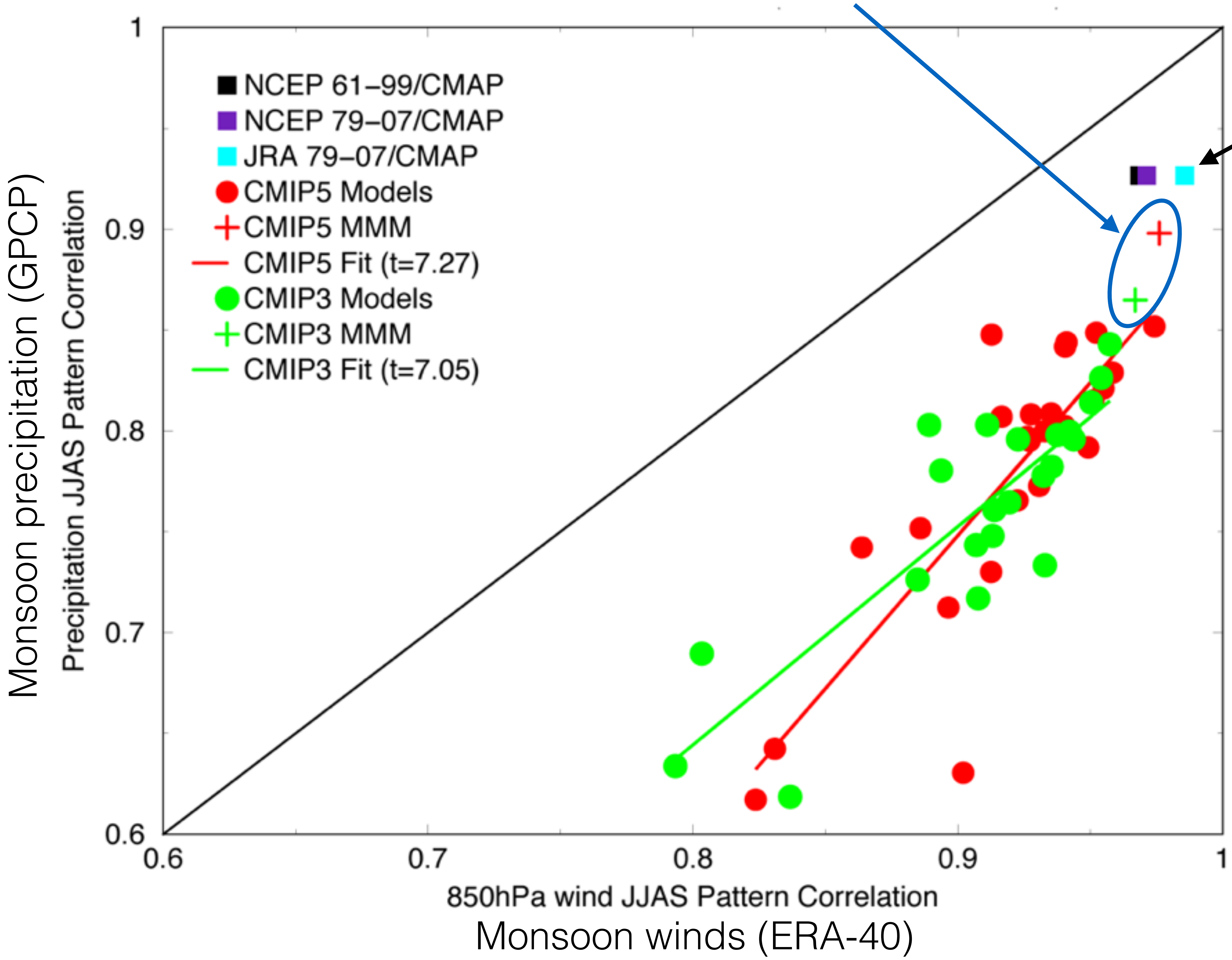
Sperber et al., *Clim. Dyn.* 2012

Simulating Monsoons

The Asian monsoon

some improvement in newer models, particularly for rainfall

other reanalysis wind estimates / CMAP precipitation

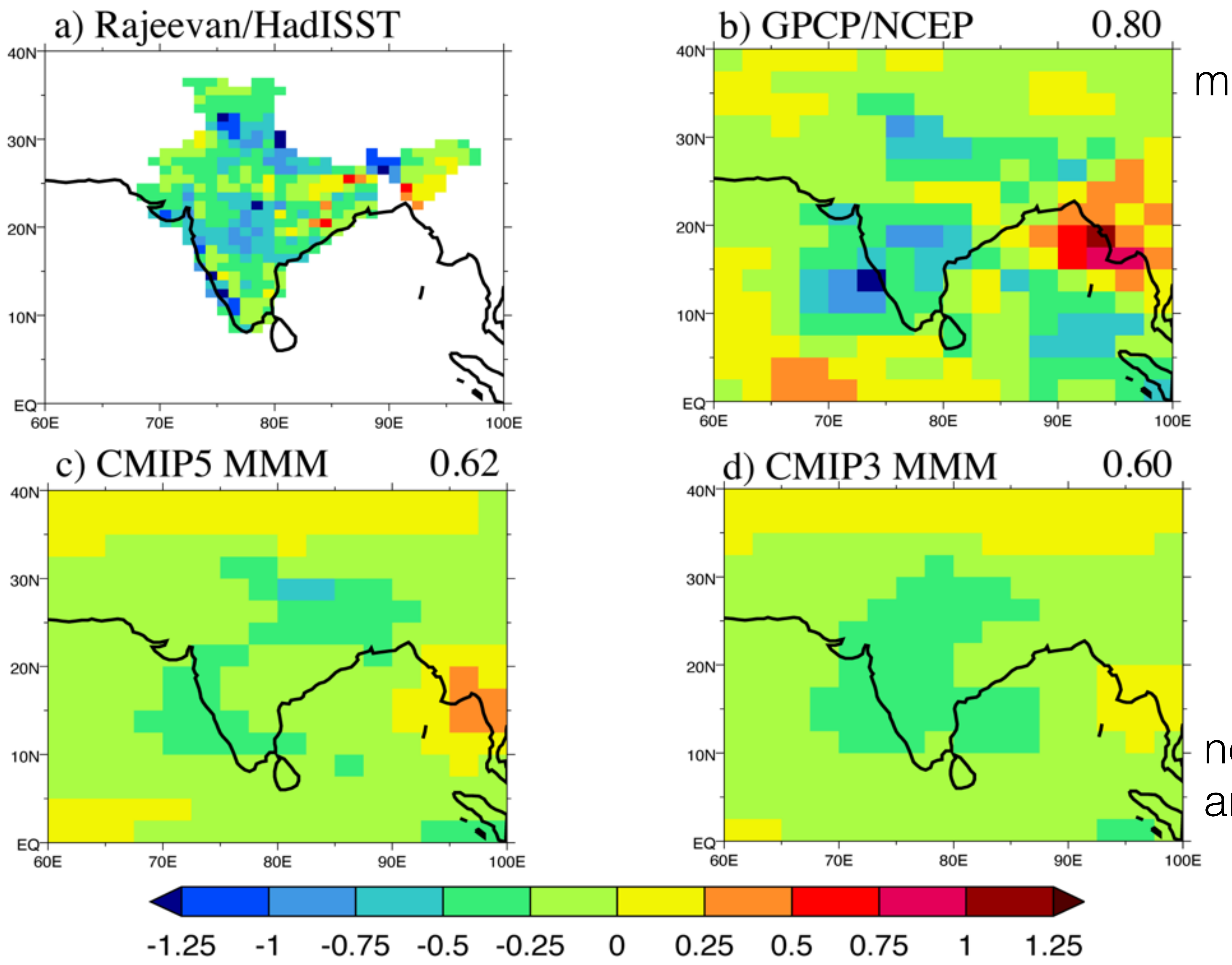


wind patterns better (relative to reanalyses) than rainfall (relative to observations)

Sperber et al., *Clim. Dyn.* 2012

Simulating Monsoons

The Asian monsoon



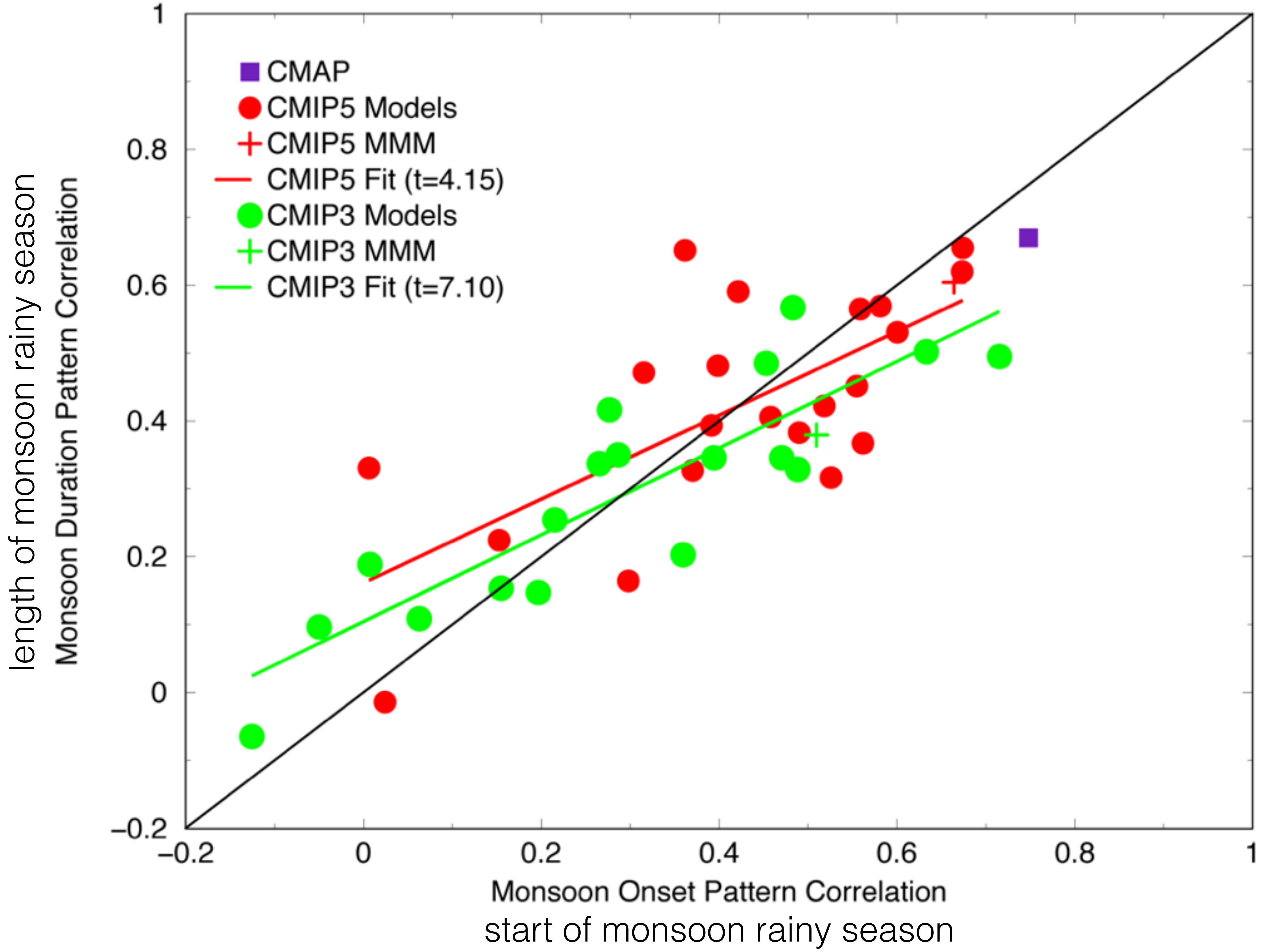
monsoon rainfall anomalies during El Niño

newer models slightly improved, but amplitude of response is still too small

Sperber et al., *Clim. Dyn.* 2012

Simulating Monsoons

The Asian monsoon



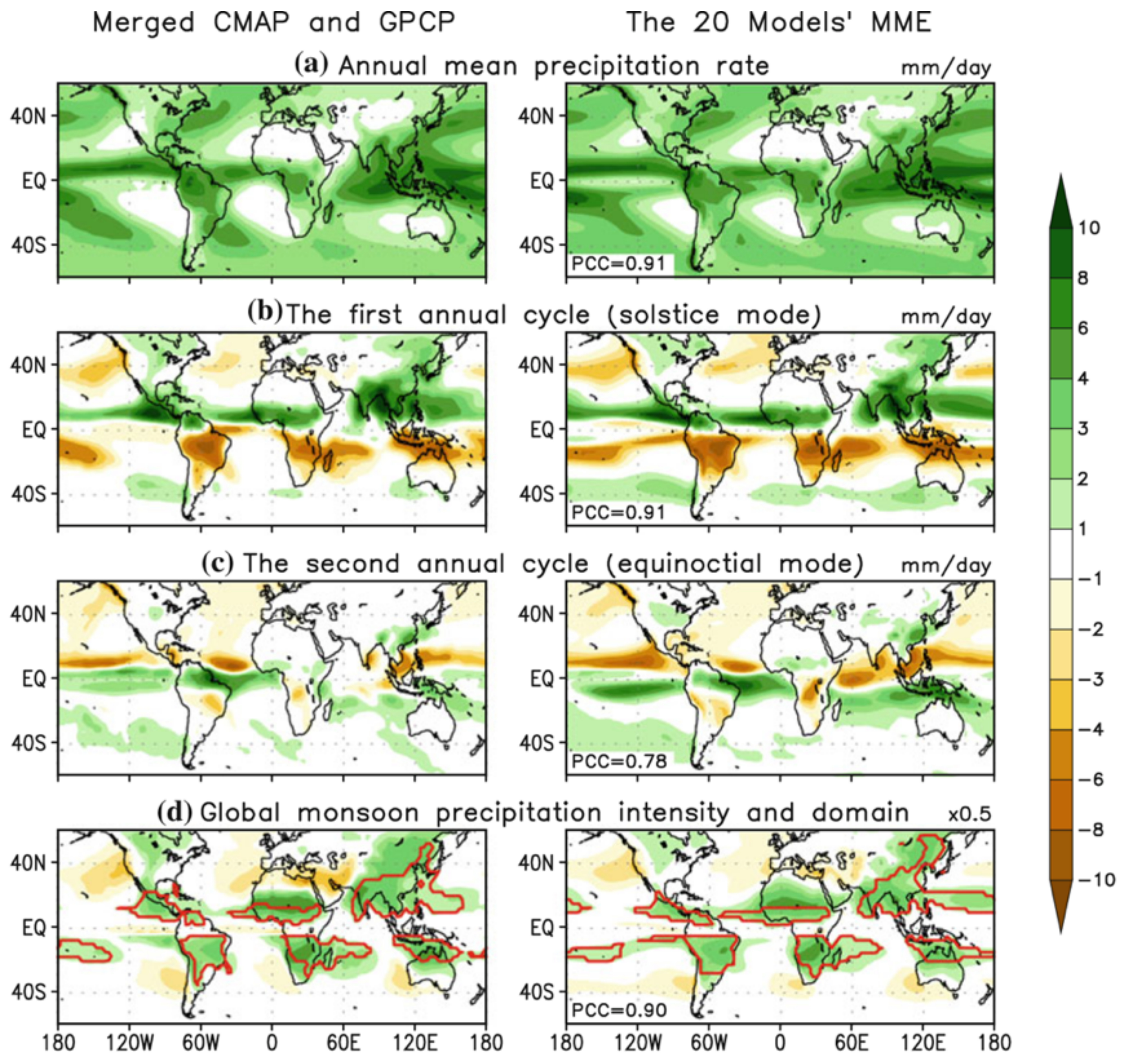
wide range of model performance simulating onset and duration of wet season

CMIP5 models again slightly improved relative to CMIP3

Sperber et al., *Clim. Dyn.* 2012

Simulating Monsoons

The global monsoon (CMIP5)



Some problem areas…

Too dry:

- Eastern Indian Ocean
- Bay of Bengal
- equatorial western Pacific
- tropical Brazil

Too wet:

- Maritime Continent
- Philippines
- high-elevation areas (like the Andes and the Tibetan Plateau)

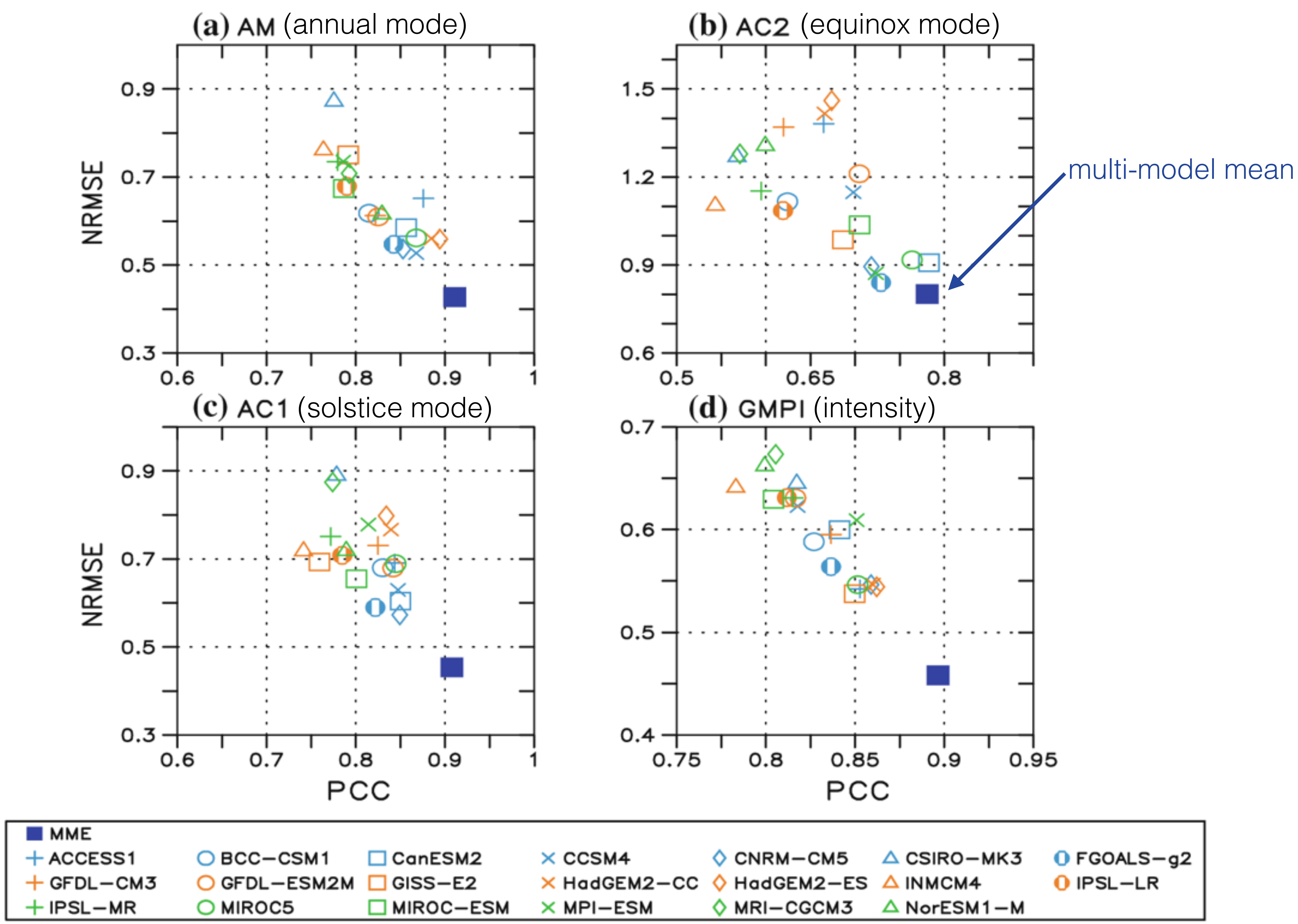
Lee & Wang, *Clim. Dyn.* 2012

Simulating Monsoons

The global monsoon (CMIP5)

- models tend to underestimate solstice mode, especially for East Asia and the South China Sea
- models tend to overestimate the equinox mode, with greater spread
- multi-model mean captures monsoon intensity well, except over East Asia and the western North Pacific

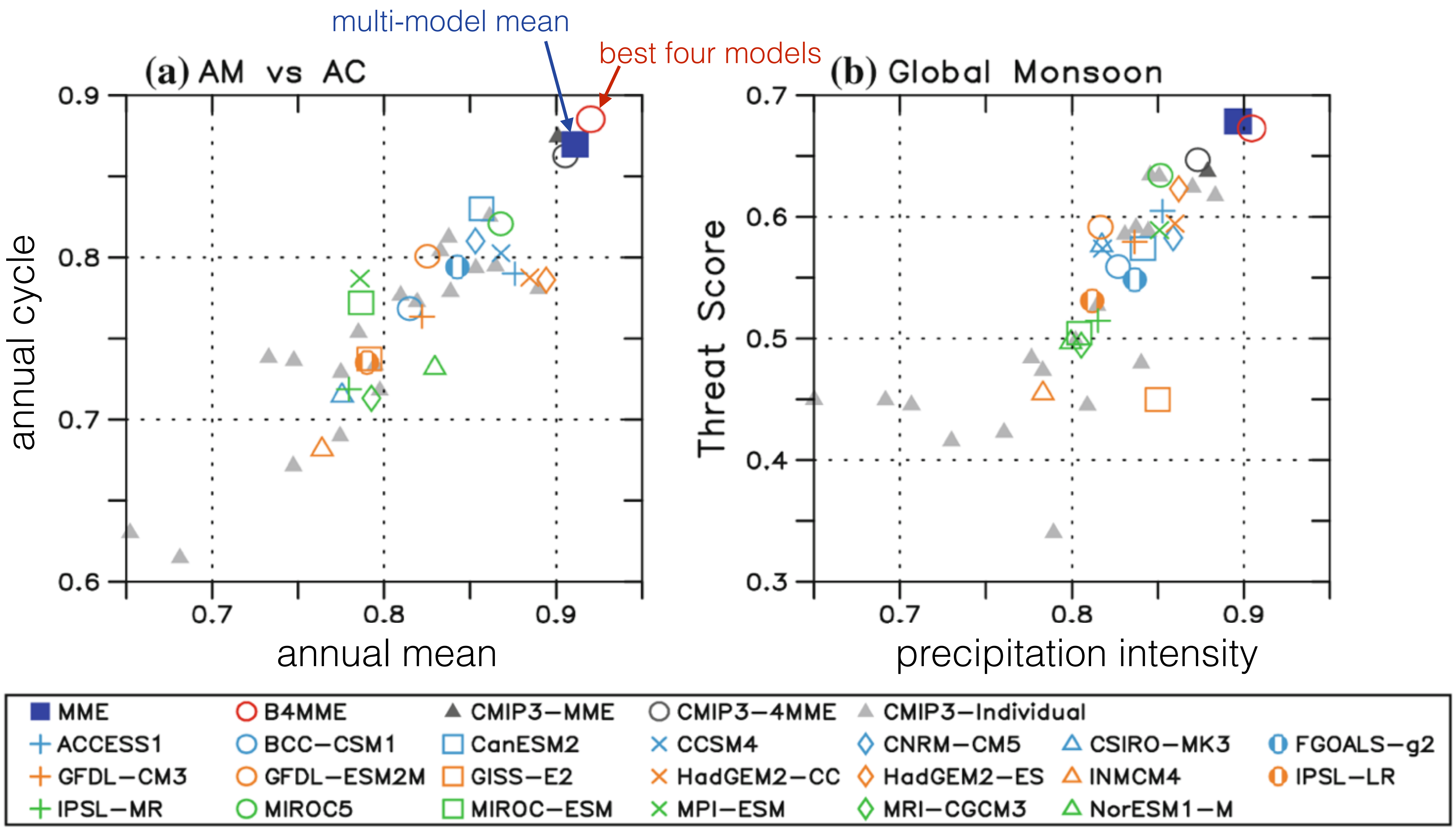
multi-model mean again better than individual models



Lee & Wang, *Clim. Dyn.* 2012

Simulating Monsoons

The global monsoon (CMIP5)

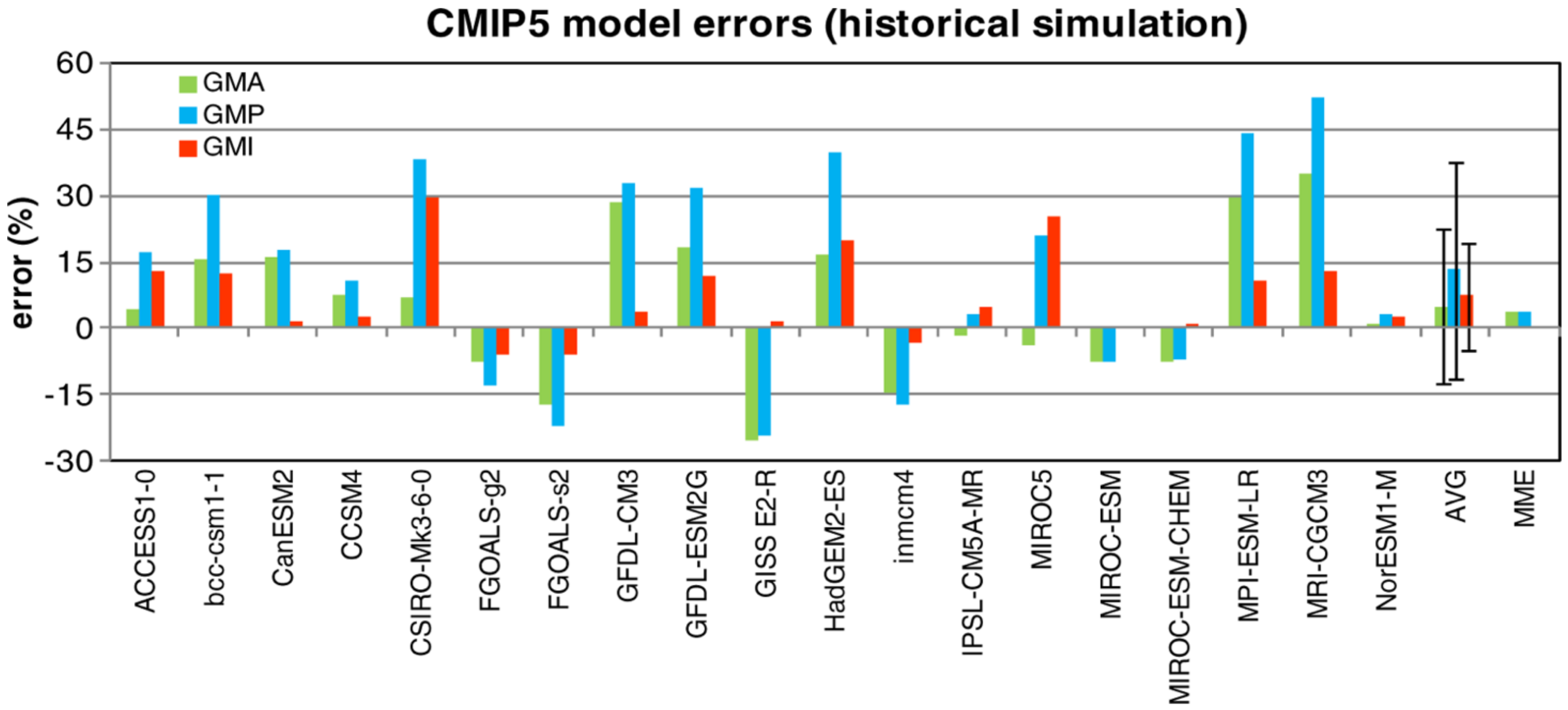


Lee & Wang, *Clim. Dyn.* 2012

Simulating Monsoons

The global monsoon (CMIP5)

multi-model mean reproduces the global monsoon, but the inter-model spread is large



CMIP5 projects future increases in area, precipitation, and intensity

Lee & Wang, *Clim. Dyn.* 2012

Monsoons

1. Monsoons are seasonal variations in winds and precipitation due to seasonal variations in heating and temperature/pressure gradients
2. Can be defined both regionally and globally
3. Arise from coupled interactions between the atmosphere, ocean, and land surface
4. The South Asian and global monsoons have been weakening over the past several decades
5. Coupled models are often able to capture the basics of monsoon dynamics, but the multi-model ensemble mean generally performs ‘better’ than any individual models
6. Model representations of the monsoon have improved over the past decade