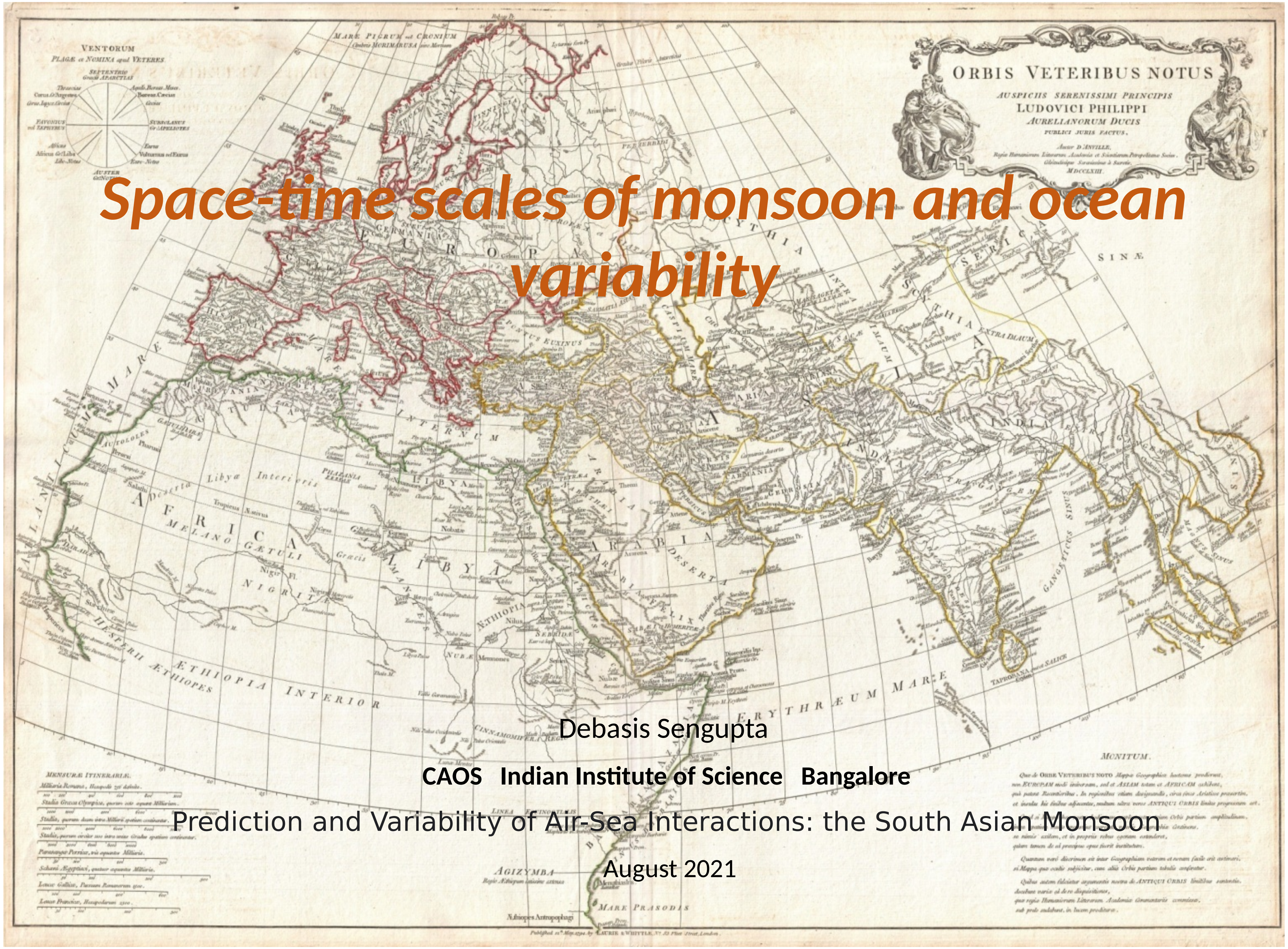


Space-time scales of monsoon and ocean variability

Debasis Sengupta

CAOS Indian Institute of Science Bangalore

Prediction and Variability of Air-Sea Interactions: the South Asian Monsoon

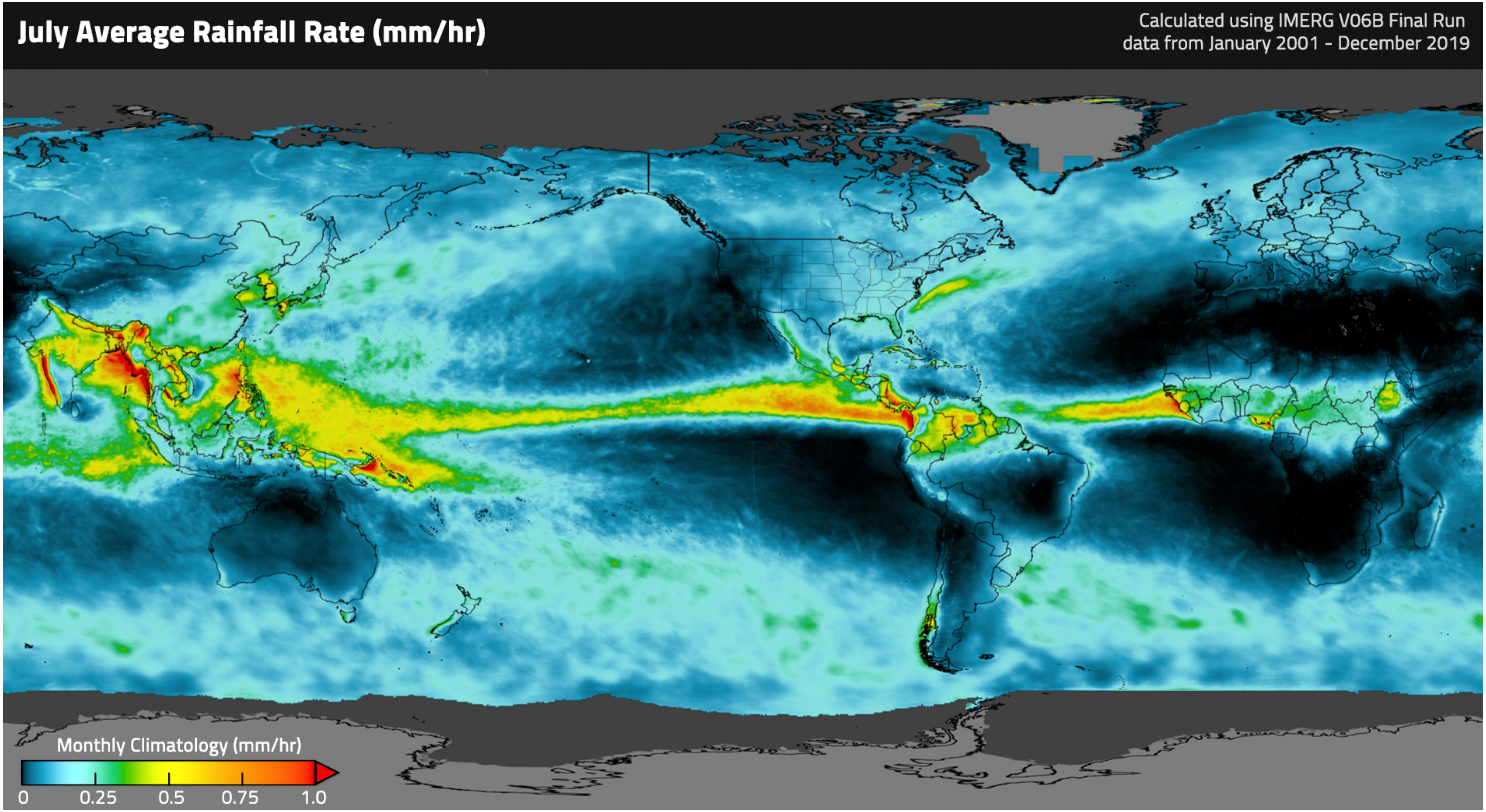
August 2021

South Asian monsoon variability

Shared time scales in atmosphere and ocean

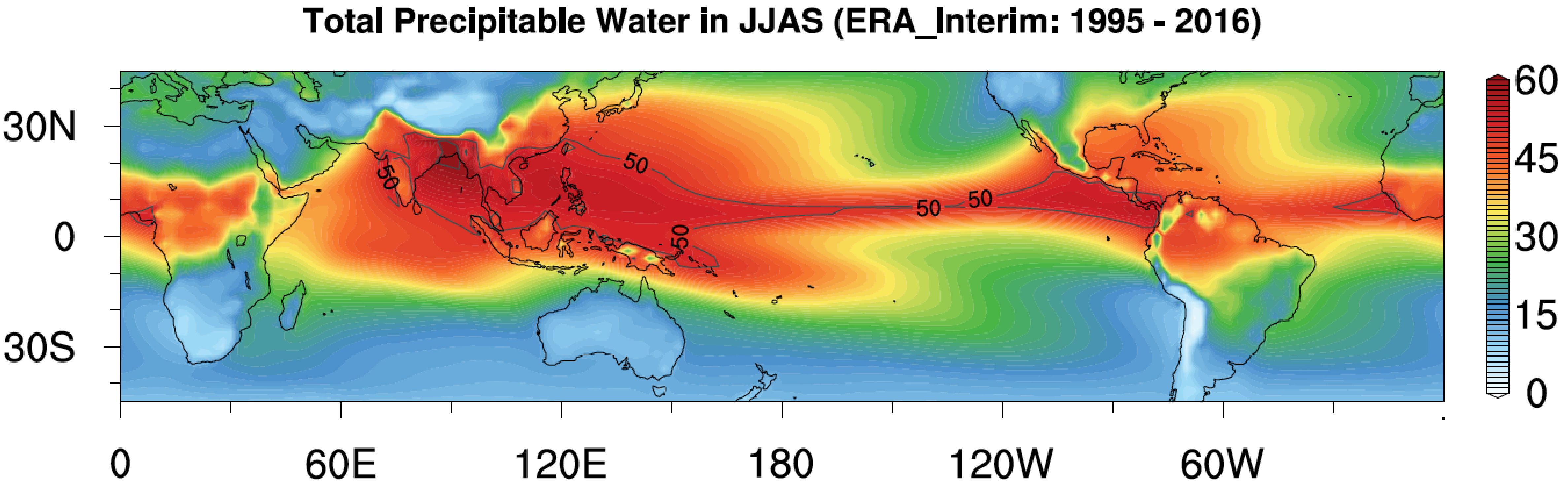
Decadal scale

Sub-seasonal scale



NASA-JAXA Global Precipitation Measurement (GPM)

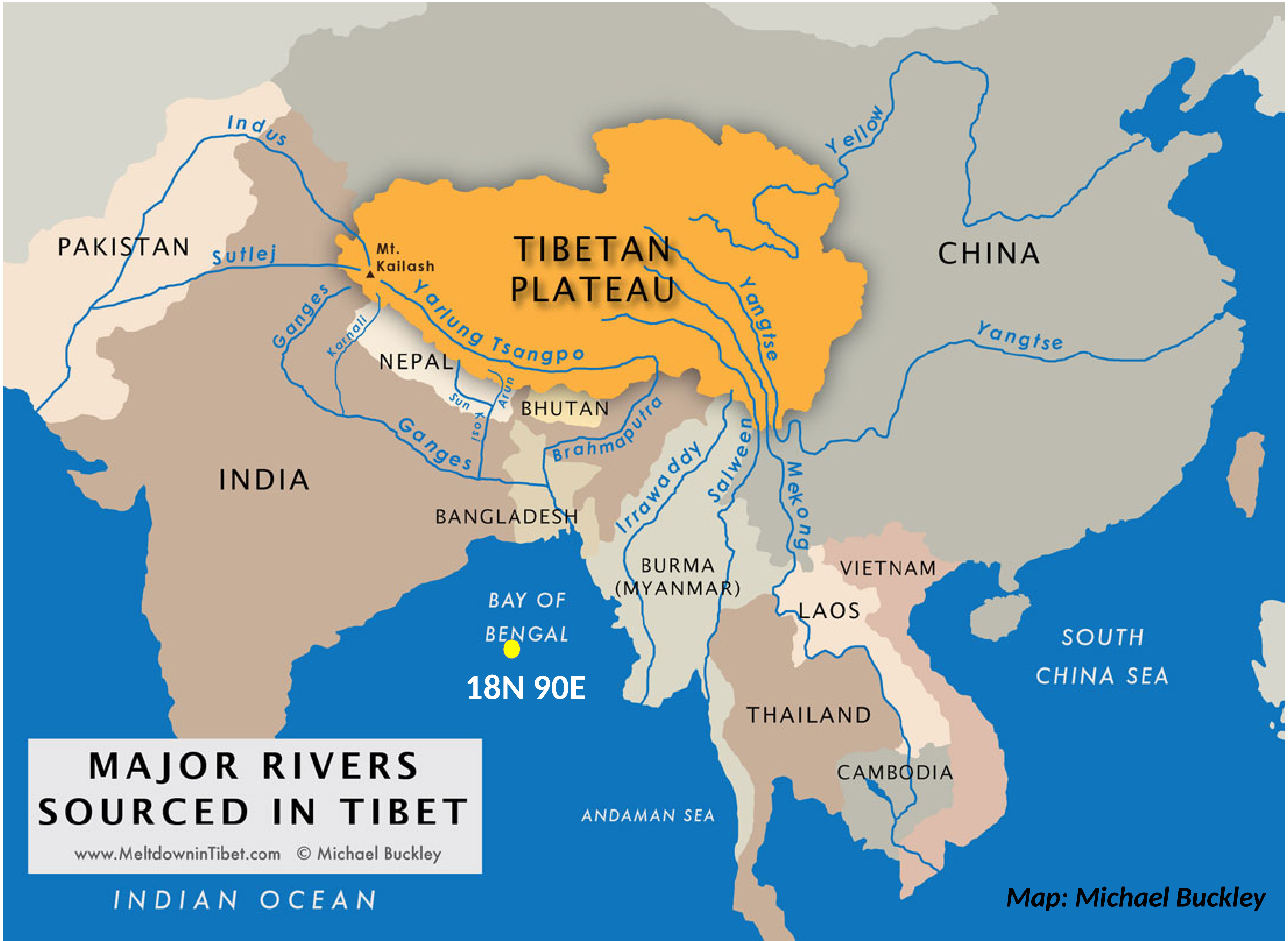
Over 10 mm per day in the Intertropical convergence zone (ITCZ)



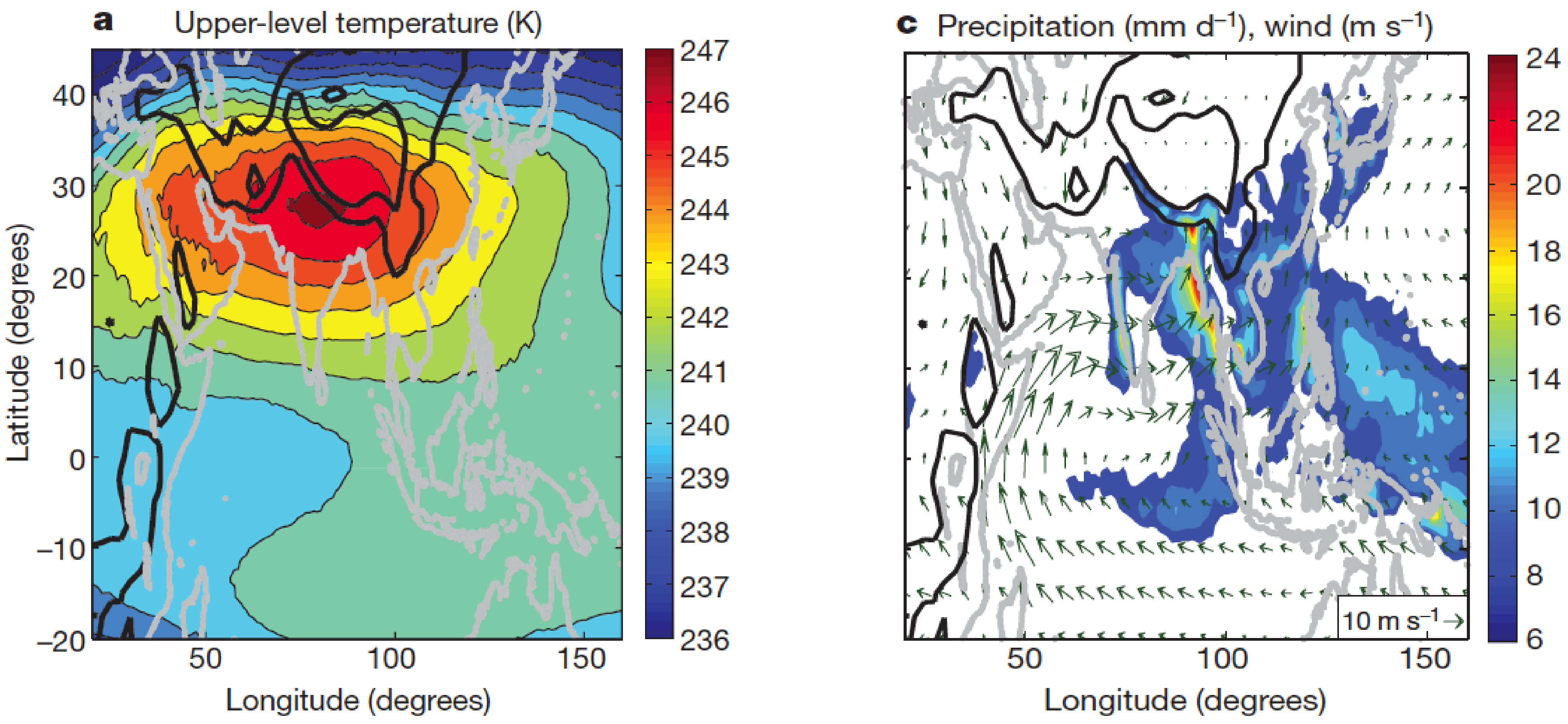
Column water vapour (mm of liquid water equivalent) June-September

Data-model blend: ECMWF Reanalysis

$$\frac{\partial W}{\partial t} + \nabla \cdot \boldsymbol{Q} = E - P \qquad \boldsymbol{Q} = \frac{1}{g} \int_{p_t}^{p_s} q\mathbf{V}\, dp$$



Map: Michael Buckley

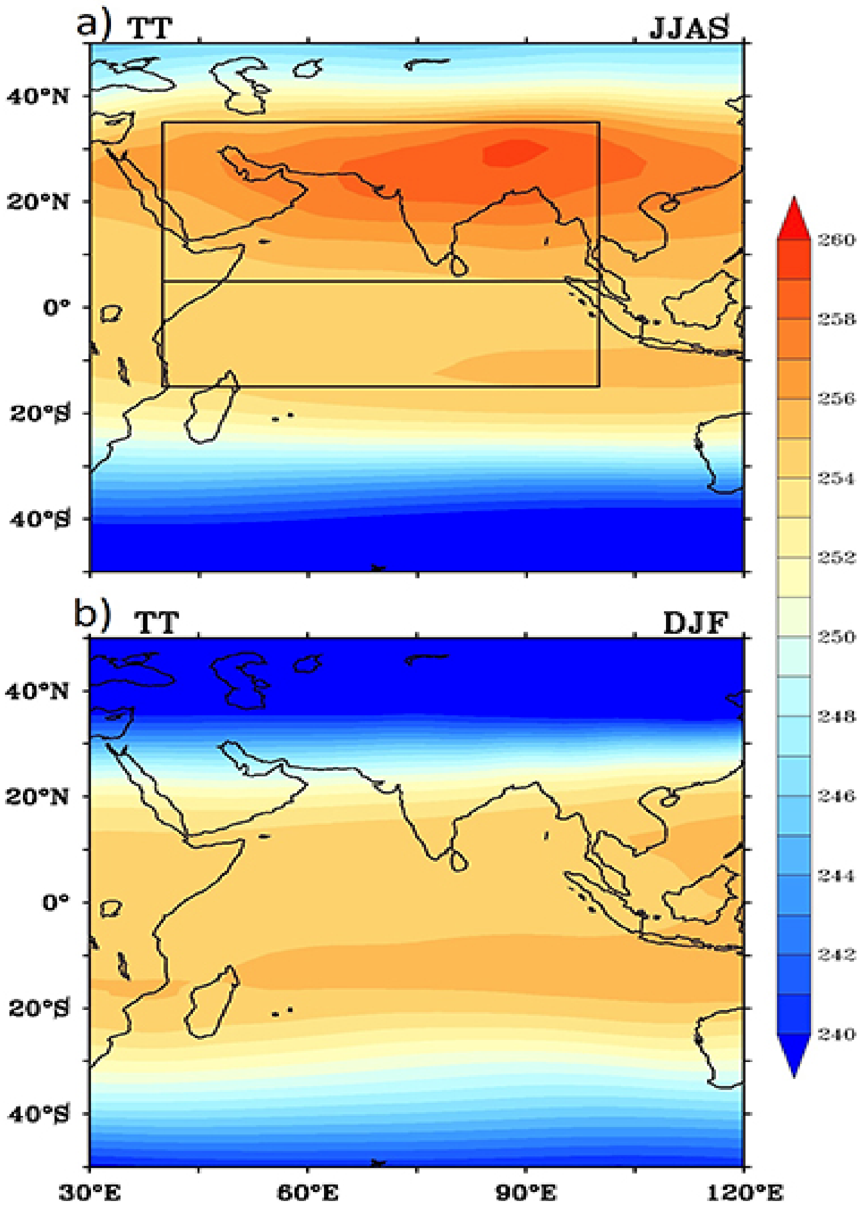


June-Aug AIRS T 450-175 hPa (6-12 km)

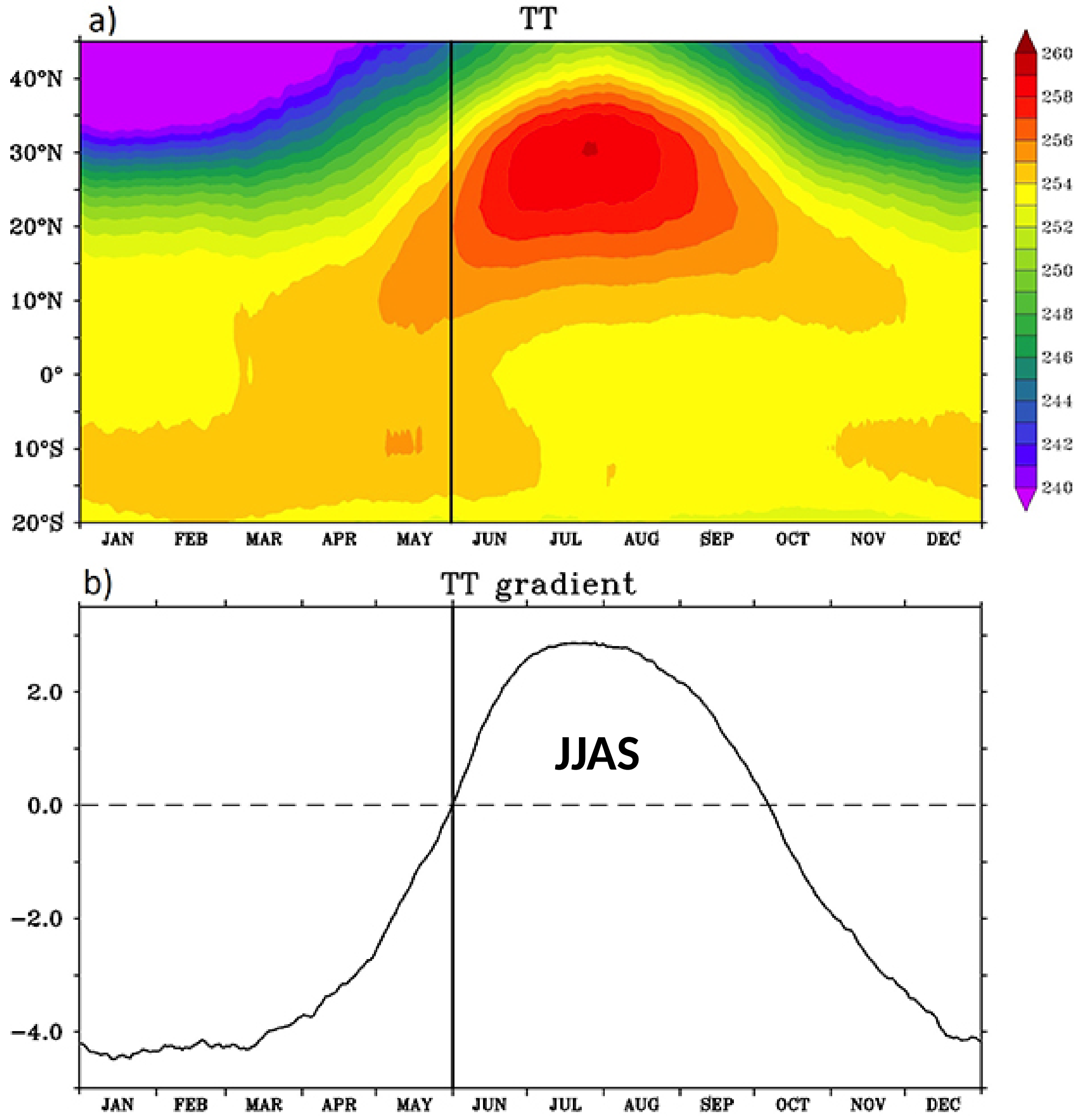
TRMM Rain (mm/day) ERA winds 850hPa

Peak upper-troposphere temperatures over India
Himalayas insulate warm, moist air from the cold and dry extratropics

Boos and Kuang *Nature* 2010

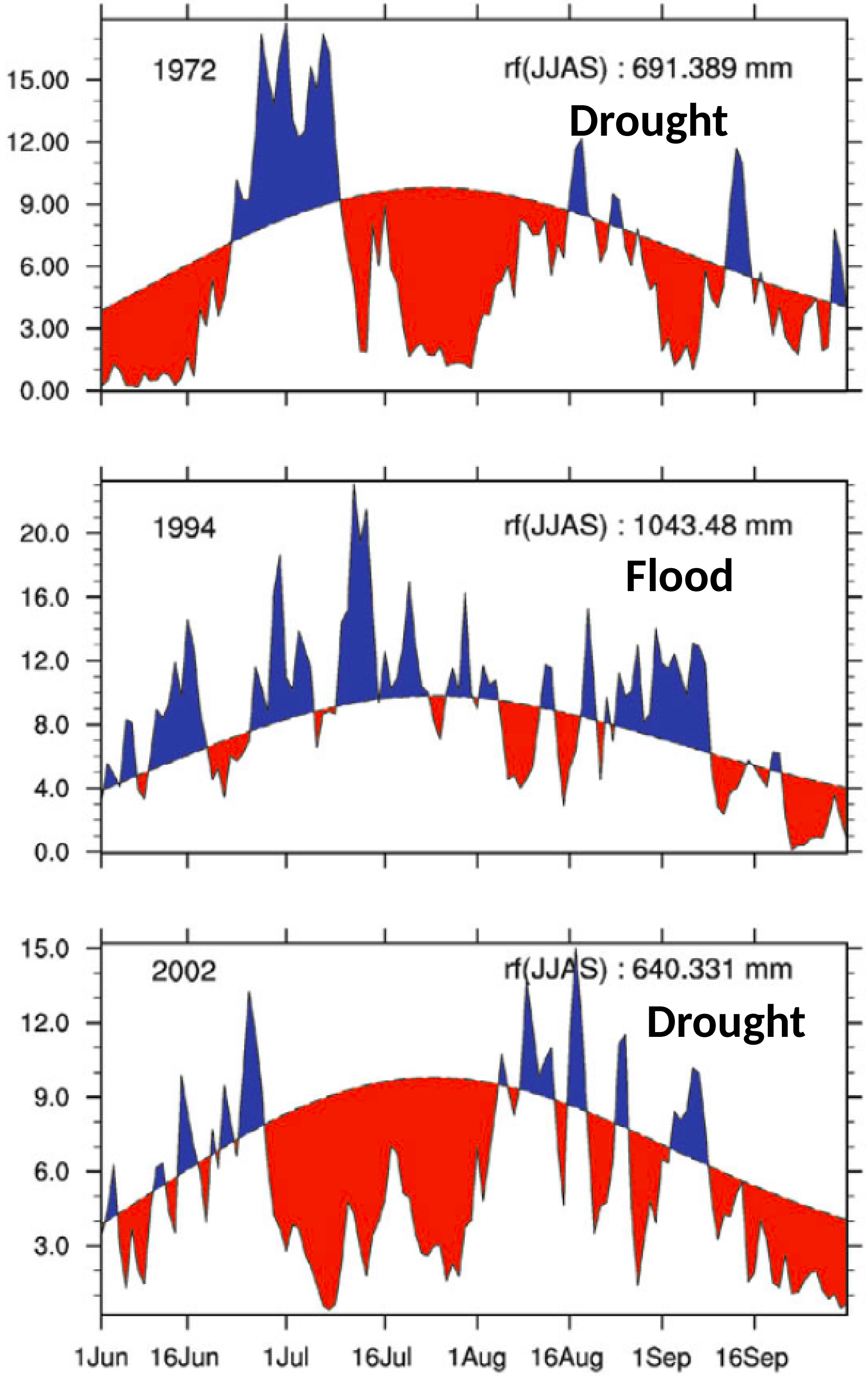


Tropospheric T 600-200 mb
North and South boxes (top)



Annual cycle of TT (70-90°E) and TT gradient (°C)

Goswami and Chakravorty 2017



Goswami 2012

India Met Dept. daily rainfall (mm/day)
Central India average

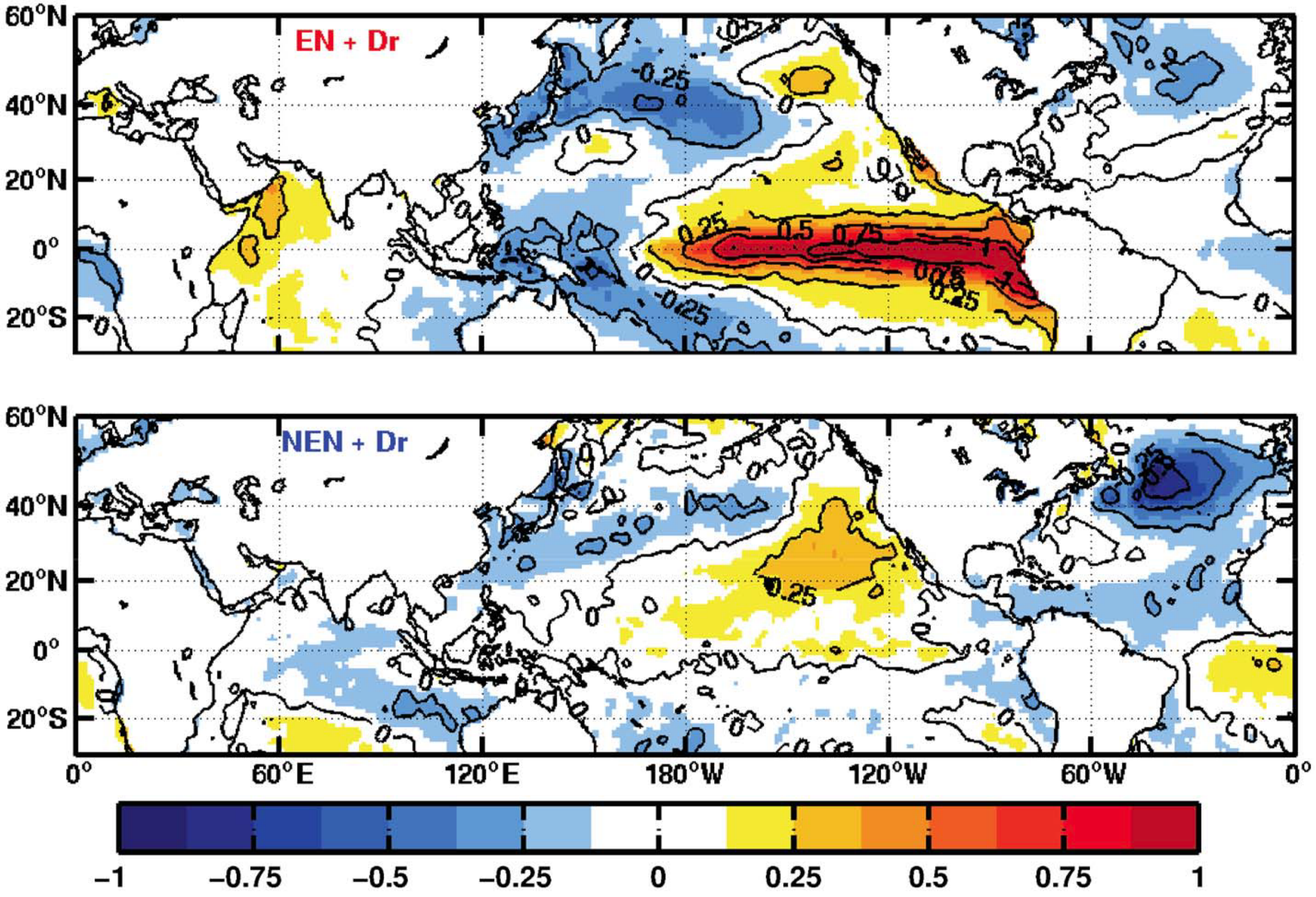
Flood year:	**1994**	**104 cm**
Drought year:	**1972**	**69 cm**
	2002	**64 cm**

Sub-seasonal "active-break" cycles
Alternate wet and dry spells

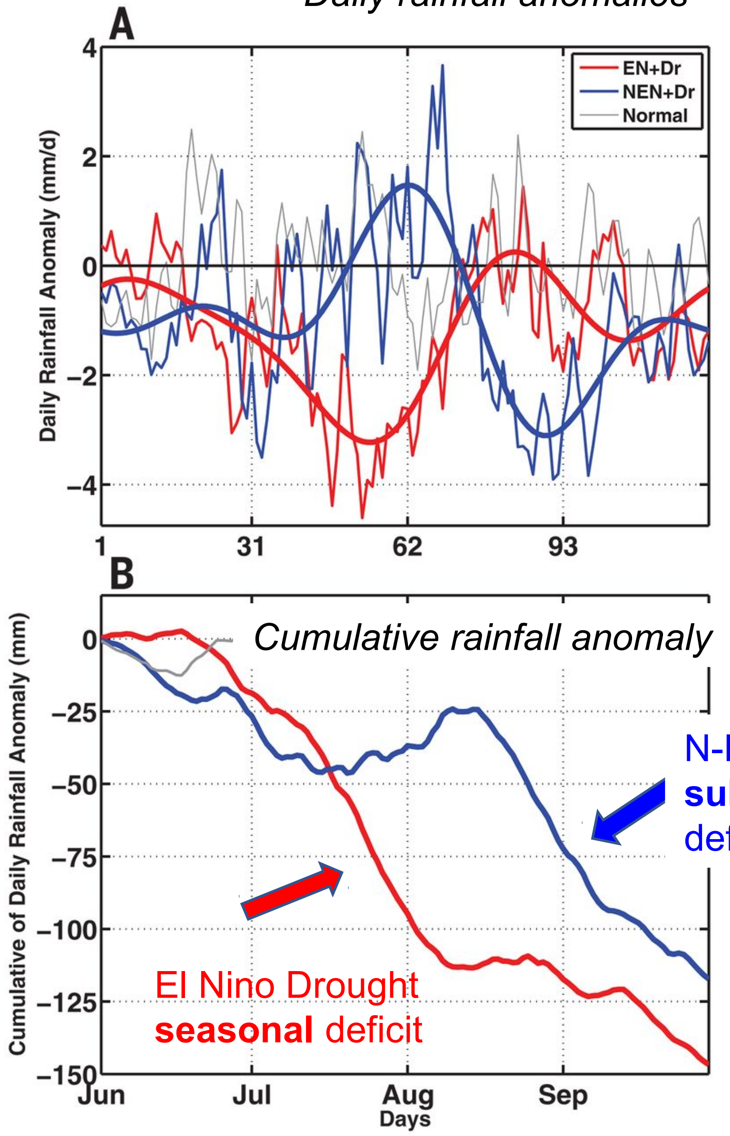
Sikka and Gadgil *Mon. Wea. Rev.* 1980 Vecchi and Harrison *J. Clim.* 2002 Gadgil *Ann. Rev. Earth Planet. Sci.* 2003 Bhat *Q. J. Royal Met. Soc.* 2006 Joseph and Sabin *Clim. Dyn.* 2008 Webster *et al. Int. Geophys. 2002*

Decadal scale

Non El Nino Monsoon Droughts



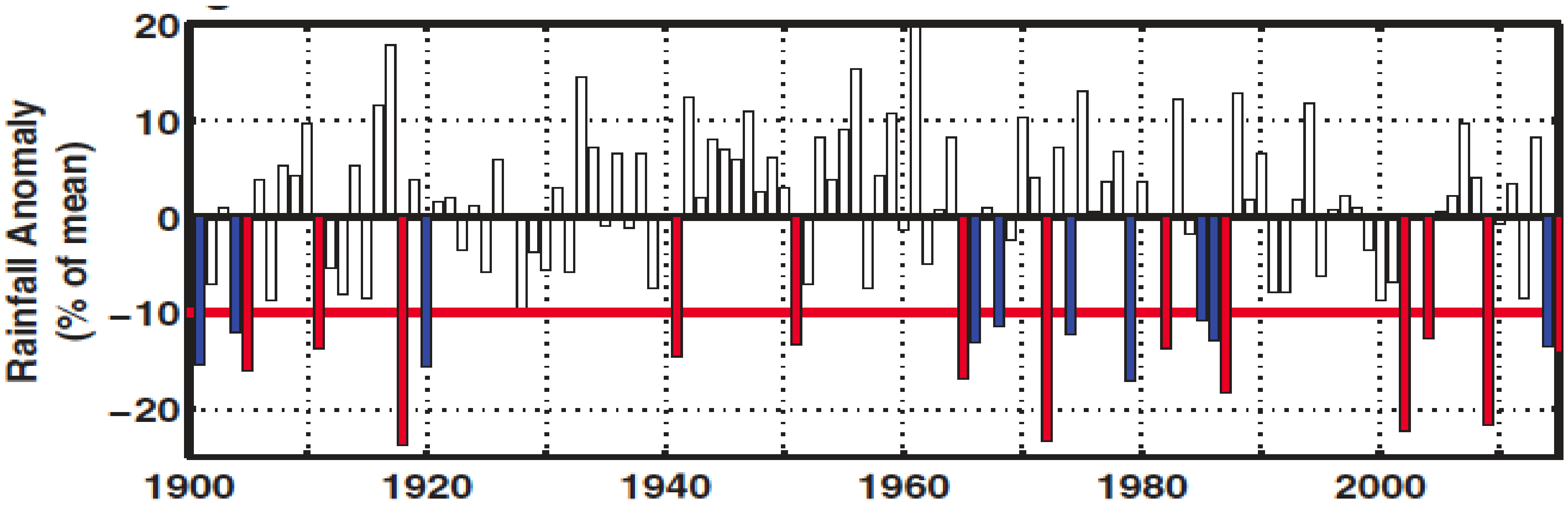
Hadley centre SST Anomaly (°C) JJAS



13 El Niño and 10 Non El Niño Droughts (1901-2015)

Borah *et al. Science* 2020

Indian Summer Monsoon Rainfall departure from mean

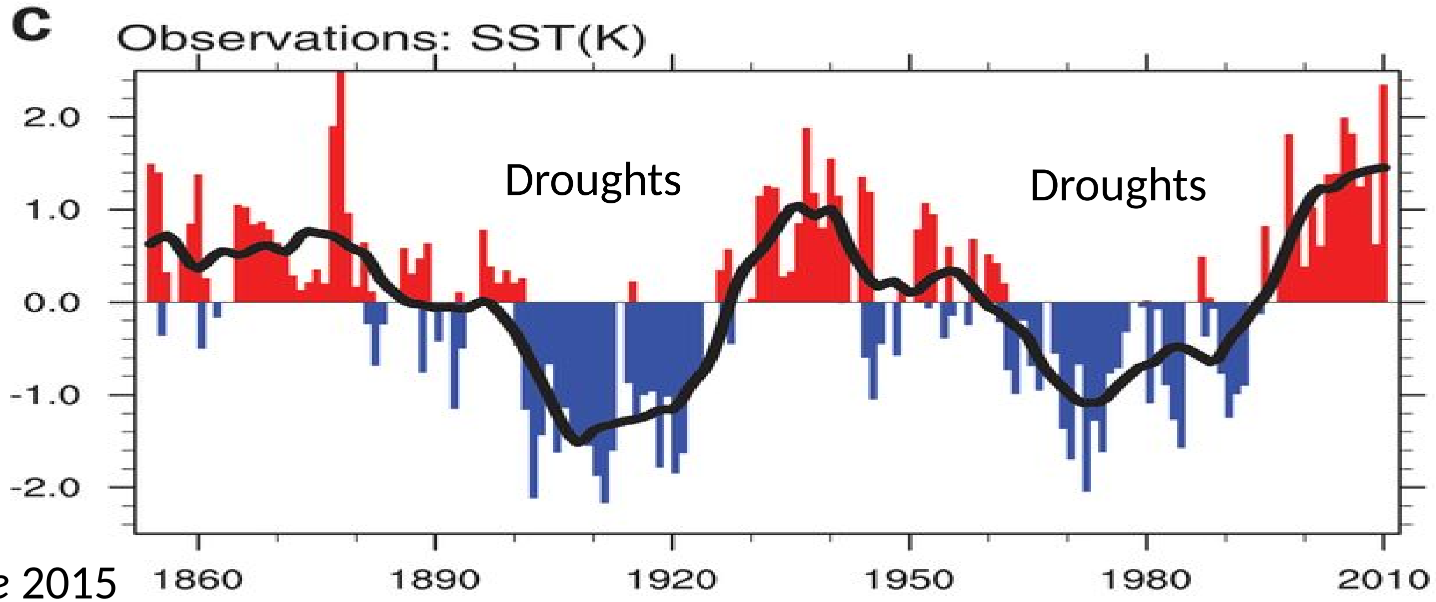


Borah *et al. Science* 2020

EN + Dr. N-EN + Dr.

Atlantic Multidecadal Oscillation (AMO)
0-60°N average north Atlantic SST

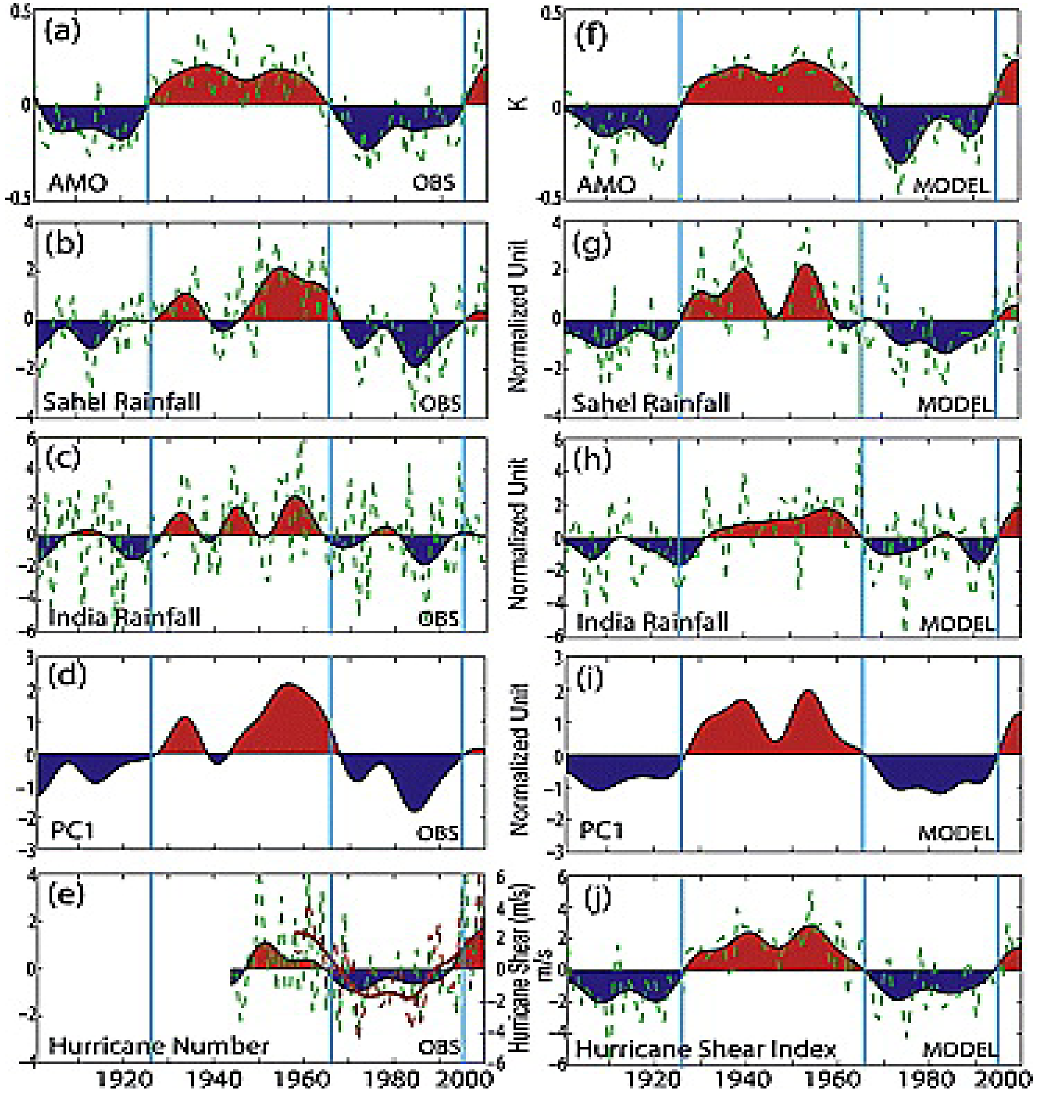
Natural "internal" mode linked to Atlantic 3-d circulation and oceanic heat transport

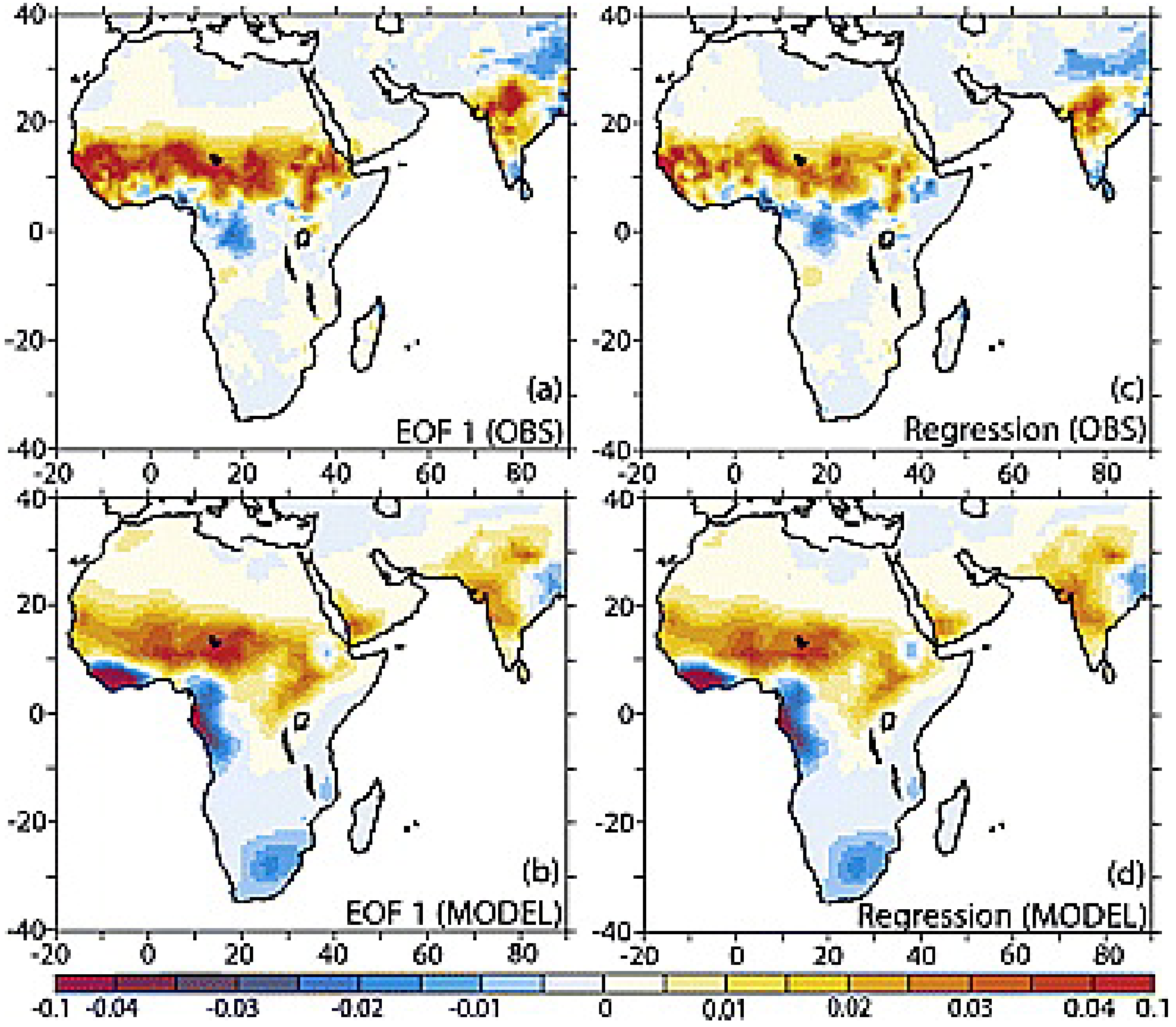


Clement *et al. Science* 2015

Normalised AMO Index and 10-yr running mean

Atlantic Multidecadal Oscillation 0-60^{o}N Atlantic SST



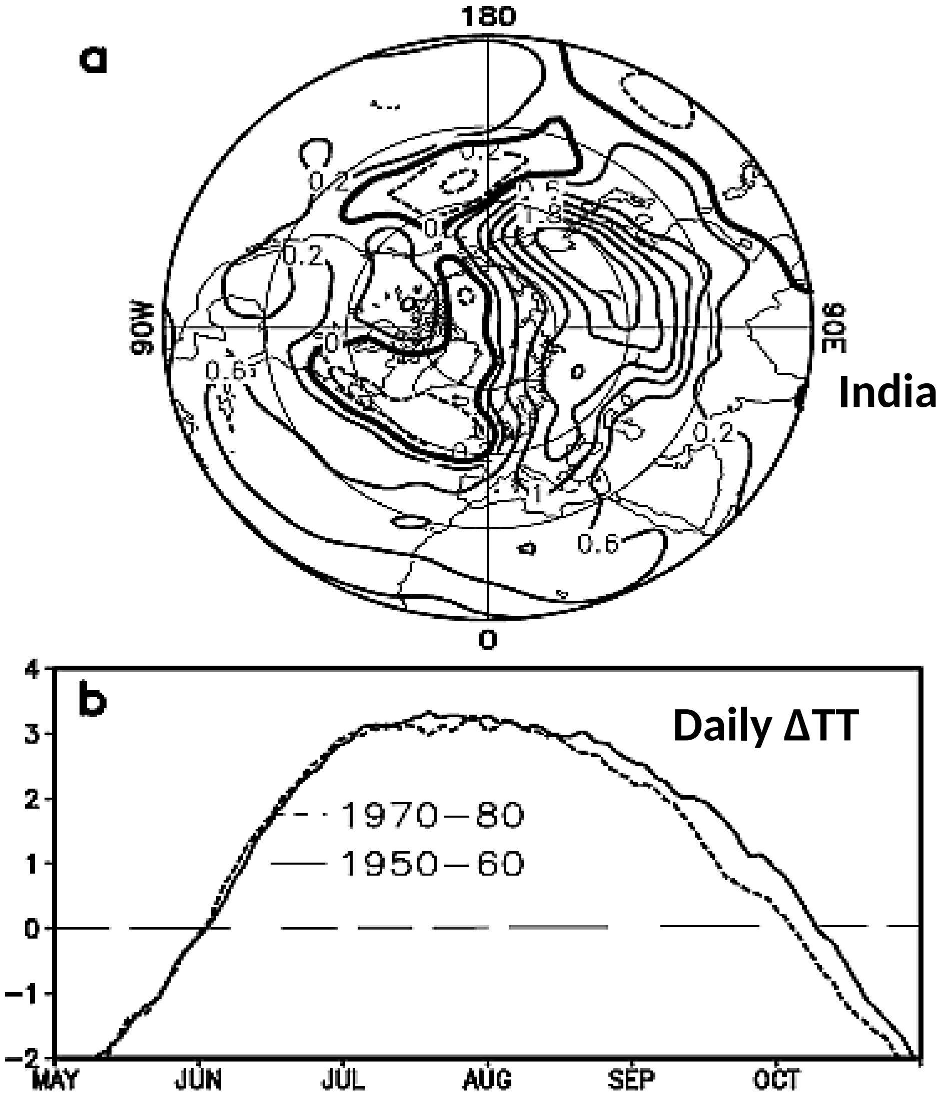


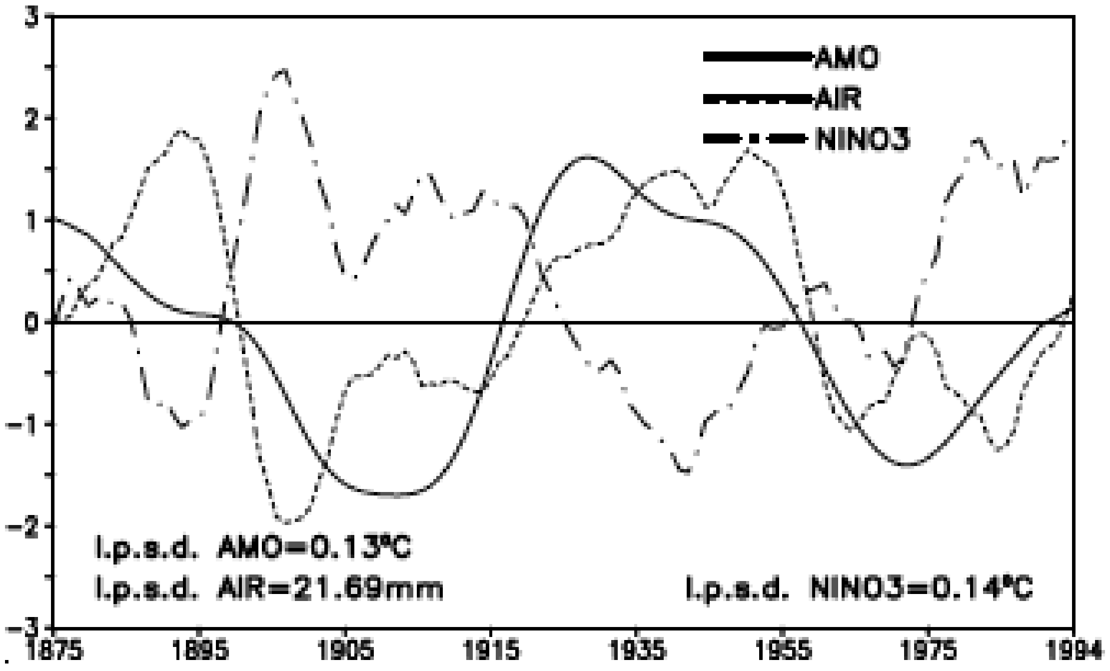
Data **Model**

GFDL CM2.1: Slab ocean in Atlantic basin

Zhang and Delworth *Geophys. Res. Lett*. **33** (17) 2006

ΔTT (°C) JAS 1950-60 (warm nAtl.) minus 1970-80 (cold nAtl.)



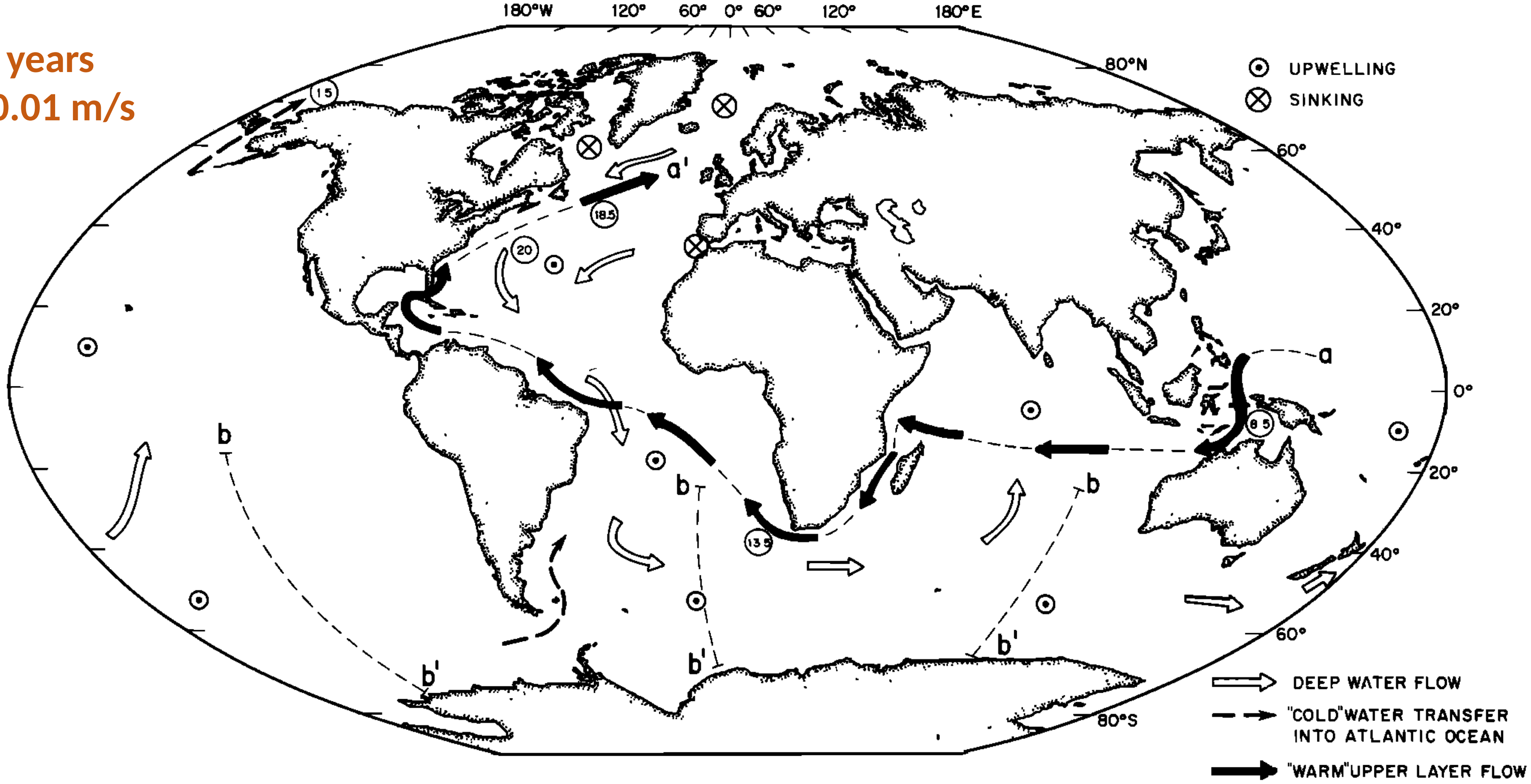


coupled ocean–atmosphere oscillation that generates AMO also …. modulates El Nino and Indian monsoon

ΔTT 600-200 hPa T(30-100E, 10-35N) – T(30-100E,15S-10N)

Goswami *et al. Geophys. Res. Lett.* 2006
Naidu *et al. Scientific Reports* 2020

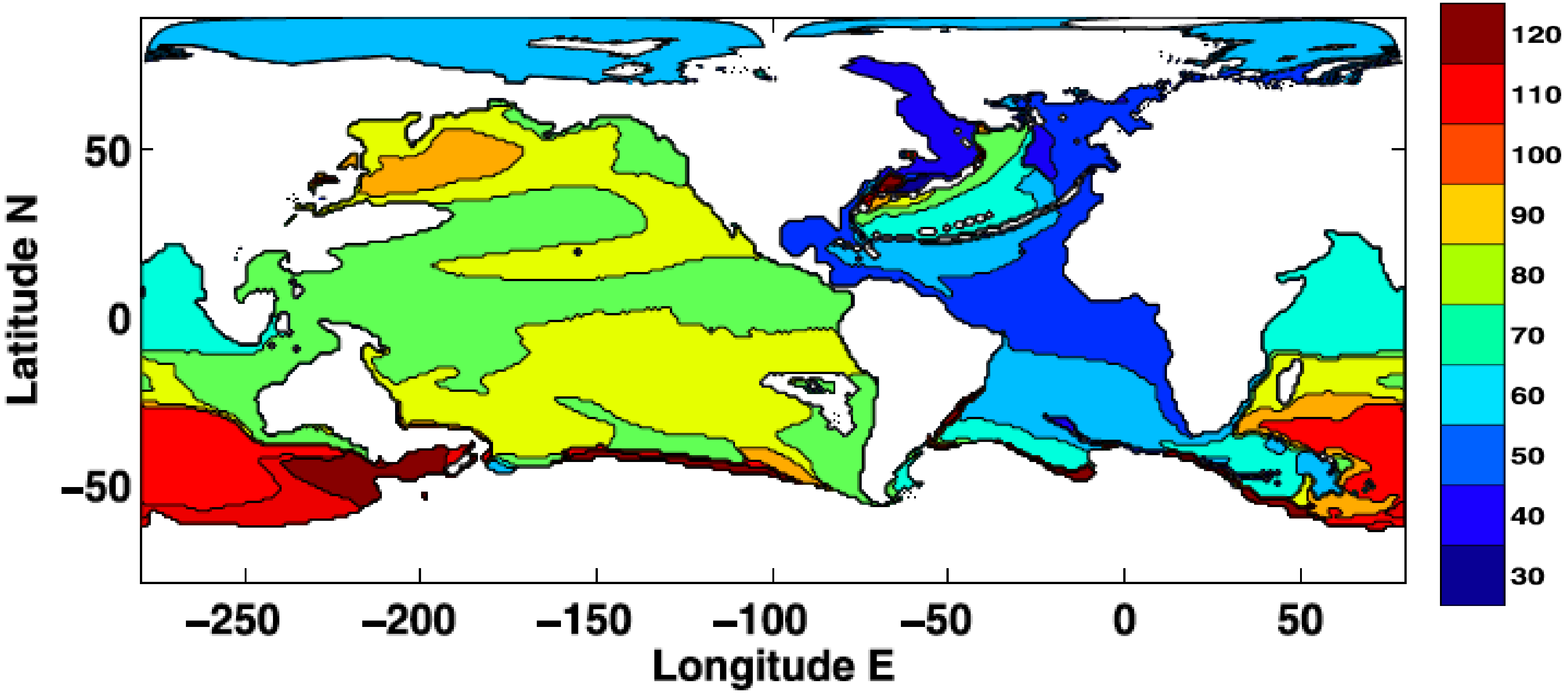
13-130 years
at 0.1-0.01 m/s



Proposed 40,000 km long upper "warm" water route of ocean thermohaline circulation to sinking in north Atlantic

Gordon *J. Geophys. Res.* 1986

Global seiching of thermocline depth (warm water volume)



3-d ocean model MOM with
Atmos. Energy Balance Model

Warm nAtlantic, cool east Pacific

North Atlantic perturbation arrives in eq. east Pacific in 80 years

**Initial adjustment via coastal and equatorial Kelvin waves,
global adjustment via slow off-equator Rossby waves**

Cessi, Bryan, Zhang *Geophys. Res. Lett.* 2004

Sub-seasonal scale and waves

Equatorially trapped waves

$$\frac{\partial u}{\partial t} - \beta y v + \frac{\partial \phi}{\partial x} = 0$$

$$\frac{\partial v}{\partial t} + \beta y u + \frac{\partial \phi}{\partial y} = 0$$

$$\frac{\partial \phi}{\partial t} + c^2 \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = 0$$

$[T] = (1/c\beta)^{1/2}$ $\quad$ $[L] = (c/\beta)^{1/2}$

$$\frac{d^2 v}{dy^2} + \left(\omega^2 - k^2 + \frac{k}{\omega} - y^2 \right) v = 0$$

$v \to 0$; when $y \to \pm\infty$

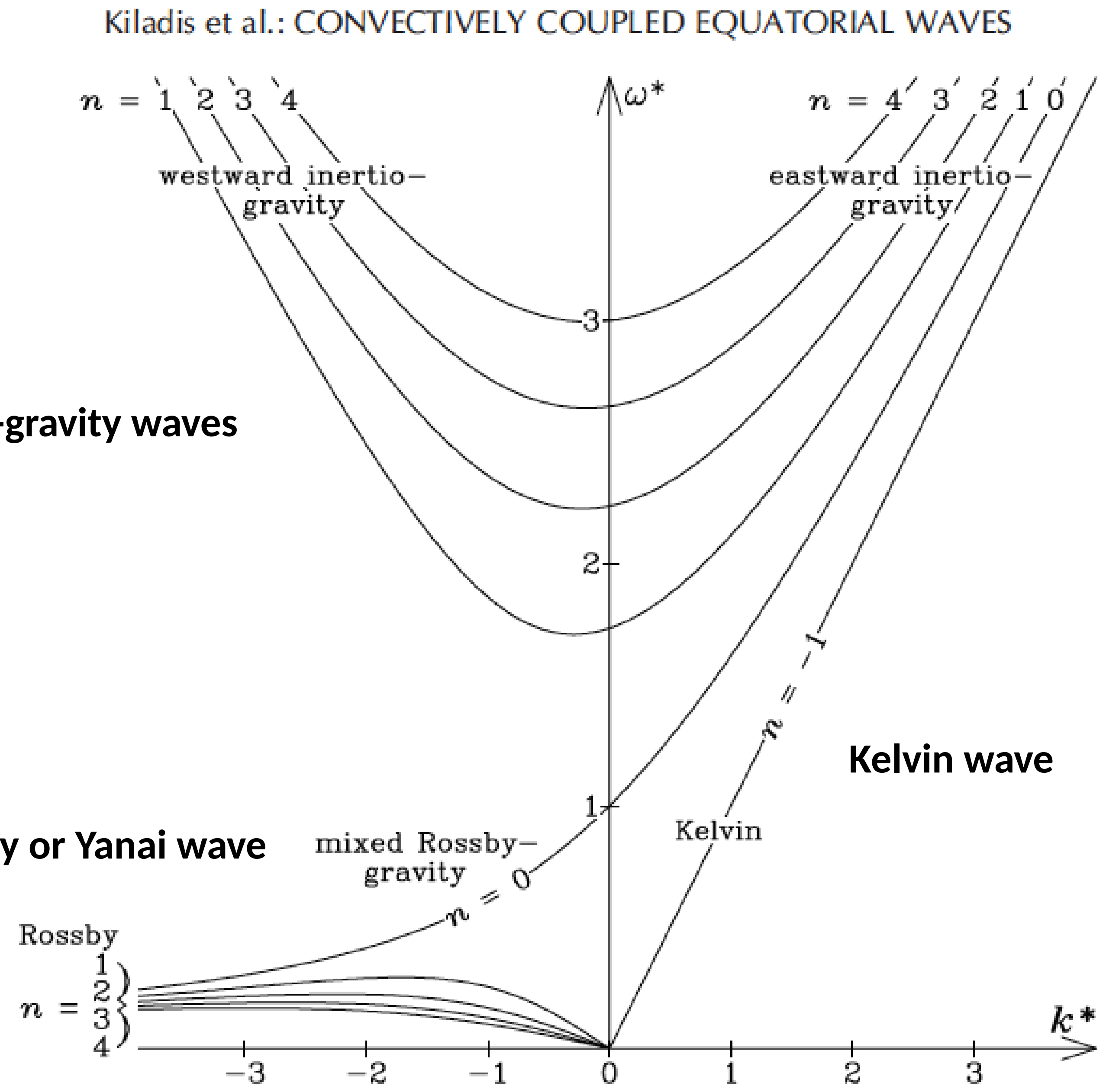
$$\omega^2 - k^2 + \frac{k}{\omega} = 2n + 1 \quad (n = 0,\ 1,\ 2,\ \ldots)$$

Then the solution of (6) is given as;

$$v(y) = C e^{-\frac{1}{2} y^2} H_n(y)$$

Matsuno *J. Met. Soc. Japan* 1966

Dispersion curves



high-frequency inertia-gravity waves

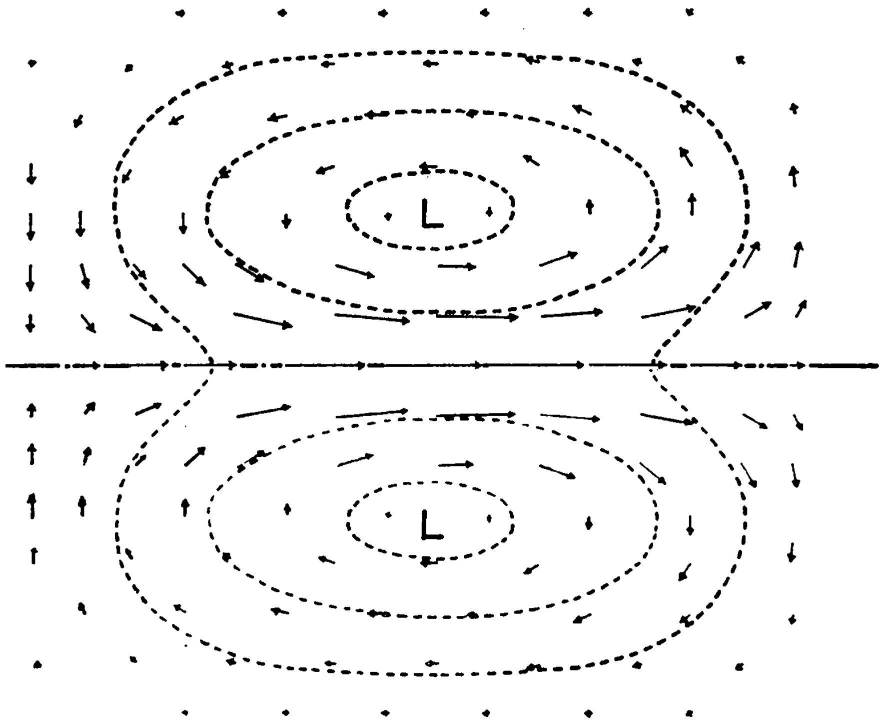
Kelvin wave

n=0 mixed Rossby-gravity or Yanai wave

low-frequency Rossby waves

Kiladis *et al*. Convectively coupled equatorial waves. *Rev. Geophys.* 2009

n=1 equatorial Rossby wave

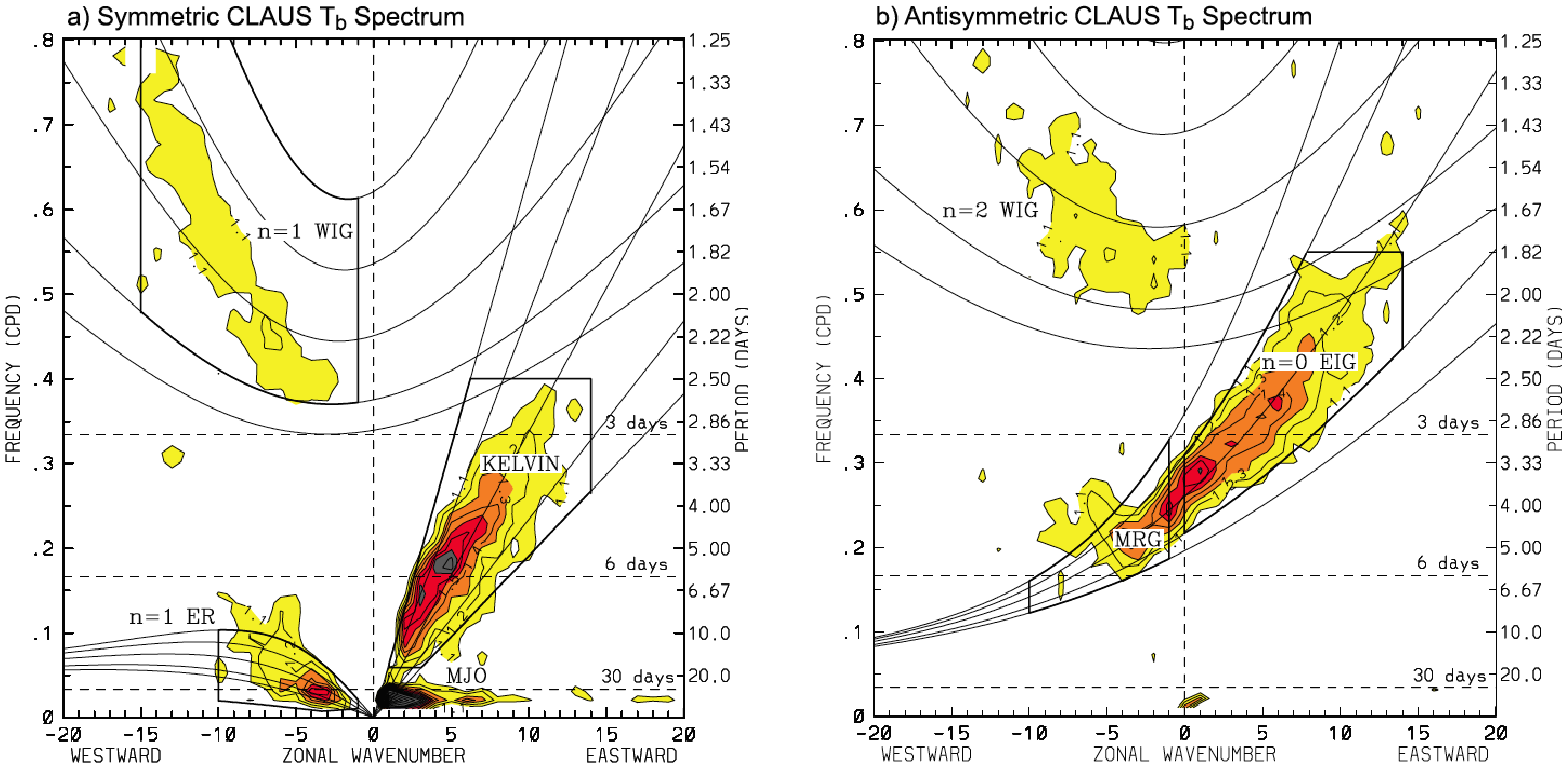


Counter-rotating vortices symmetric about equator

It would be most interesting if we find .... trapped waves in the actual atmosphere.

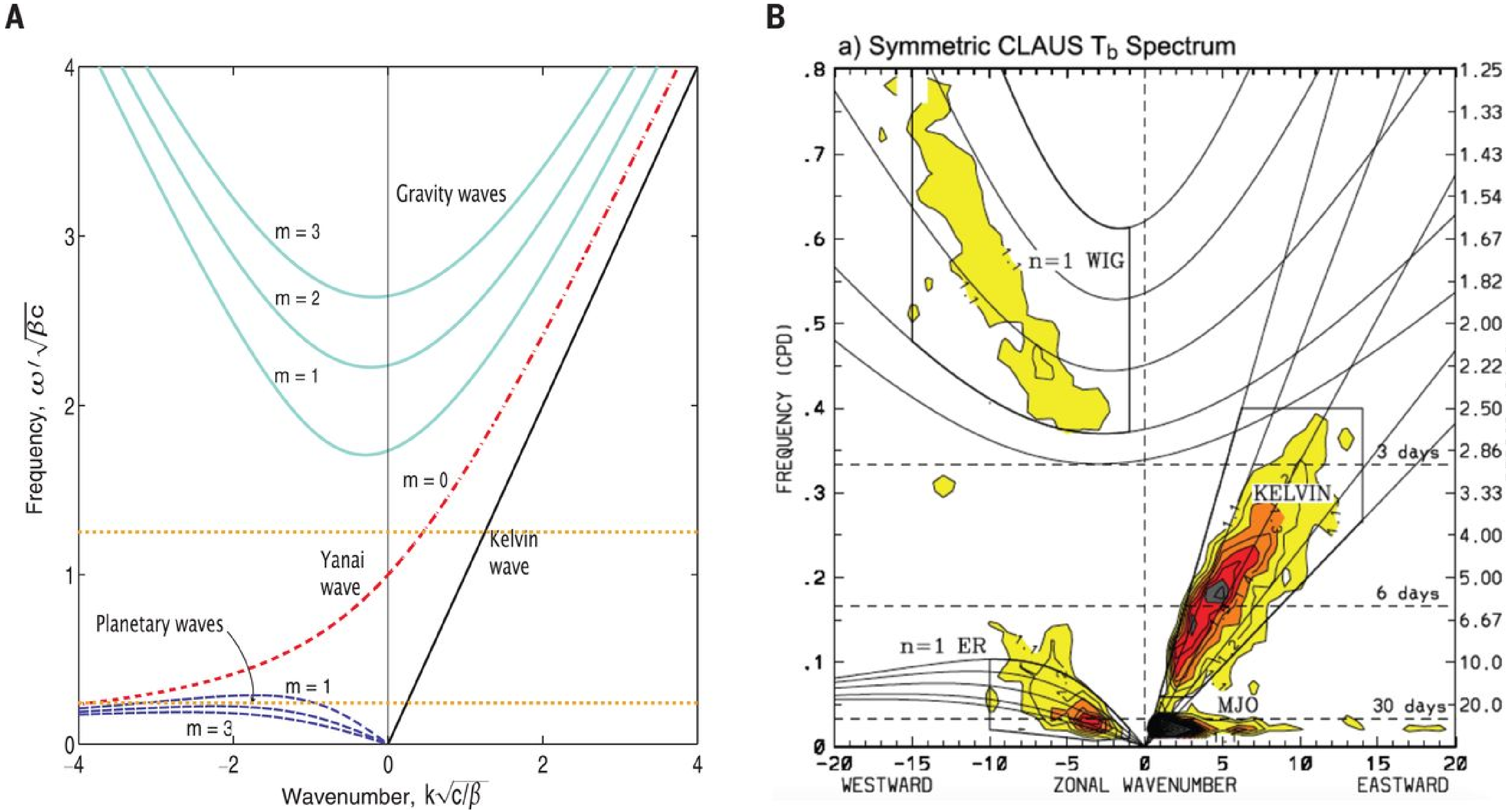
Matsuno *J. Met. Soc. Japan* 1966

Space-Time spectra of brightness temperature 15°S-15°N



Kiladis *et al. Rev. Geophys.* 2009

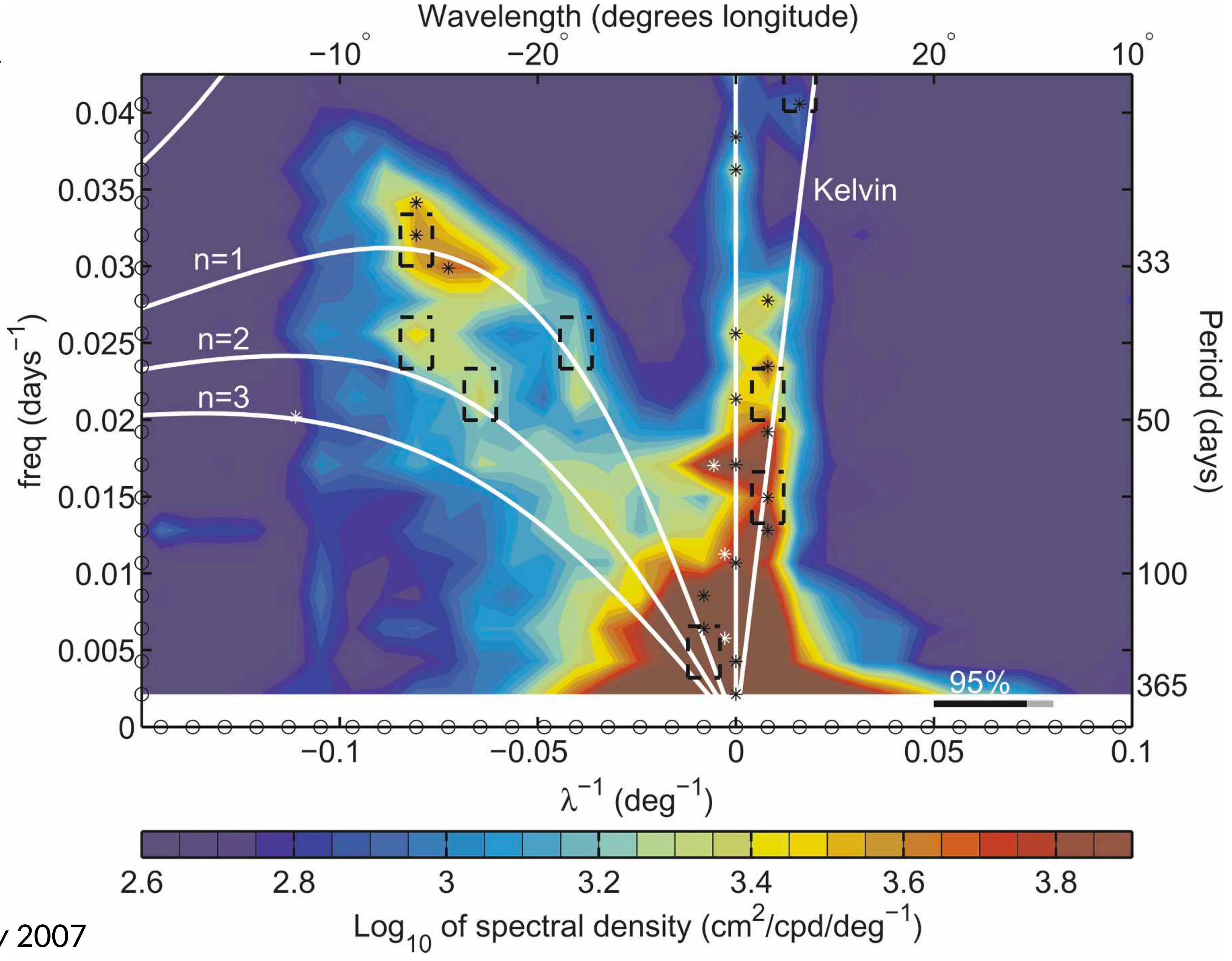
Dispersion spectrum of equatorial waves



"topological origin for …. the Kelvin and Yanai modes, owing to breaking of time-reversal symmetry by Earth's rotation"

Delplace, Marston and Venaille *Science* 2017

Pacific 7°S-7°N SSH anomaly
TOPEX/Poseidon



Farrar *J. Phys. Oceanography* 2007

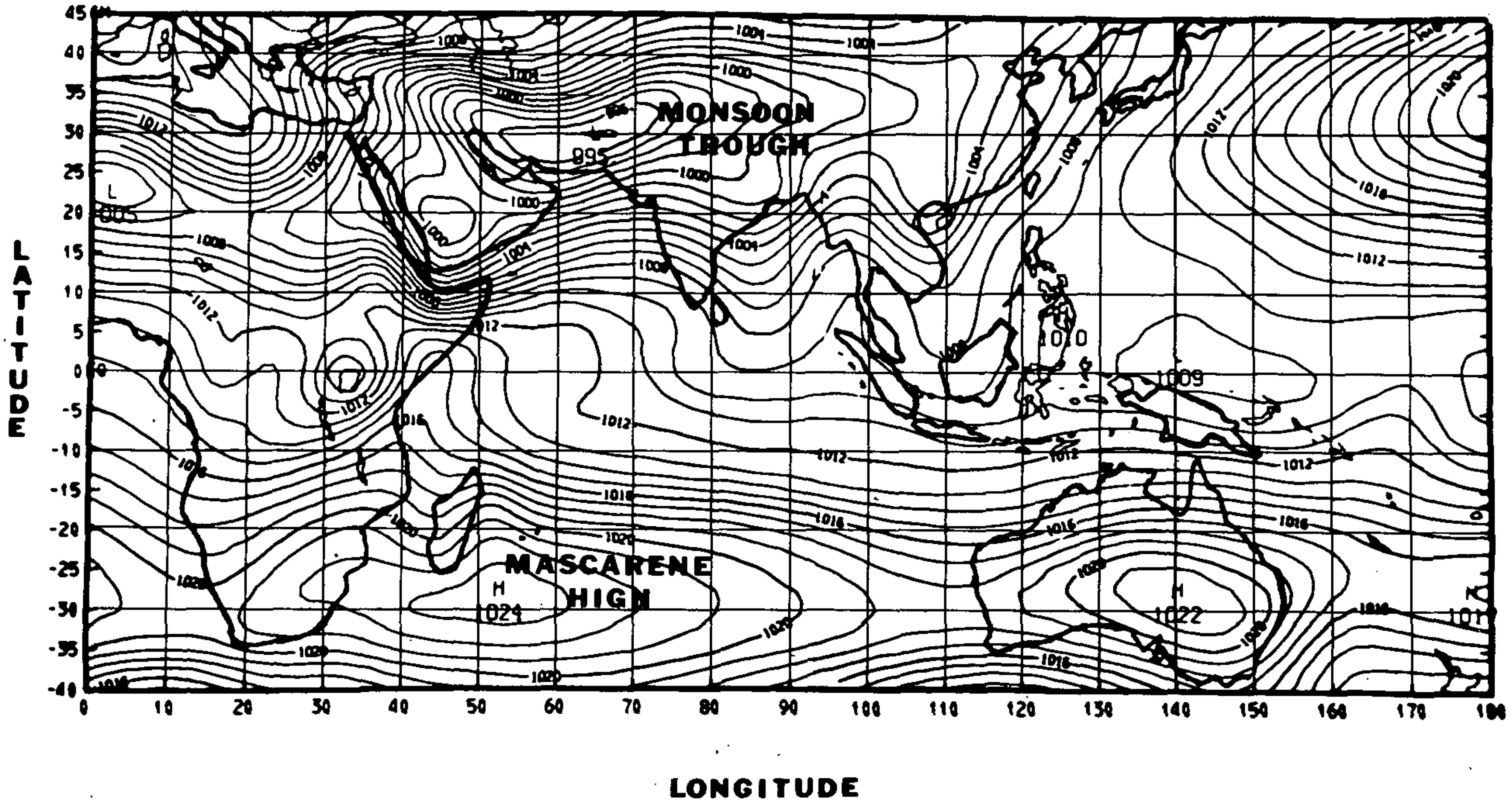
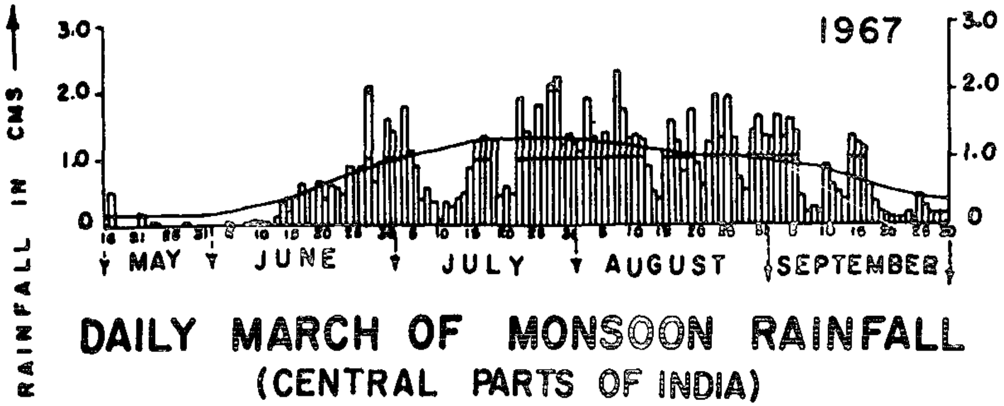
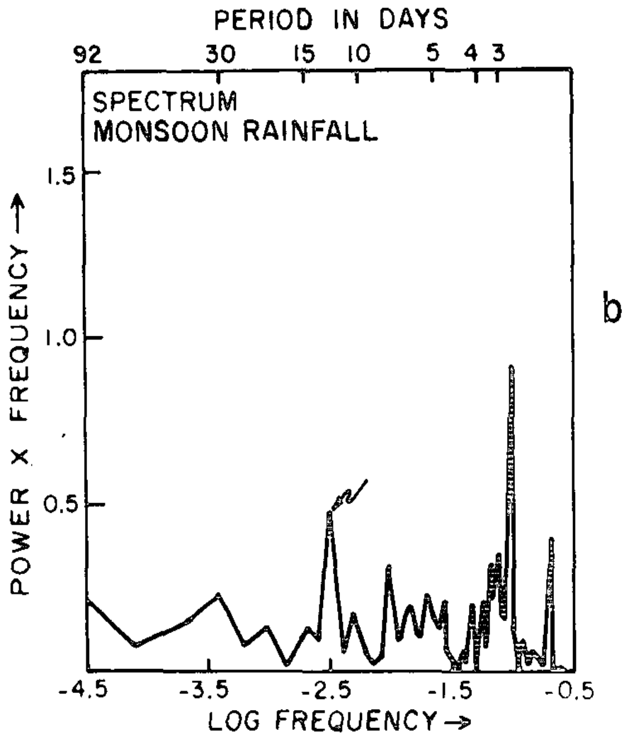


FIG. 2. Mean sea-level pressure for July (courtesy of Henry Van de Boogard).

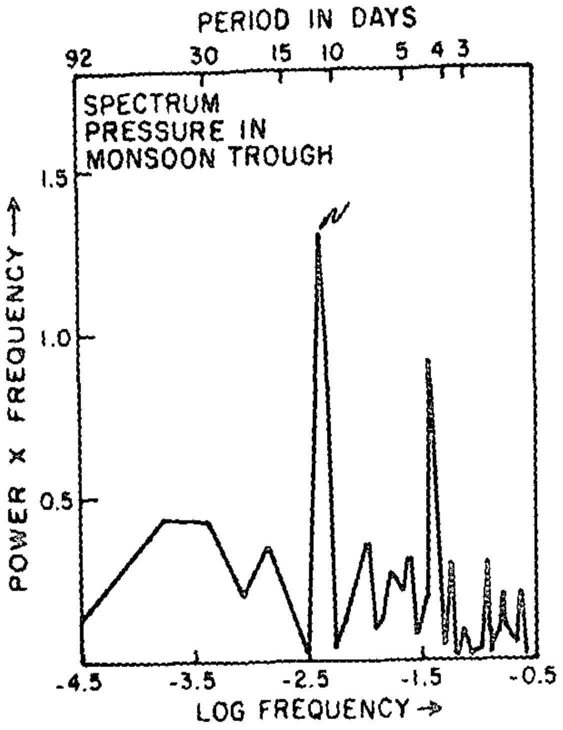
“There seems to exist a quasi-biweekly oscillation in almost all elements of the monsoon system”

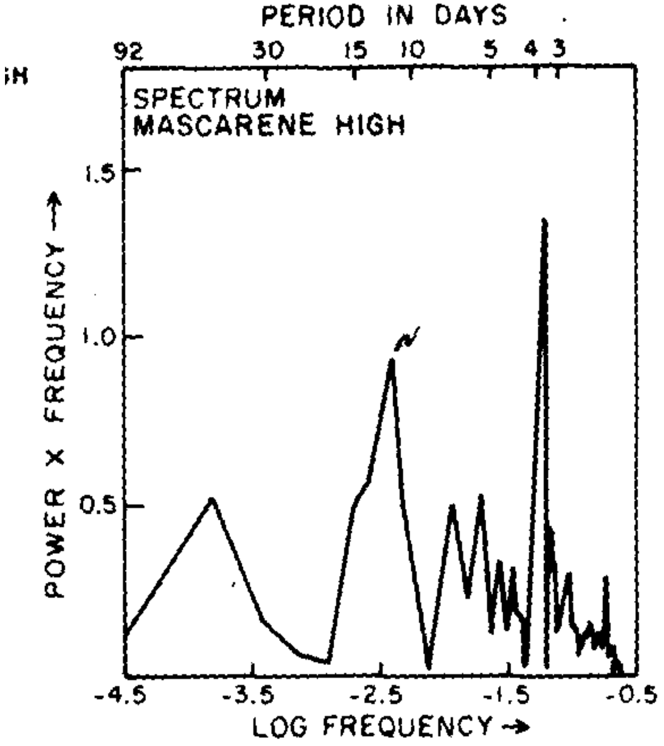
Krishnamurti and Bhalme Oscillations of a monsoon system. Part I. *J. Atmos. Sciences* 1976





CI rainfall and spectrum





Variance-preserving spectra of SLP Monsoon Trough, Mascarene High

Possible origins of quasi-biweekly oscillation

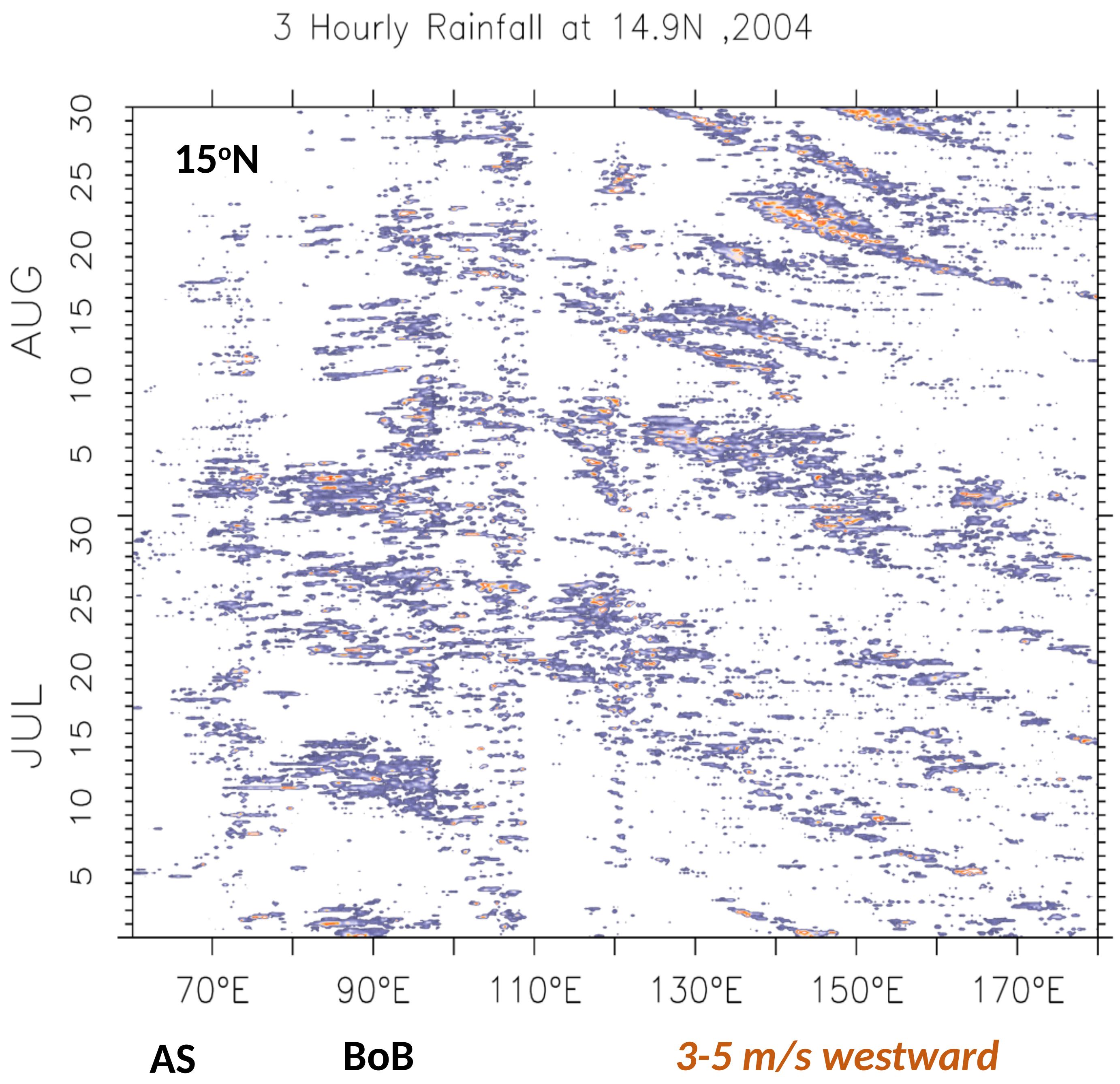
1. Planetary scale propagating waves

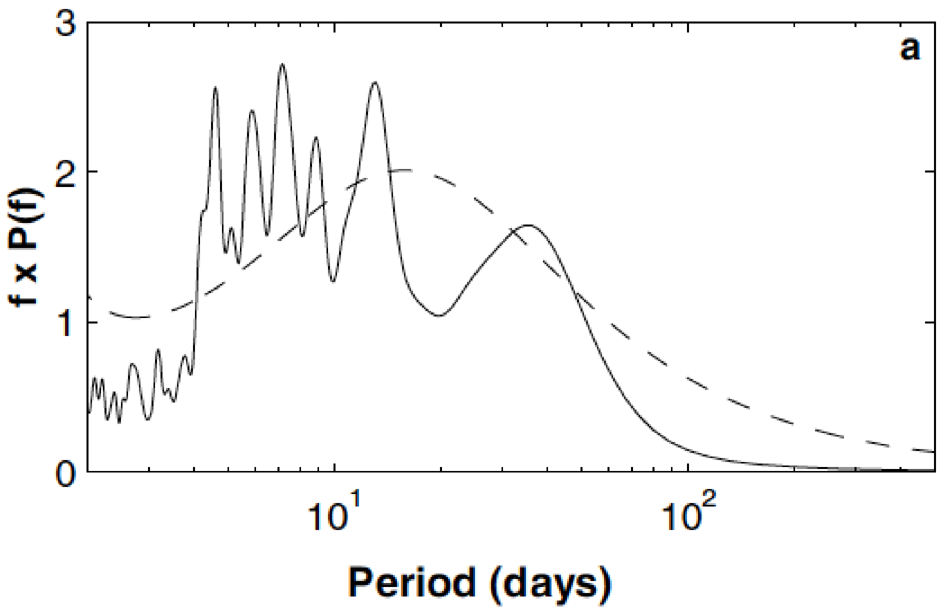
2. Surface heat flux changes stability and clouds

Clouds change stability and surface heat flux

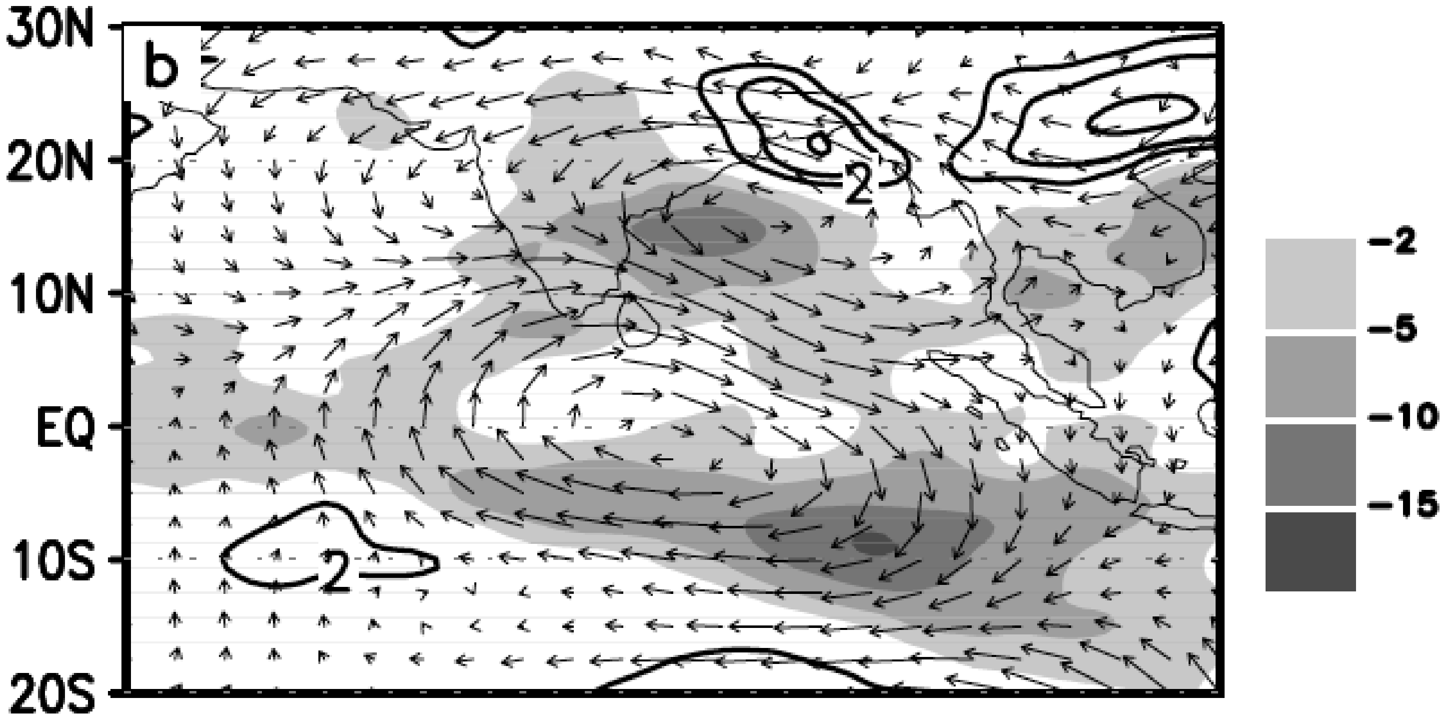
Krishnamurti and Bhalme *J. Atmos. Sci.* 1976

TRMM 0.25° 3 hourly rainfall July-August 2004 along 15°N





Power spectrum Bay of Bengal Rainfall GPCP 1992-2001

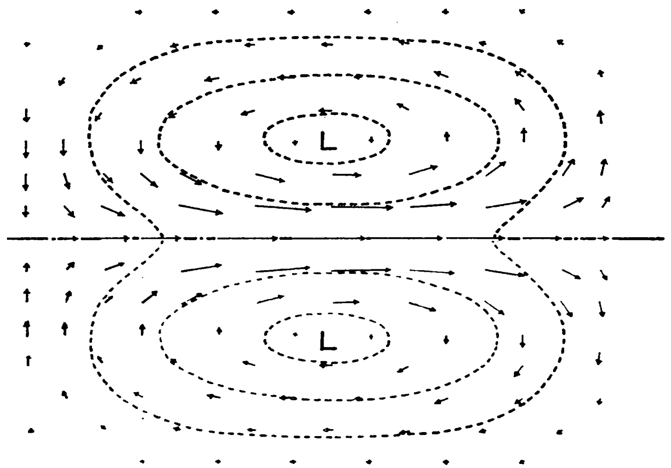


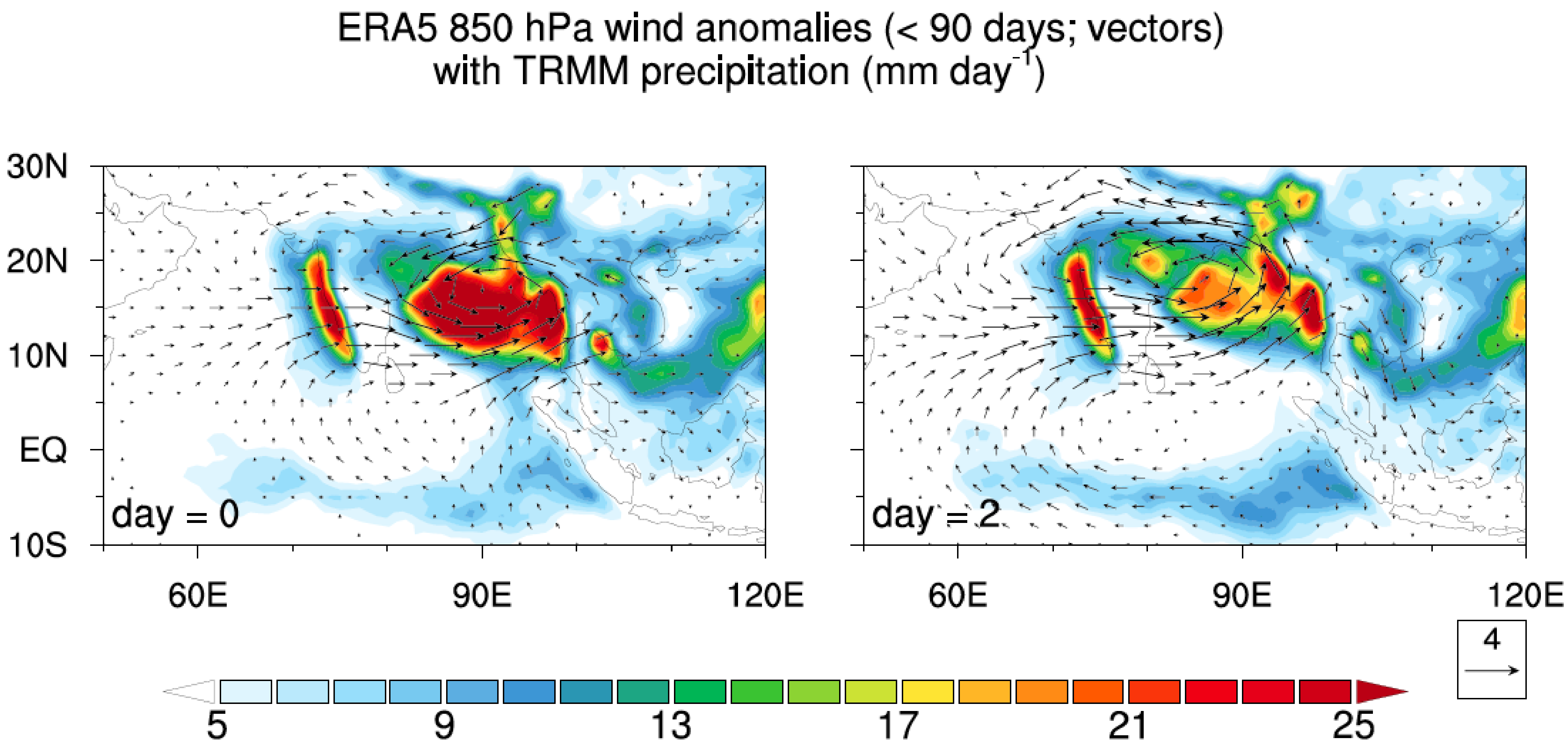
JJAS 1992-2001 10-20 day filtered OLR (W/m²), winds

Chatterjee and Goswami *Q. J. Royal Met. Soc.* 2004

a double-cell structure, one centered at 15°–20°N and one at the equator. Both cells move coherently westward…

Chen and Chen *Mon. Weather Rev.* 1993

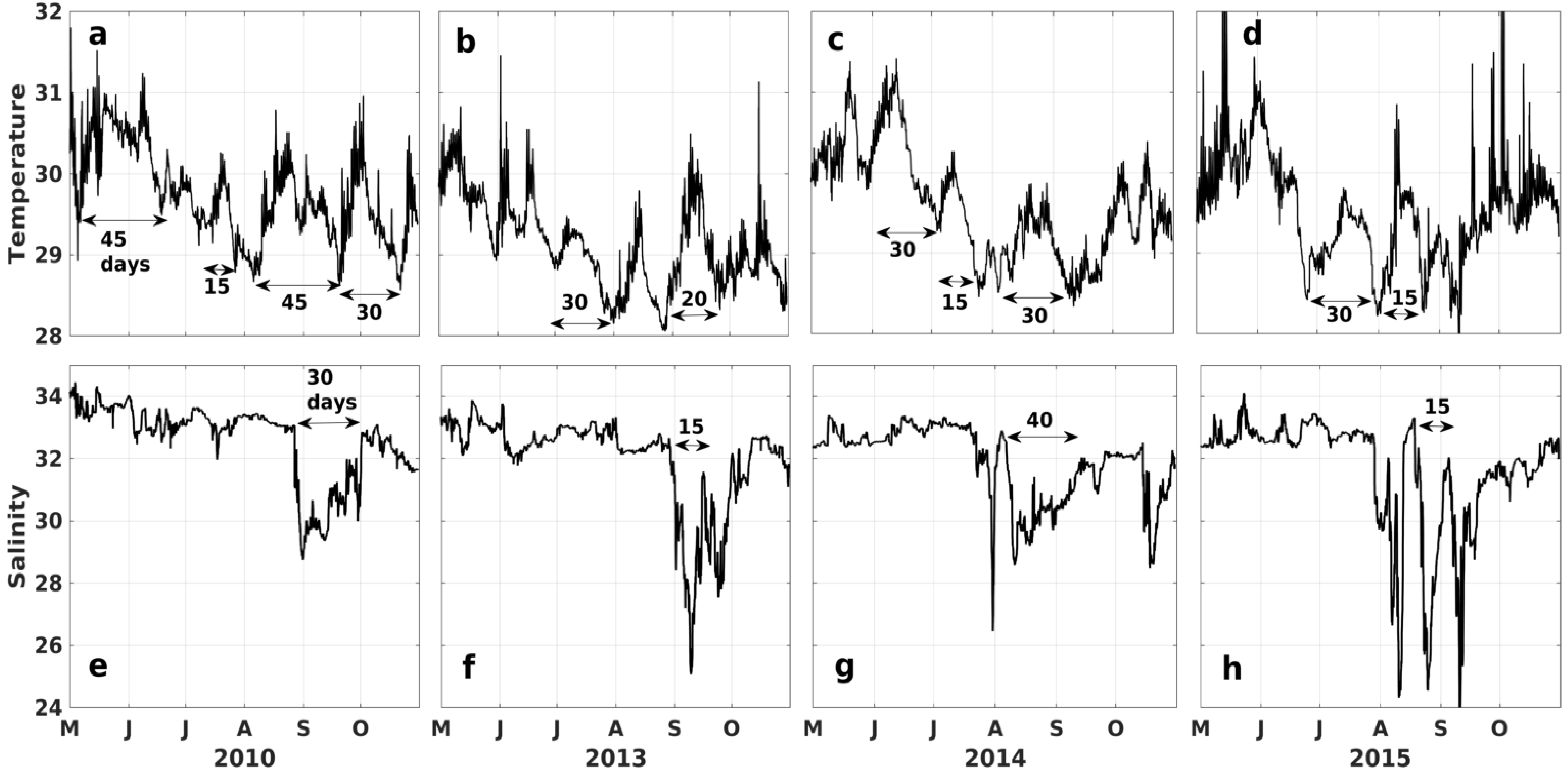




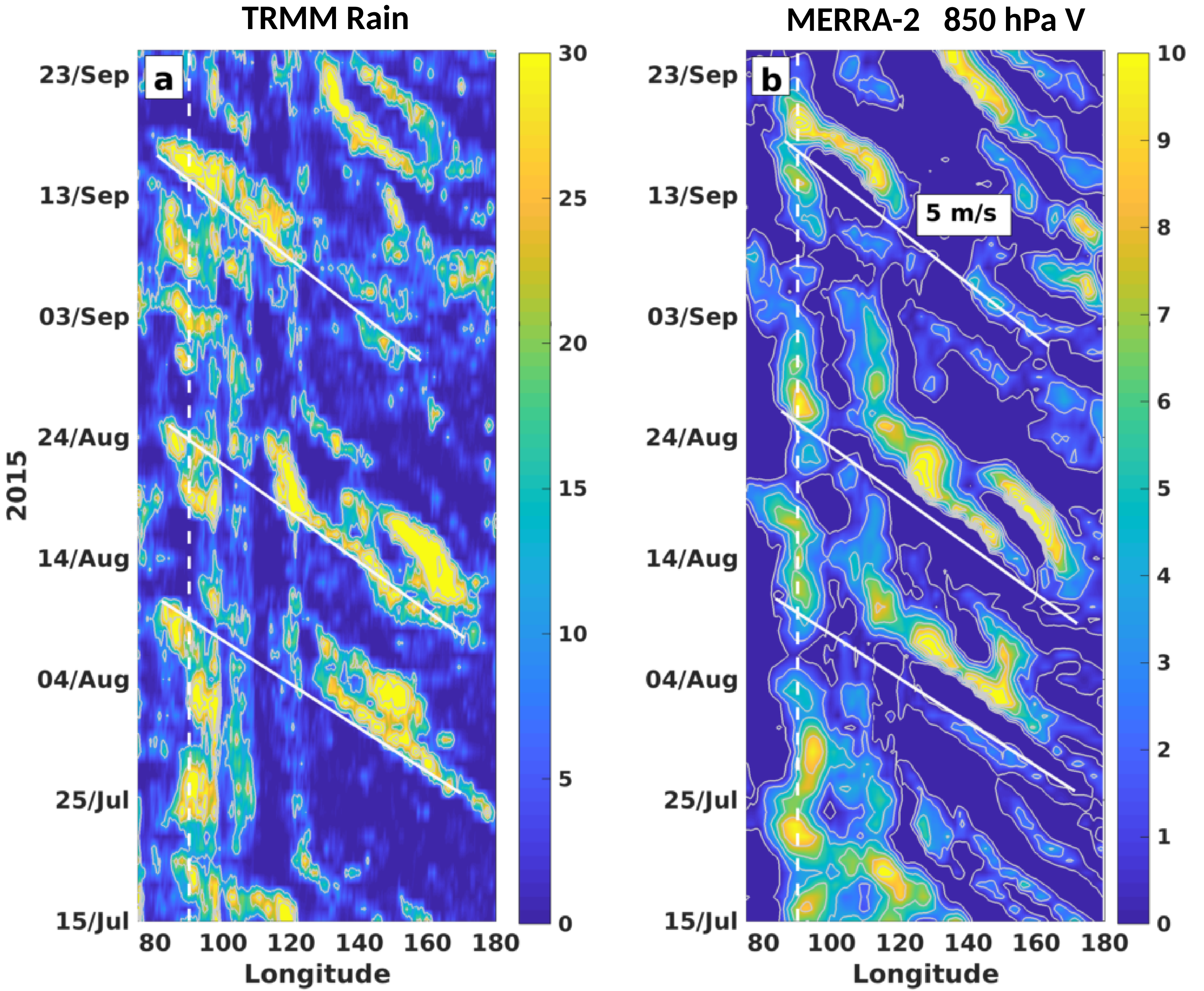
Daily Precipitation and sub-seasonal wind anomalies

Composite 122 heaviest rainfall events over BoB 1998-2017

Bay of Bengal T and S at 1 m depth 18°N moorings May-October



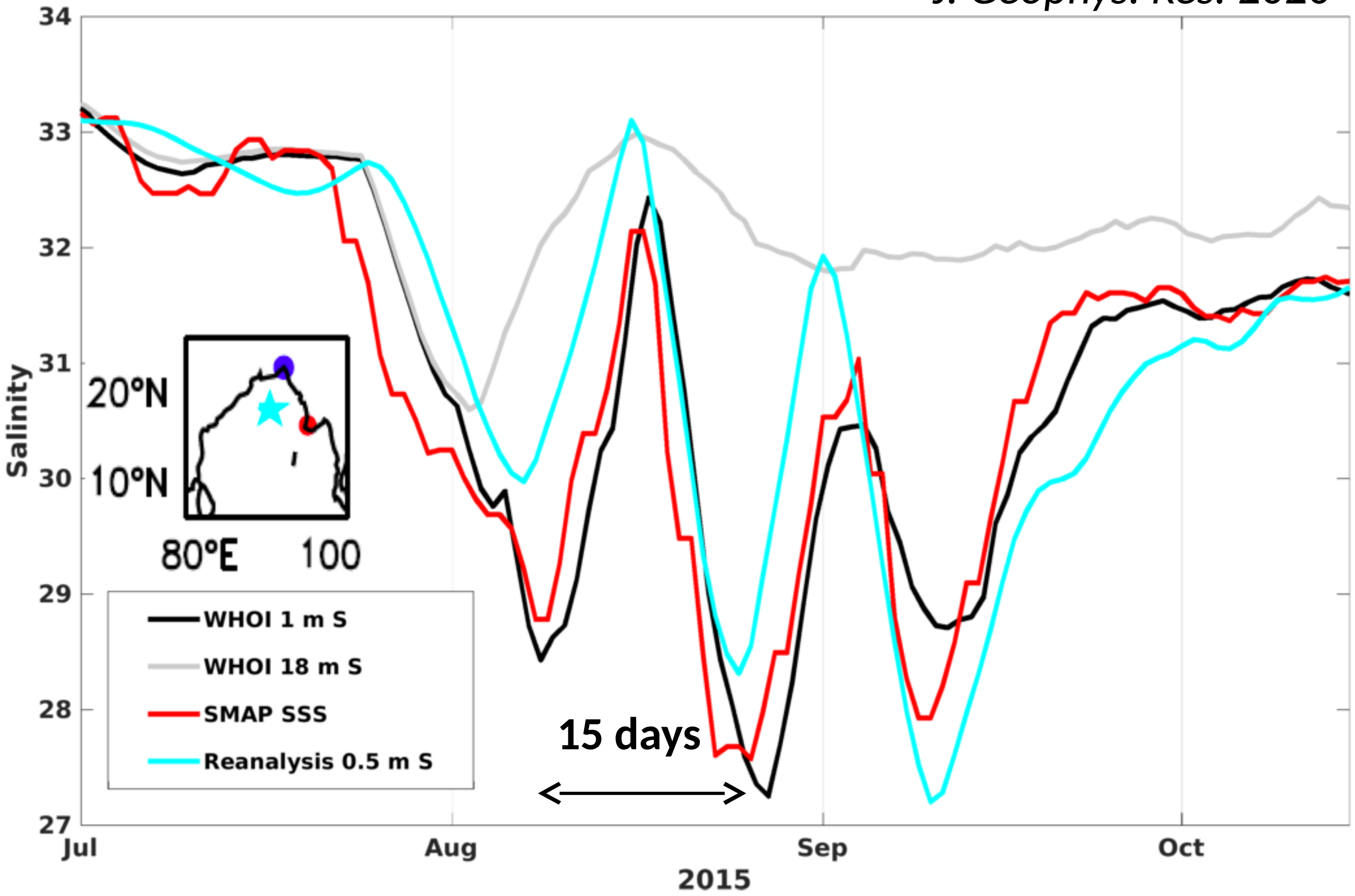
10-16°N
average



Summer 2015

Summer 2015 salinity at 1 m depth 18°N 89.5°E

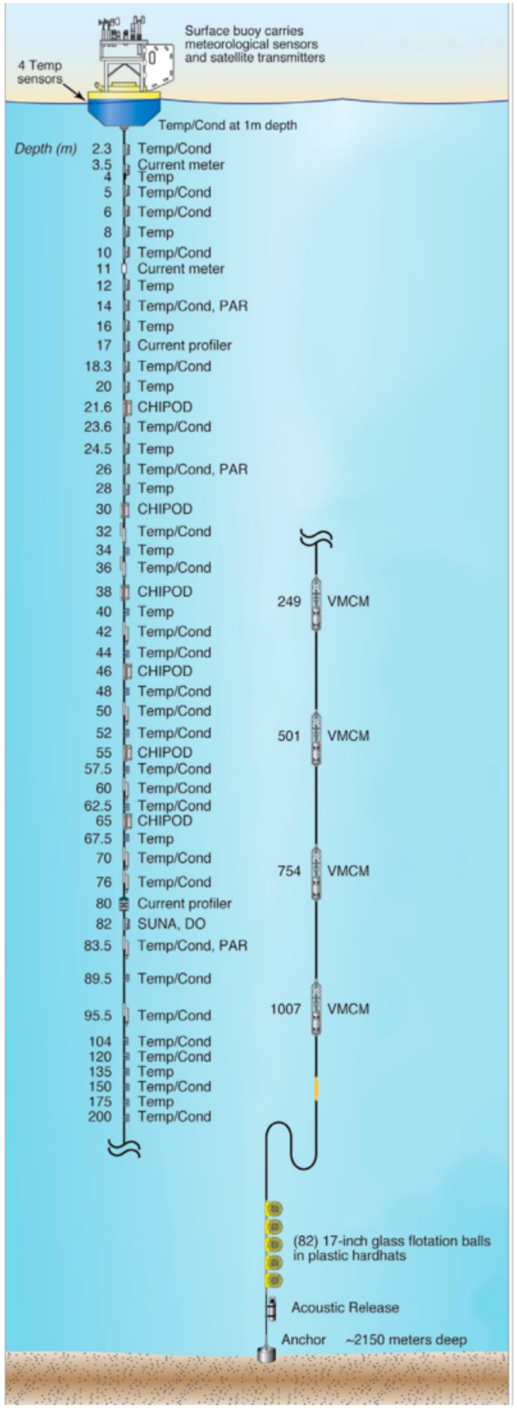
Sree Lekha *et al.*
J. Geophys. Res. 2020



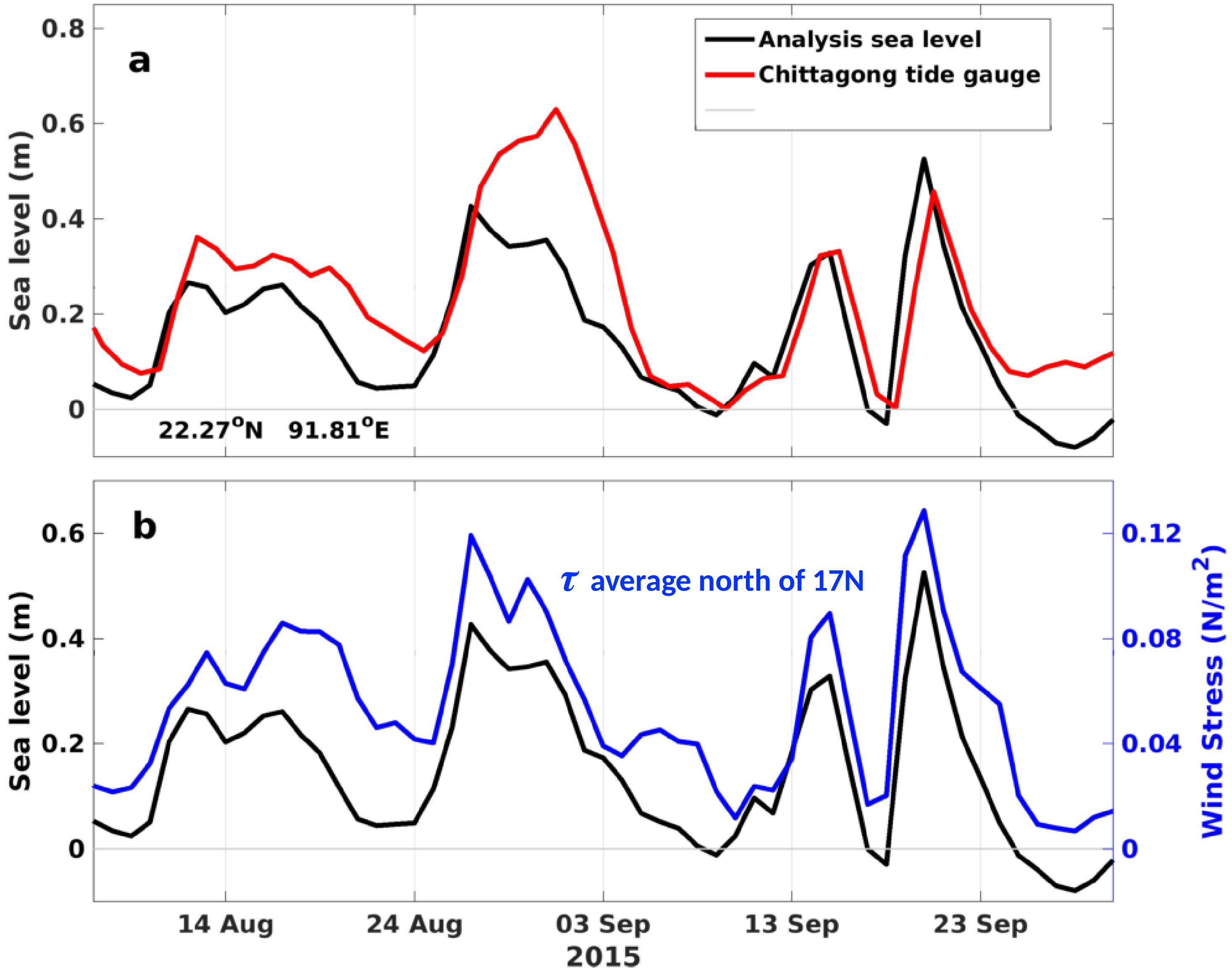
River water enhances shallow density stratification by 3 kg/m³

SMAP satellite SSS
Fore et al. 2016

Daily 1/12° Ocean Analysis (NEMO, ECMWF surface fluxes)
Lellouche *et al.* 2016



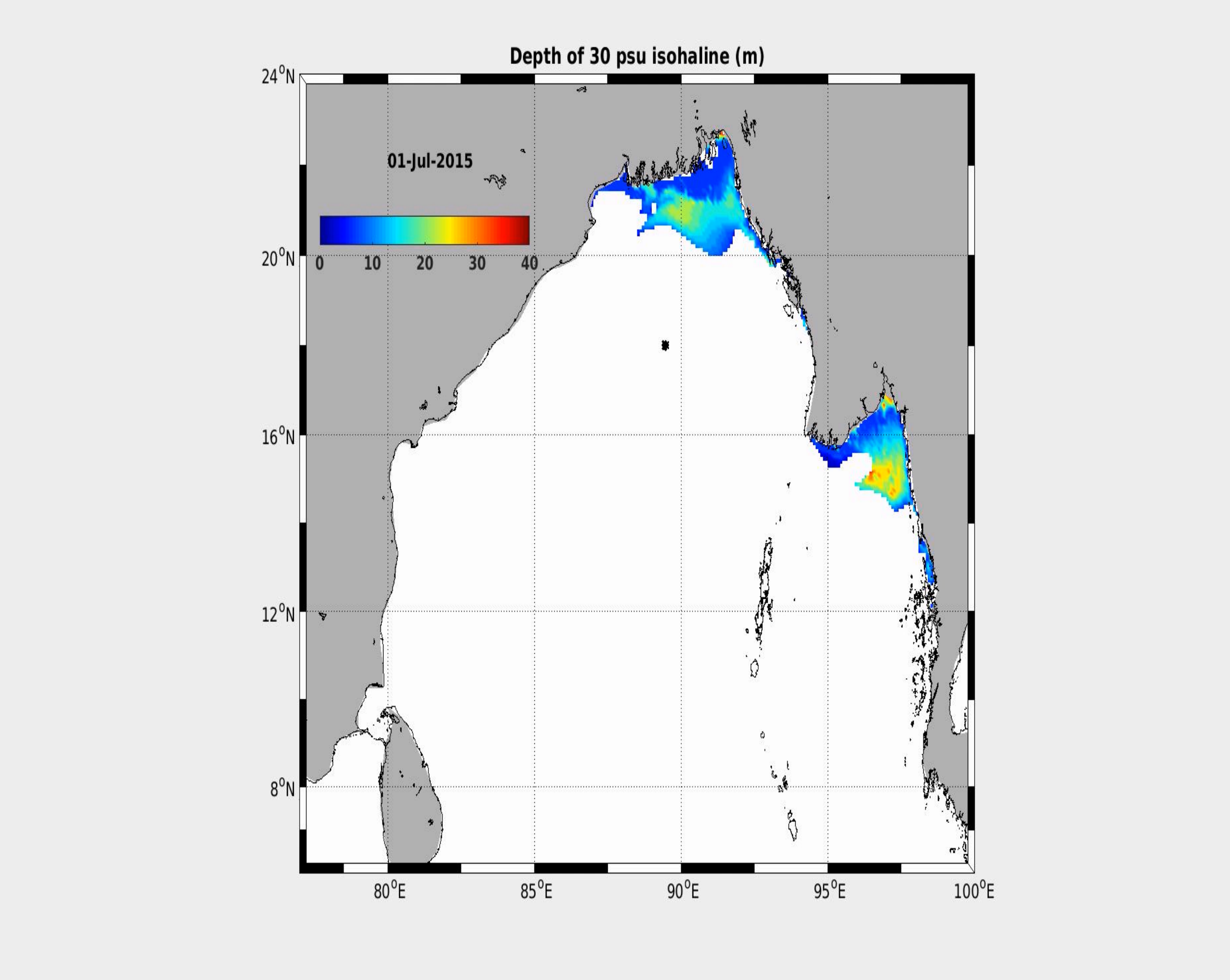
10-20 day variations: Sea Level



Sea Level (m) at Chittagong, Bangladesh

North Bay of Bengal surface wind stress (N/m^2)

Daily 1/12° Ocean Analysis (NEMO, ECMWF surface fluxes)



Fluctuations of the summer monsoon atmosphere and ocean have Coherent variability in time

The time scales of monsoon variability are not independent of one another For example, sub-seasonal variations and seasonal mean are closely related