Systematic Errors in Monsoon Simulation: Importance of Equatorial Indian Ocean Processes

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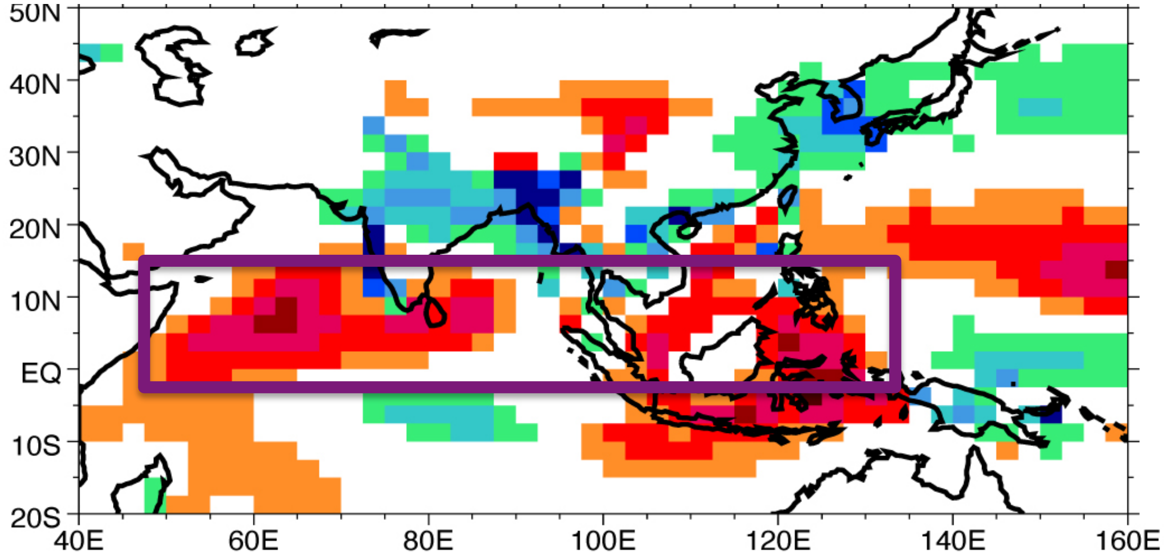
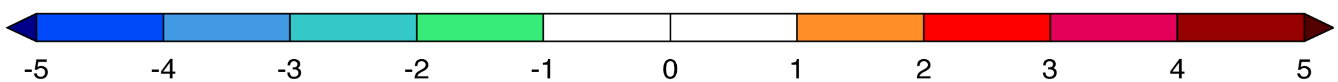
CMIP3 MMM – GPCP



JJAS - Precipitation

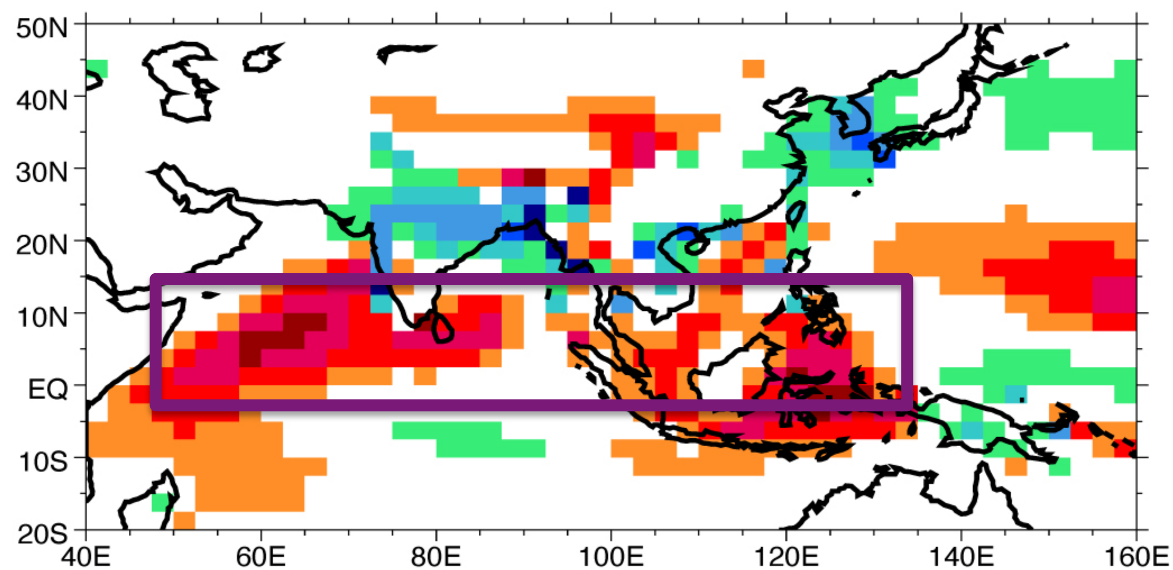
(Sperber, Annamalai et al. 2013)

(mm/day)



"+ve errors along the climatological low-level flow"

CMIP5 MMM – GPCP



Irrespective resolutions, physical parameterizations employed CMIP5 models simulate +ve rainfall errors over **WEIO**, TWP and MC; Negative rainfall errors over **S.Asia**, East Asian monsoon front

Talk Outline

- **Uniqueness of the Equatorial Indian Ocean**

    (i) WJs are fast oceanic processes

    (ii) Errors in coupled processes (Bjerkens' feedback)

- **Biases in Moist Processes**

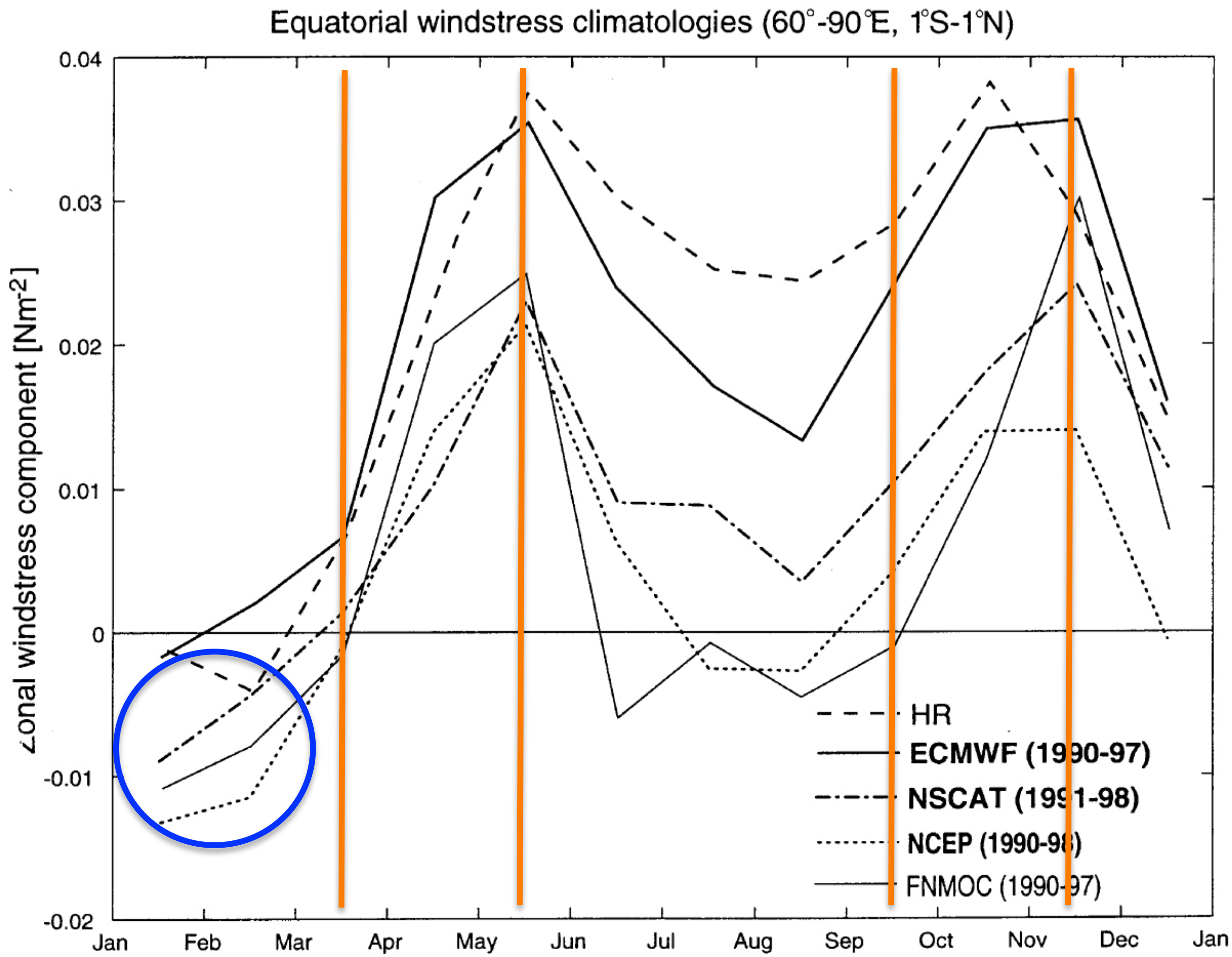
    Moisture and moist static energy budgets (SST errors)

- **Idealized experiments with Coupled model for Earth Simulator (CFES)**

    CMIP5 bias is due to EIO errors

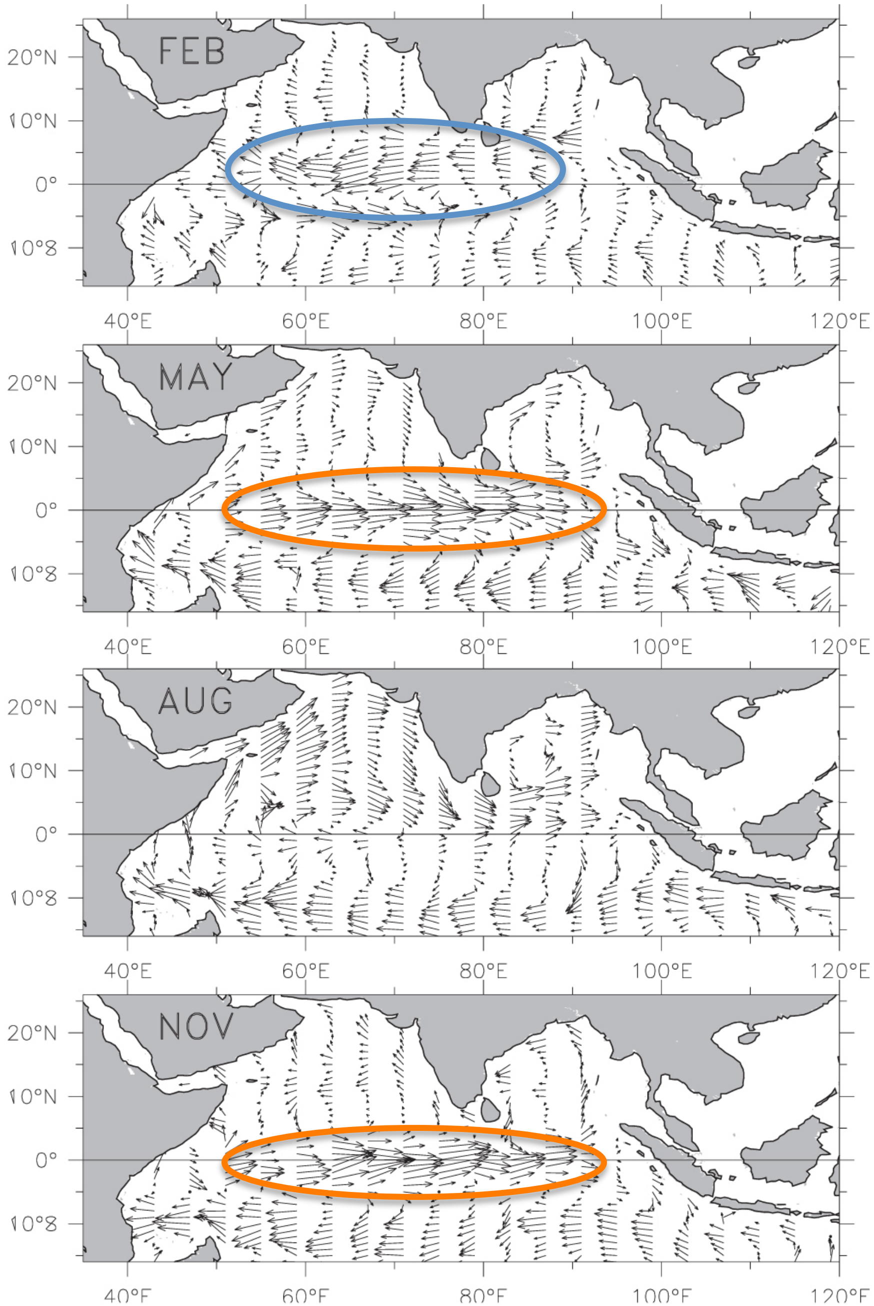
- **Conclusion and Discussion**

Uniqueness of the Equatorial Indian Ocean



Schott and McCreary (2001)

Surface currents



FEB

MAY

Equatorial eastward jets advect upper-layer warm waters from western to eastern EIO (Wyrtki 1971)

AUG

NOV

Wyrtki Jets (WJs) are fast oceanic processes

- Thanks to Jay

WJ dynamics are captured by the upper-ocean, zonal-momentum balance along the equator. For a linear, 1½-layer (reduced-gravity) model, it is

$$u_t + p_x = \frac{\tau^x}{\rho_o H}$$

Consider wind patch of amplitude $\Delta\tau$ and zonal extent L, initially no pressure gradient, and Coriolis force is zero at the Equator,

$$u=\Delta\tau(\rho_o H)t.$$ ← Zonal current accelerates

$$t_k = L/c$$ ← Time-taken by the Kelvin wave

$$\tilde{u} = [\Delta\tau/(\rho_o H)]t_k$$ ← Speed of the Jet

With $\Delta\tau = 0.5$ dyn/cm^2, $H = 50$ m, $L = 2500$ km, and $c = 250$ cm/s (a typical speed for baroclinic mode), $t_k = 10^6$ sec (~10 days) and hence $\tilde{u} = 1$ m/s.

1. Near-equatorial surface **westerlies during Intermonsoons** (Apr-May; Oct-Nov)

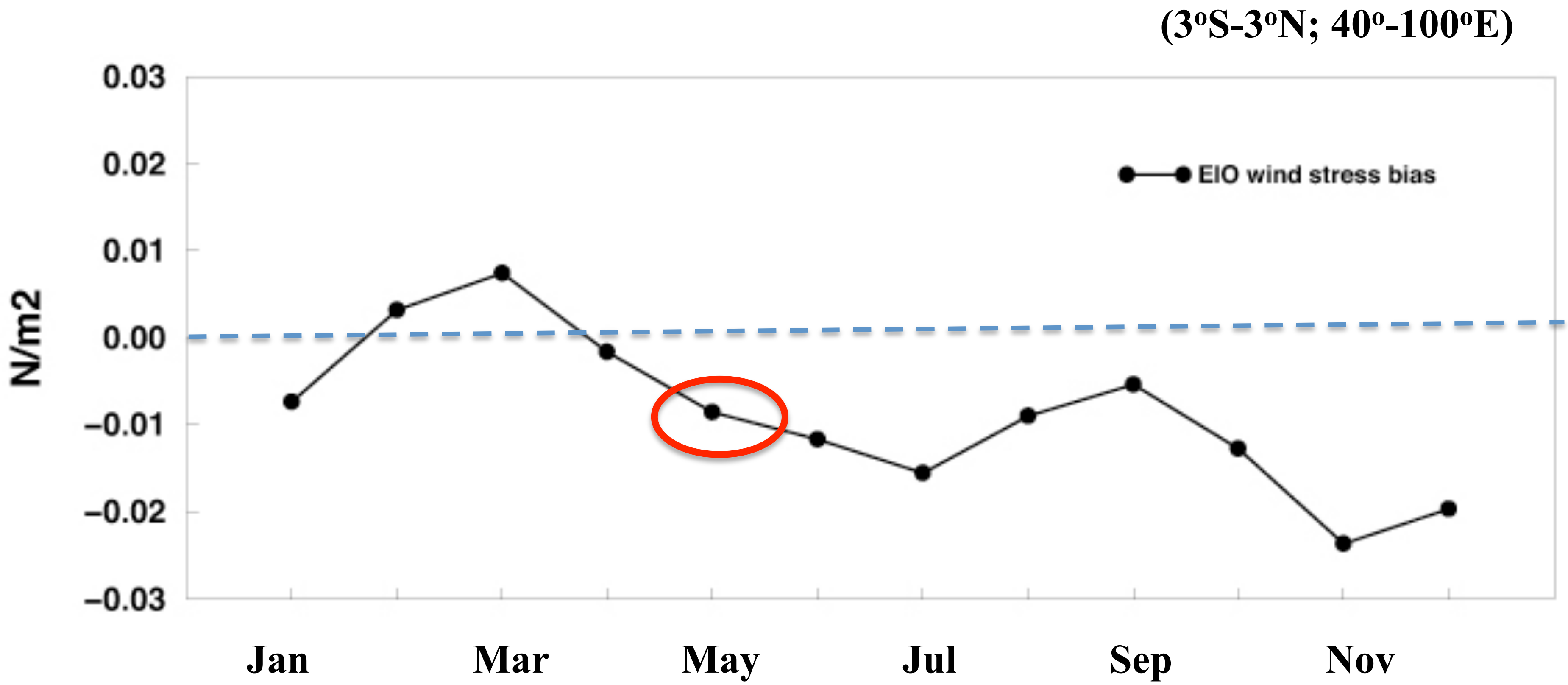
2. **Ocean response**

   (i) Equatorial, eastward flowing currents termed Wyrtki Jets (WJs)
   (ii) Force oceanic Kelvin and Rossby waves (impact on thermocline)

3. WJs are **fast oceanic processes** and advect warm water from western to eastern EIO
   WJs are important in the EIO coupled process **(Bjerknens' feedback)**

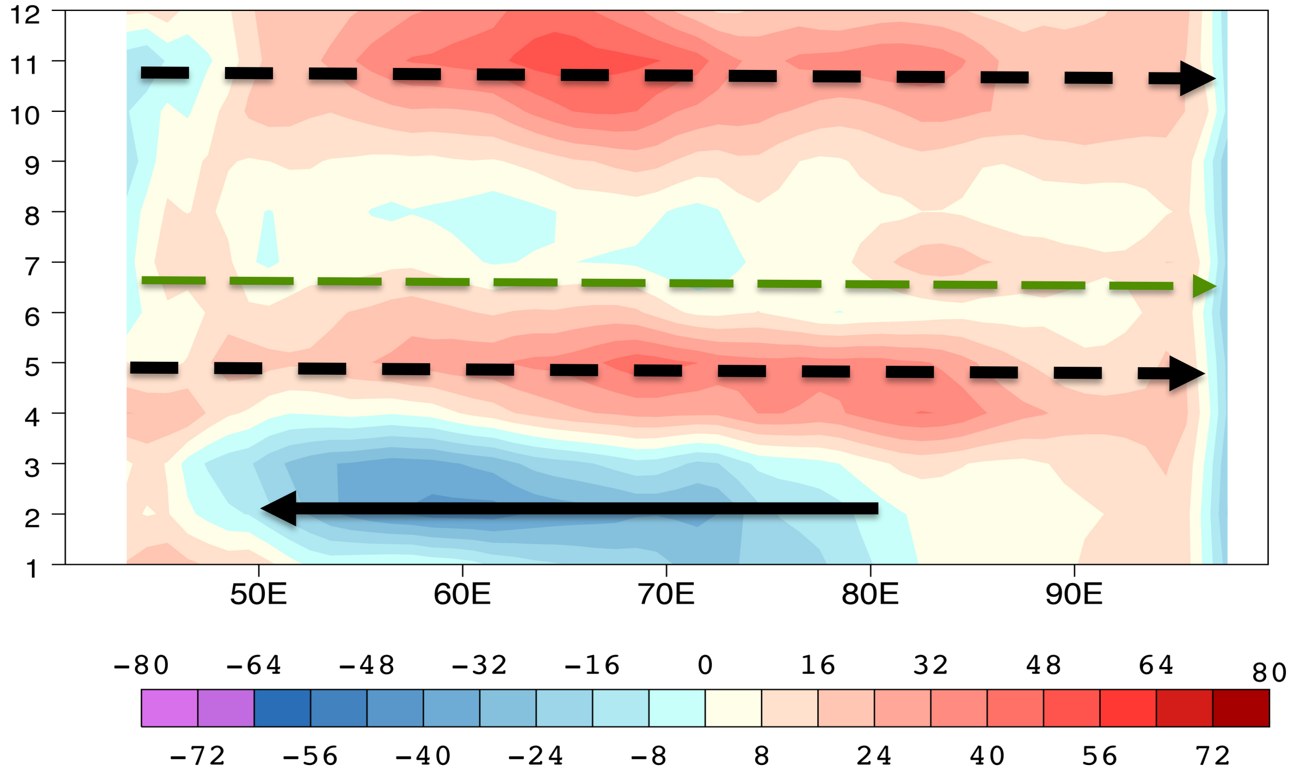
"Unlike equatorial Pacific and Atlantic – no easterly wind"

$\Delta\tau$ **CMIP5 MMM *minus* ERA_INT**



Compared to climatology: In May 40-45% weaker and in November 70% weaker

$\Delta\tau$ a measure of Bjerkens' feedback in the Equatorial Indian Ocean



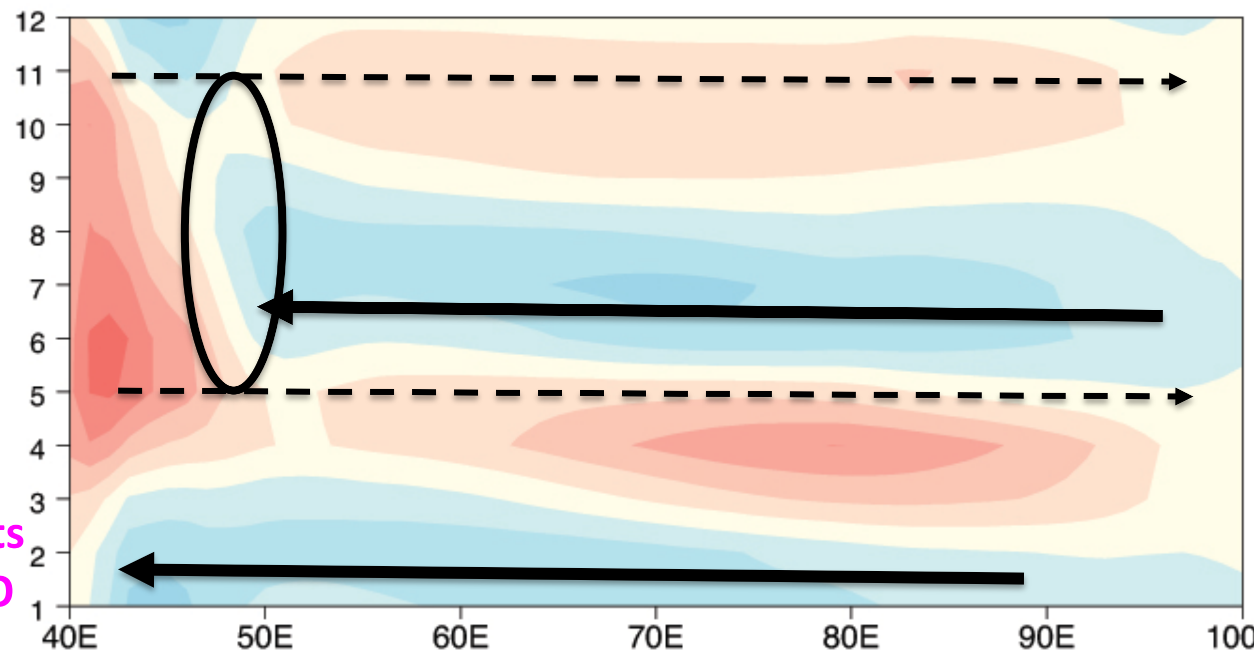
3°S-3°N – surface currents

Observations

(cm/s)

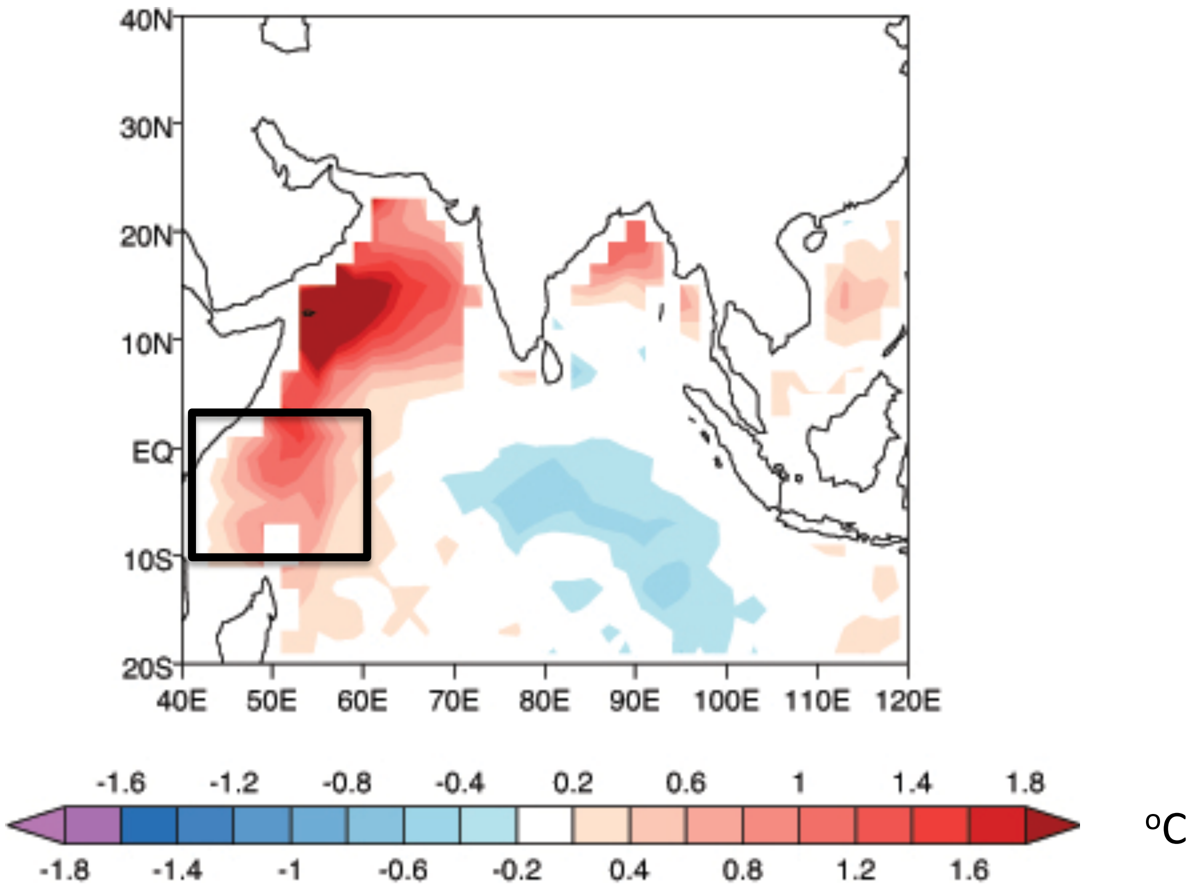
3°S-3°N – surface currents

CMIP5 MMM



1. **Weak eastward WJs**
2. **Unrealistic westward currents**
3. **Pile-up of warm waters WEIO**

June *minus* May SST tendency bias (CMIP5 MMM)

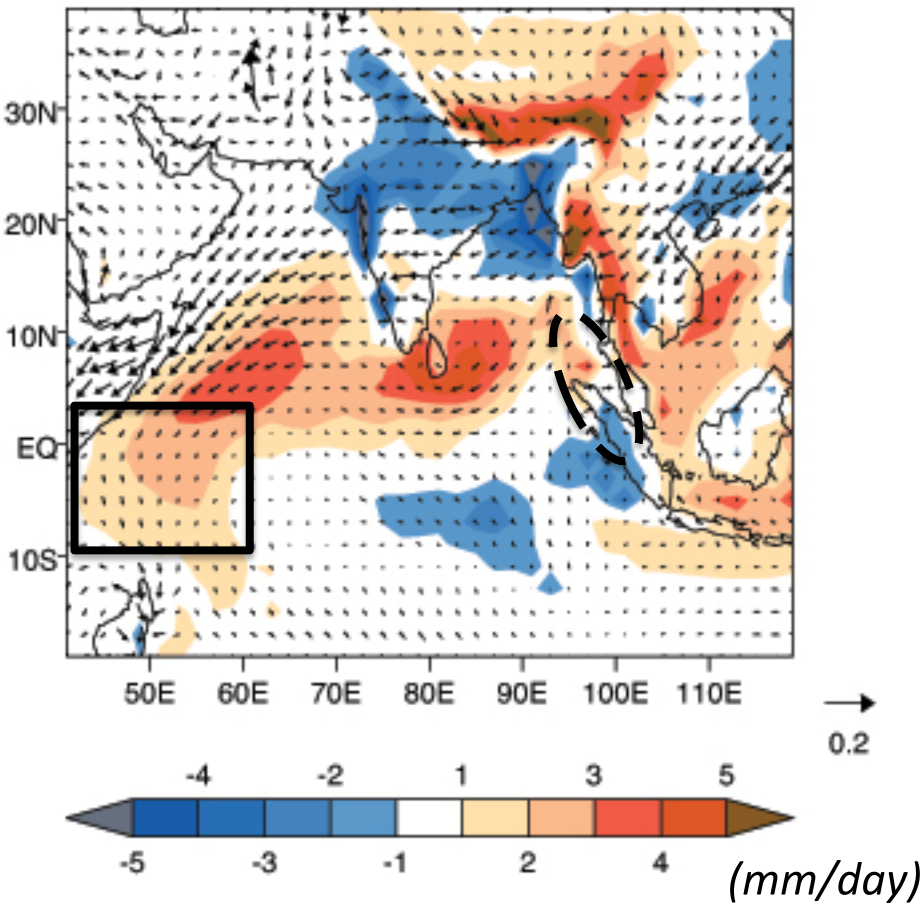


Errors in air-sea interactions (Bjerknes feedback) along EIO?

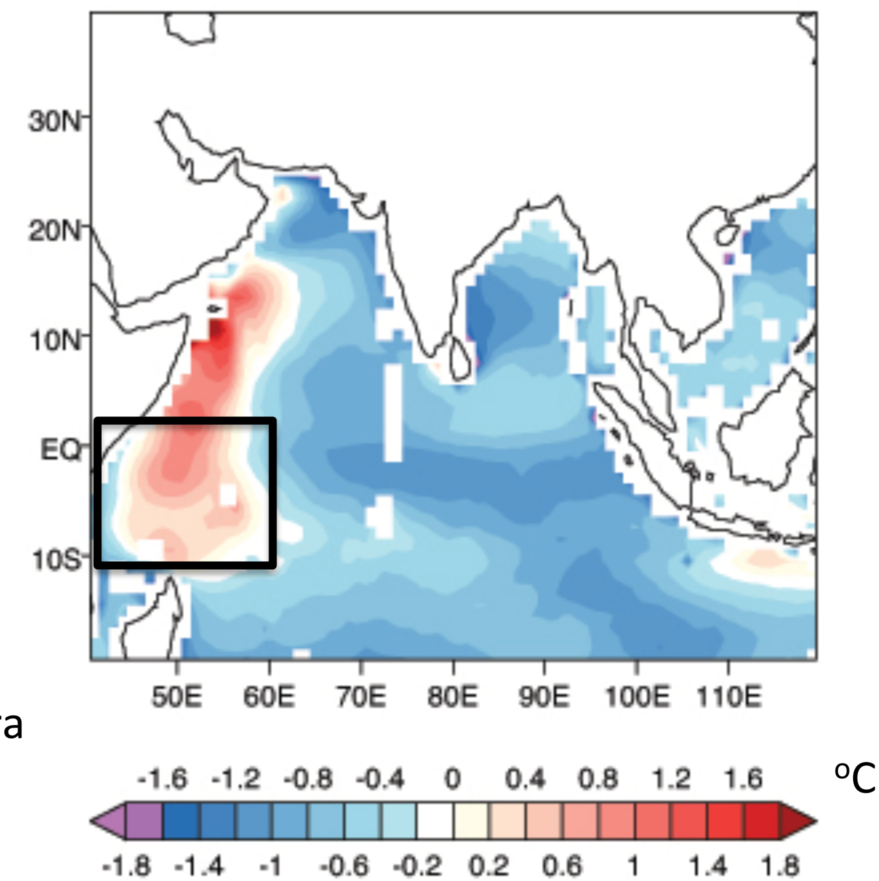
Wyrkti Jets are important component in the EIO coupled processes

(CMIP5 MMM) bias JJAS

Precipitation / wind stress

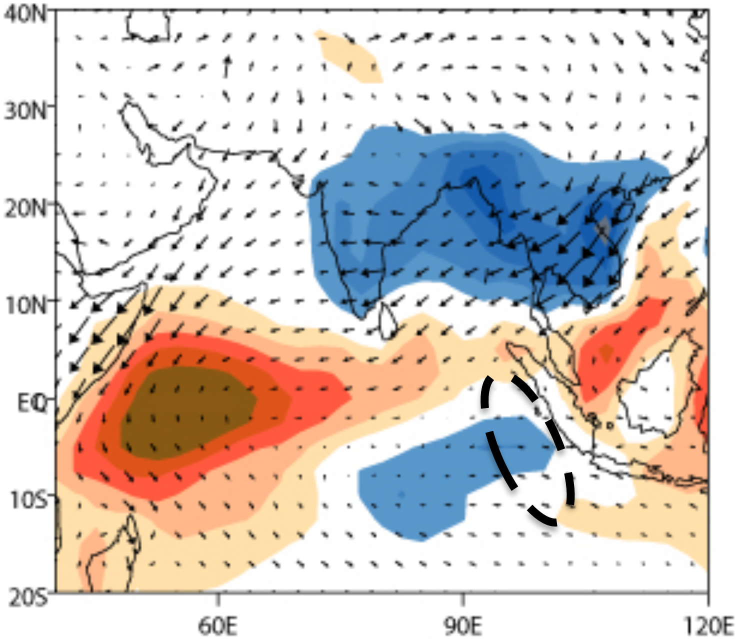


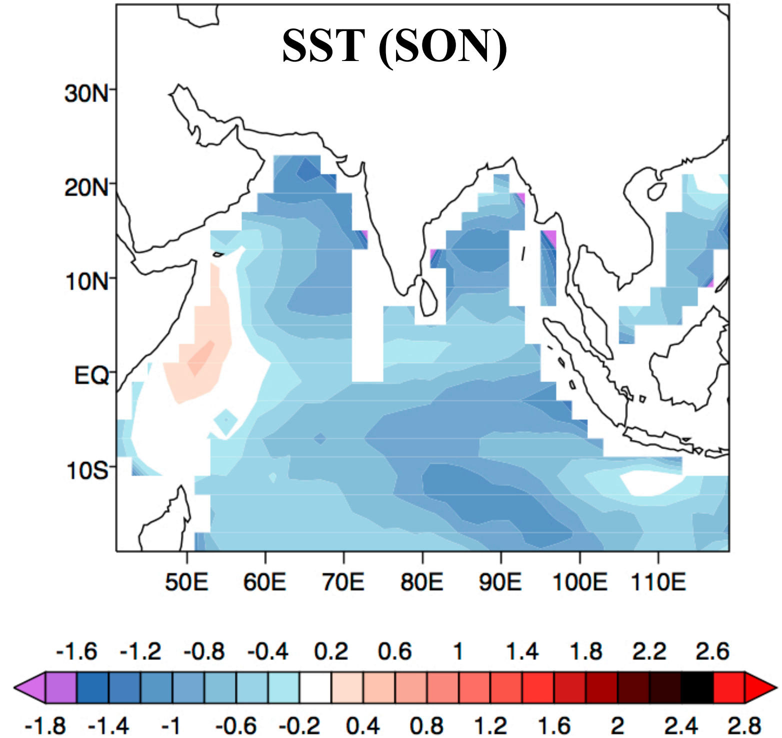
SST

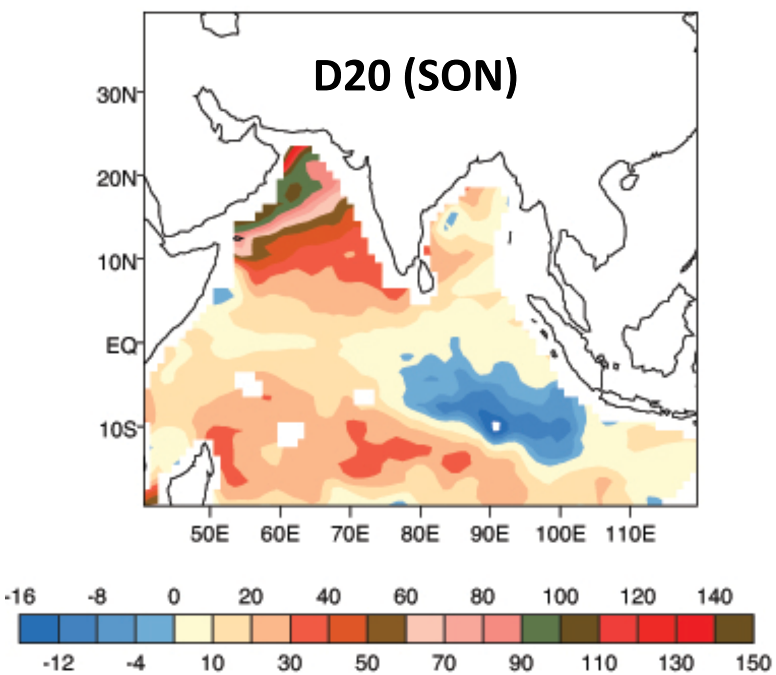


1. Lack of upwelling-favorable winds off Sumatra
2. Center of action appears to be over WIO
3. WIO Precip anom – equatorial atmos KW

Precip + wind stress (SON)



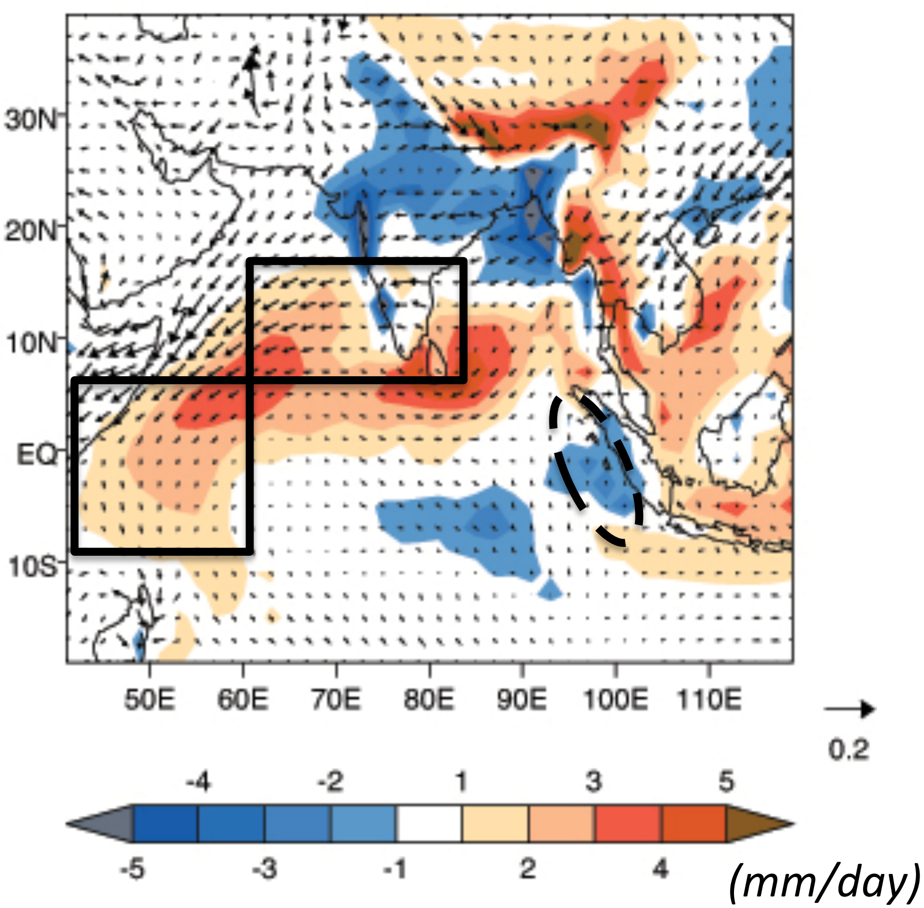




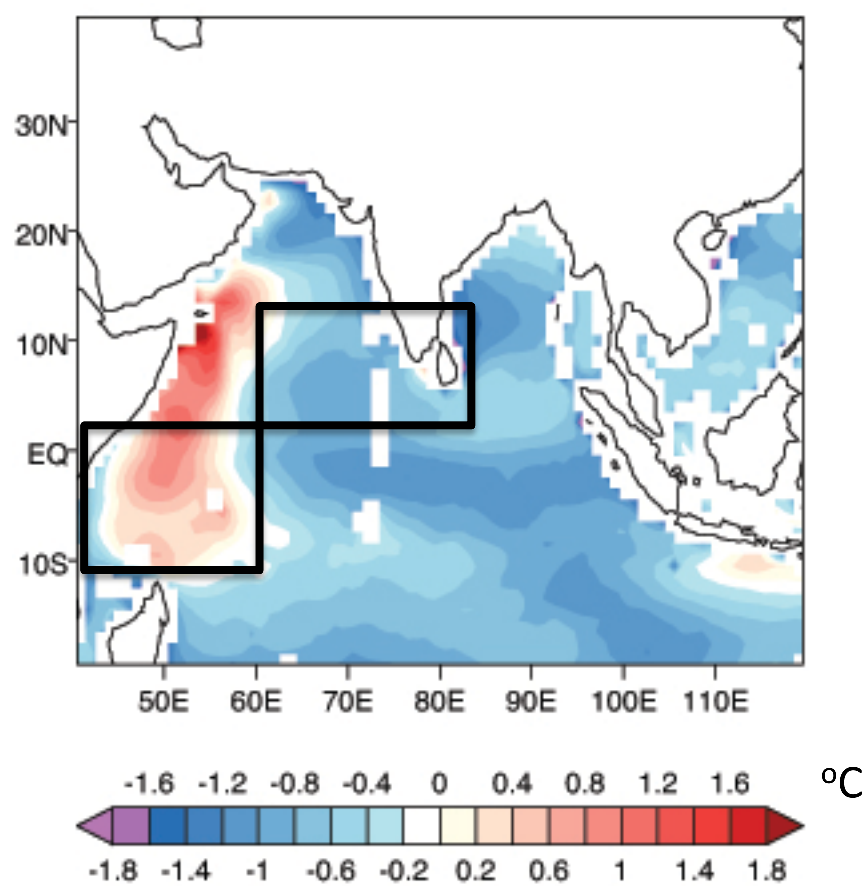
- Lack of upwelling-favorable winds off Sumatra
  - perhaps due to lack of organized –ve precip anom
- SST gradient exists along EIO
- Precip anomalies intensify over western EIO – force atmospheric Kelvin wave – easterly bias
- Thermocline deeper everywhere except EEIO (Jay's talk tomorrow)
- BJ feedback exists during May-November
- Western EIO – **"hot spot"**
- North-south dynamical linkage stronger!

Biases in moist processes

Precipitation / wind stress



SST



1. **REG1 (10°S-5°N; 40°-60°E)**
2. **REG2 (5°-15°N; 60°-85°E)**

The vertically integrated moisture budget is

$$P = -\langle \boldsymbol{V} \cdot \boldsymbol{\nabla} q \rangle - \left\langle \omega \frac{\partial q}{\partial p} \right\rangle + LH, \qquad (1)$$

where P is precipitation, $\langle \boldsymbol{V} \cdot \boldsymbol{\nabla} q \rangle$ and $\langle \omega q_p \rangle$ are horizontal and vertical advection (or horizontal divergence) of moisture, respectively, and LH is the latent heat flux at the surface. In these quantities, $\boldsymbol{V}$ is the horizontal velocity vector, $\boldsymbol{\nabla}$ is the gradient operator, ω is vertical pressure velocity, q is the specific humidity, and angle brackets designate vertical integration.

Why MSE budget analysis?

- lack of SST gradient over the tropical Indo-Pacific warm pool

Representation of interaction between cumulus convection and large-scale circulation

[Quasi-equilibrium concept of Arakawa and Shubert (1979)]

requires consideration of moisture and temperature, represented by MSE (*m*)

$$m = C_p T + gz + Lq$$

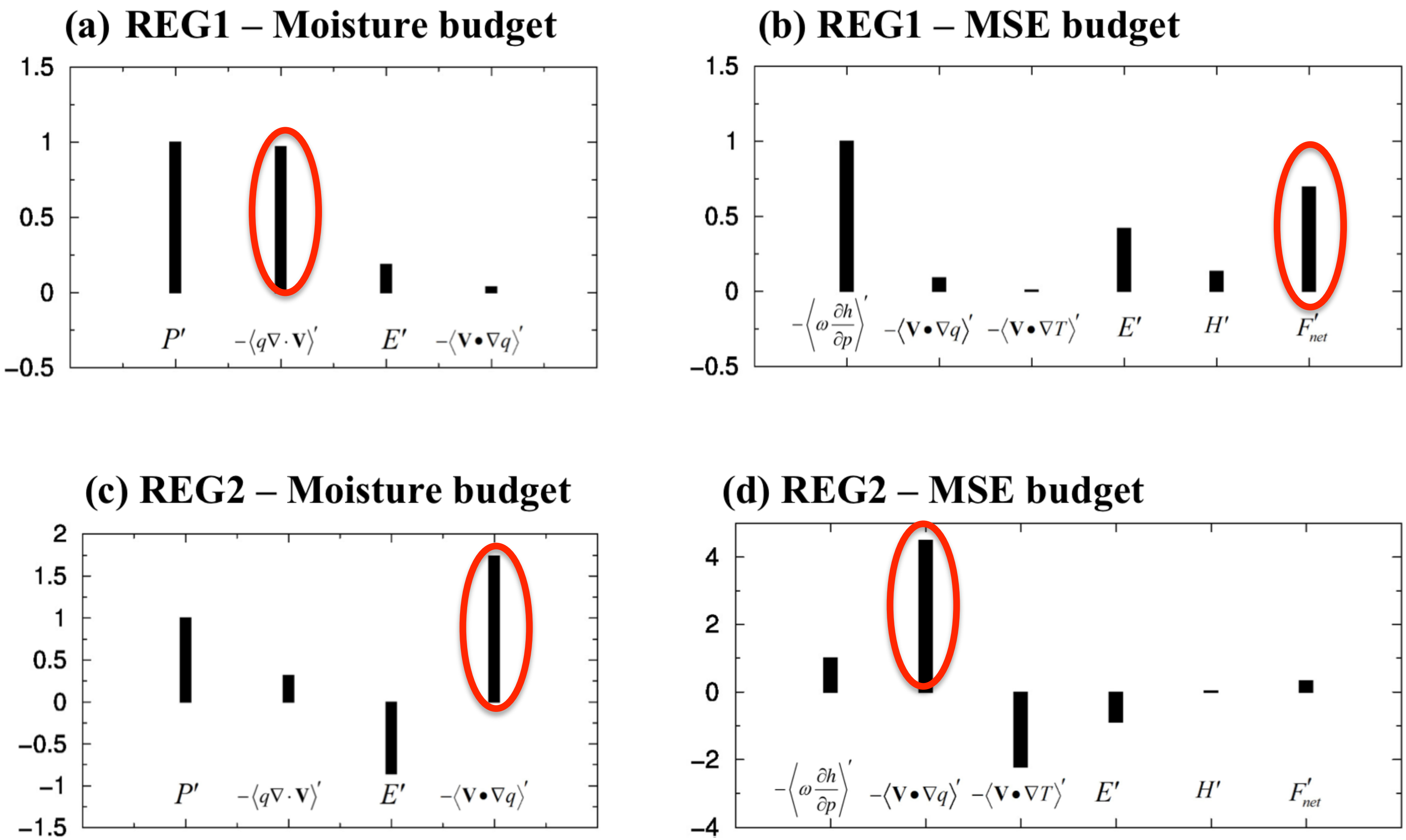
Vertically integrated MSE tendency is approximately given by

$$\left\langle \frac{\partial m}{\partial t} \right\rangle = -\left\langle \overline{V} \bullet \nabla m \right\rangle - \left\langle \omega \frac{\partial m}{\partial p} \right\rangle + LH + SH + \left\langle LW \right\rangle + \left\langle SW \right\rangle$$

"storage" "adiabatic terms" "diabatic terms"

1. Deep tropics – above PBL – no horizontal T variations
2. Entropy forcing: LH, SH, LW, SW, moisture variations

Neelin and Held 1987
Raymond et al. 2009
Bretherton et a. 2005
Su and Neelin 2005

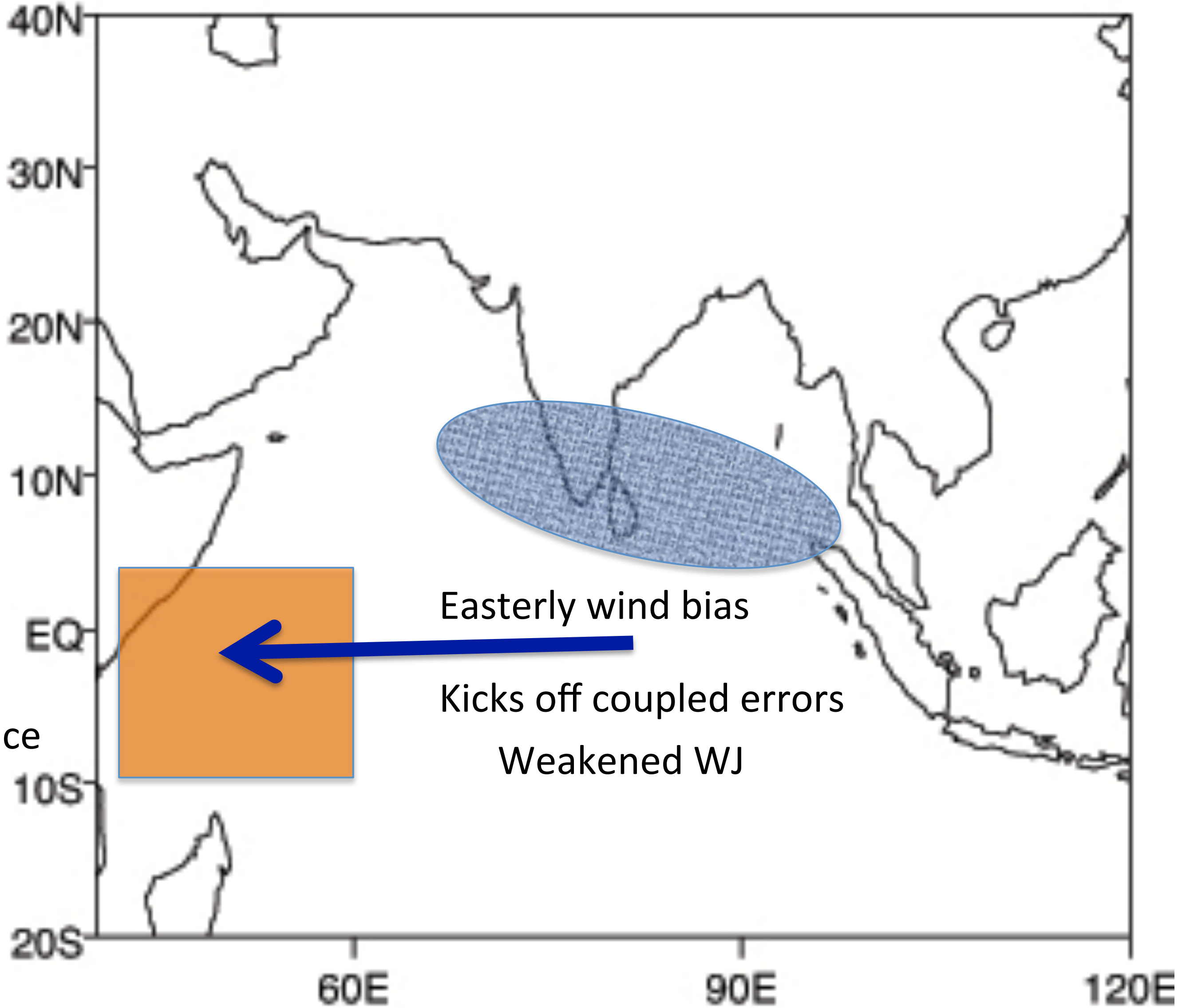


REG1 - SST errors initiator
Cloud-radiation feedbacks

REG 2 - Convective instability due to moist advection

-

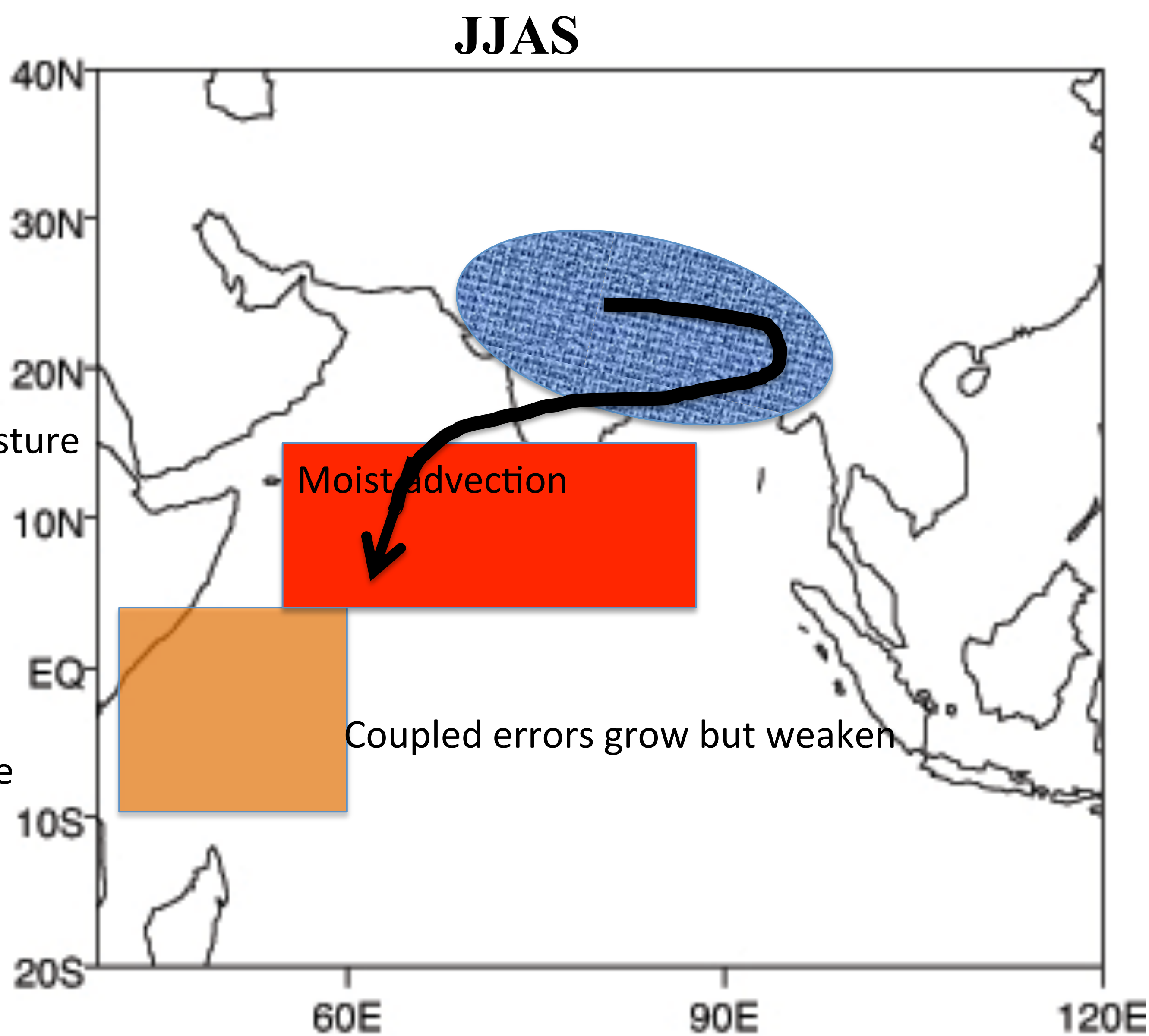
May



SST errors
M Convergence
Evaporation
Precip errors

Consequence: moisture transport into the northern Indian Ocean is weakened.

S Asia dry
Rossby wave
Advects moisture



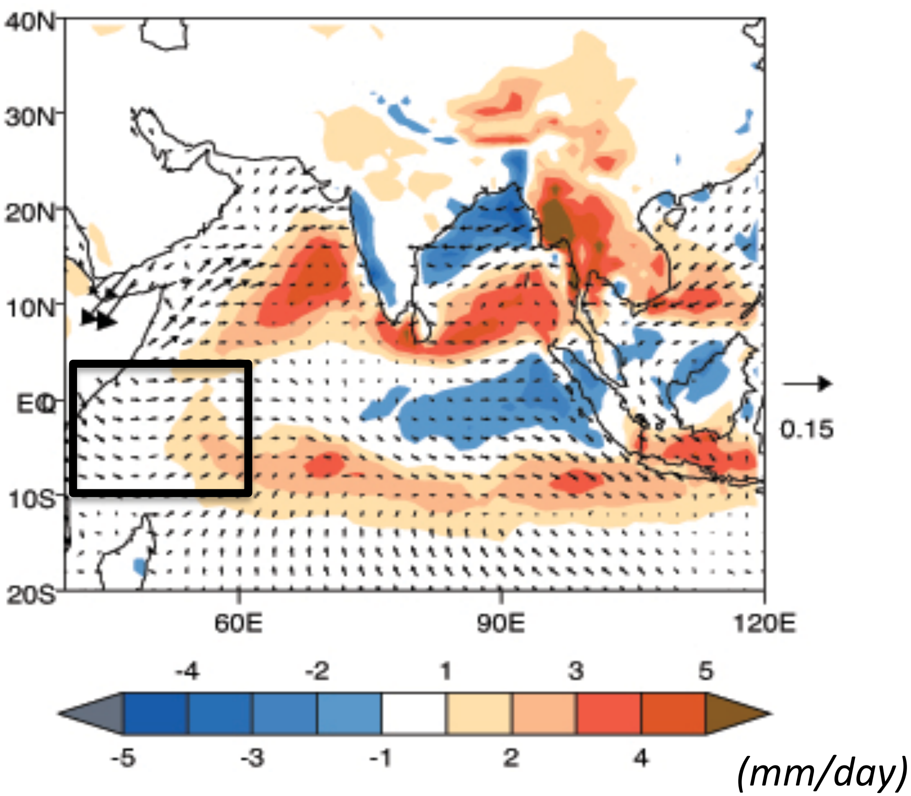
SST errors
M Convergence
Evaporation
Precip errors

Weakened monsoon – moist→advection into Arabian Sea - rainfall in REG2

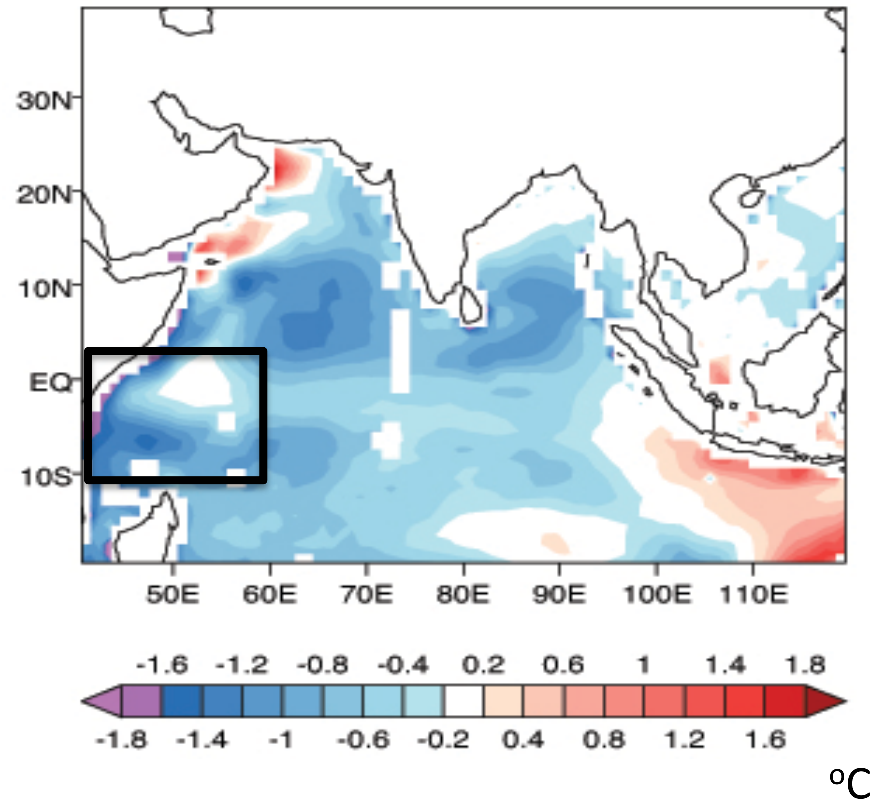
Idealized experiments with Coupled model for Earth Simulator (CFES)

Biases in CFES (Coupled model for Earth Simulator)

JJAS Precipitation / wind stress



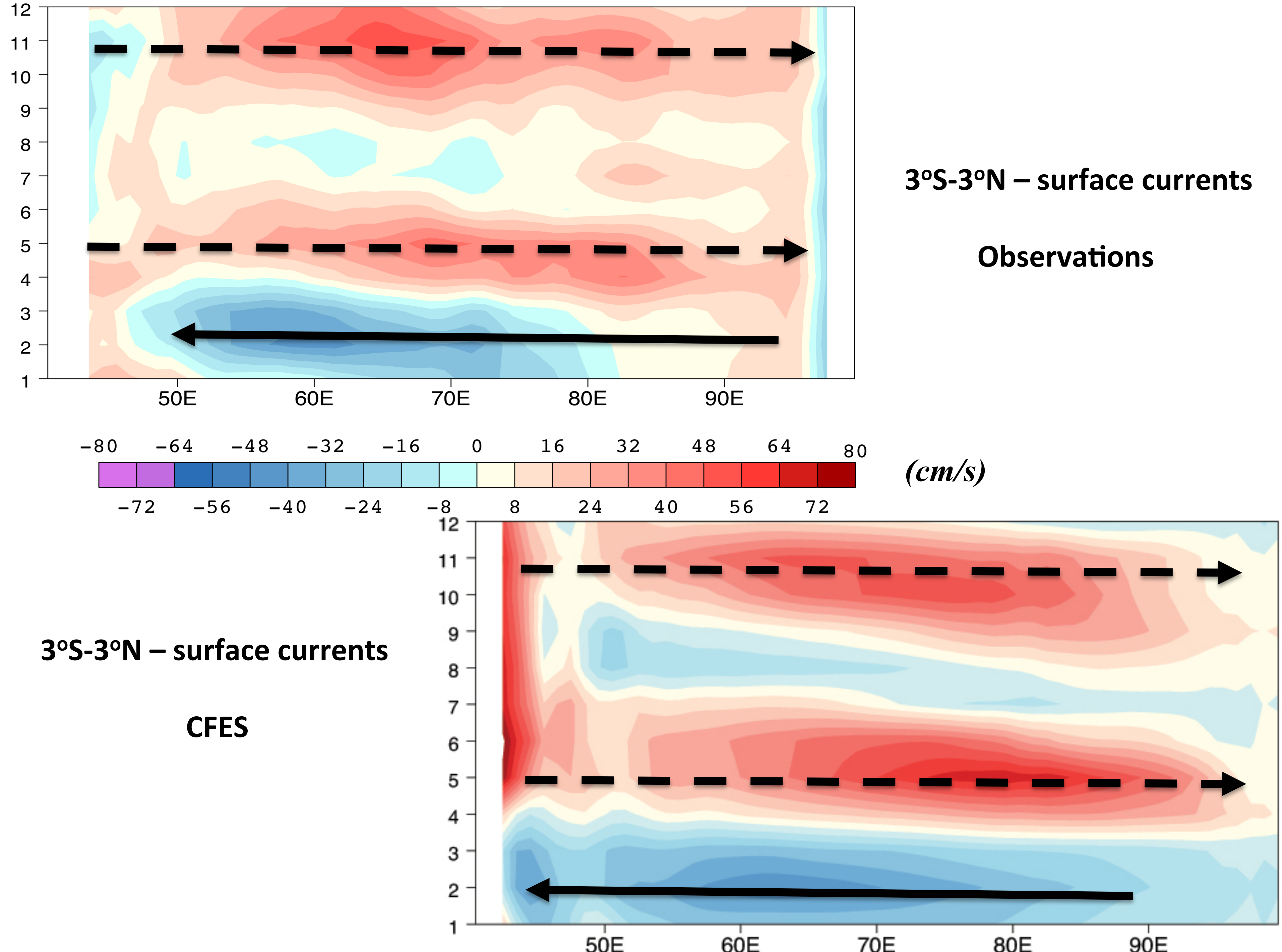
JJAS SST



Model biases exist – magnitudes are less compared to CMIP5 errors -

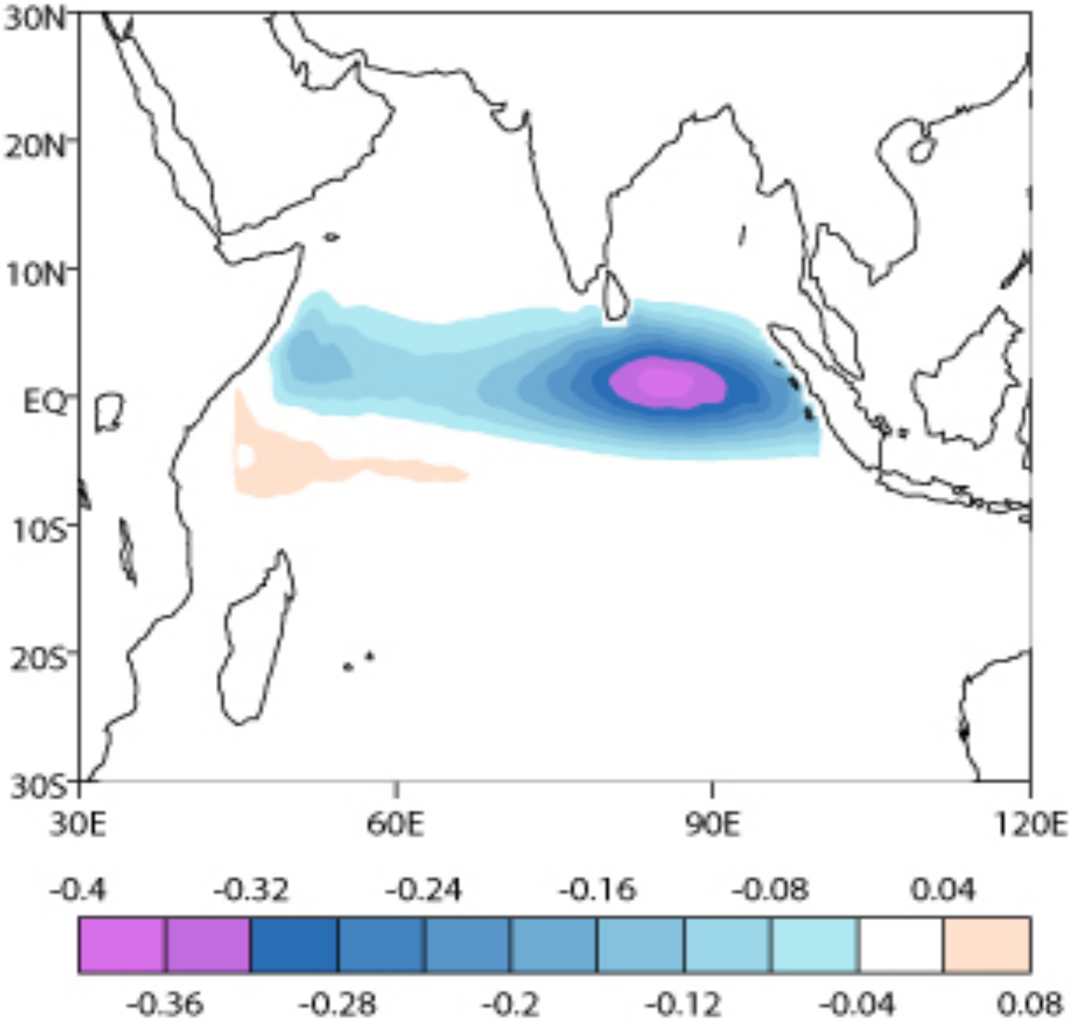
Precip and SST biases over western EIO are NOT collocated as in CMIP5 models

$\Delta\tau$ integrated along the EIO is near-zero



3°S-3°N – surface currents
Observations
12
11
10
9
8
7
6
5
4
3
2
1
50E
60E
70E
80E
90E
-80
-64
-48
-32
-16
0
16
32
48
64
80
-72
-56
-40
-24
-8
8
24
40
56
72
(cm/s)
3°S-3°N – surface currents
CFES
12
11
10
9
8
7
6
5
4
3
2
1
50E
60E
70E
80E
90E

T_{aux} anomaly - imposed



1. Imposed throughout A/C
2. Imposed during spring and fall only

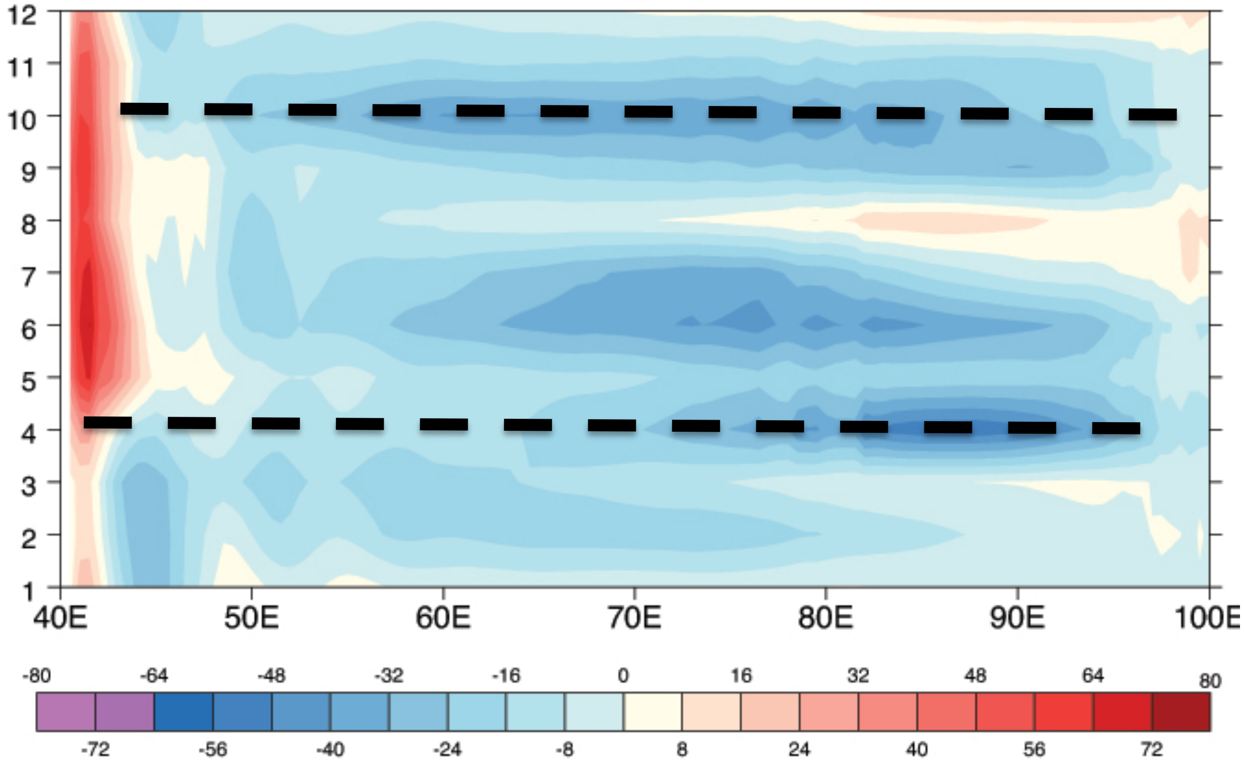
dyn/cm^2

Could have perturbed ….

Precip or SST or Thermocline

EXP2 SPRING_FALL $\Delta\tau$

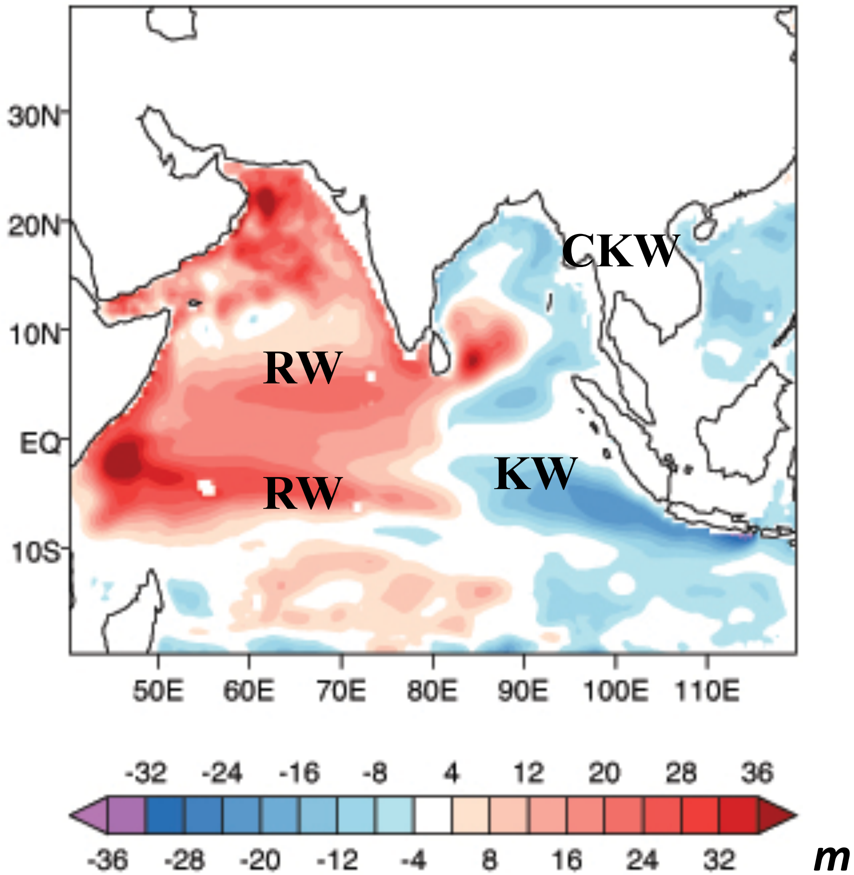
3ºS-3ºN – surface currents



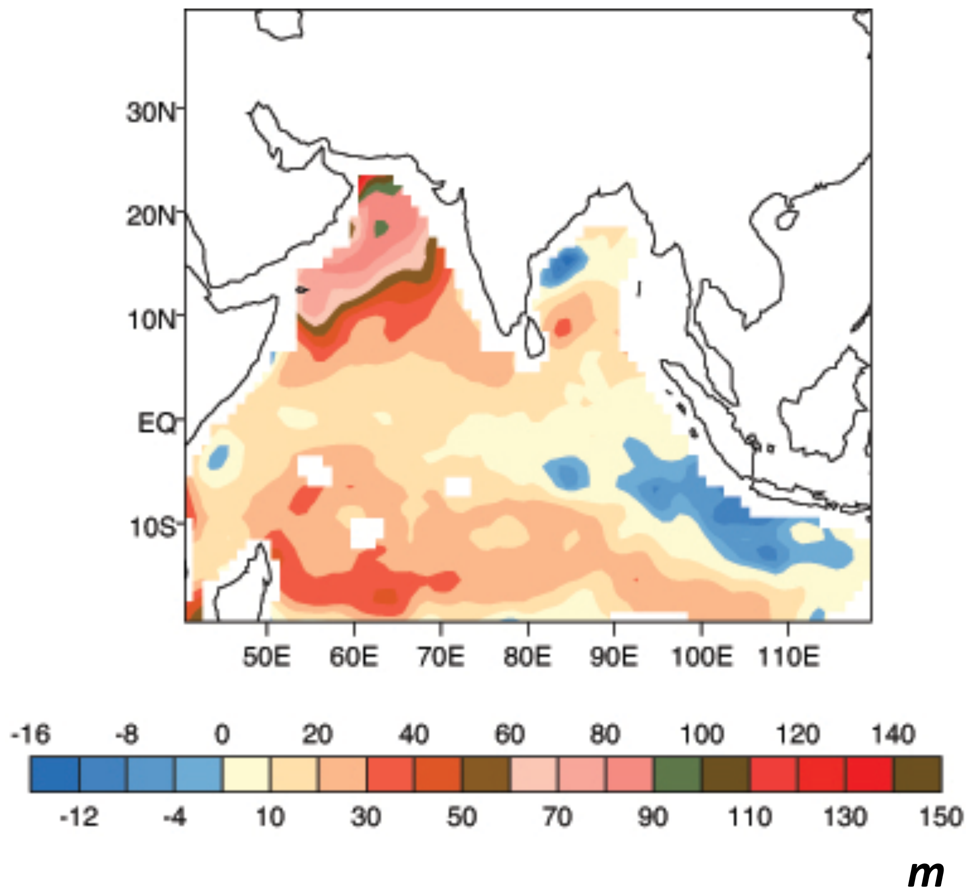
(cm/s)

EXP2 *minus* CTL

D20_JJAS

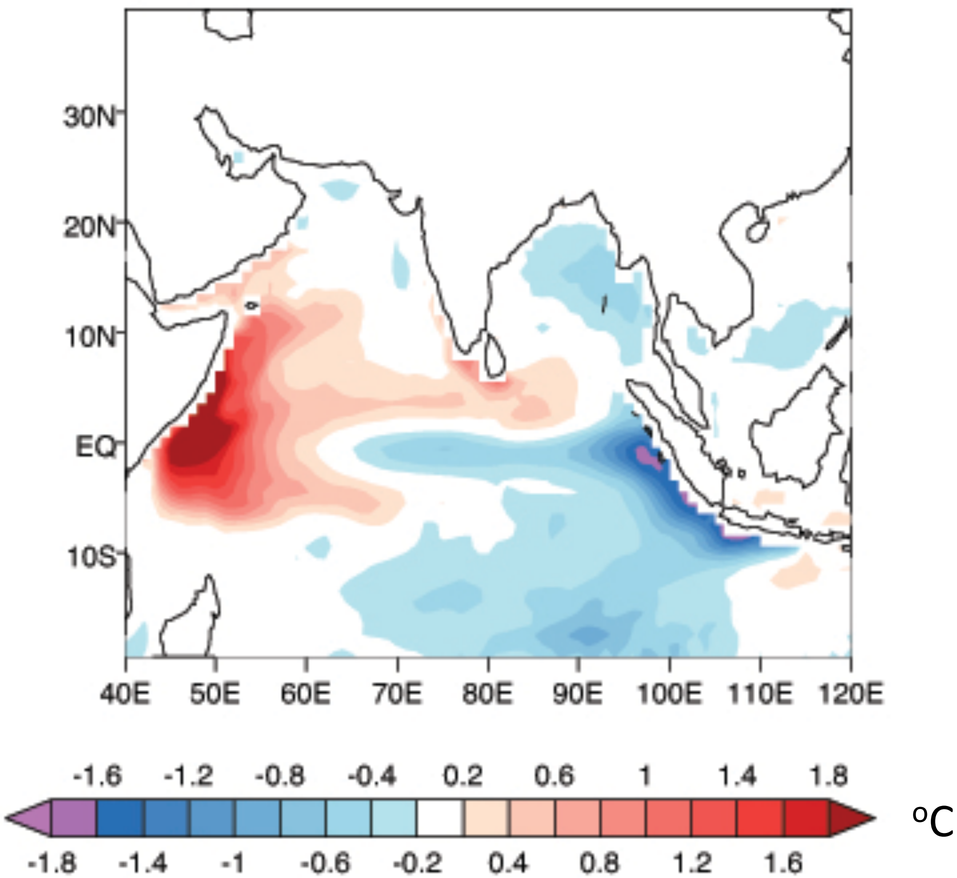


CMIP5 bias D20_JJAS

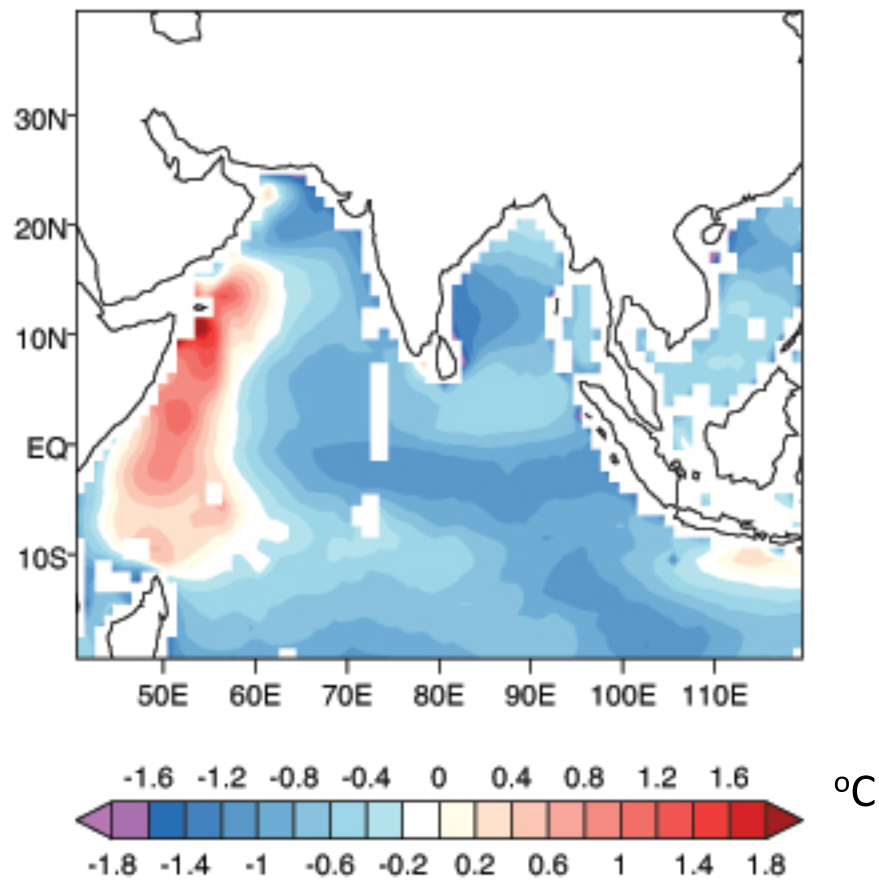


EXP2 *minus* CTL

SST_JJAS



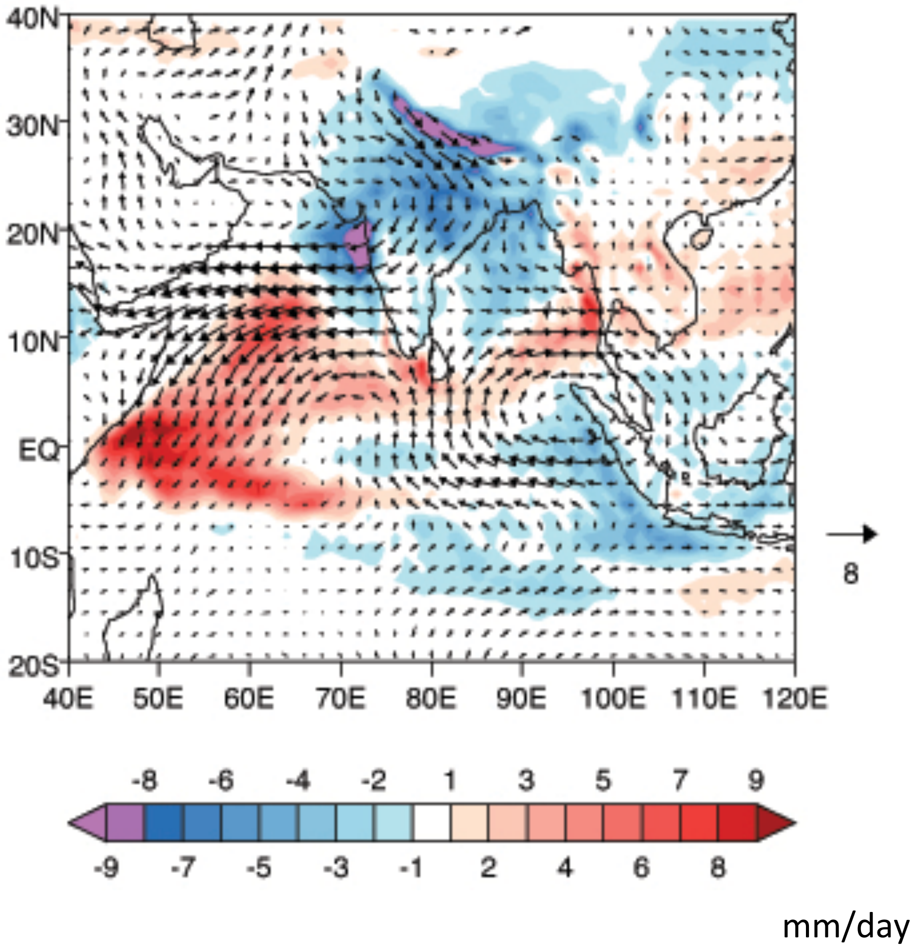
CMIP5 bias SST_JJAS



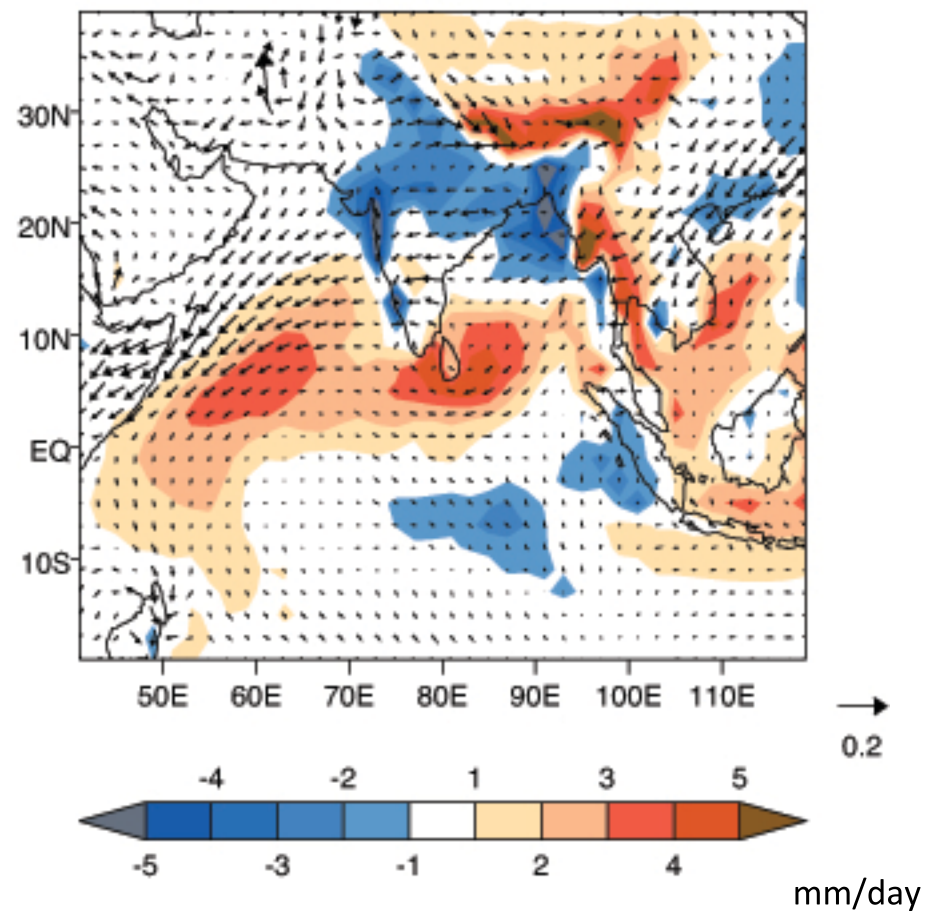
Cold SST bias over northern BoB – induced by coastal Kelvin wave (D20)
Could have contributed to monsoon weakening – later in the season (examining now)

EXP2 *minus* CTL

Precip / wind 850hPa

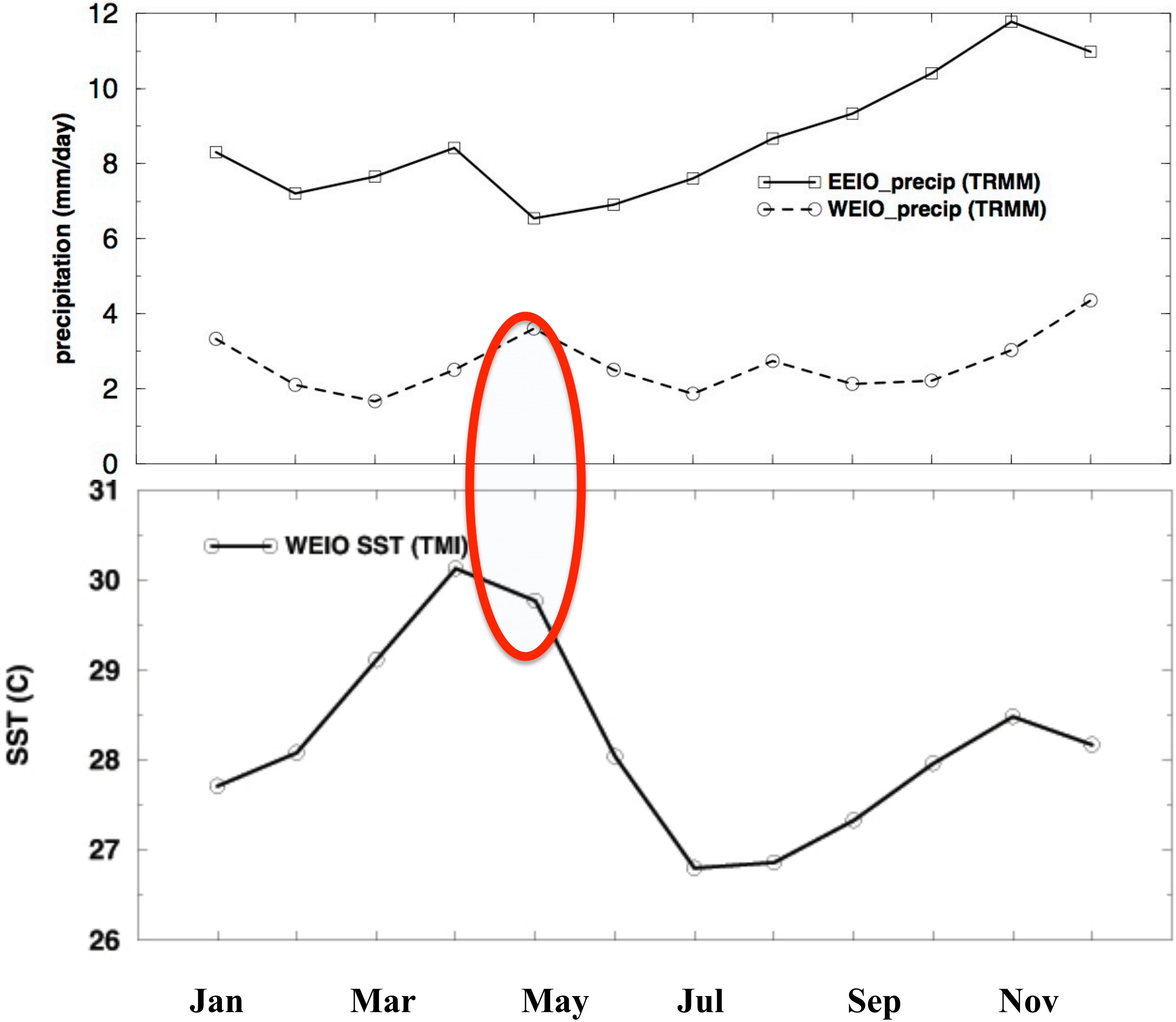


CMIP5 bias – Precip / wind stress



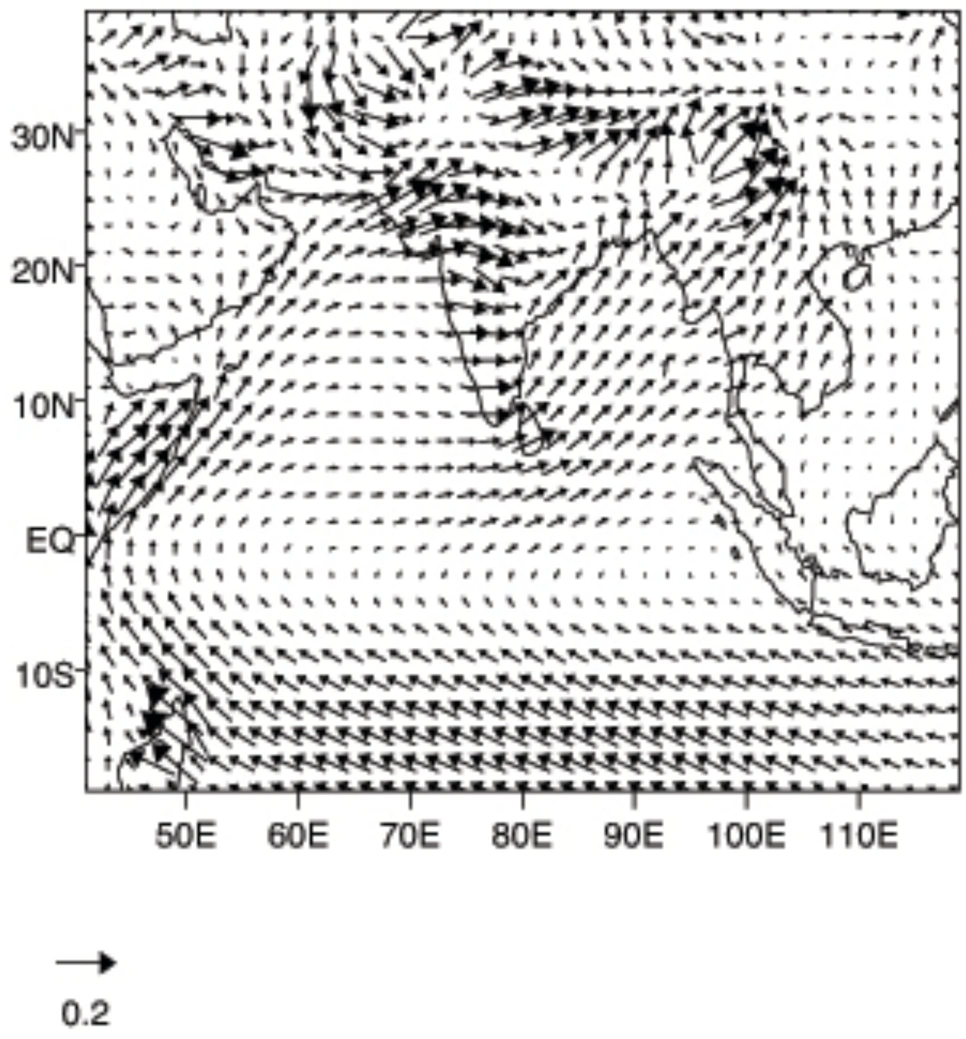
Asymmetric response – errors in western EIO

May-June: time-window in the annual cycle



precipitation (mm/day)
EEIO_precip (TRMM)
WEIO_precip (TRMM)
SST (C)
WEIO SST (TMI)
Jan
Mar
May
Jul
Sep
Nov

Wind stress – May clim (ERA_INT)



Conclusion

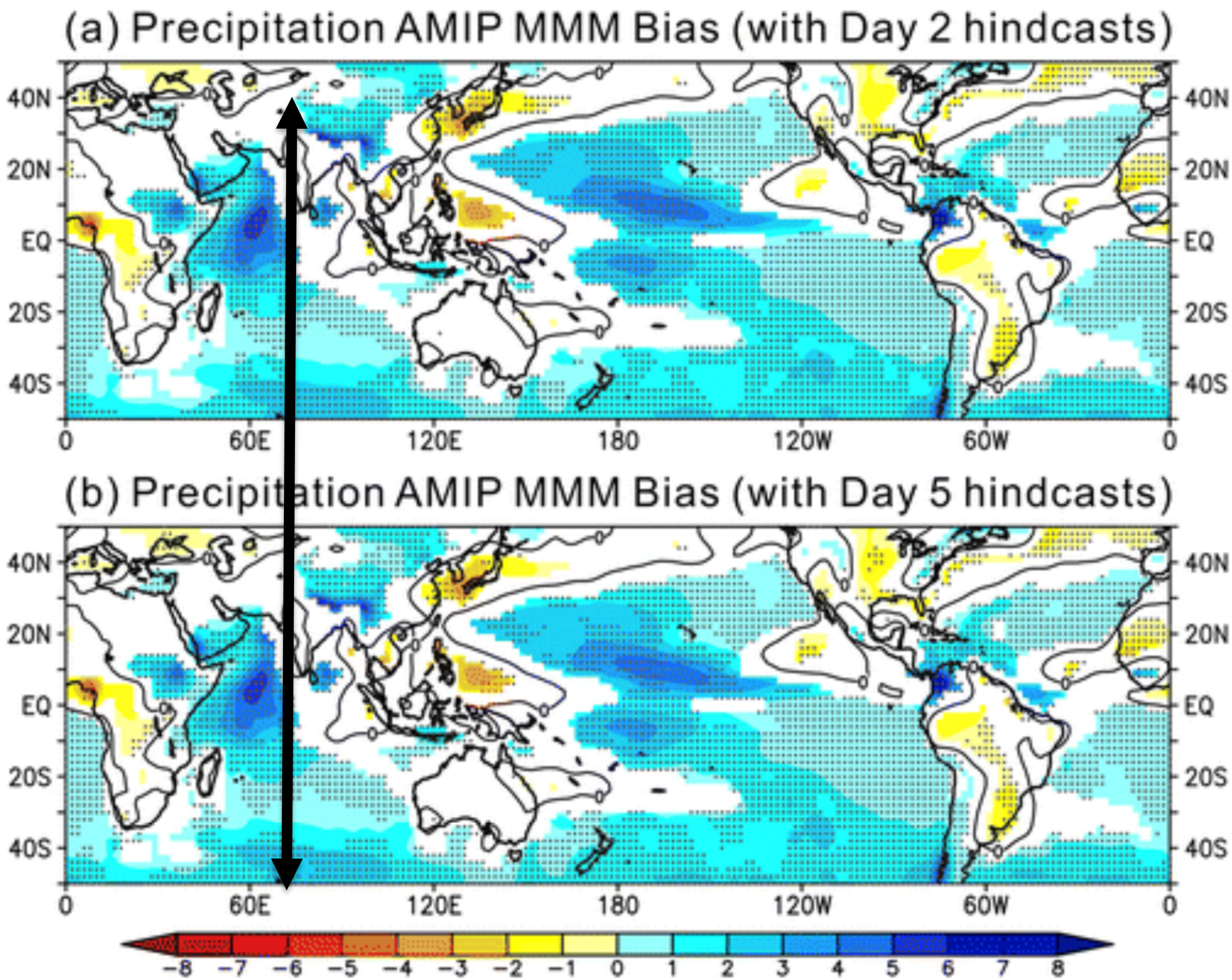
Errors in EIO Coupled Processes lead to
Errors in Summer Monsoon Simulation

Discussion

- **“time-window” in the Annual Cycle –**
  Errors develop over western EIO during May

- **$\Delta\tau$ in May – initiate errors in WJs and coupled processes –**
  Jay has a working hypothesis – talk tomorrow

Slides for discussion



Ma et al. 2014, JC

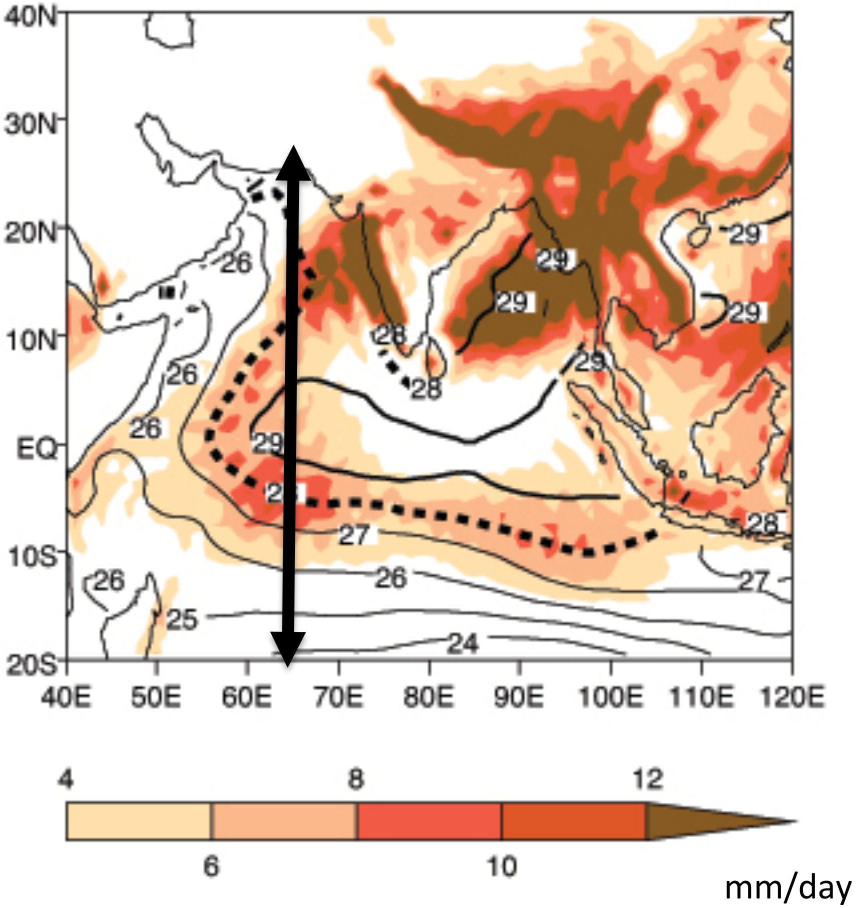
"no SST errors"

Martin et al (2012)

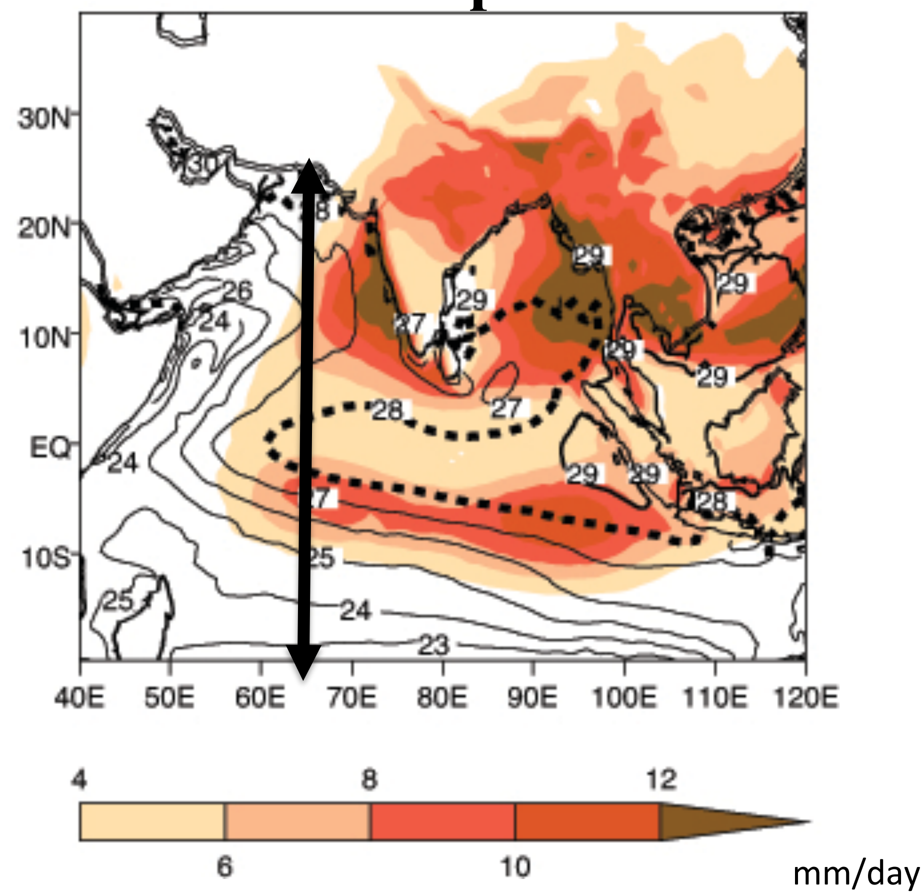
UKMO – similar results

1. **Dry bias over continental India – not clear**
2. **Rainfall errors over Maritime Continent and tropical west Pacific - unclear**

AFES – Precip/SST

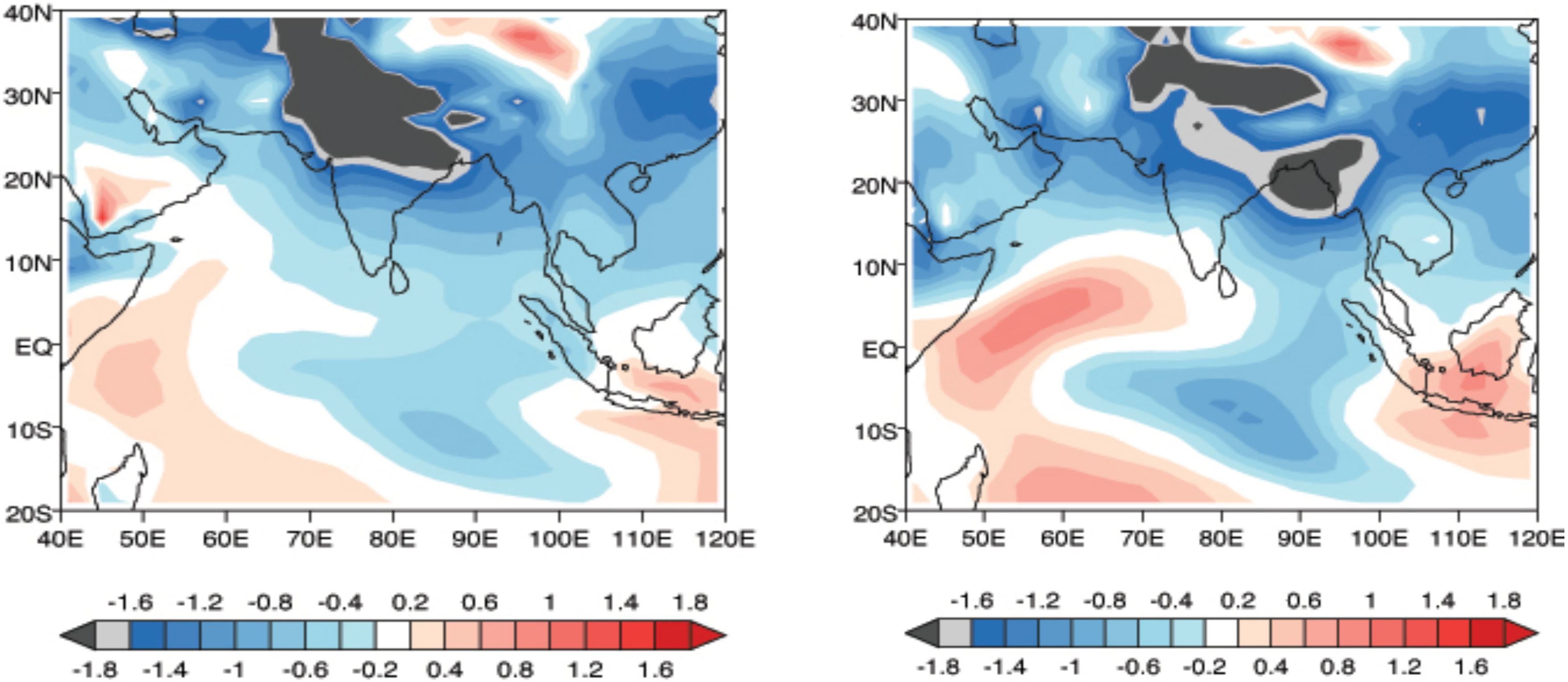


CFES – Precip/SST



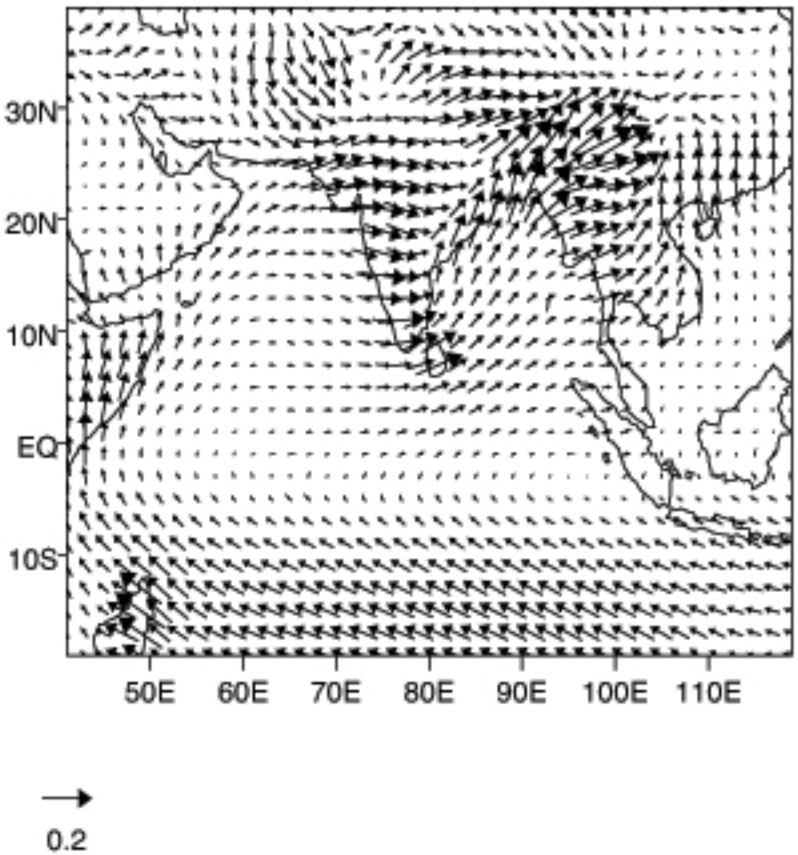
redistribution of EIO precipitation is more realistic in CFES

(a) Specific humidity 1000 – 850 hPa **(b) Specific humidity 700 – 400 hPa**

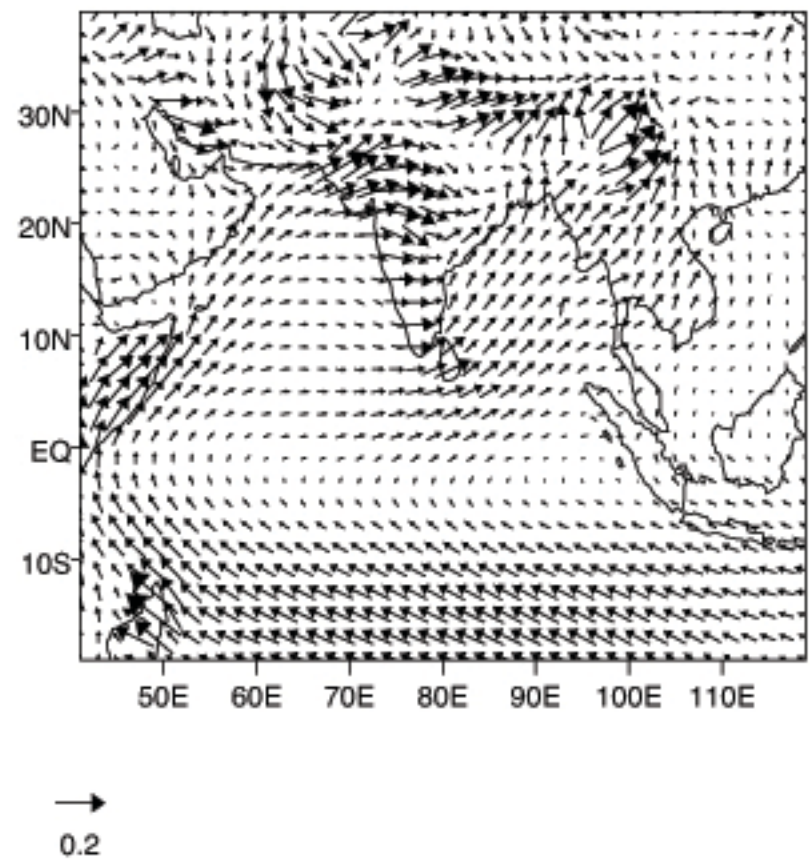


"issues related to entrainment parameterization in models?"

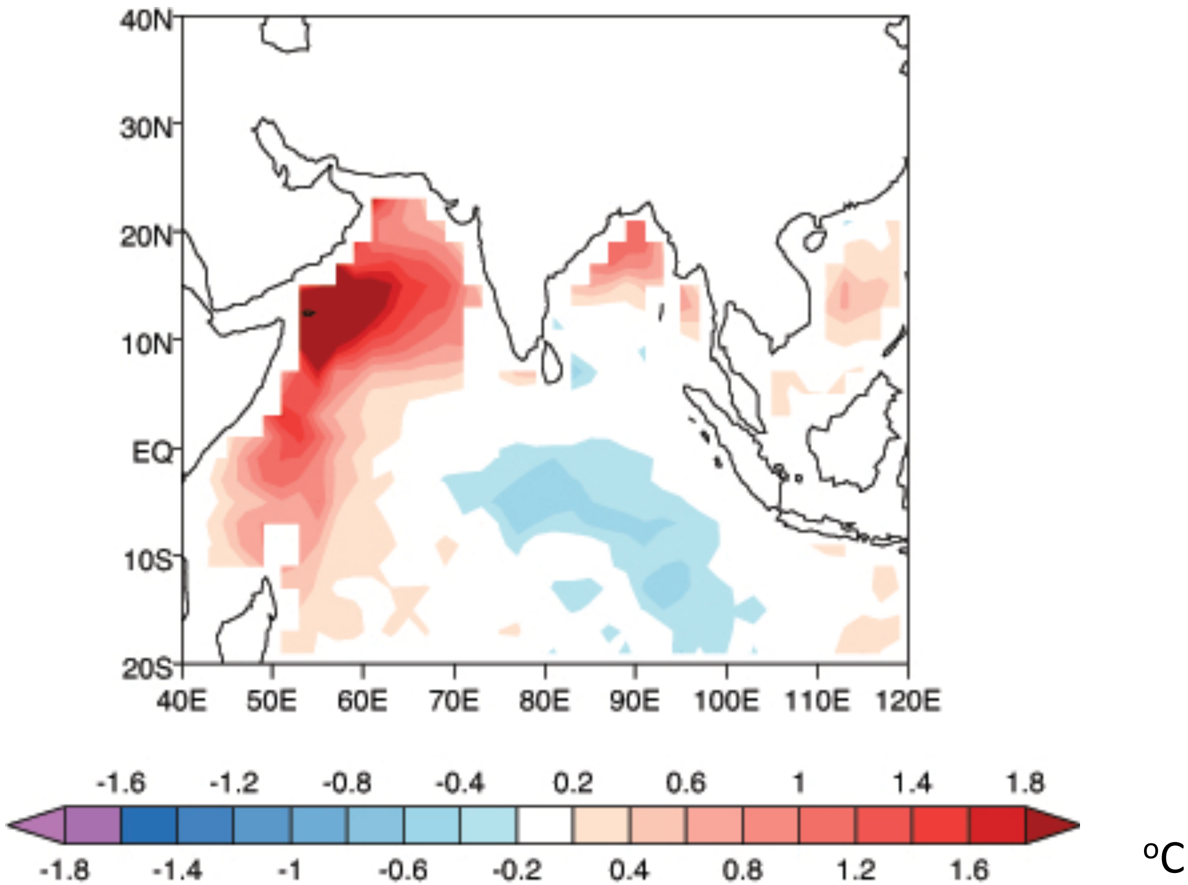
Wind stress – May clim (CMIP MMM)

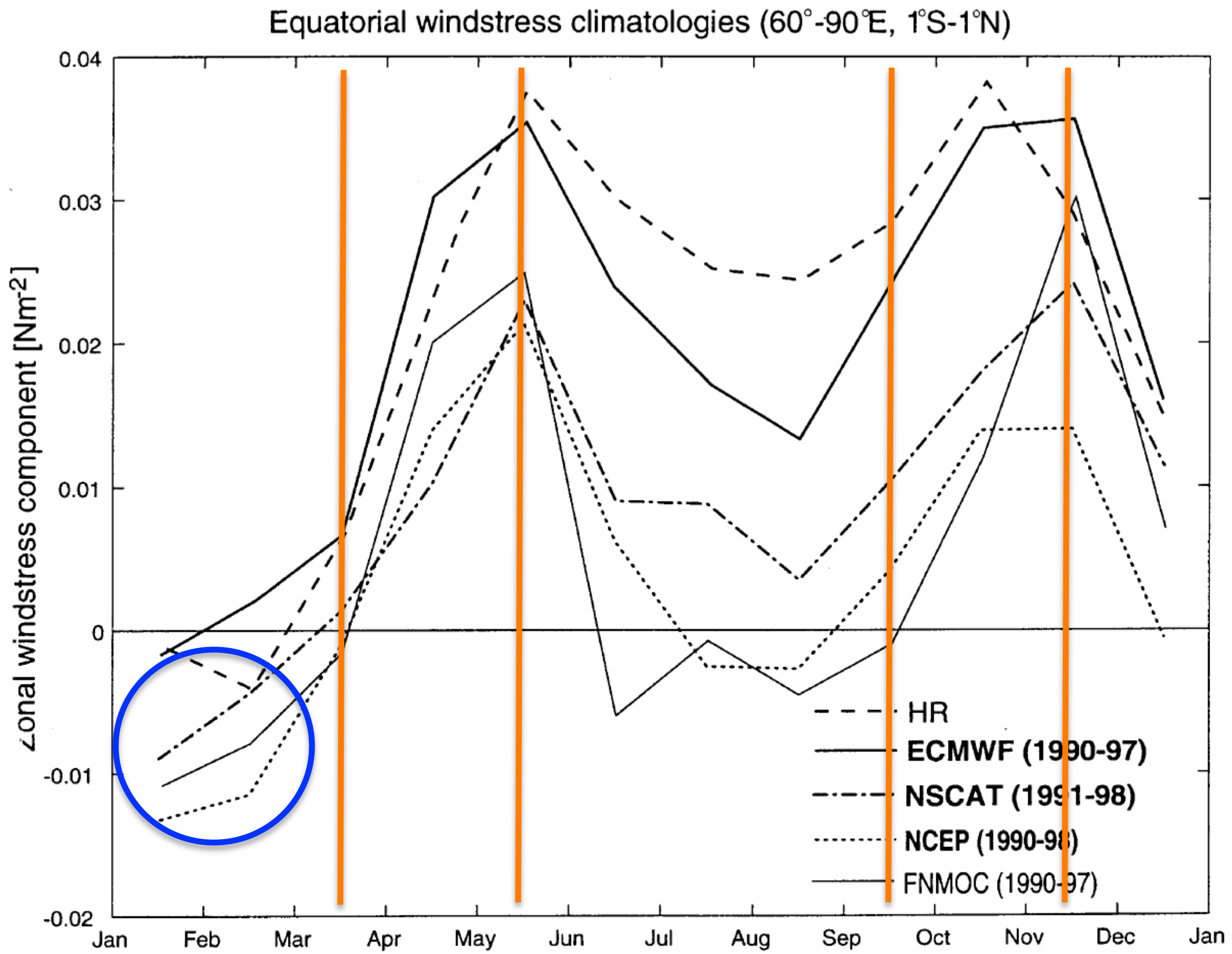


Wind stress – May clim (ERA_INT)



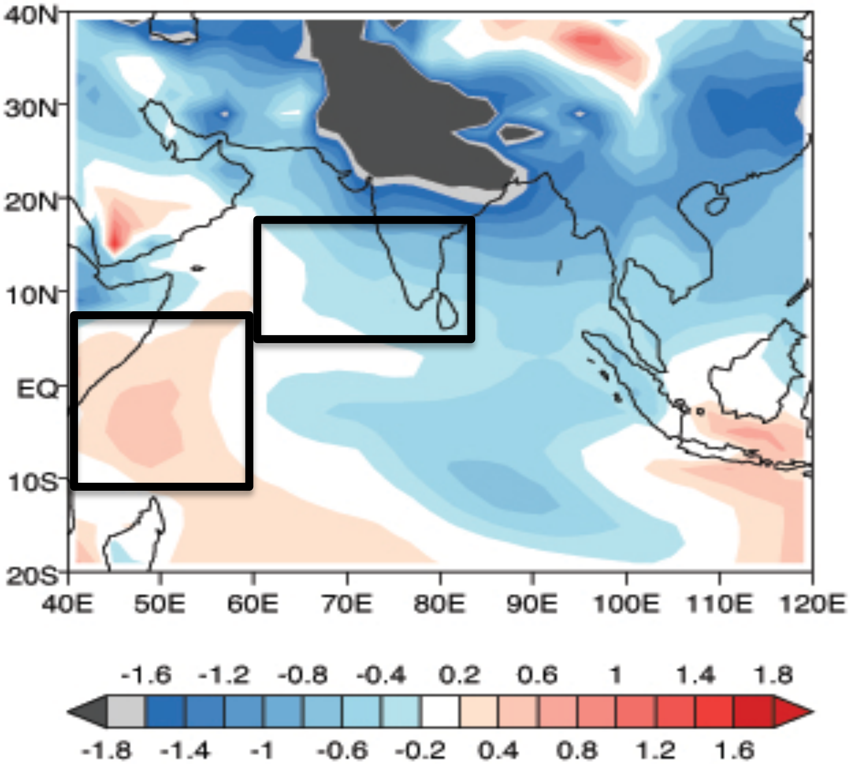
June *minus* May SST tendency bias



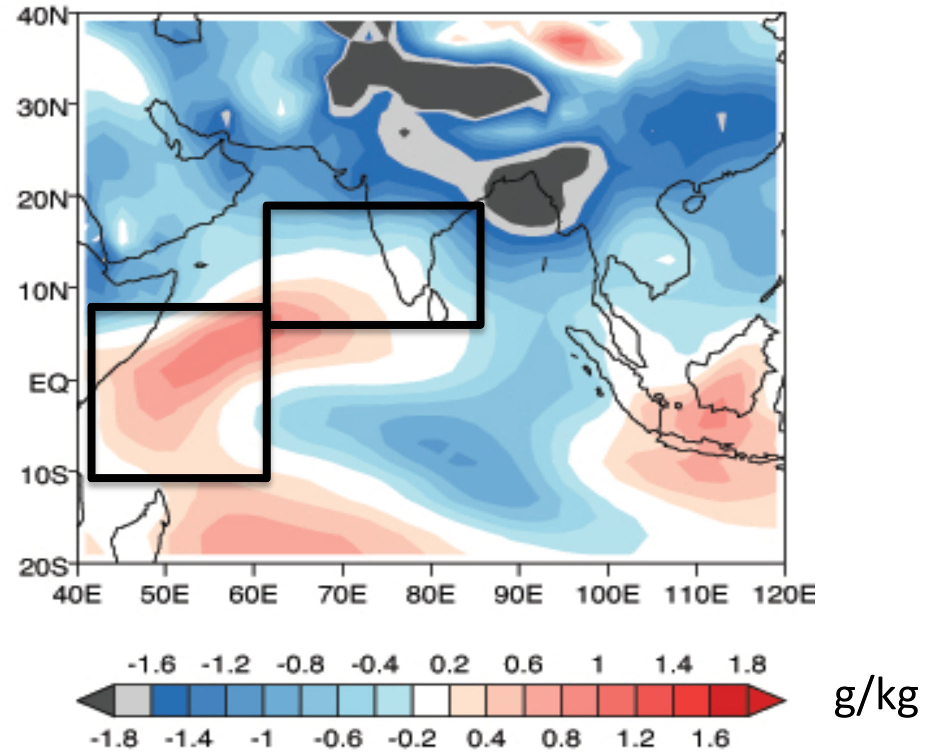


Schott and McCreary (2001)

(a) Specific humidity 1000 – 850 hPa



(b) Specific humidity 700 – 400 hPa



BL moisture – initiate convection

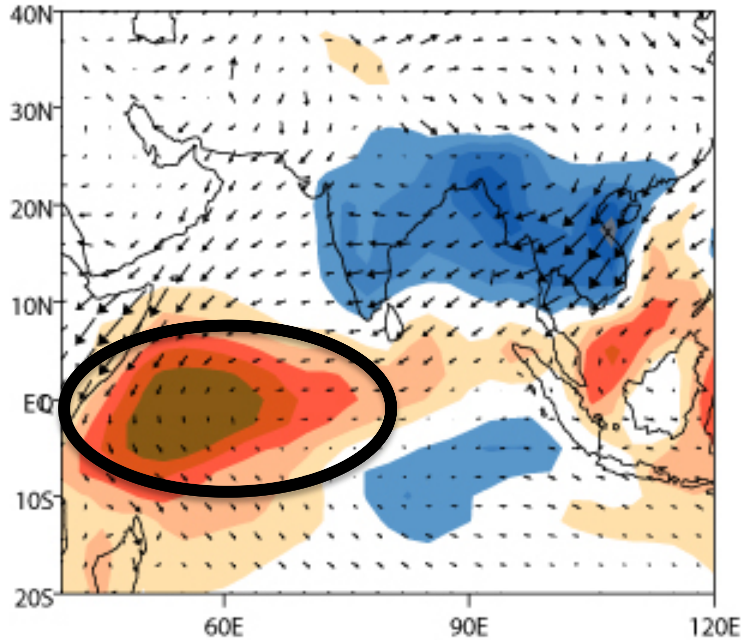
- REG1 - local maximum
- REG2 - normal/negative

Free troposphere – intensity of precip

- REG1 - moderate
- REG2 – high values

JJA

SON

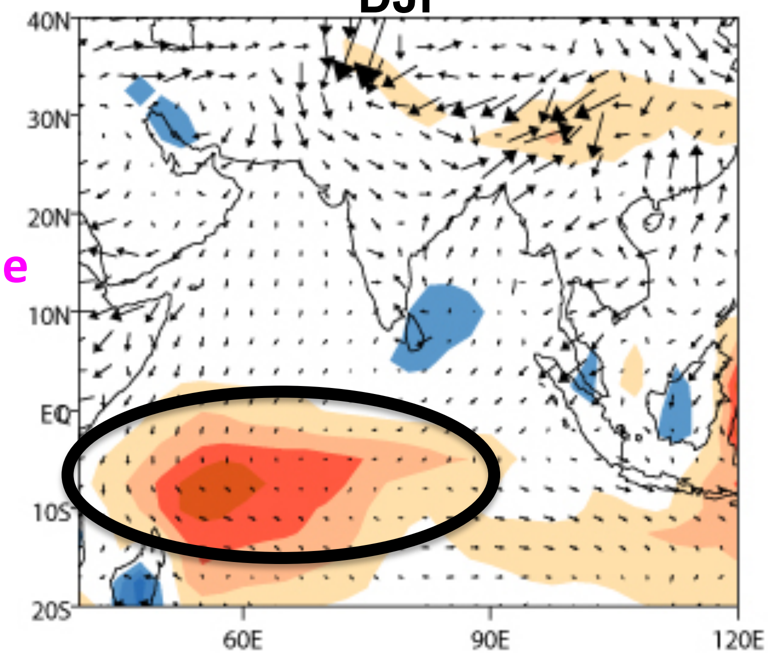


CMIP5 MMM

minus

Observations

DJF

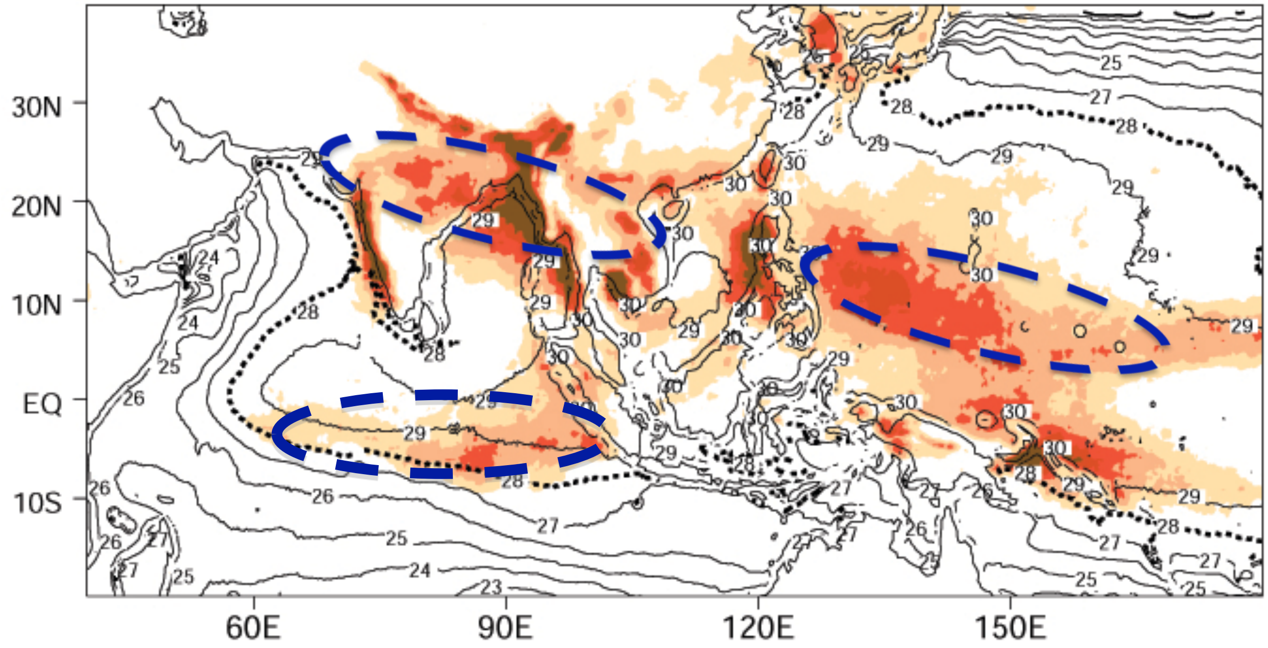


10°S-10°N positive rainfall errors persist throughout the Annual cycle

Precipitation

Wind stress

(variables of interest to SST)



Precipitation and SST

1. Regional rainfall zones
2. High-SST/Orography
3. Different SST threshold (tropospheric T/CRH)

E-W asymmetry NIO

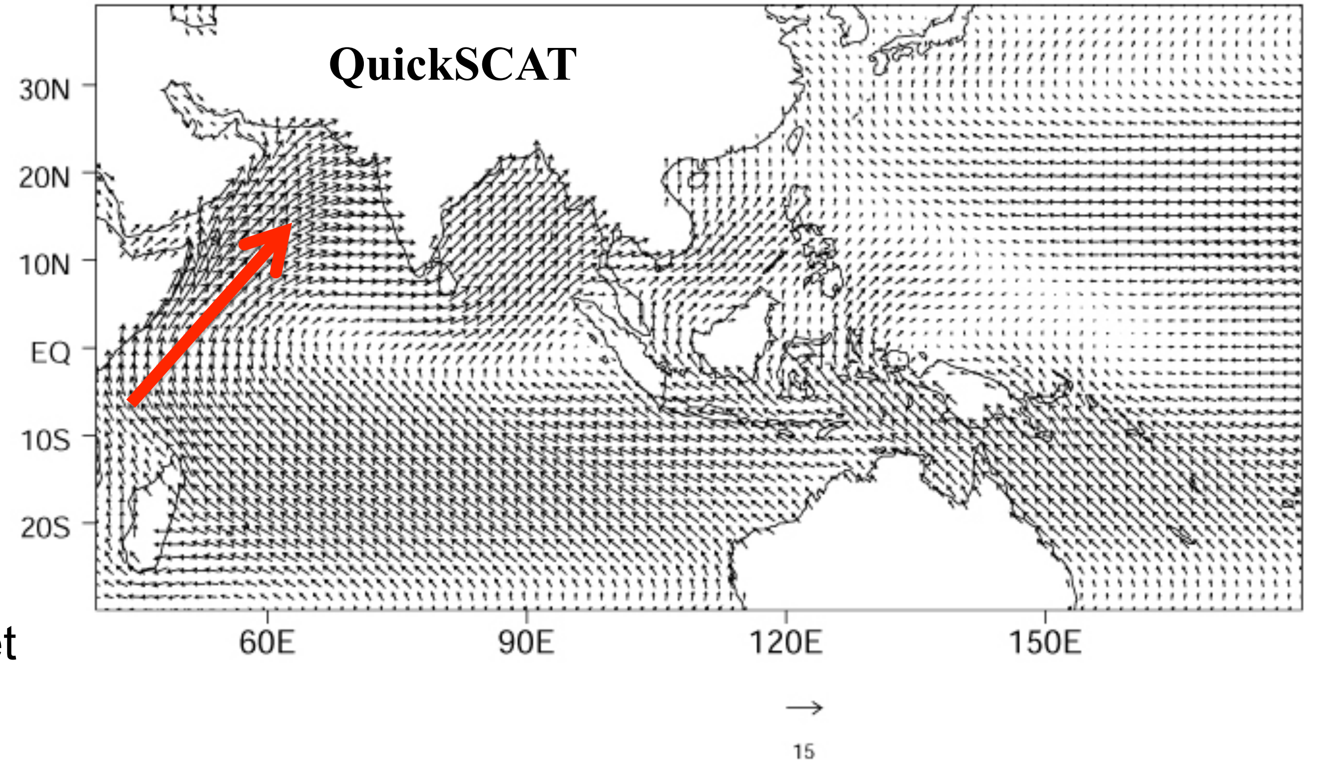
SST – upwelling

RW dynamics

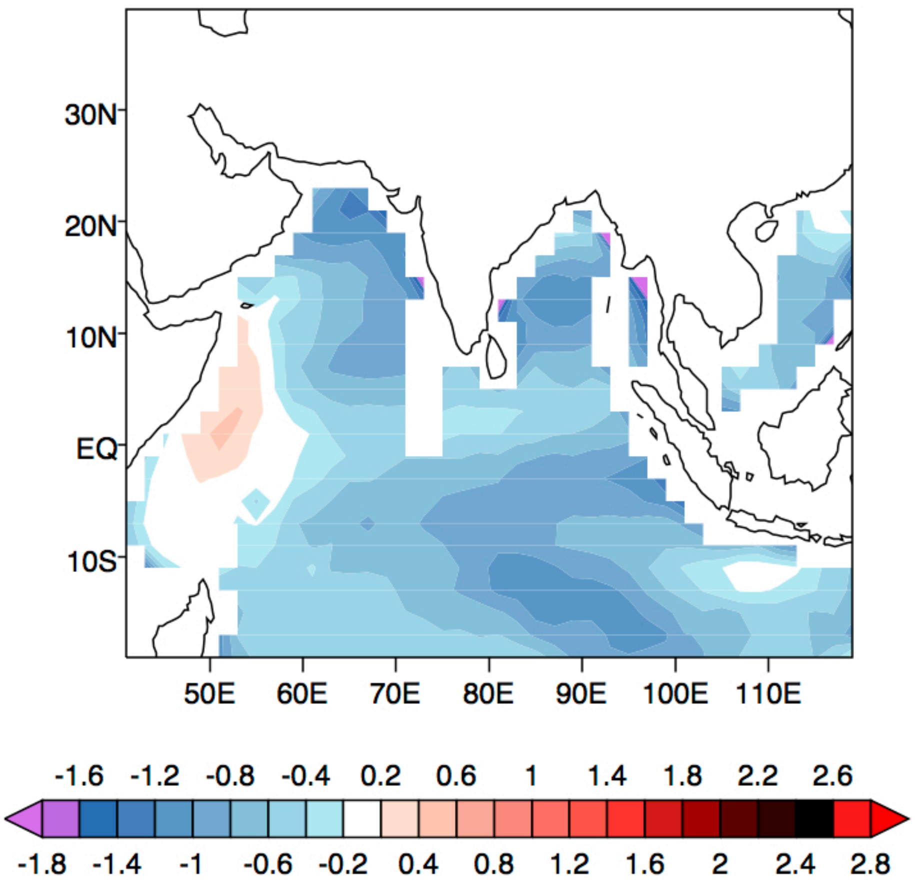
Jet axis

Shear vorticity
A/C circulation
(dynamic not
thermodynamic
Control)

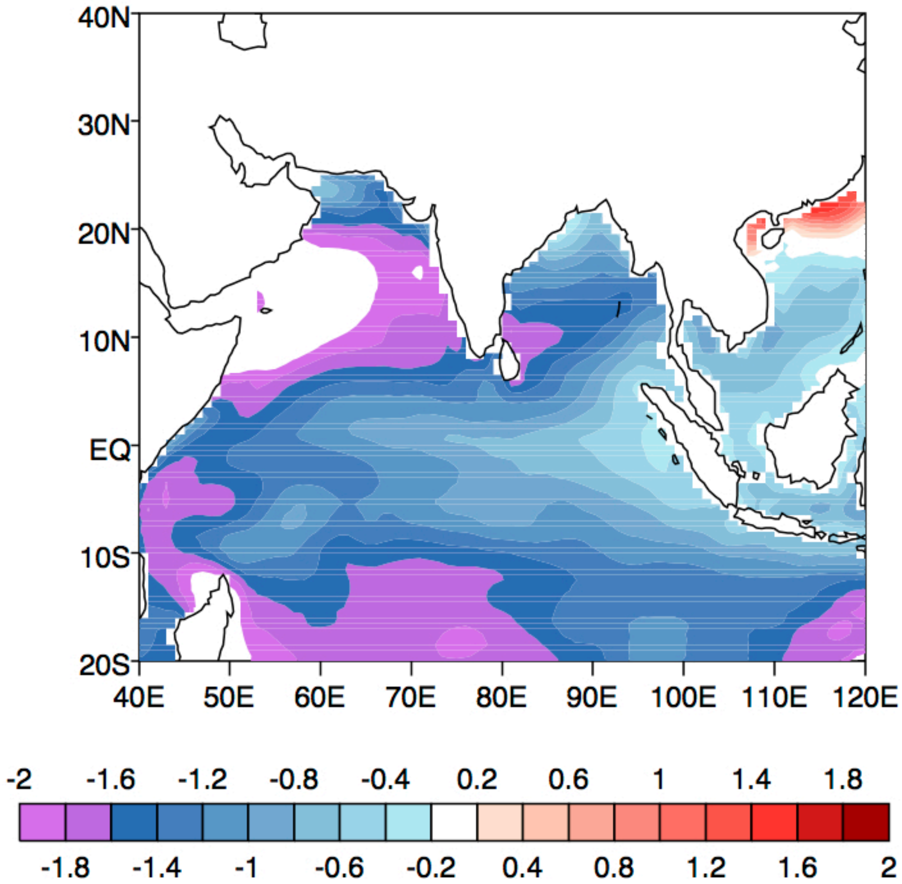
Frictional forces – African highlands – Jet intensity – upwelling

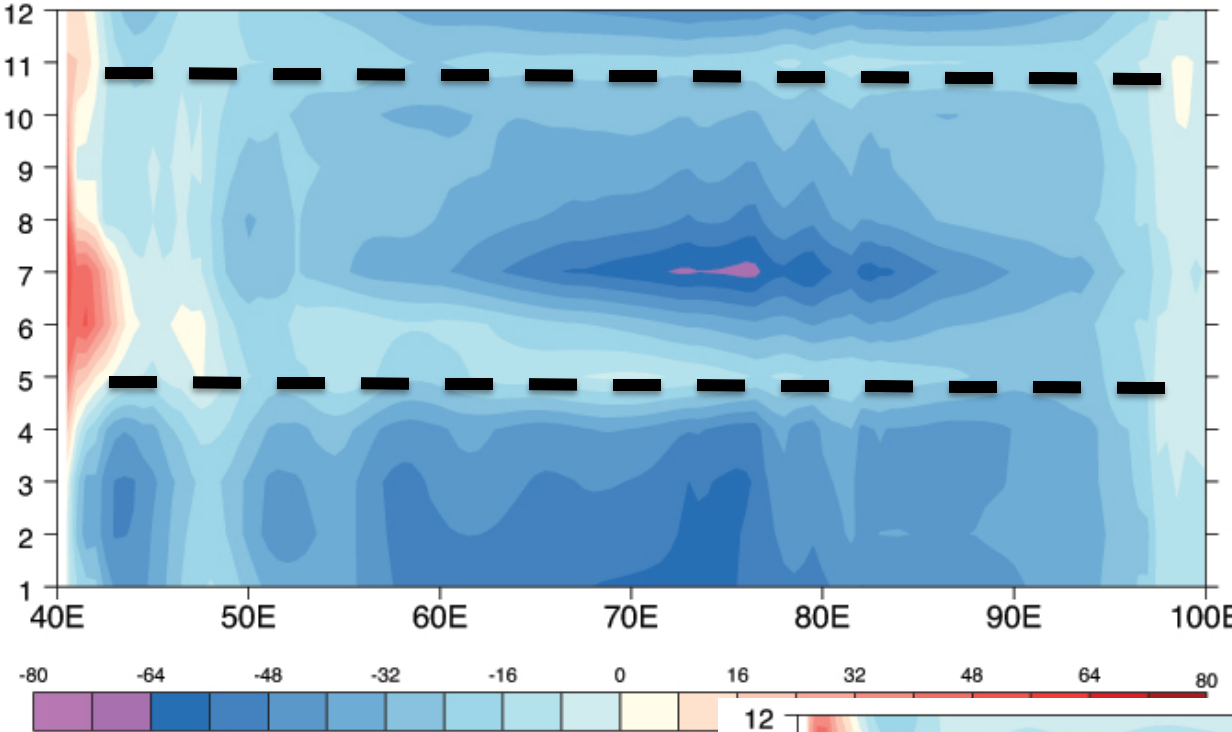


SST bias in SON



SST bias in May

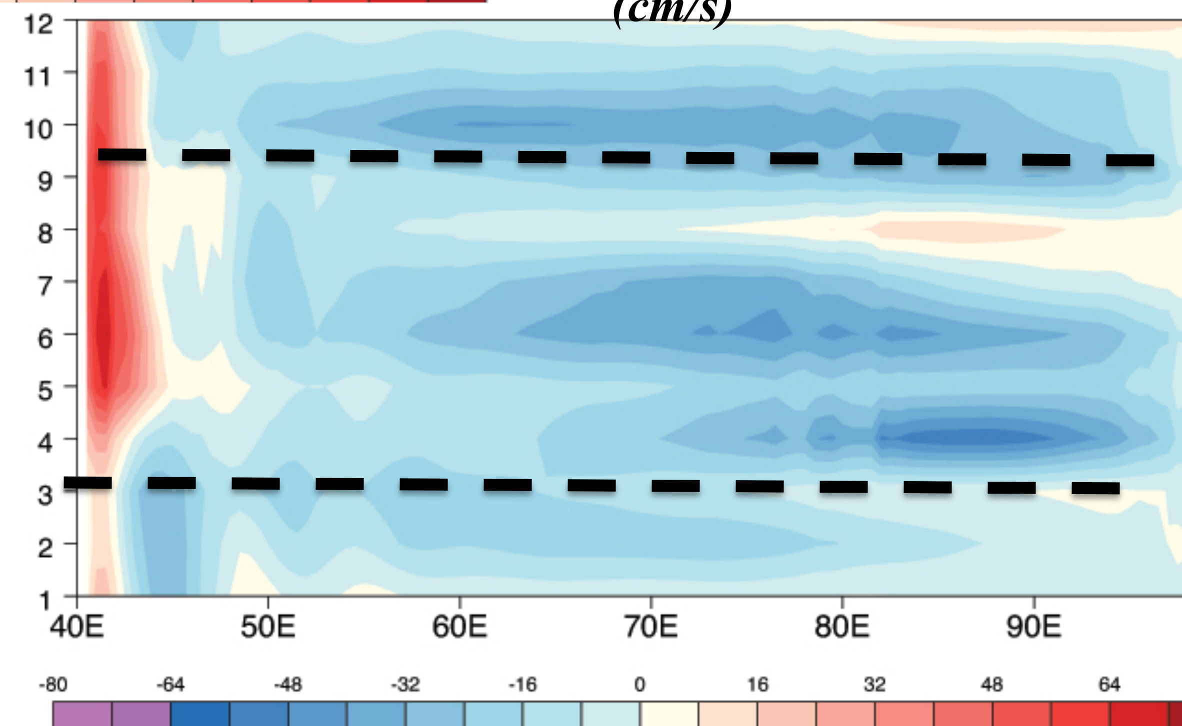




3^oS-3^oN – surface currents

EXP1 Easterly bias_AC

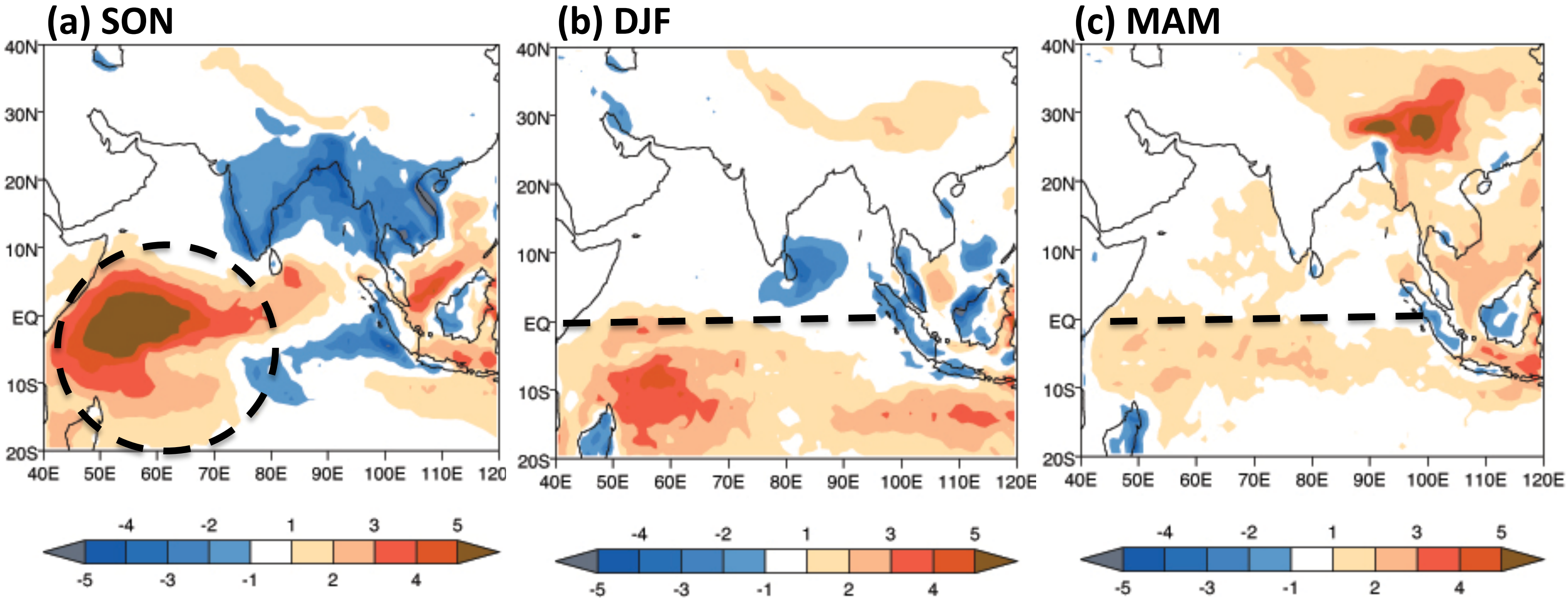
(cm/s)



3^oS-3^oN – surface currents

EXP2 Easterly bias_ SPRING_FALL

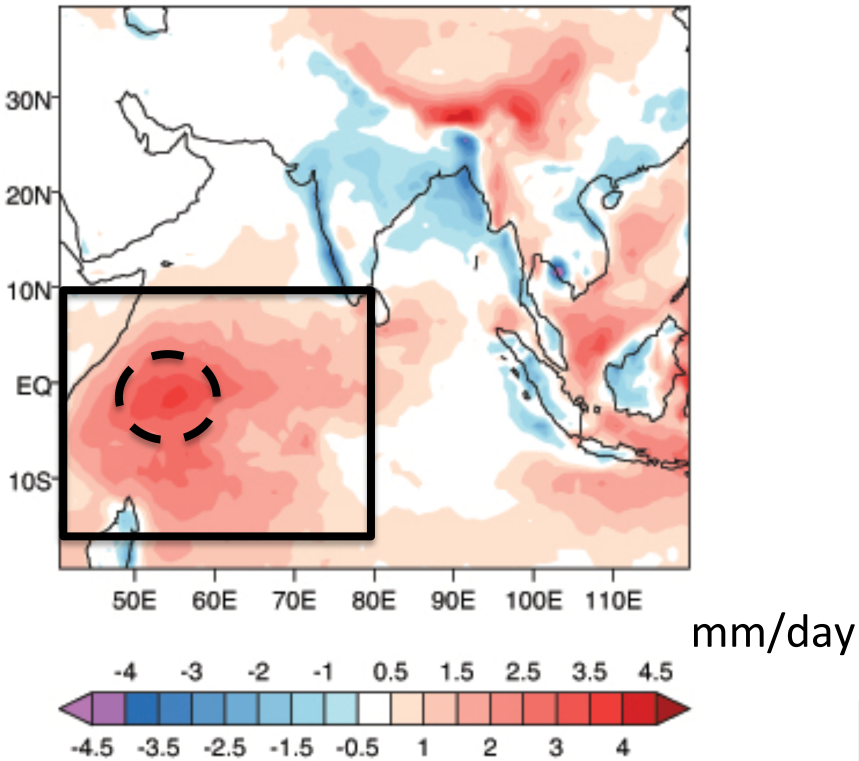
(40-50% weaker than in EXP1)

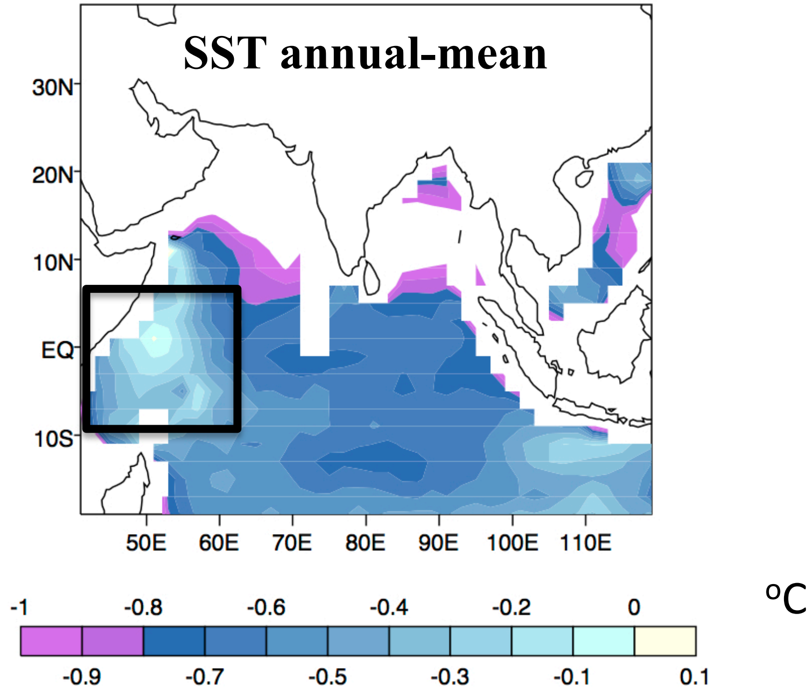


SON

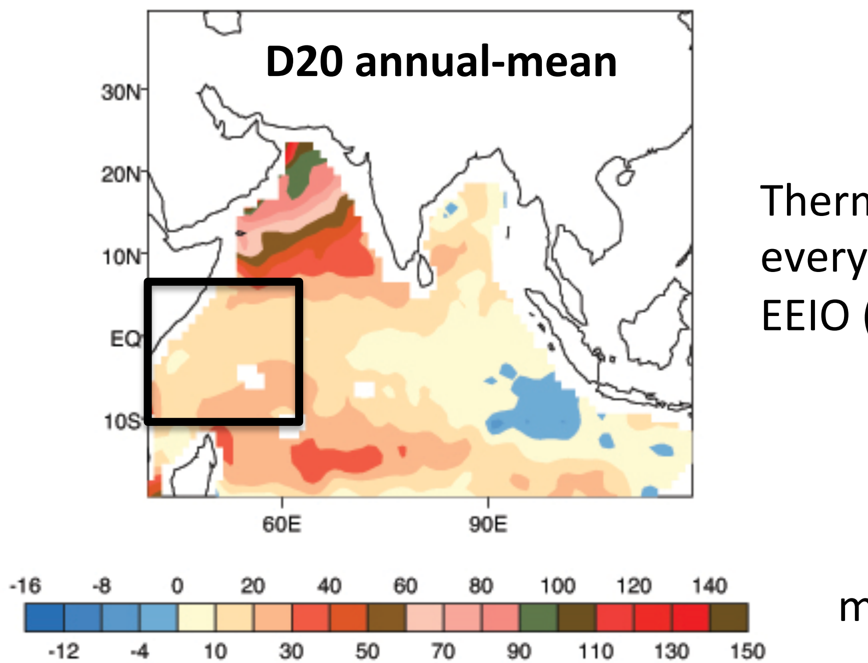
1. Lack of upwelling-favorable winds off Sumatra
2. North-south linkage (weak east-west along EIO)

Precip annual-mean



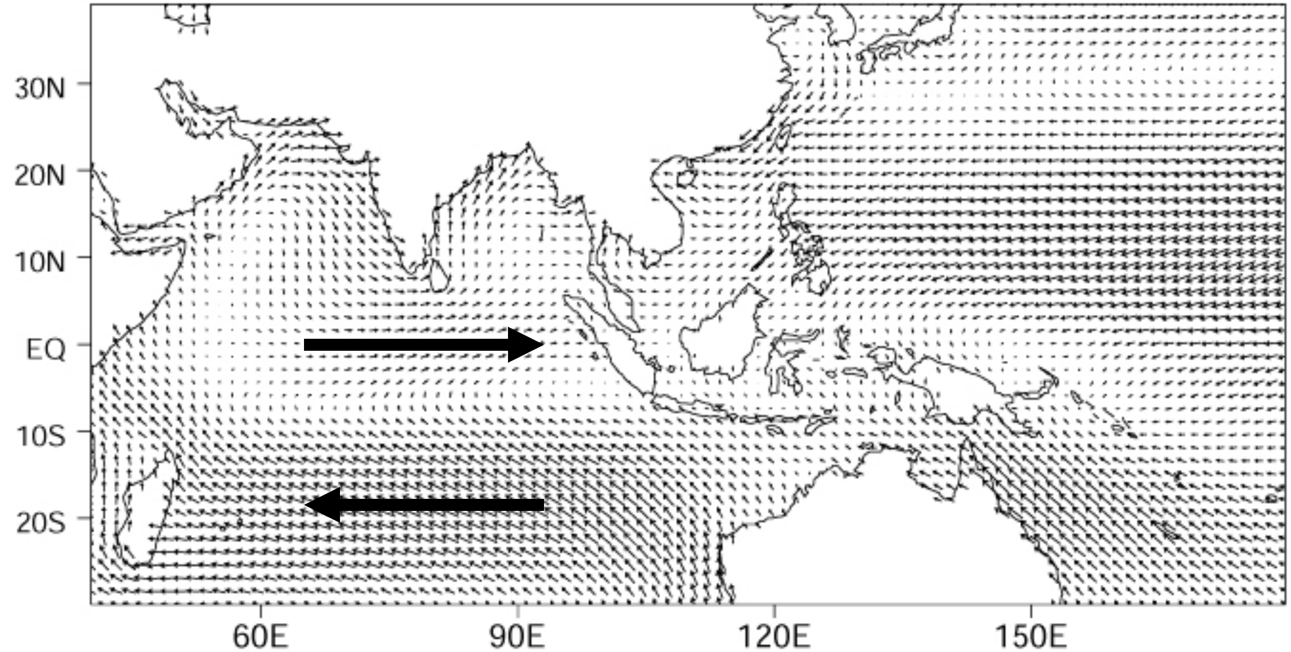


near-equatorial WIO
“hot-spot”
Ocean-atmosphere interaction



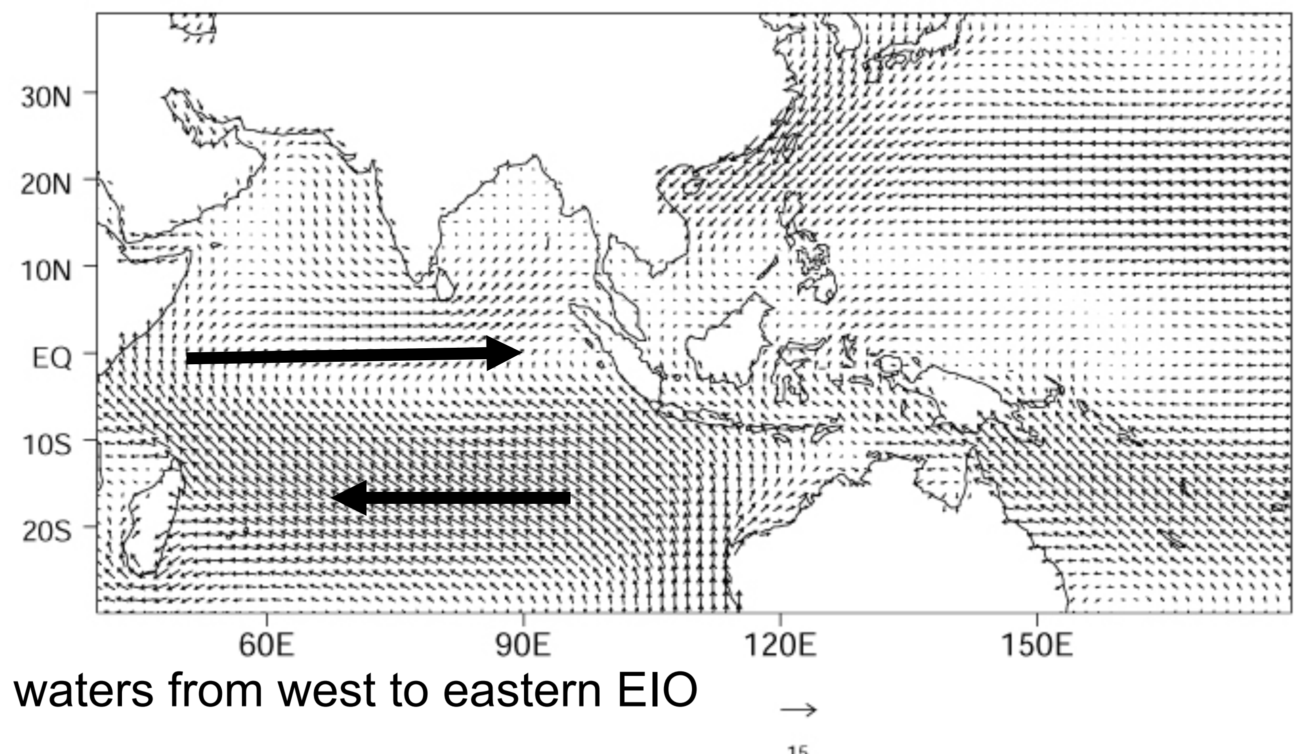
Thermocline deeper everywhere except EEIO (Jay’s talk)

Asymmetric response –
western EIO



QSCAT winds (MAM)

QSCAT winds (SON)



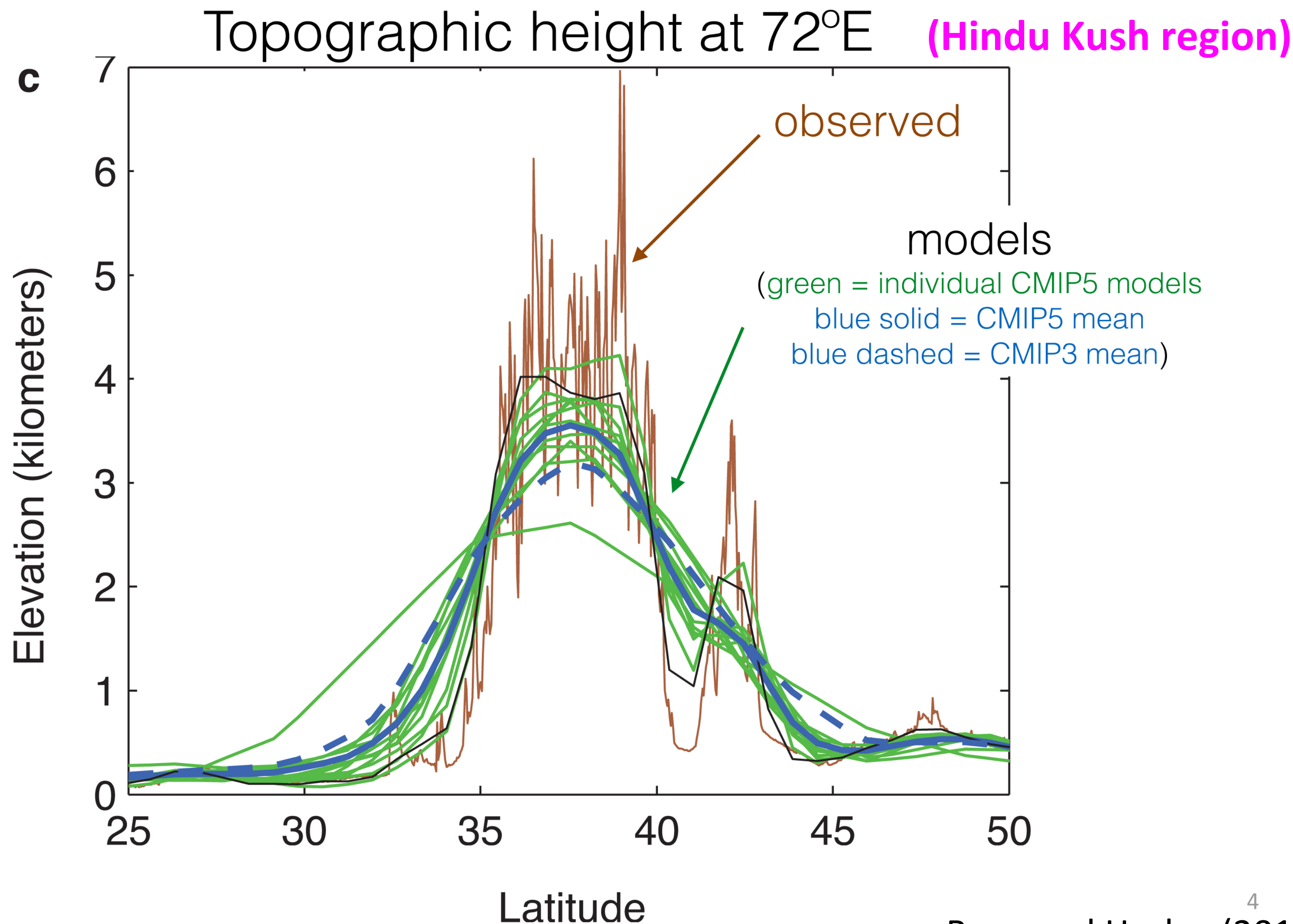
Equatorial eastward
Wyrtki Jets
Advect upper-layer warm waters from west to eastern EIO

Sources of errors (suggested so far)

(i) Misrepresentation of **Orography** (advect low MSE air)

(ii) **Fast** atmospheric processes

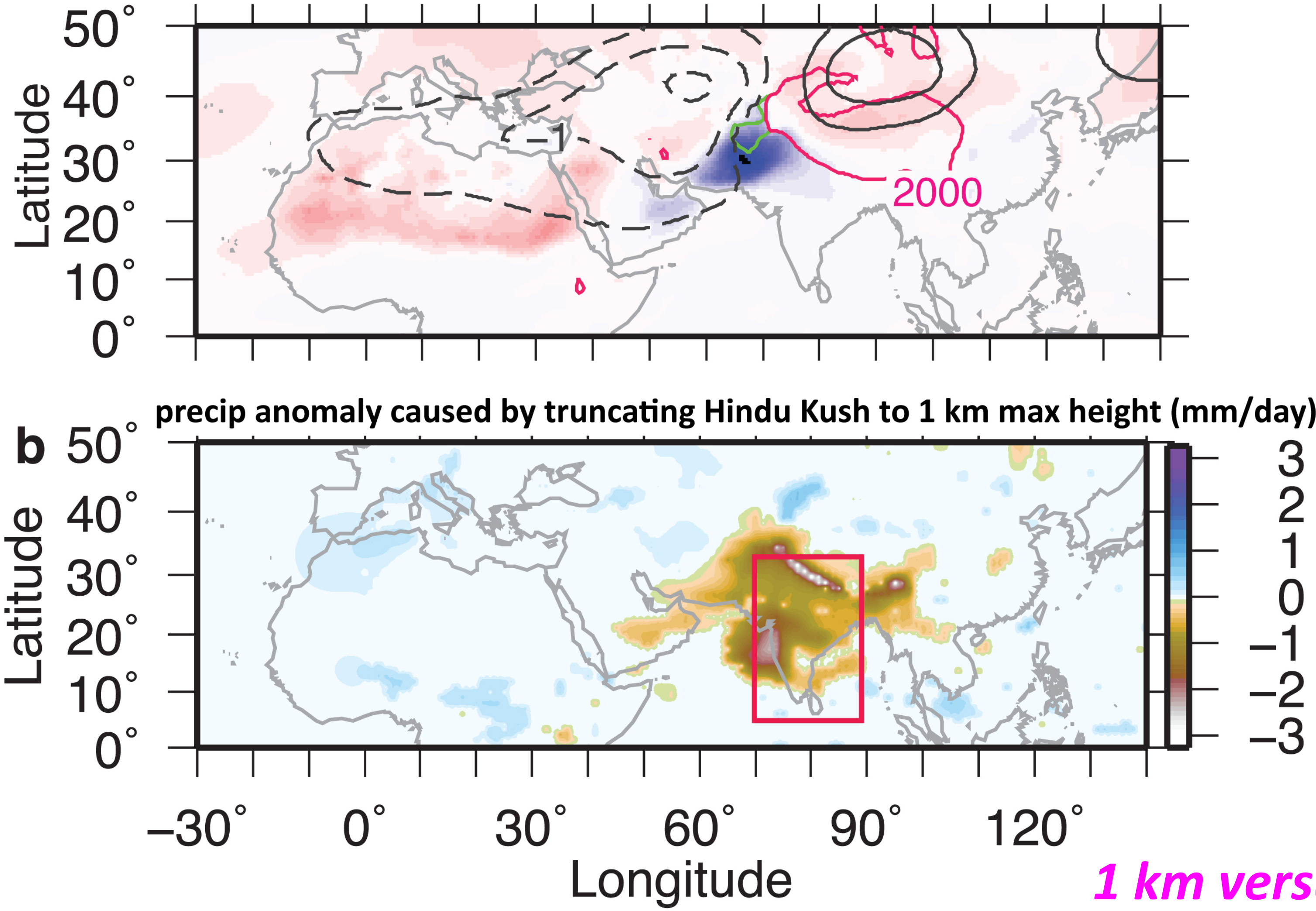
Model topography is overly smoothed



Boos and Hurley (2013)

Modified topography recreates CMIP bias

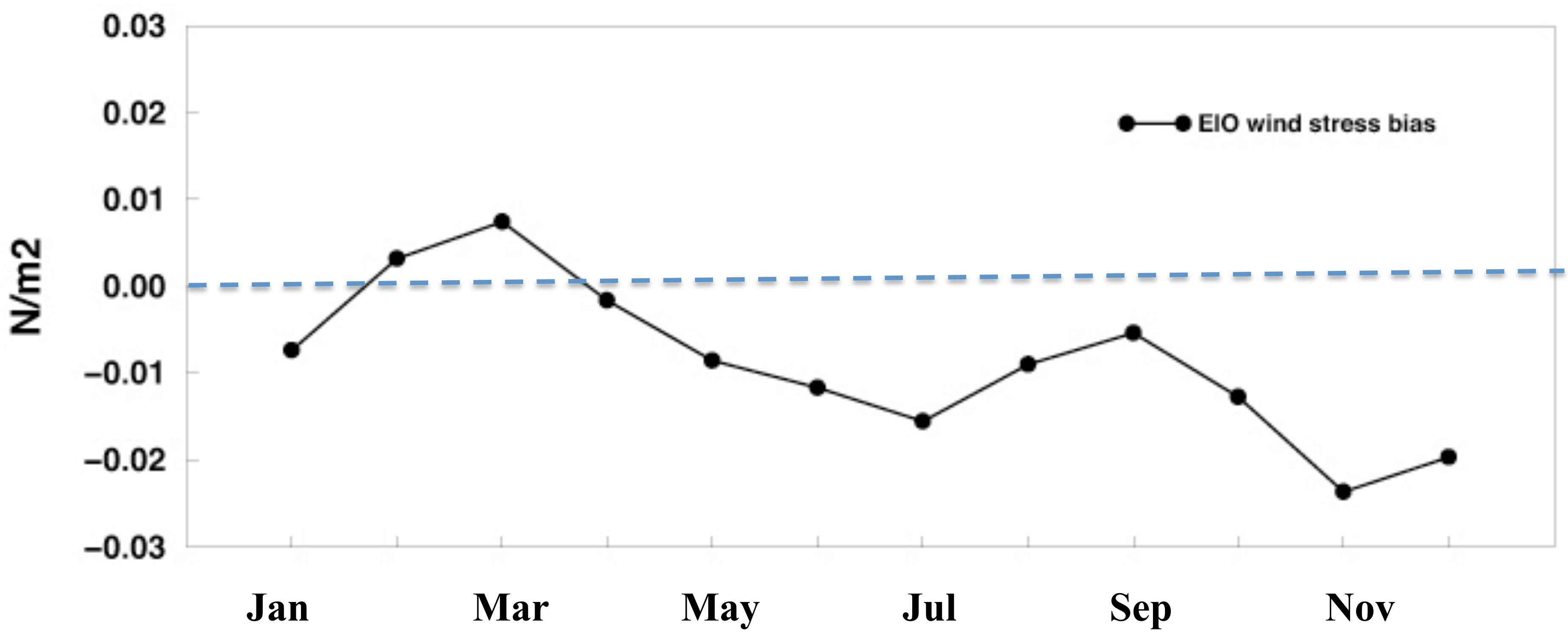
Errors in surface h (colors) and
upper-tropospheric temperature (contours, negative dashed)
green and **pink** contours are 1.5 km surface altitude in **control** and **perturbed** model
(CESM5 0.9x1.25 coupled model, rcp8.5 scenario)



1 km versus 3 km CMIP5

CMIP5 MMM *minus* ERA_INT

(3°S-3°N; 40°-100°E)



"ocean-atmosphere interaction initiated in spring – weakens in late summer – peaks in fall – weakens in winter"

Asymmetric response – errors in western EIO forces biases everywhere!