# Systematic errors in monsoon simulation and process-based diagnostics

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INTERNATIONAL PACIFIC RESEARCH CENTER

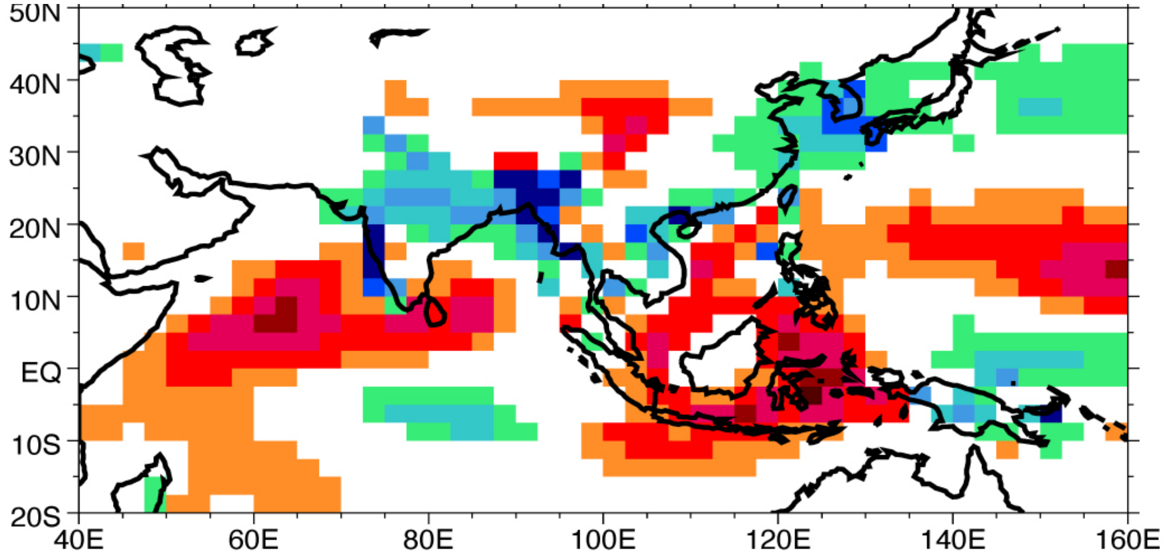
# Talk Outline

- Persistence of systematic errors over the Asian-Australian monsoon system
- Sources of systematic errors (limitations in these studies)

  *(i) Misrepresentation of Orography*
  *(ii) Fast atmospheric processes (convection)*
  *(iii) Fast oceanic processes (Wyrtki Jet along EIO)*

- Process-based diagnostics (Identify robust precursors)

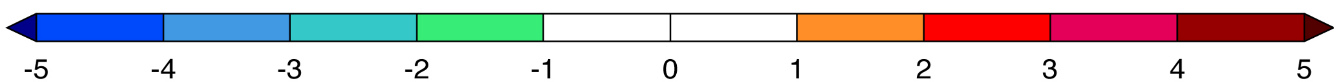
## CMIP3 MMM – GPCP




# JJAS - Precipitation

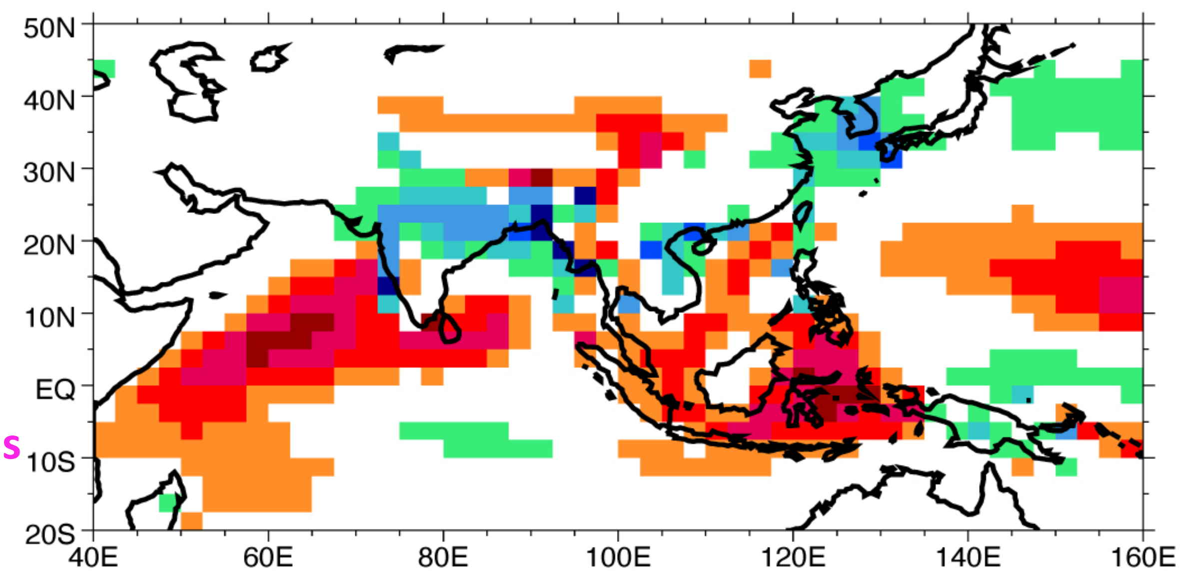
**(Sperber, Annamalai et al. 2013)**

*(mm/day)*




**“+ve errors along the climatological flow”**

## CMIP5 MMM – GPCP




Errors in

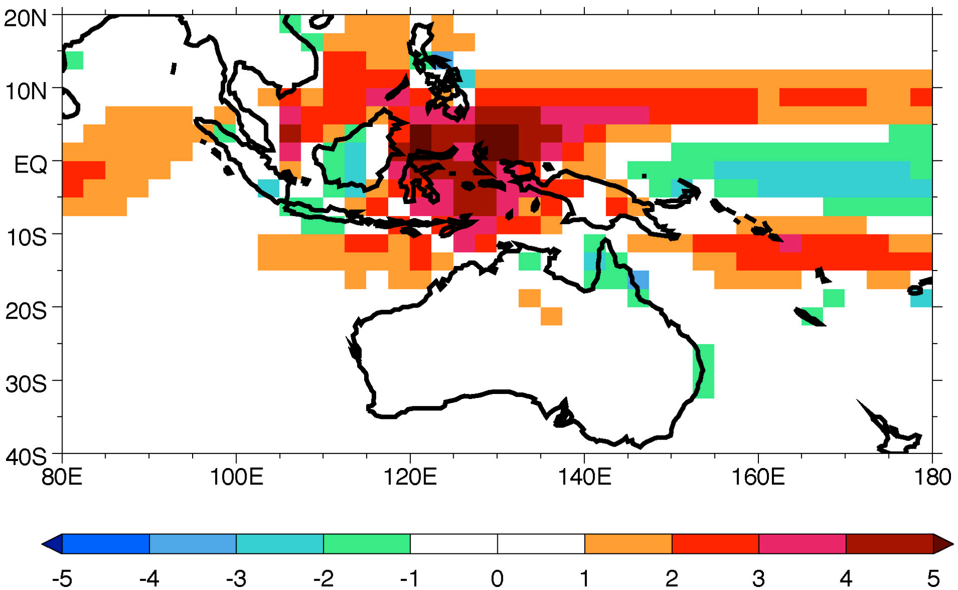
(i) coupled processes and persist thru’ AC

(ii) MC - land-sea breeze

(iii) Land-atmosphere -

**Uncertainties in future projections may not have reduced**

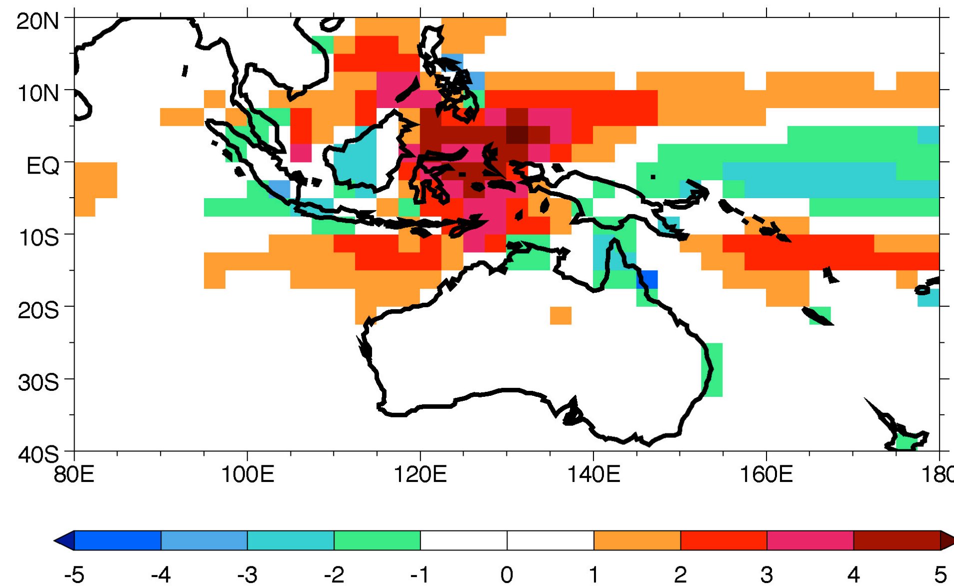
## CMIP3 MMM – GPCP




## DJF - Precipitation

Positive errors over MC persist thru A/C

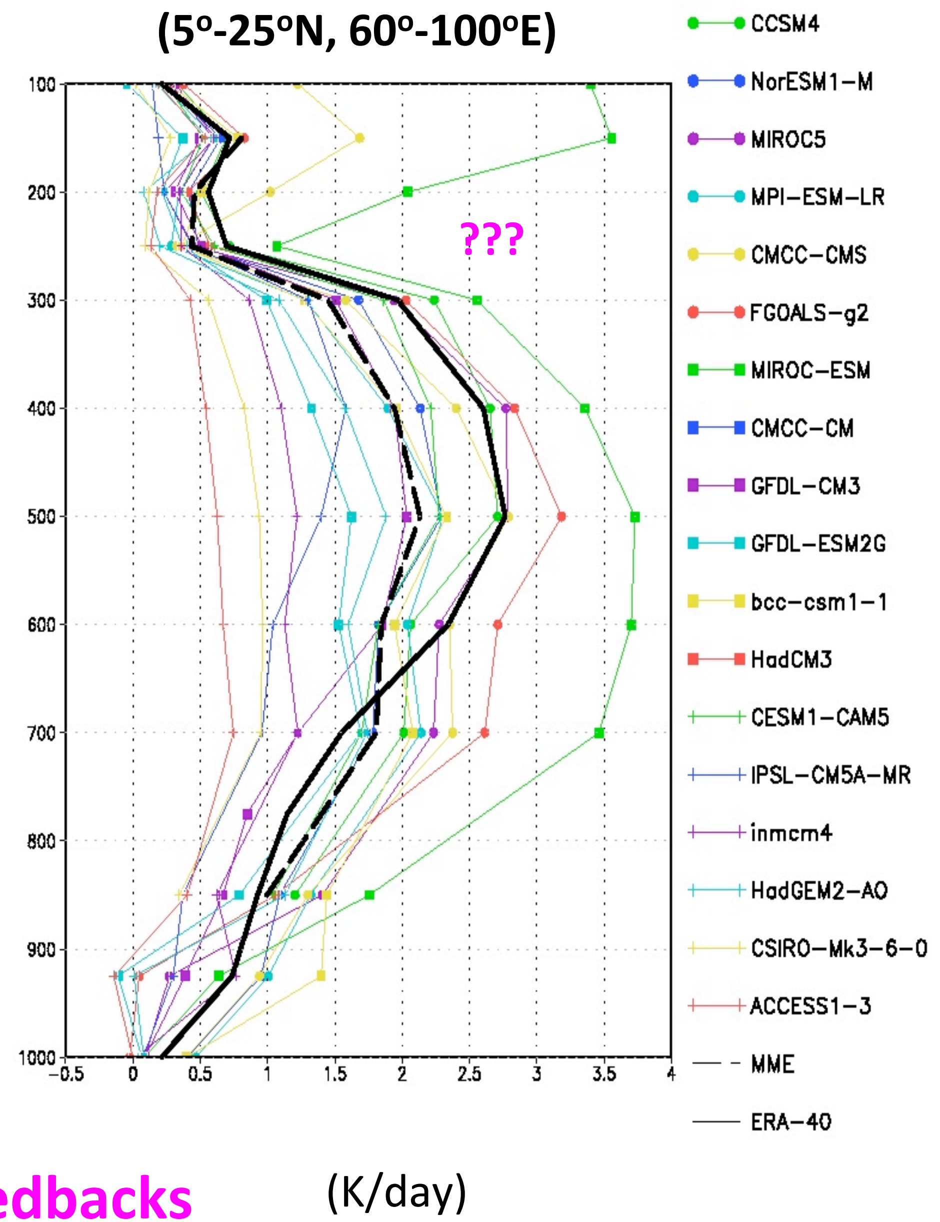
## CMIP5 MMM – GPCP




Uncertainties persist in future projections - Perhaps due to persistence of systematic errors

# Vertical distribution of diabatic heating (Q)

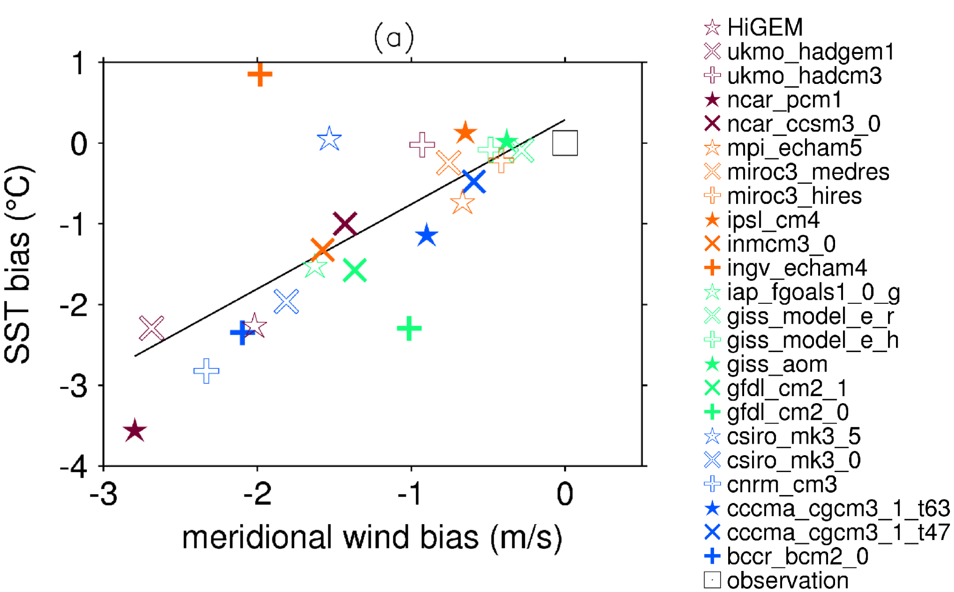
1. Vertical Cloud distribution
2. Cloud-radiation interaction
3. Too much shallow?
4. Too little stratiform?

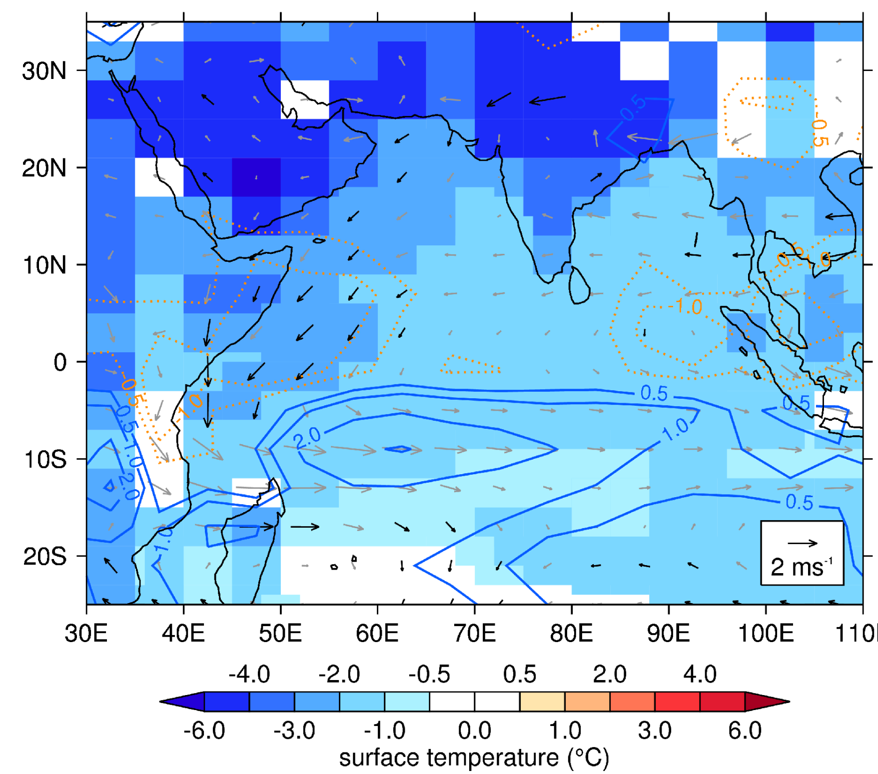



"moisture-convection" feedbacks

(Cherchi, Annamalai et al. 2014)

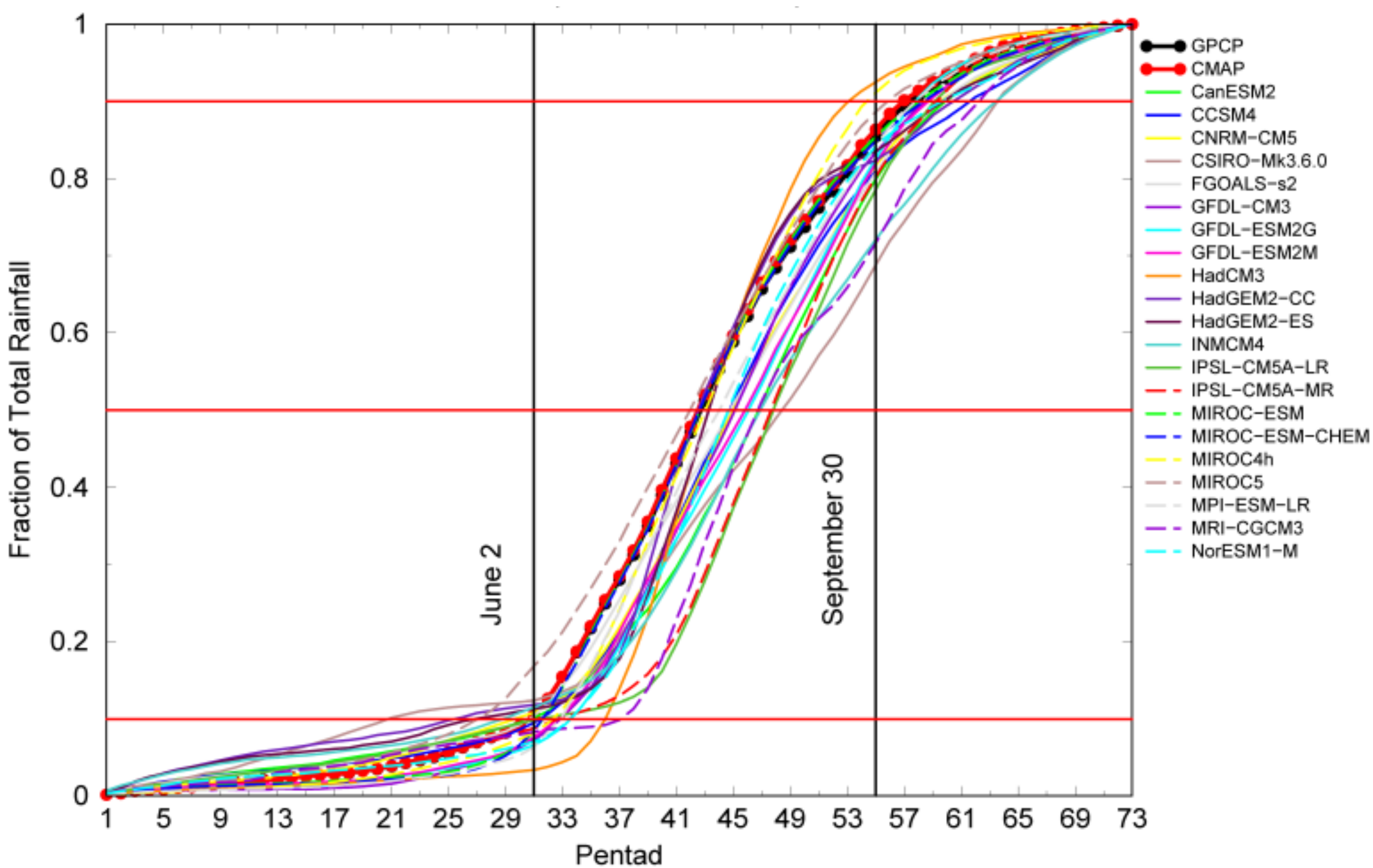
- Many CMIP models exhibit cold SSTs in the northern Arabian Sea during <u>winter and spring</u>.
- These link a series of coupled biases in the Indian Ocean.




From Marathayil, Turner, Shaffrey & Levine (2013) *Environ. Res. Letts.*

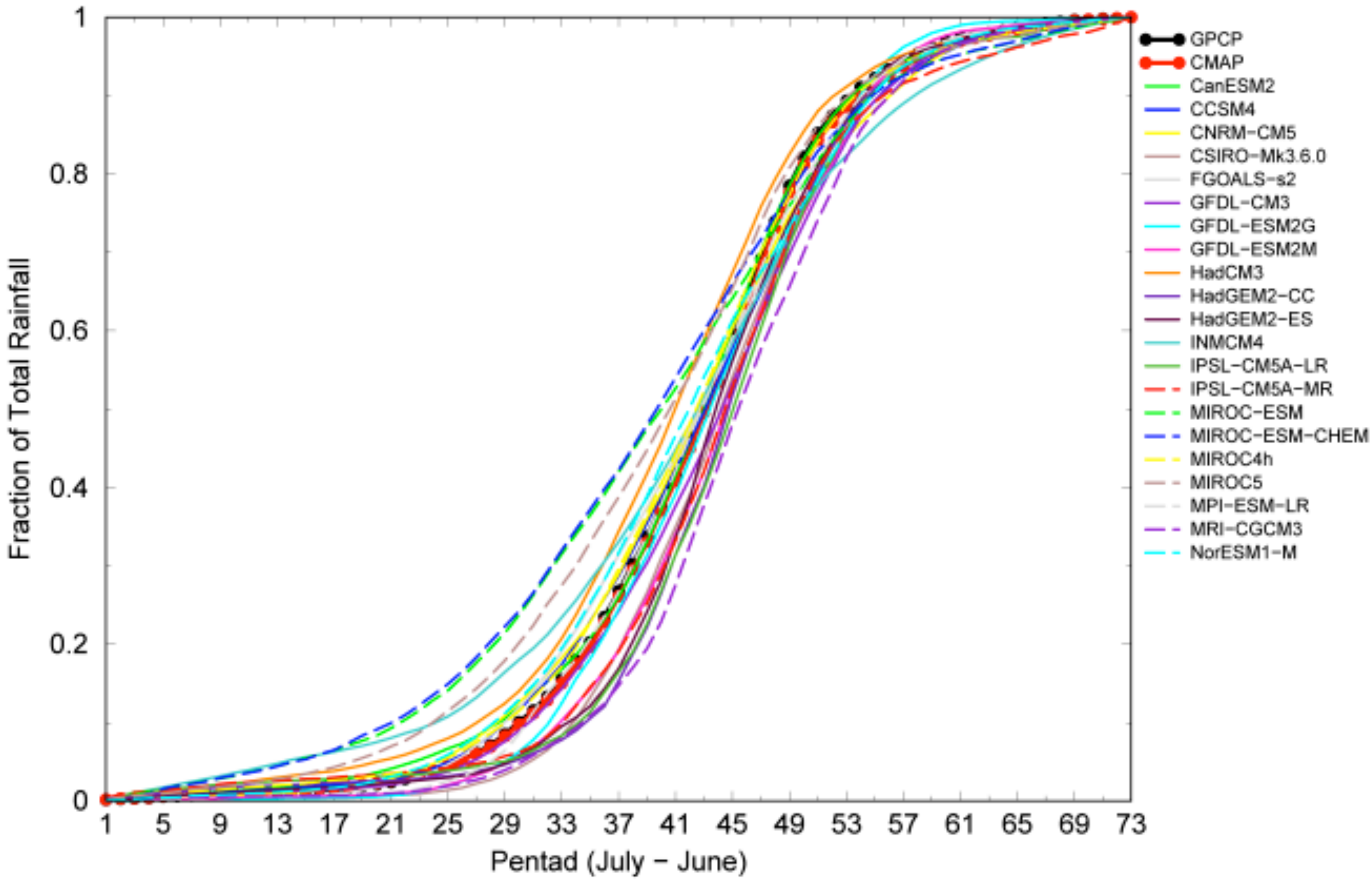
# AIR (fractional accumulation)




Sperber and Annamalai (2014) Climate Dynamics
Onset is further delayed in future projections (Sperber and Annamalai 2017)

Tropical precipitation annual cycle delay – SST amplitude and phase
(Tan et al. 2008; Biasutti and Sobel 2009; Biasutti 2013; Dwyler et al. 2014) ;

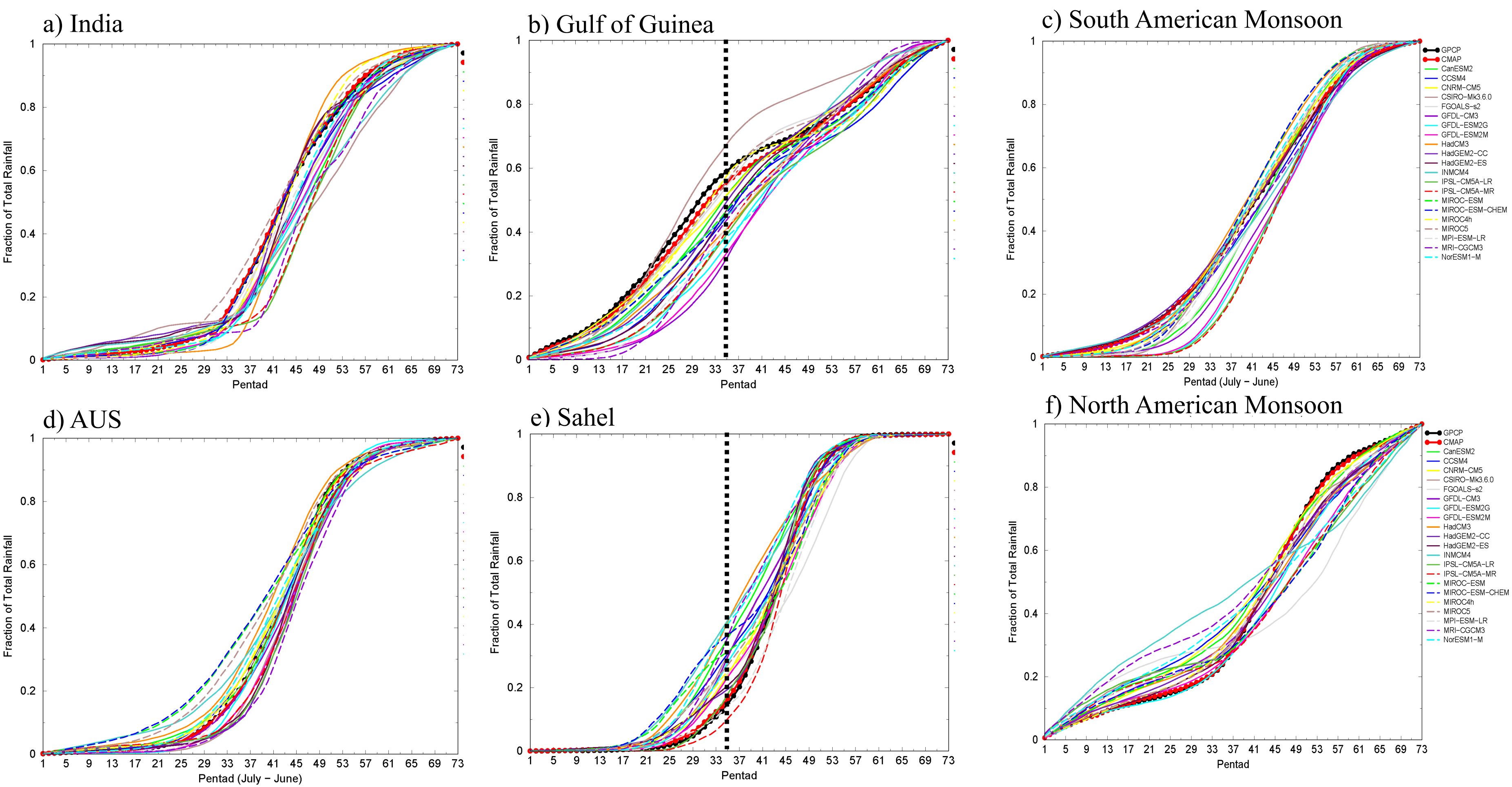
# Australia - fractional




Onset is systematically early over Australia (No models capture the Asia-Australian monsoon)

# Climatological rainfall: fractional accumulation (CMIP5: Various monsoon domains)

- India, Gulf of Guinea, SAM: most models **late annual cycle**
- Sahel and NAM: most models **early annual cycle**




Sperber and Annamalai (2014, Clim, Dyn)

Onset is further delayed in future projections (Sperber and Annamalai 2017)

SST amplitude and phase (Biasutti and Sobel 2009; Biasutti 2013; Dwyler et al. 2014)

# Sources of systematic errors of mean monsoon

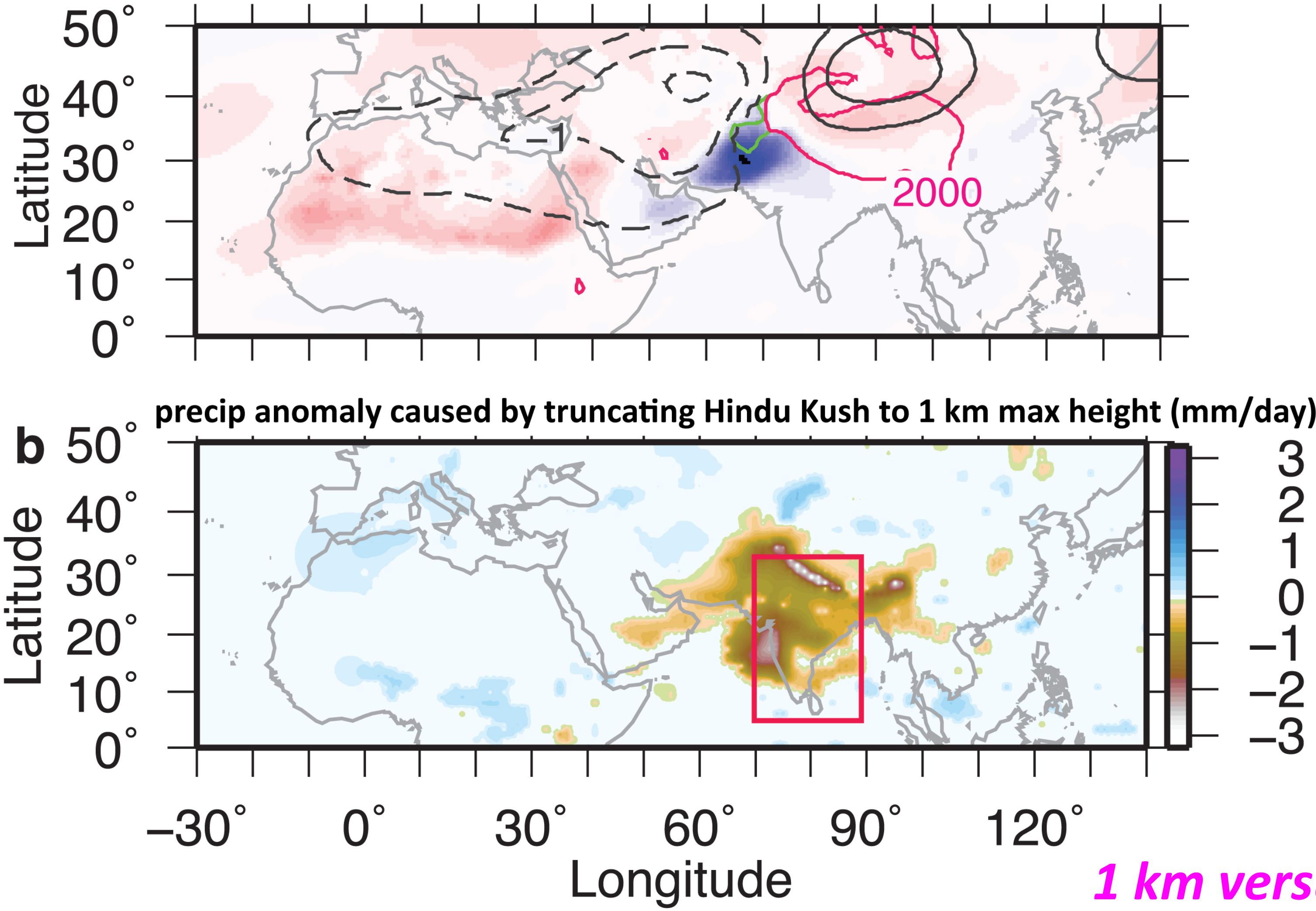
(i) Misrepresentation of **Orography** (advect low MSE air)

(ii) **Fast** atmospheric processes (convection)

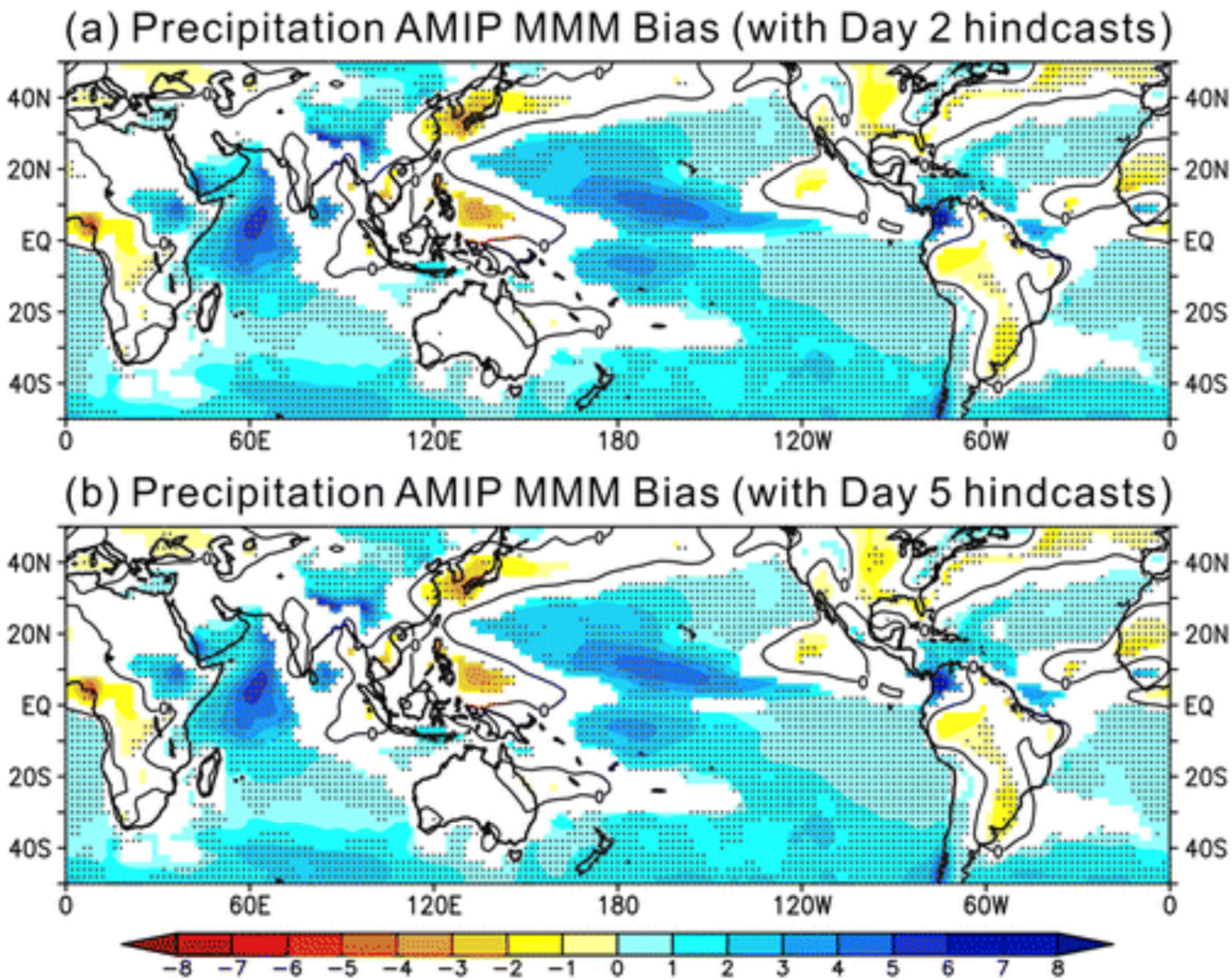
(iii) Fast **oceanic** processes (Wyrtki Jet along EIO)

# 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*



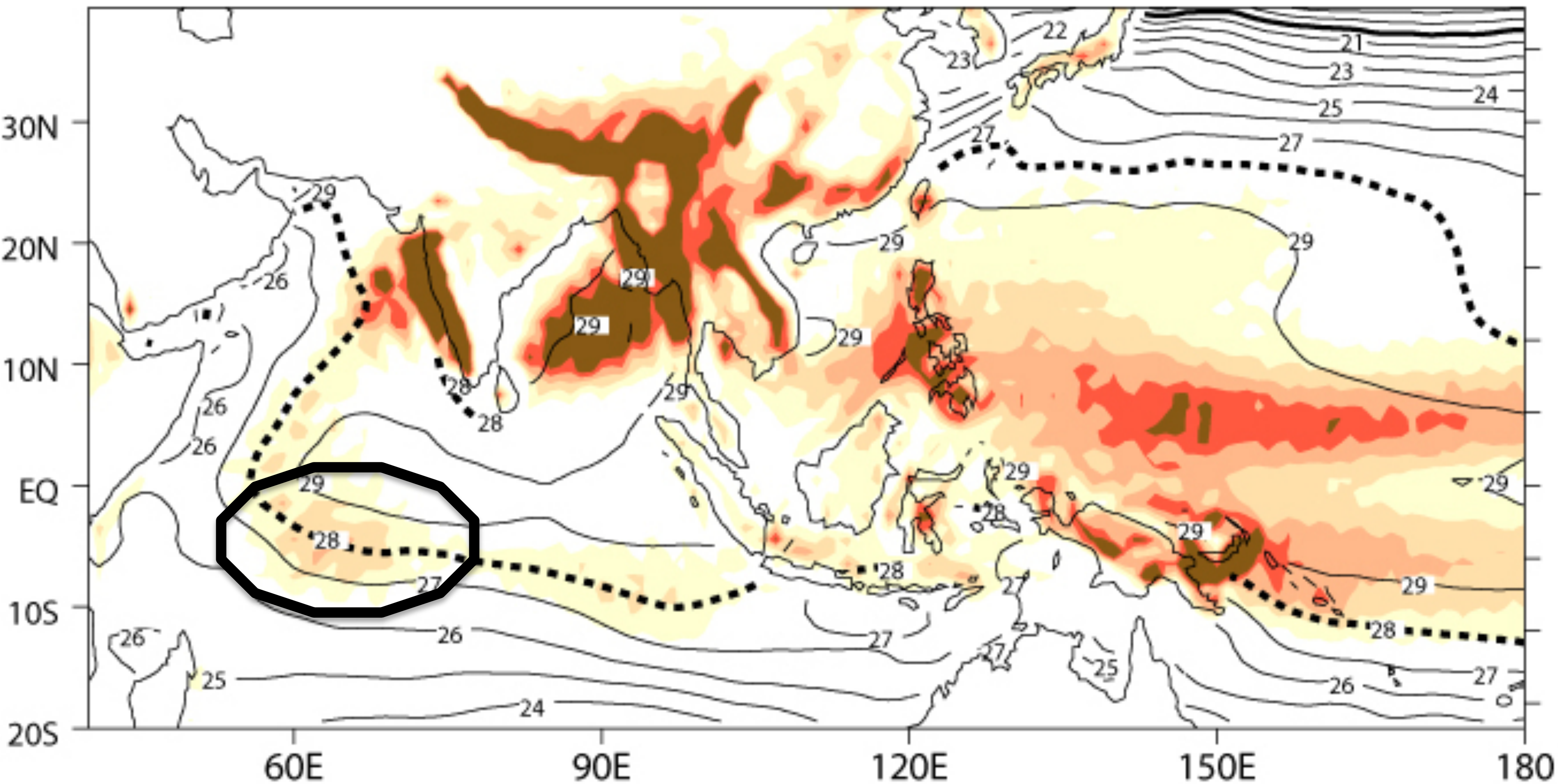

**Ma et al. 2014, JC**

**"no SST errors"**

Bush et al. 2015

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

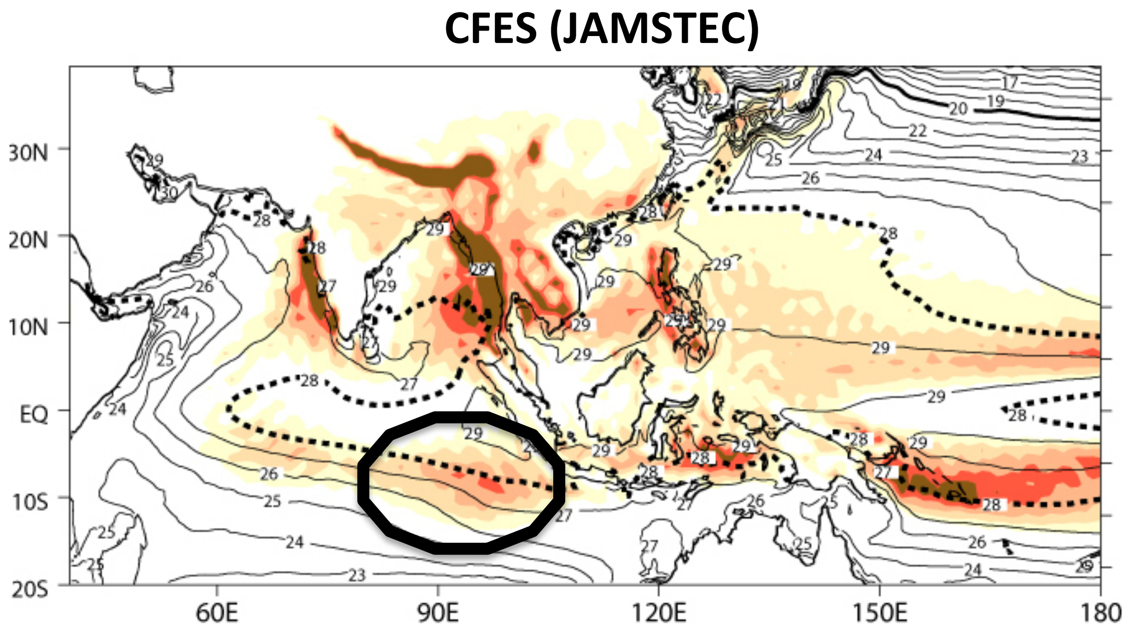
# JJAS Rainfall and SST Climatology – AFES (forced with TMI SST)



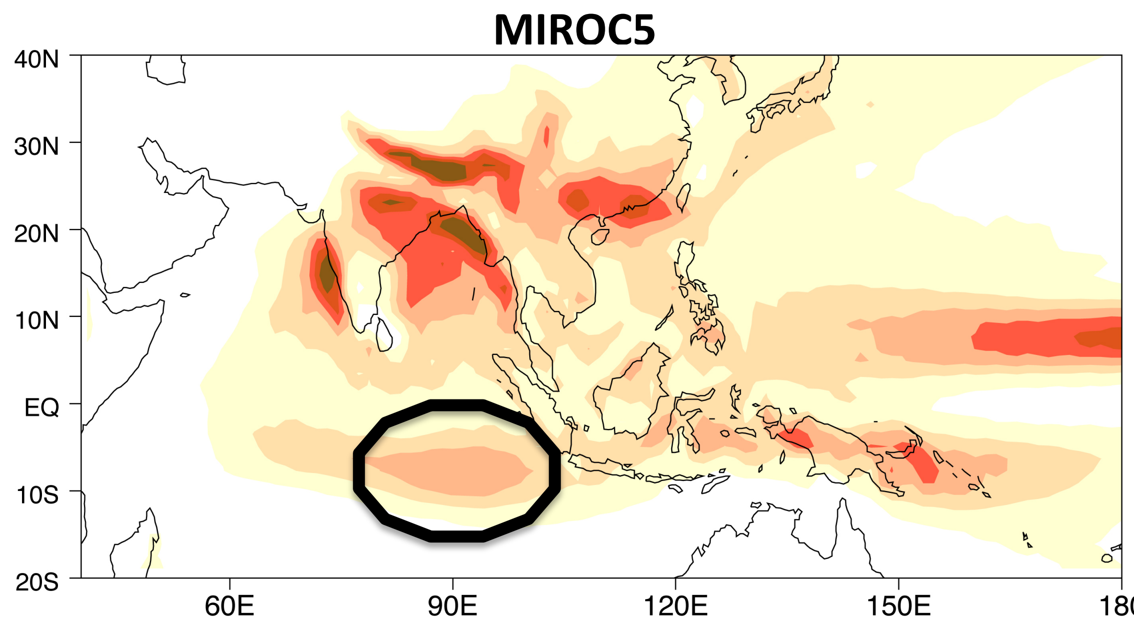

Too much rainfall over BoB – less rainfall over equatorial eastern Indian Ocean

Local rainfall maxima over equatorial western Indian Ocean

# JJAS Rainfall and SST Climatology



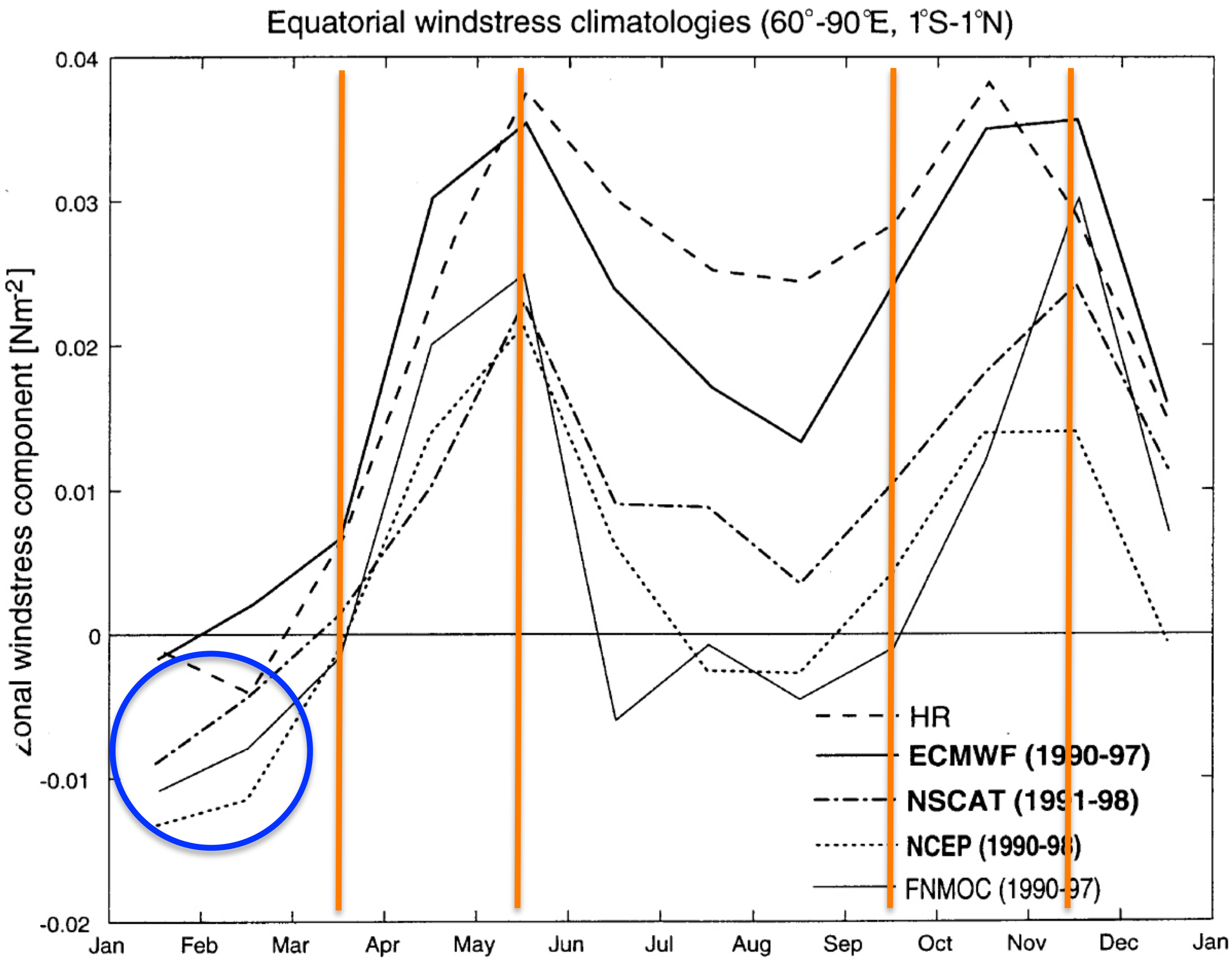

CFES – a laboratory tool




Rainfall maximum over BoB – realistic

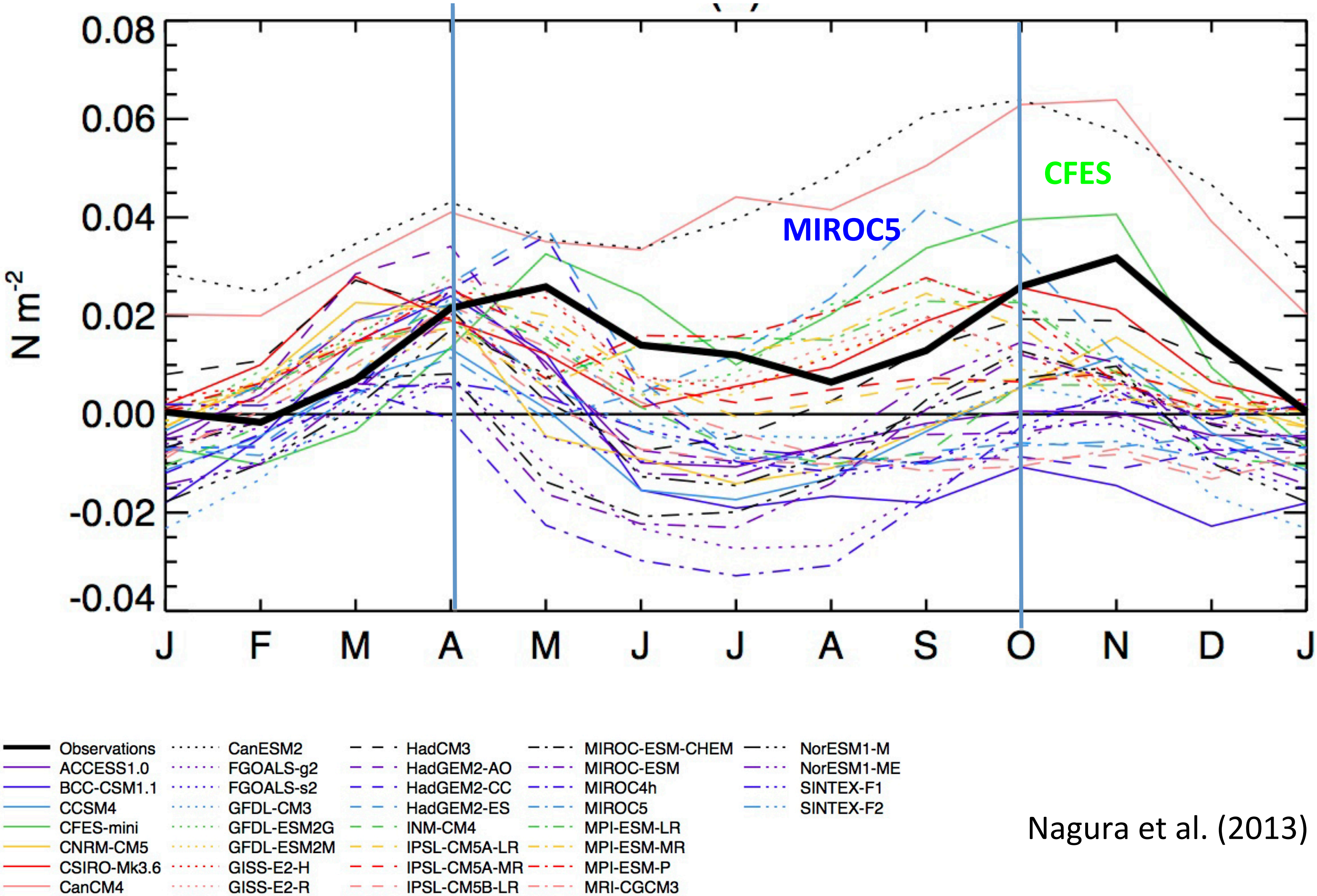
EEIO experiences local rainfall maxima

# Uniqueness of the Equatorial Indian Ocean




Schott and McCreary (2001)

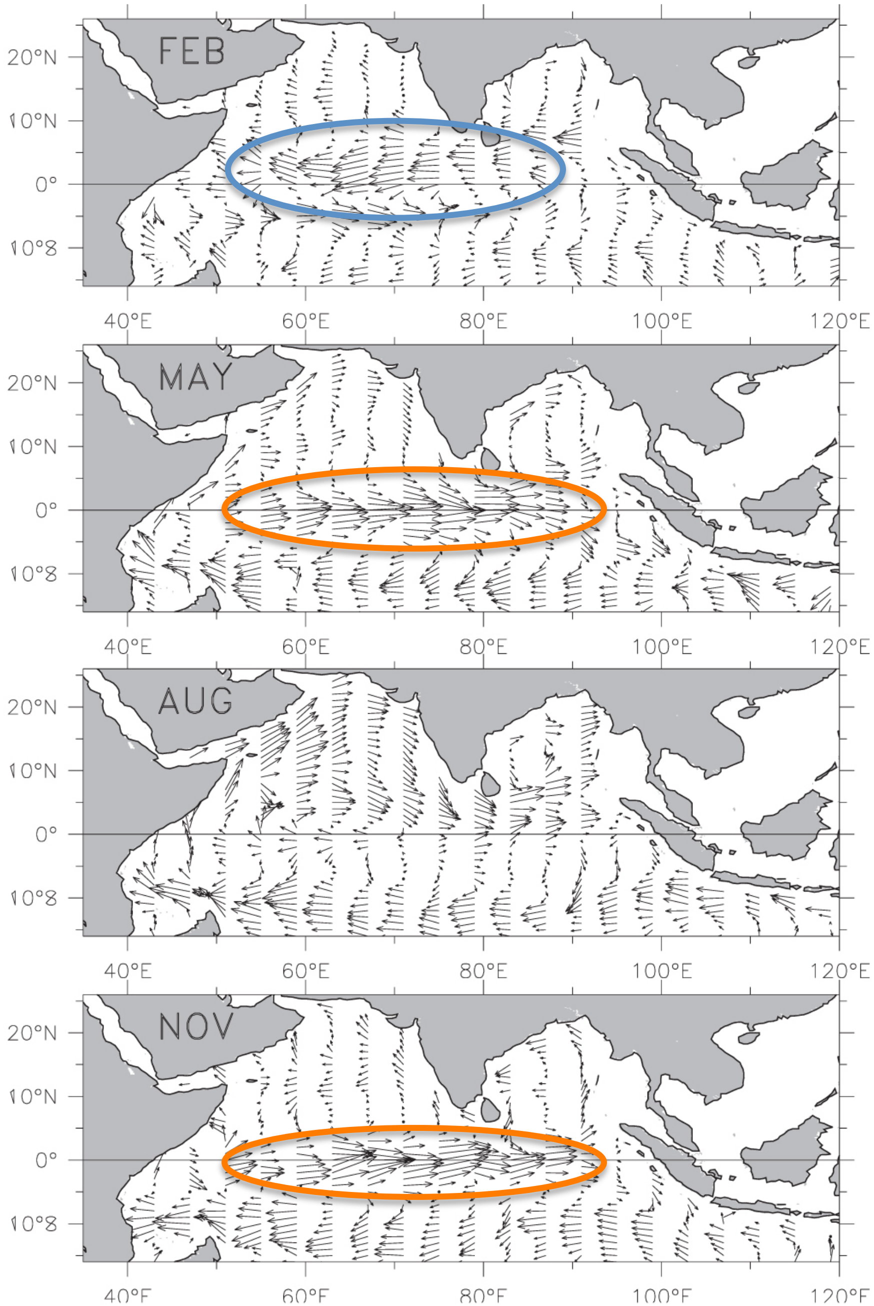
Equatorial Indian Ocean wind stress (CMIP5 models)




Nagura et al. (2013)

"errors in SST/precip –> wind stress errors"

# Surface currents




FEB

MAY

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

AUG

NOV

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

2. **Ocean response**

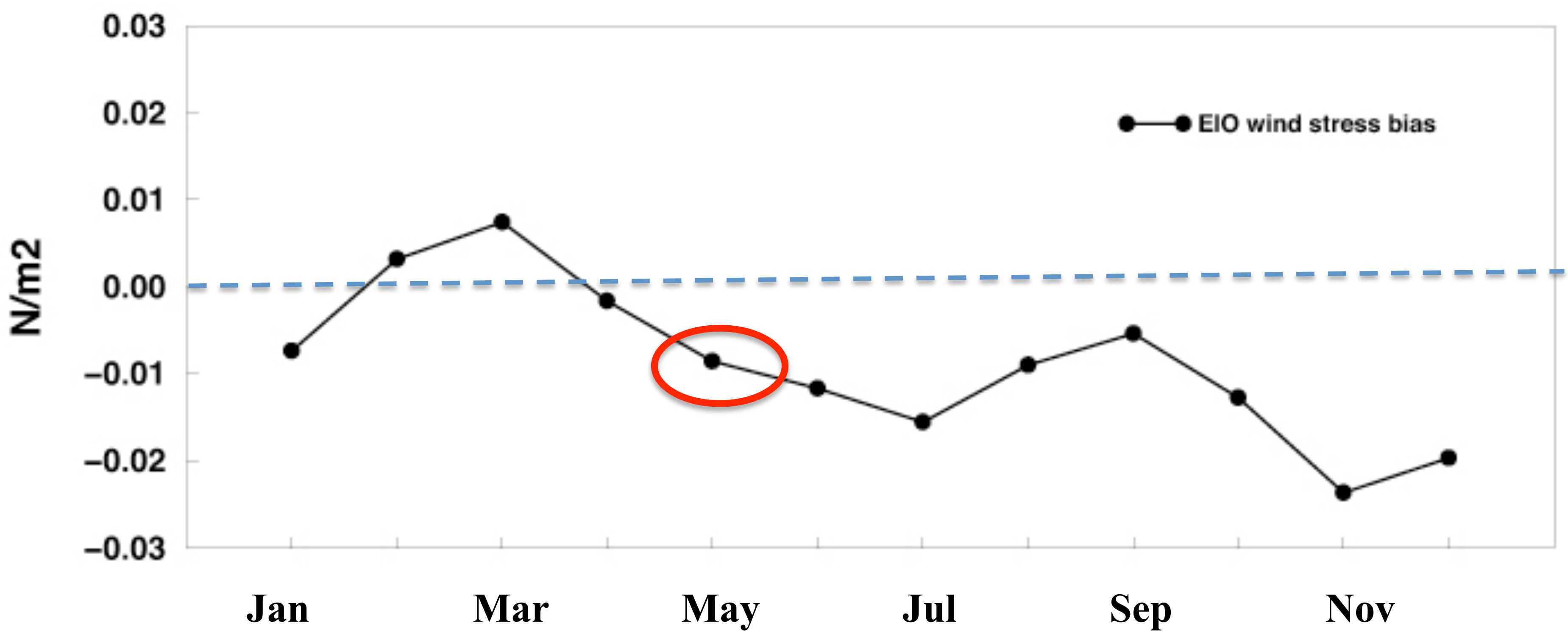
   (i) Equatorial, eastward flowing currents termed Wyrtki Jets (WJs)
   (ii) Force oceanic Kelvin and Rossby waves (impact on thermocline)

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"

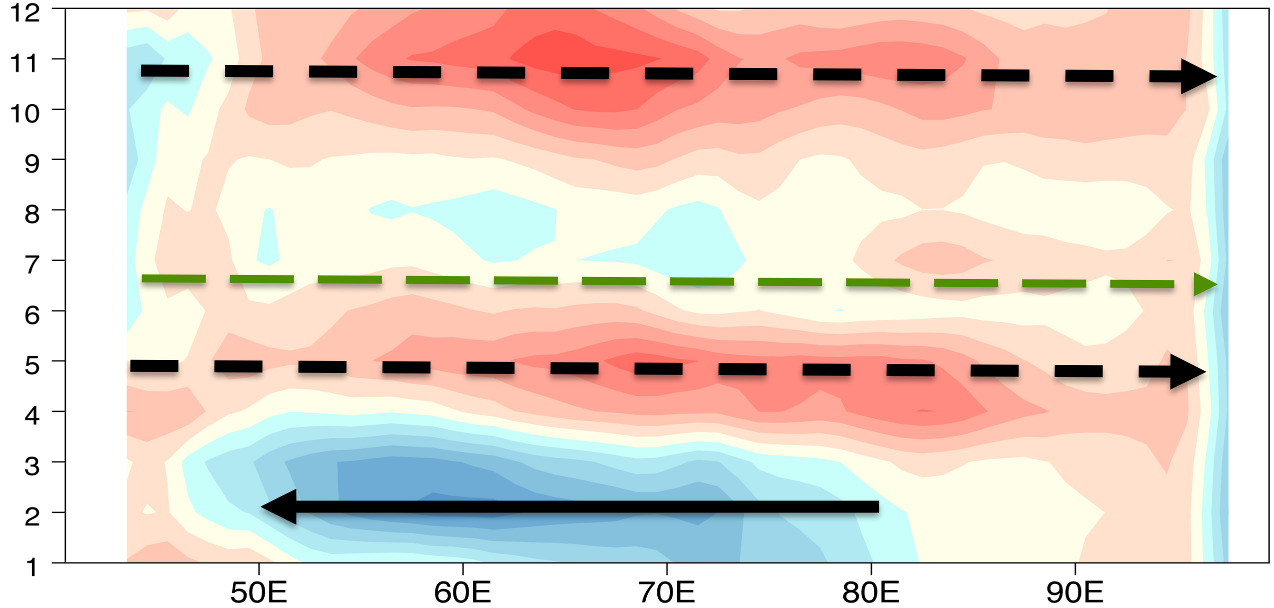
Δτ CMIP5 MMM *minus* ERA_INT

(3ºS-3ºN; 40º-100ºE)



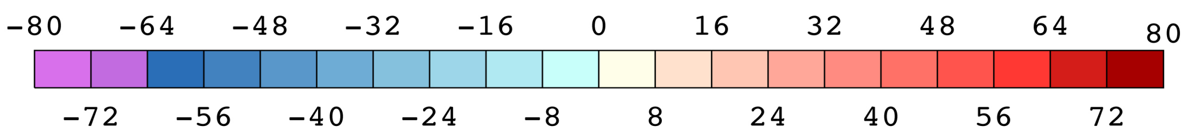

Compared to climatology: In May 40-45% weaker and in November 70% weaker

Δτ a measure of Bjerkens' feedback in the Equatorial Indian Ocean




**3°S-3°N – surface currents**

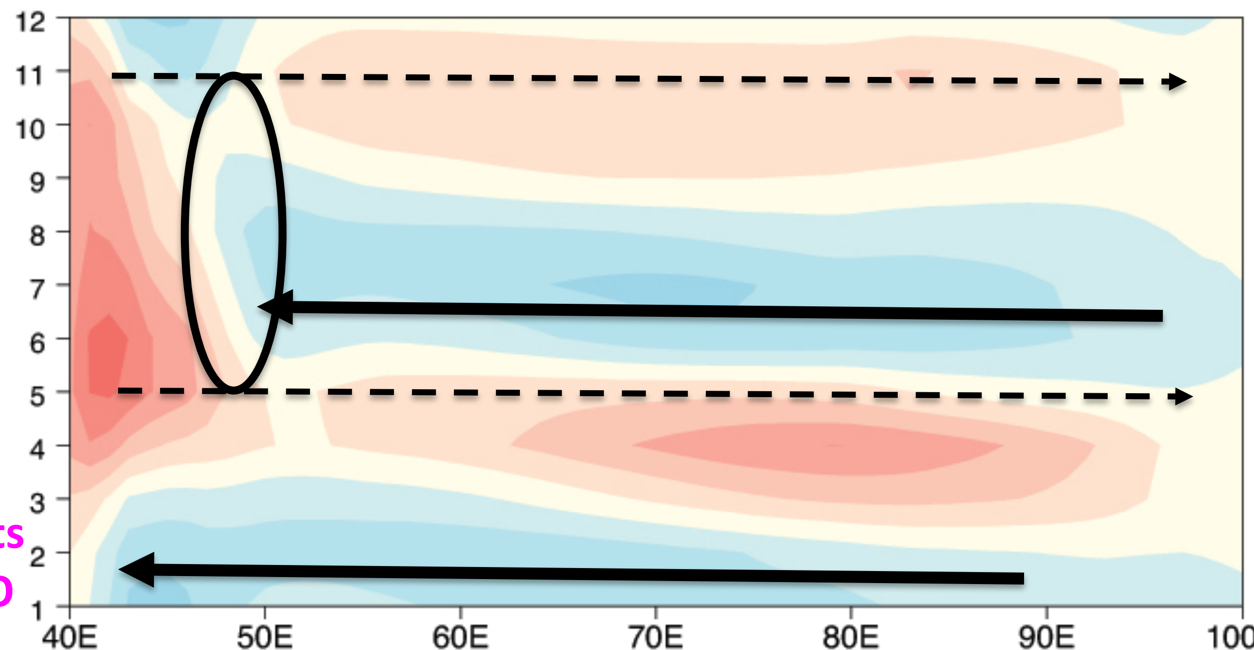
**Observations**




***(cm/s)***

**3°S-3°N – surface currents**

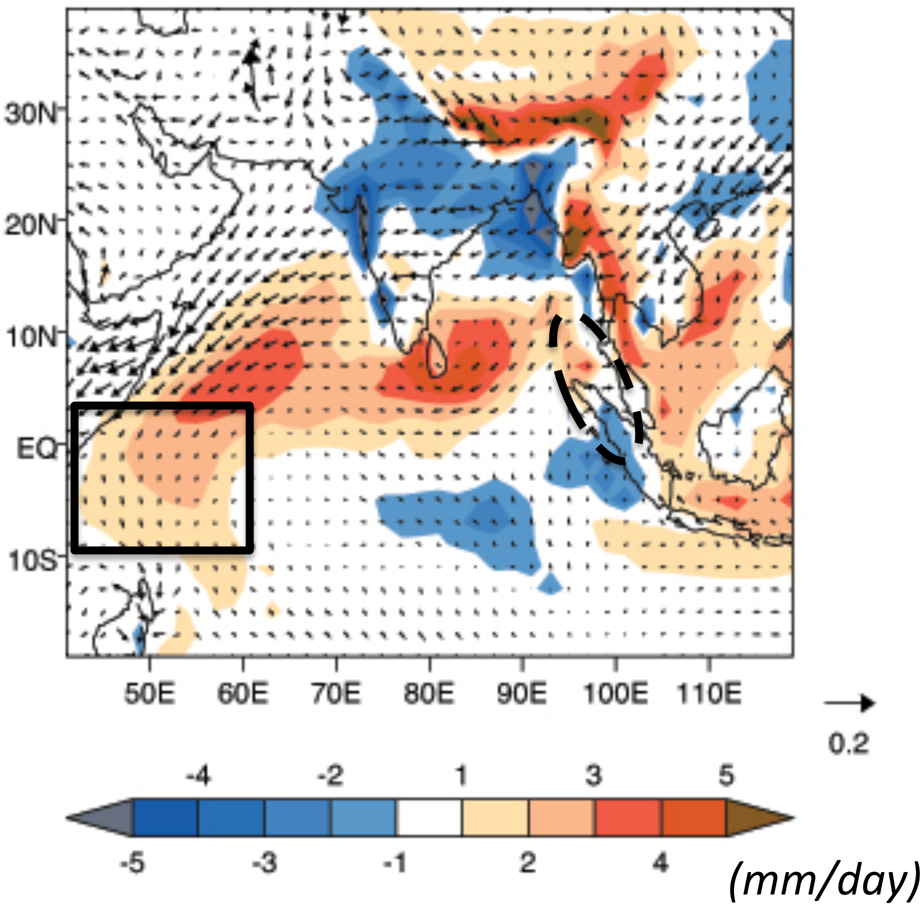
**CMIP5 MMM**



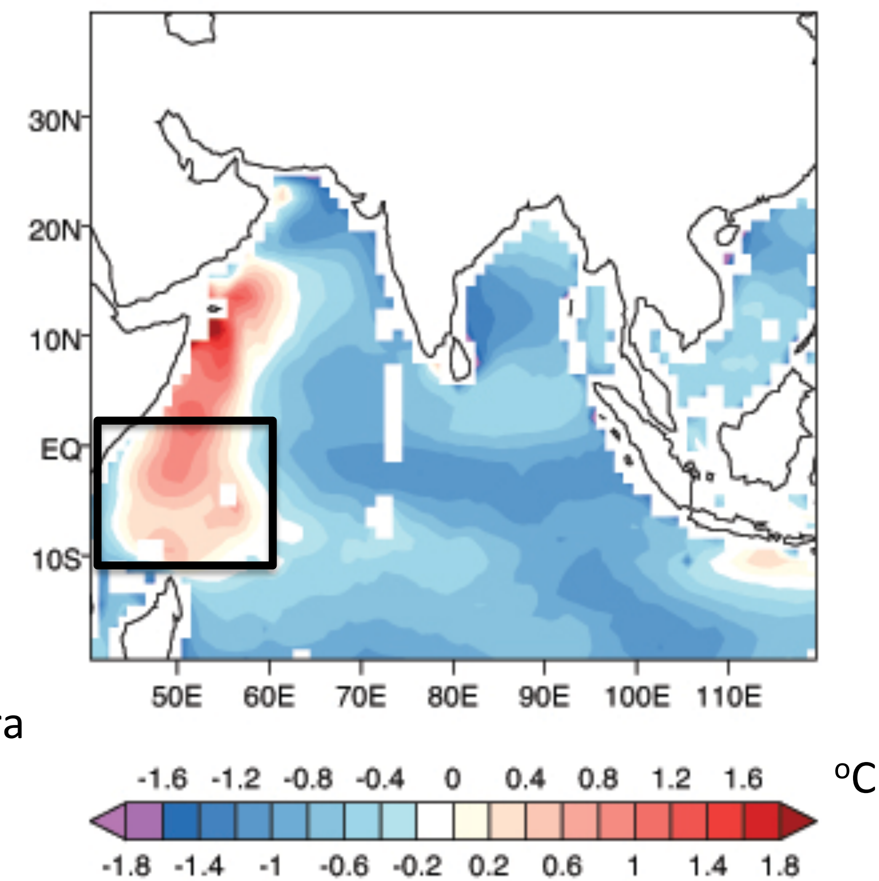

1. **Weak eastward WJs**
2. **Unrealistic westward currents**
3. **Pile-up of warm waters WEIO**

# (CMIP5 MMM) bias JJAS

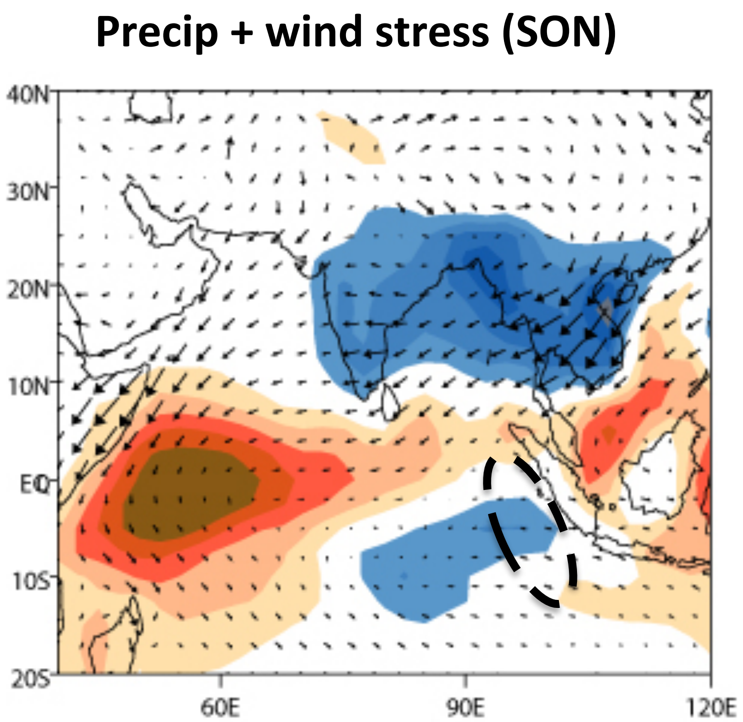
## Precipitation / wind stress

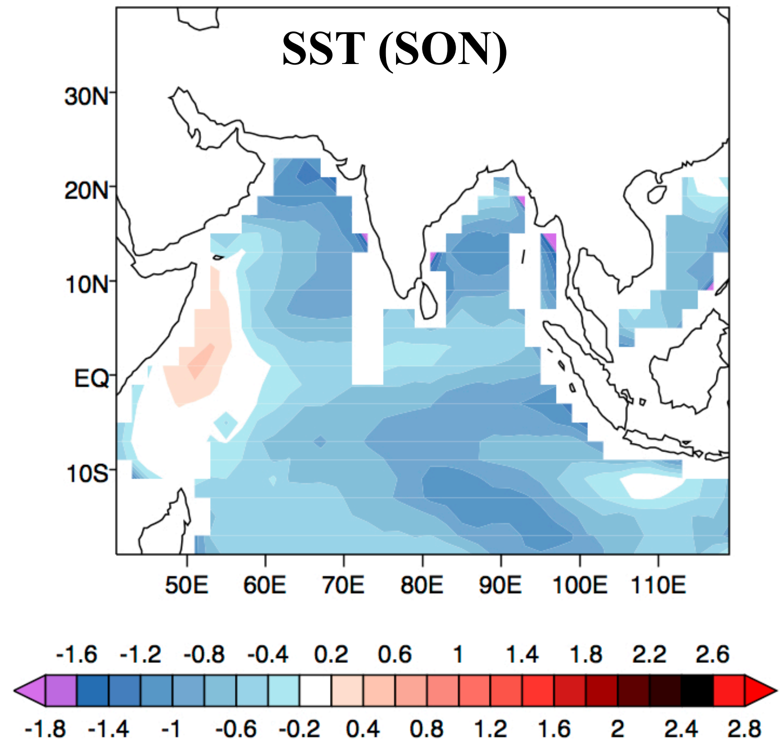


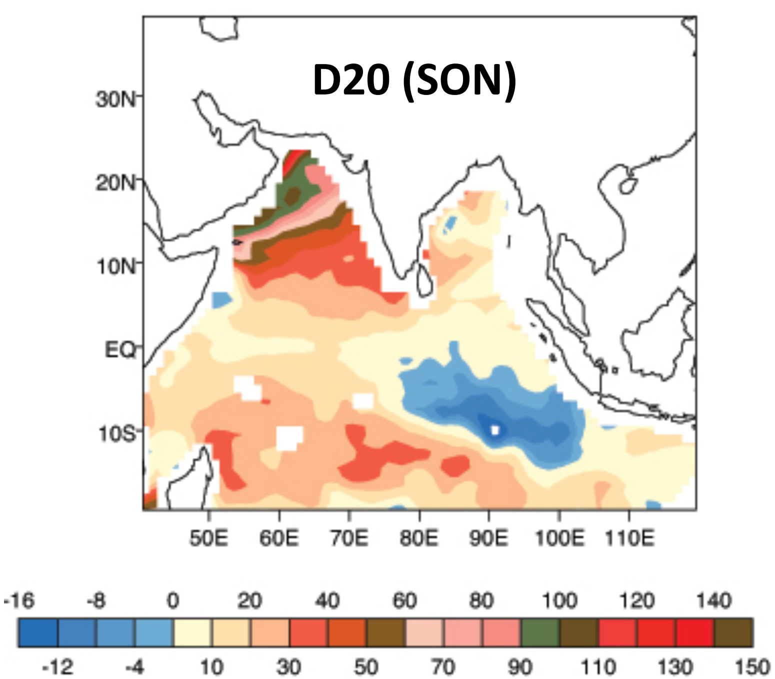

## SST




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



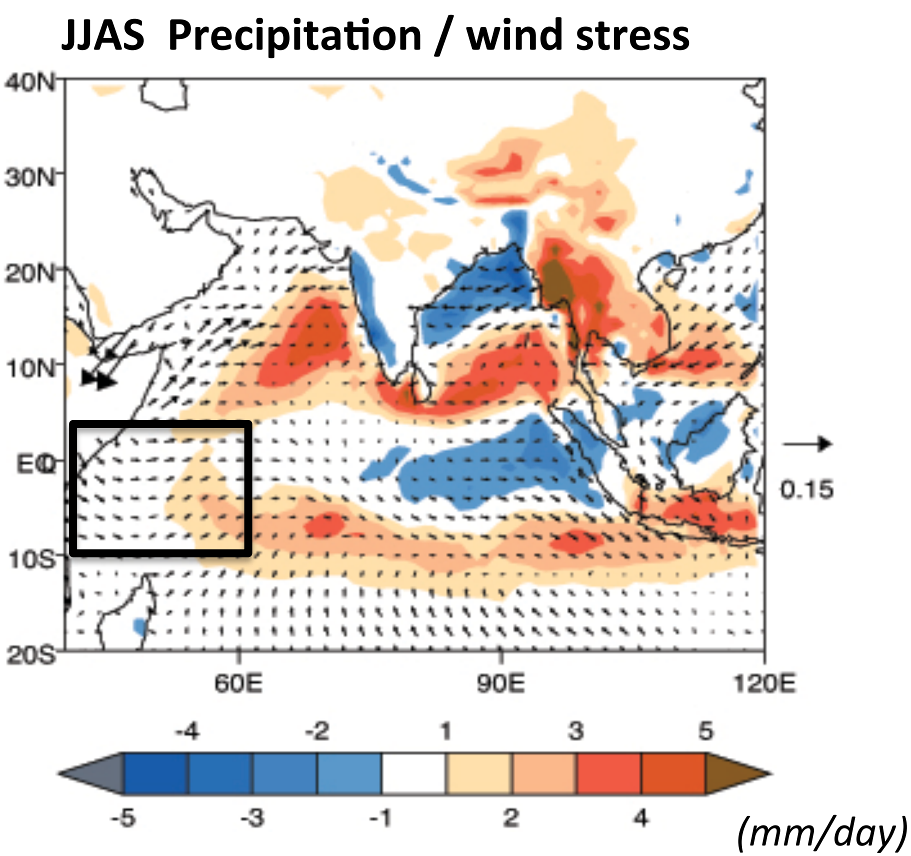



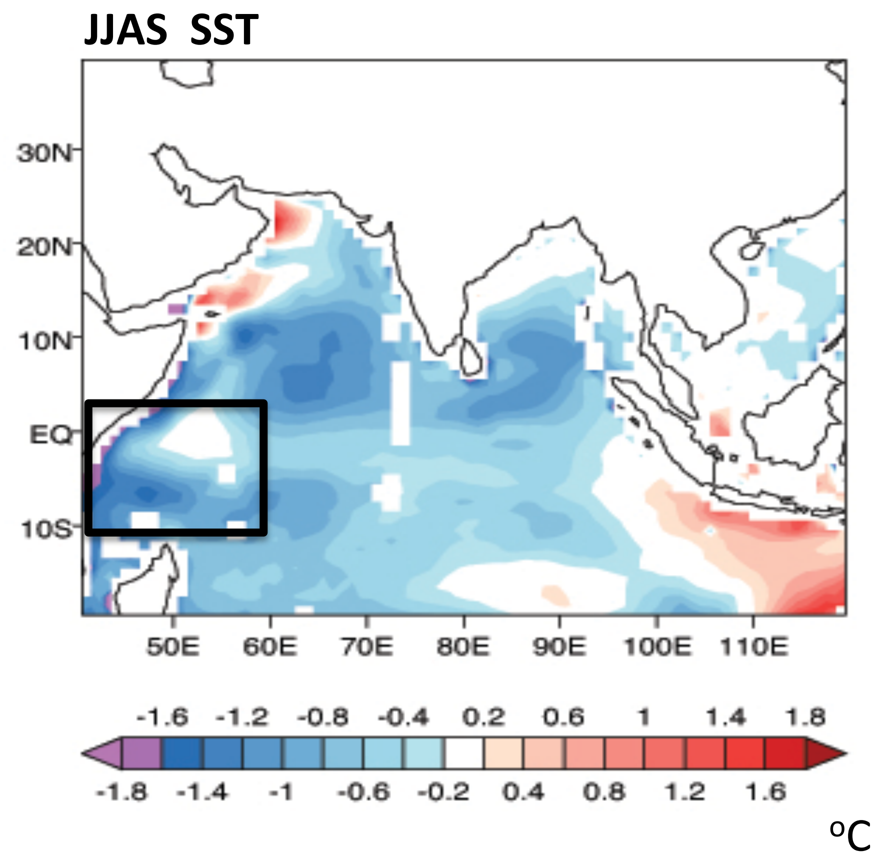




- Lack of upwelling-favorable winds off Sumatra
  - perhaps due to lack of organized –ve precip anom
- SST gradient exists along EIO
- Precip anomalies intensify over western EIO – force atmospheric Kelvin wave – easterly bias
- Thermocline deeper everywhere except EEIO (Jay's talk tomorrow)
- BJ feedback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

# Idealized experiments with Coupled model for Earth Simulator (CFES)

# Biases in CFES (Coupled model for Earth Simulator)



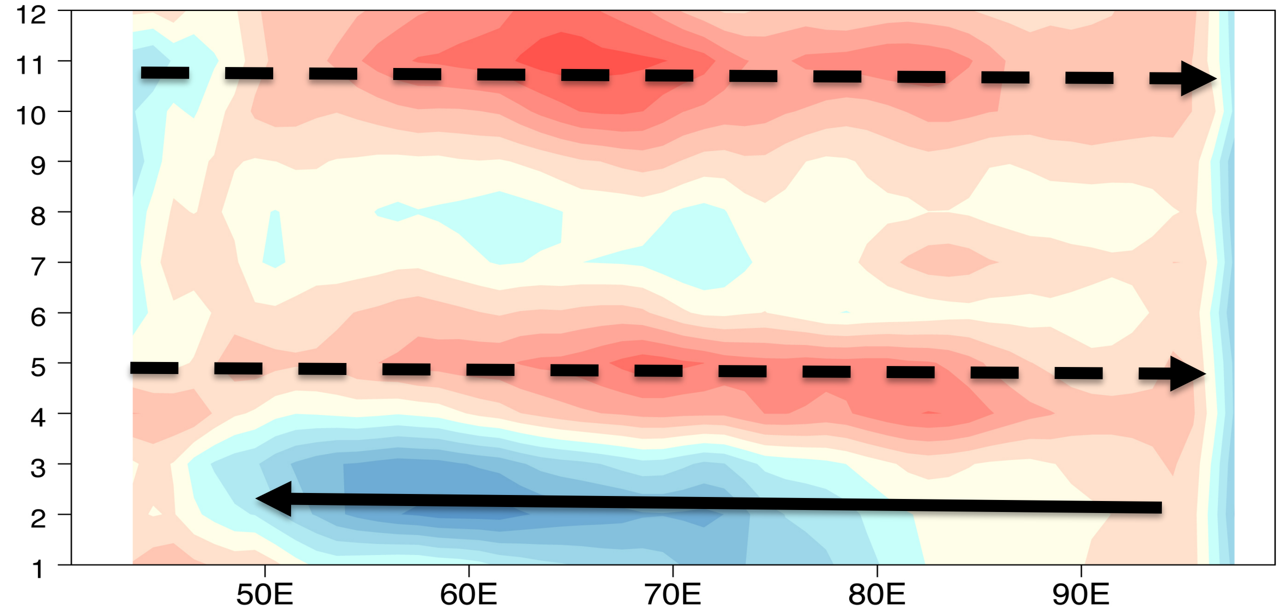

Model biases exist – magnitudes are less compared to CMIP5 errors -

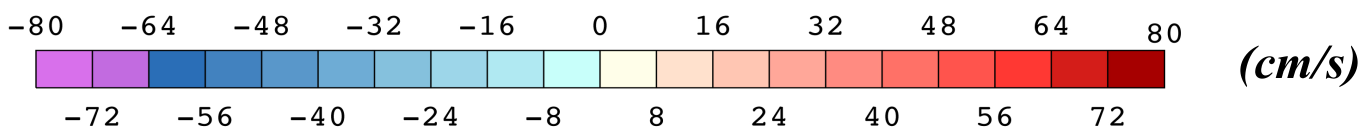
Precip and SST biases over western EIO are NOT collocated as in CMIP5 models

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

**3°S-3°N – surface currents**

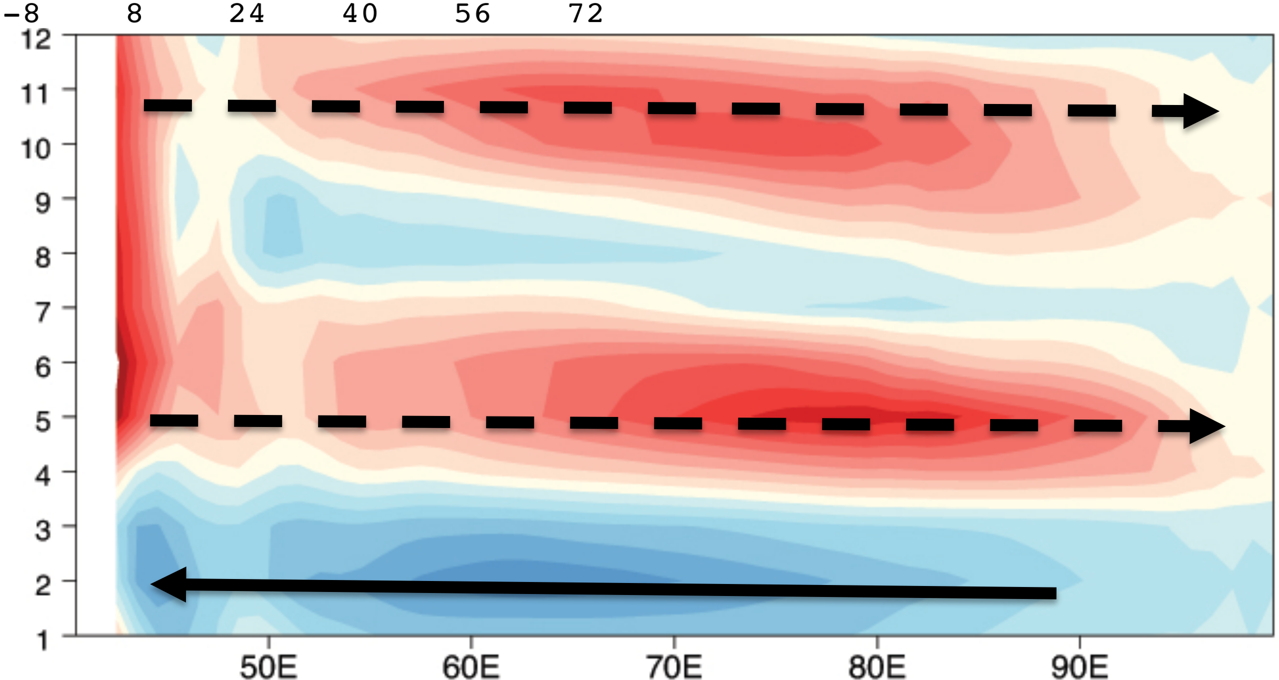
**Observations**



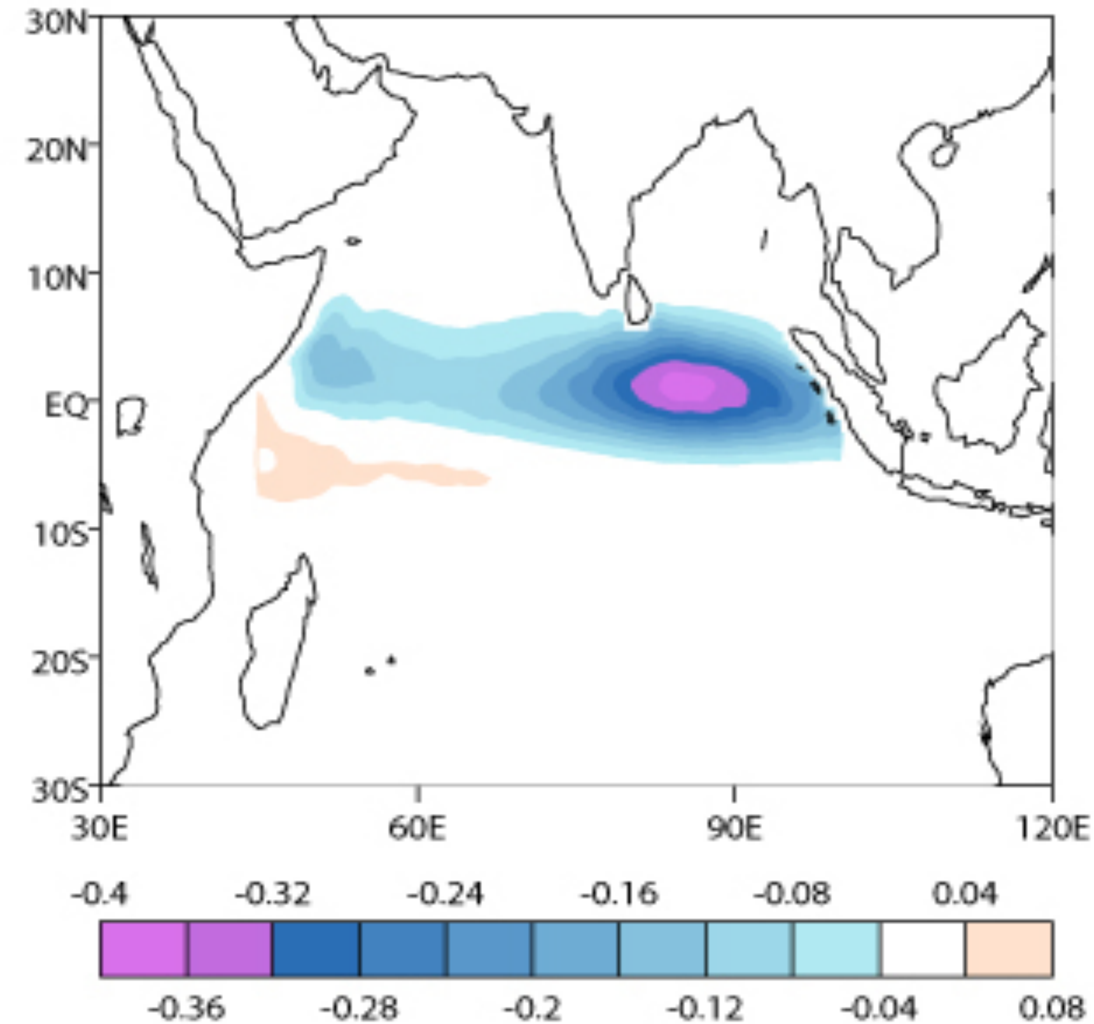




**3°S-3°N – surface currents**

**CFES**



# $T_{aux}$ anomaly - imposed




dyn/cm$^2$

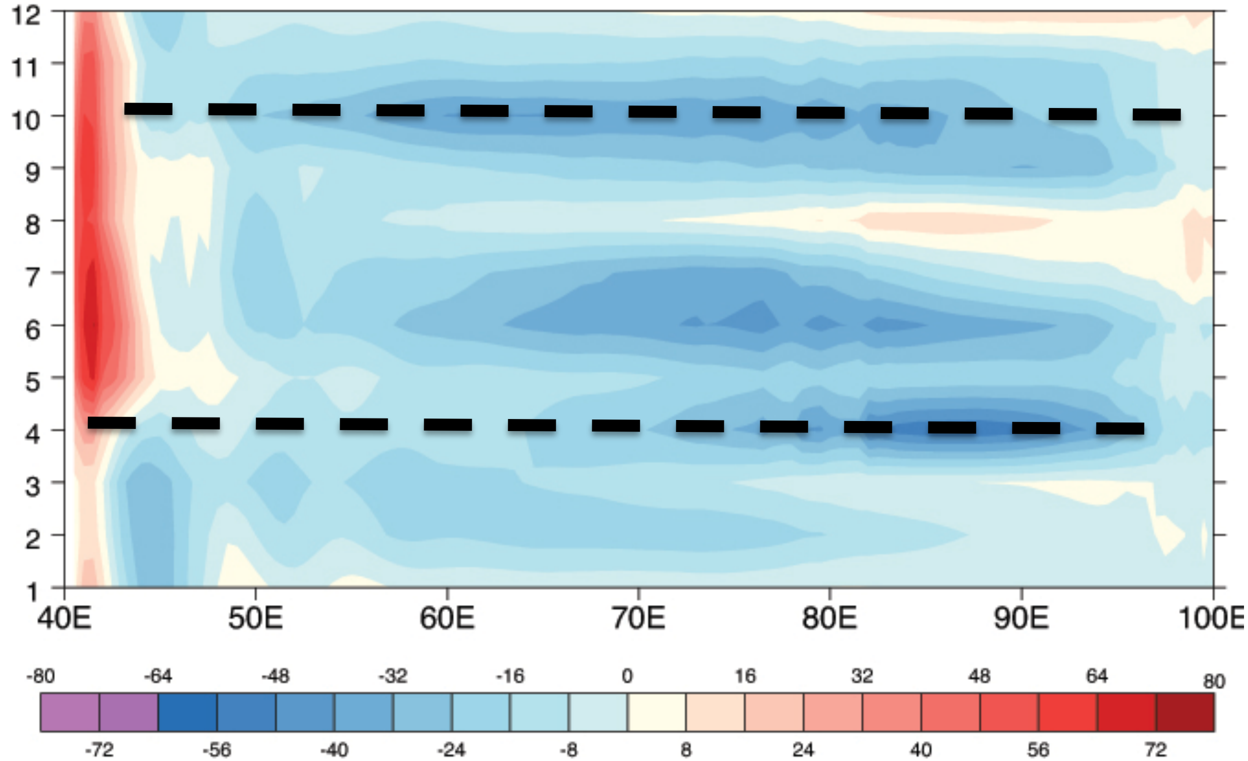
1. Imposed throughout A/C
2. Imposed during spring and fall only

Could have perturbed ….

Precip or SST or Thermocline

# EXP2 SPRING_FALL Δτ

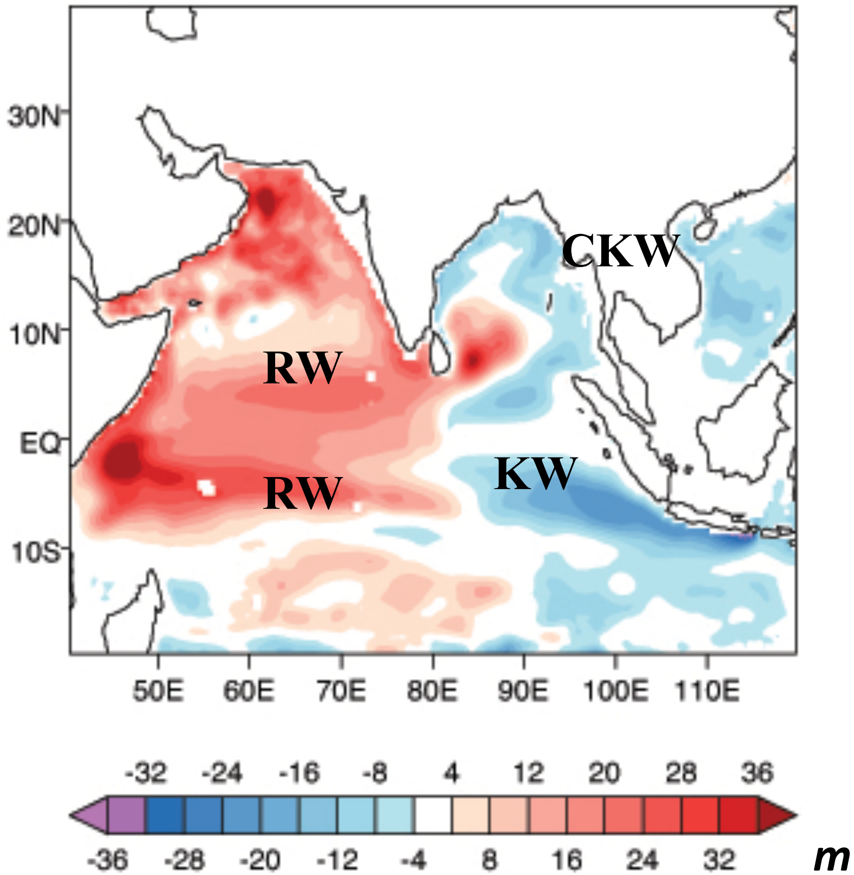
## 3ºS-3ºN – surface currents



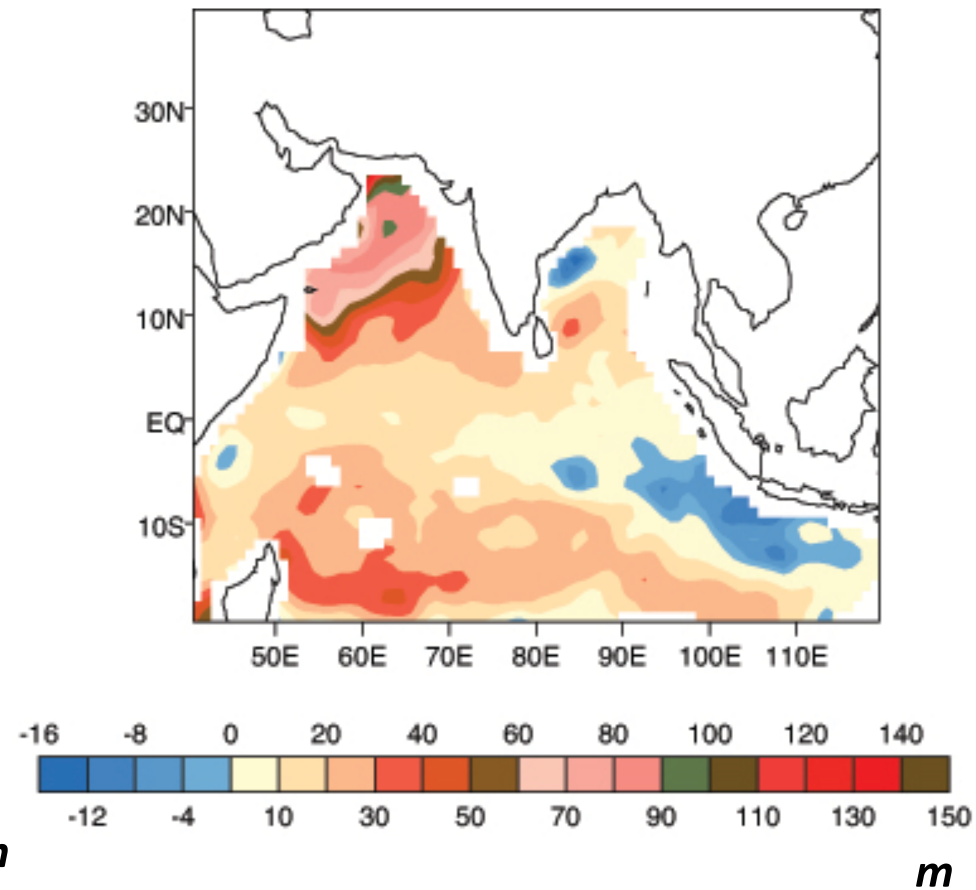

*(cm/s)*

# EXP2 *minus* CTL

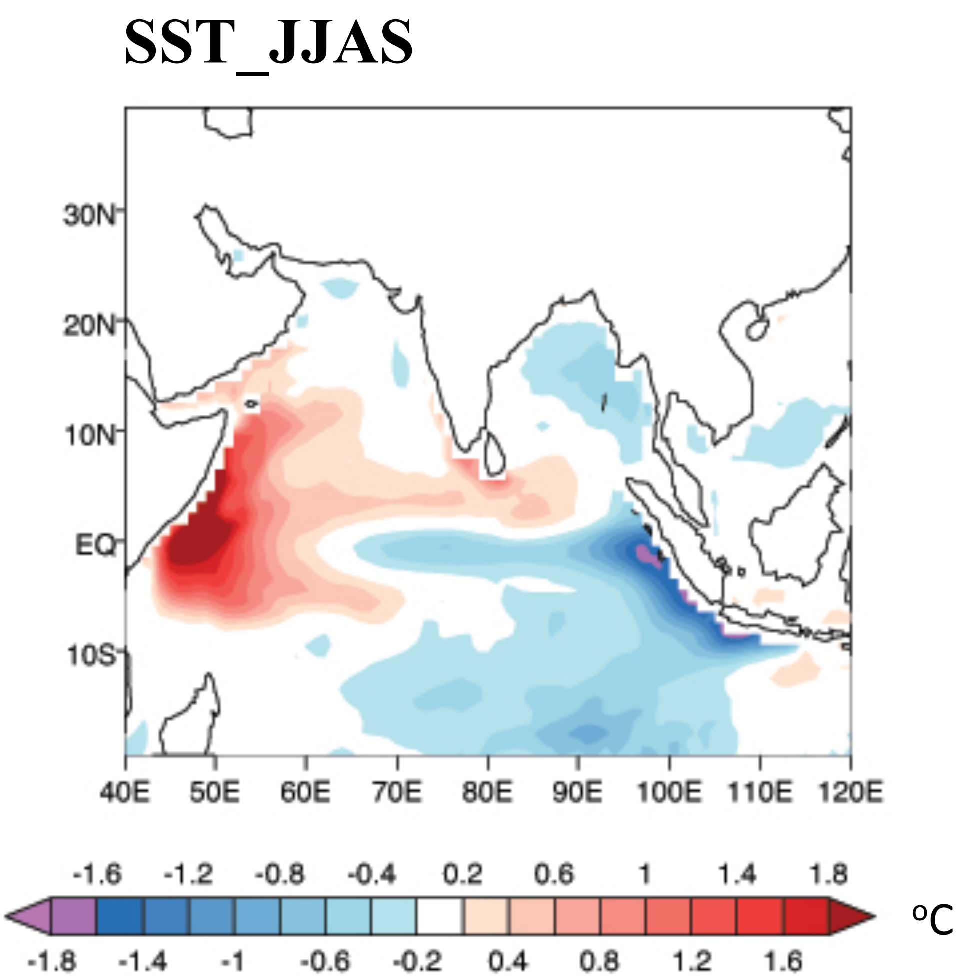
## D20_JJAS

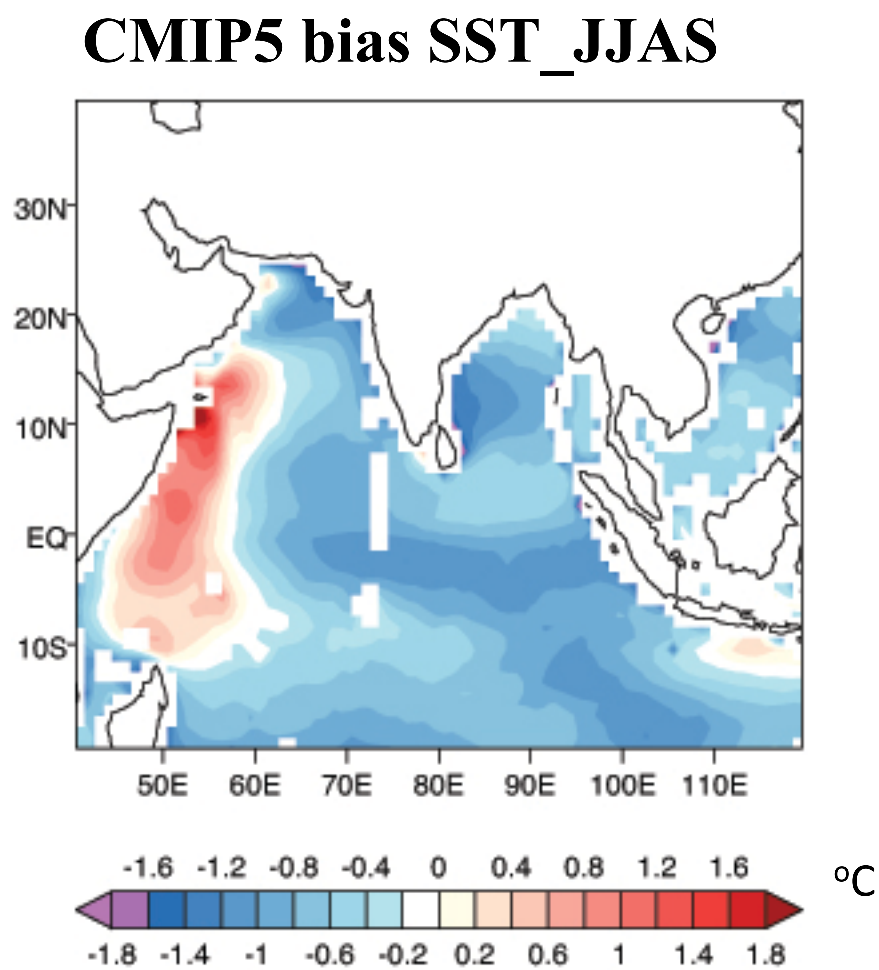



## CMIP5 bias D20_JJAS



# EXP2 *minus* CTL

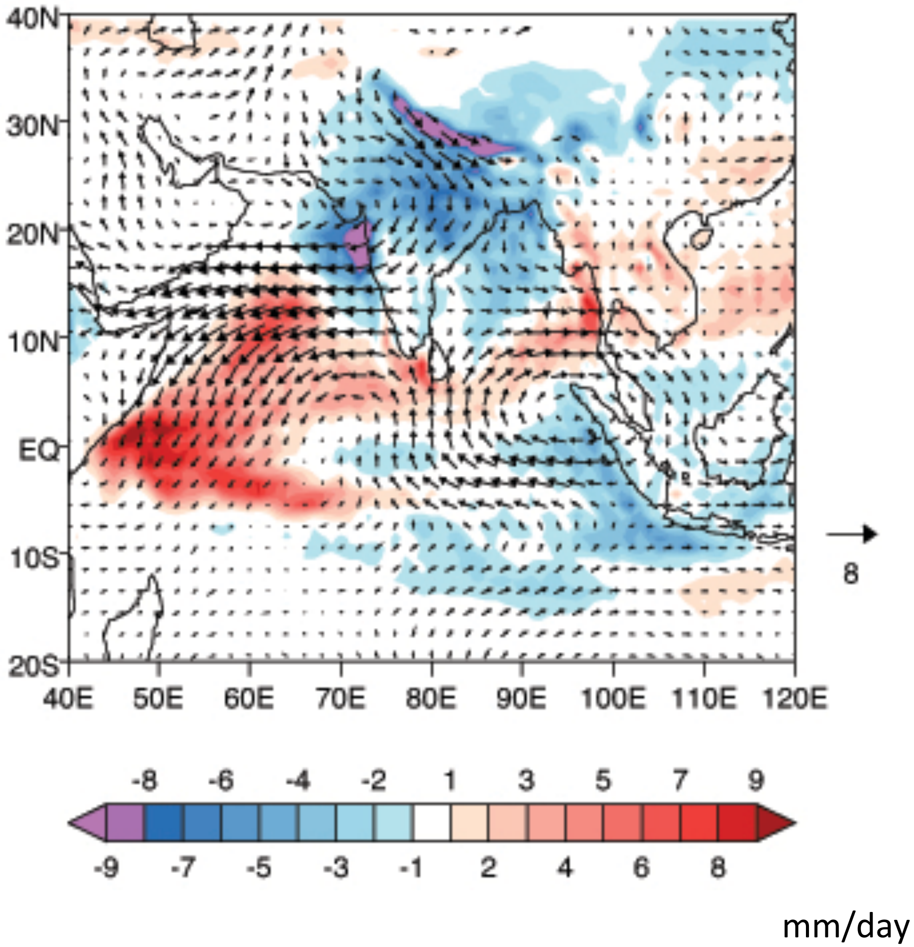


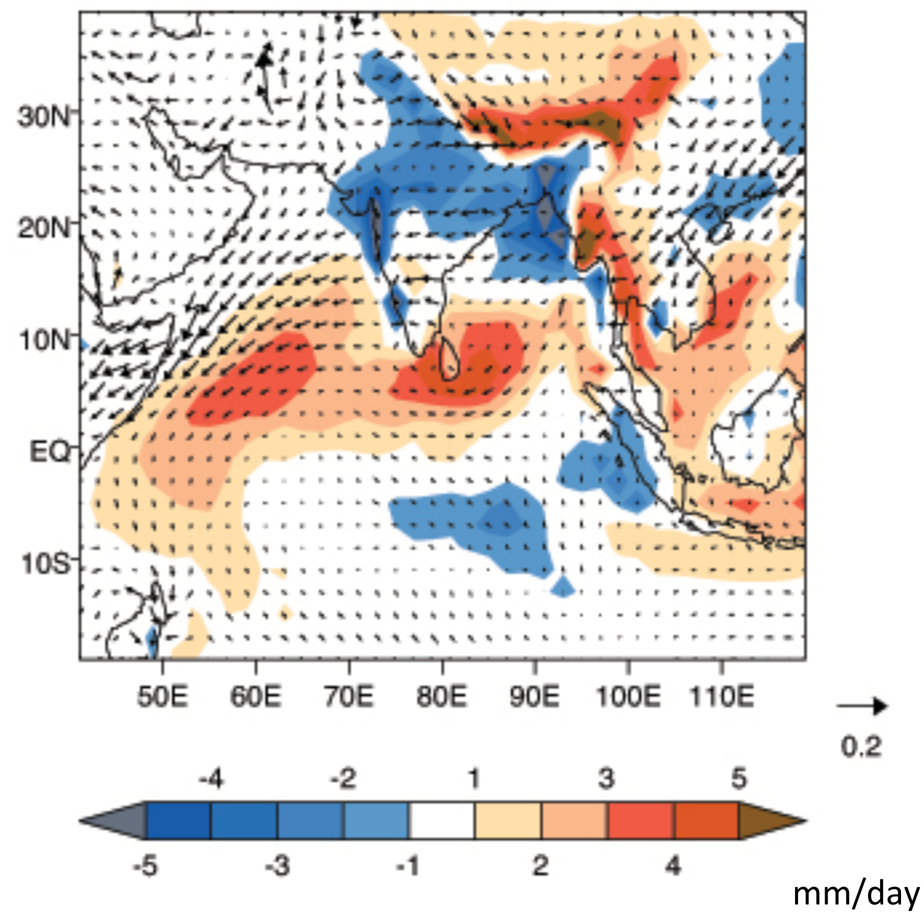

Cold SST bias over northern BoB – induced by coastal Kelvin wave (D20)
Could have contributed to monsoon weakening – later in the season (examining now)

# EXP2 *minus* CTL

**Precip / wind 850hPa**




**CMIP5 bias – Precip / wind stress**

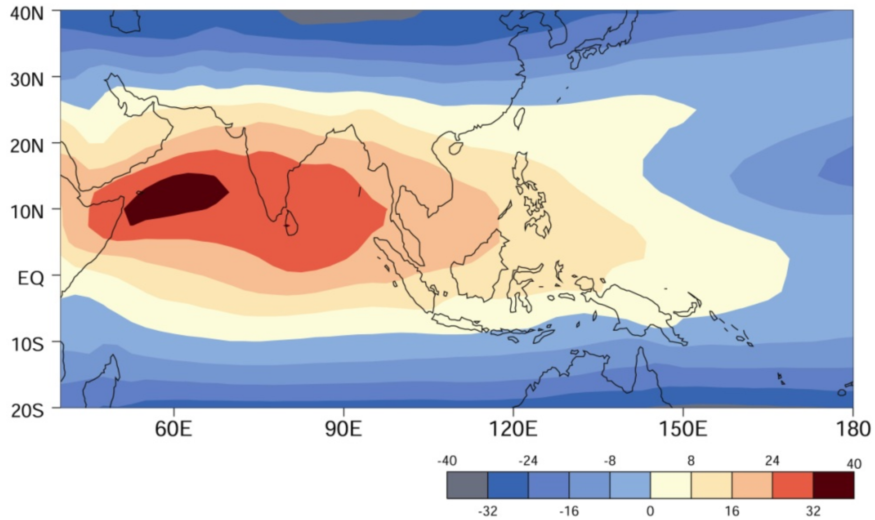


# Summary for Case I

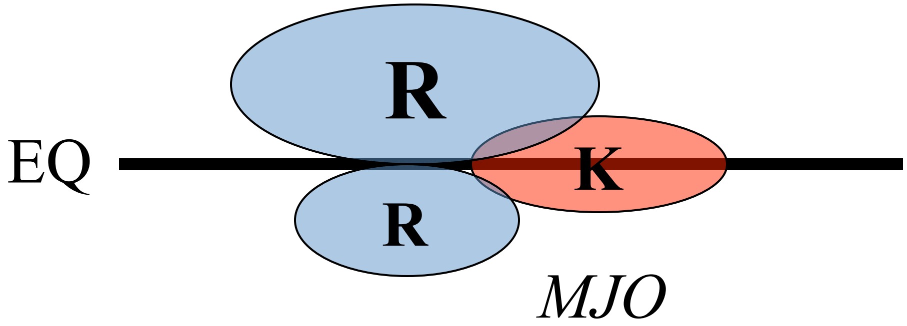
**Misrepresentation of EIO coupled processes could lead systematic errors in the simulation of mean monsoon precipitation climatology**

# Mean Monsoon and Intraseasonal Variability

Zonal Vertical Shear




Lau and Peng (1990)
Wang and Xie (1997)
Annamalai and Sperber (2005)

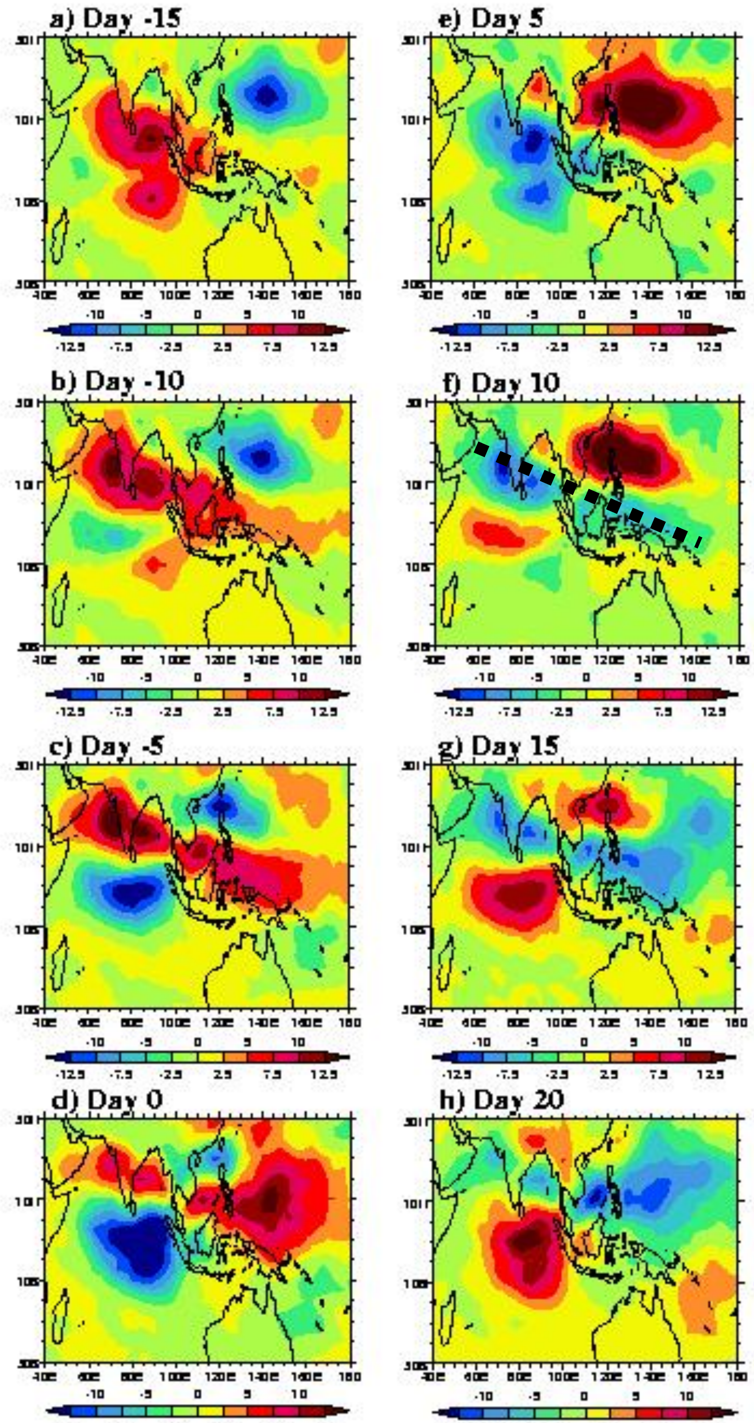


**Initiation**

# CsEOF

Annamalai and Sperber (2005)

**Amplification**



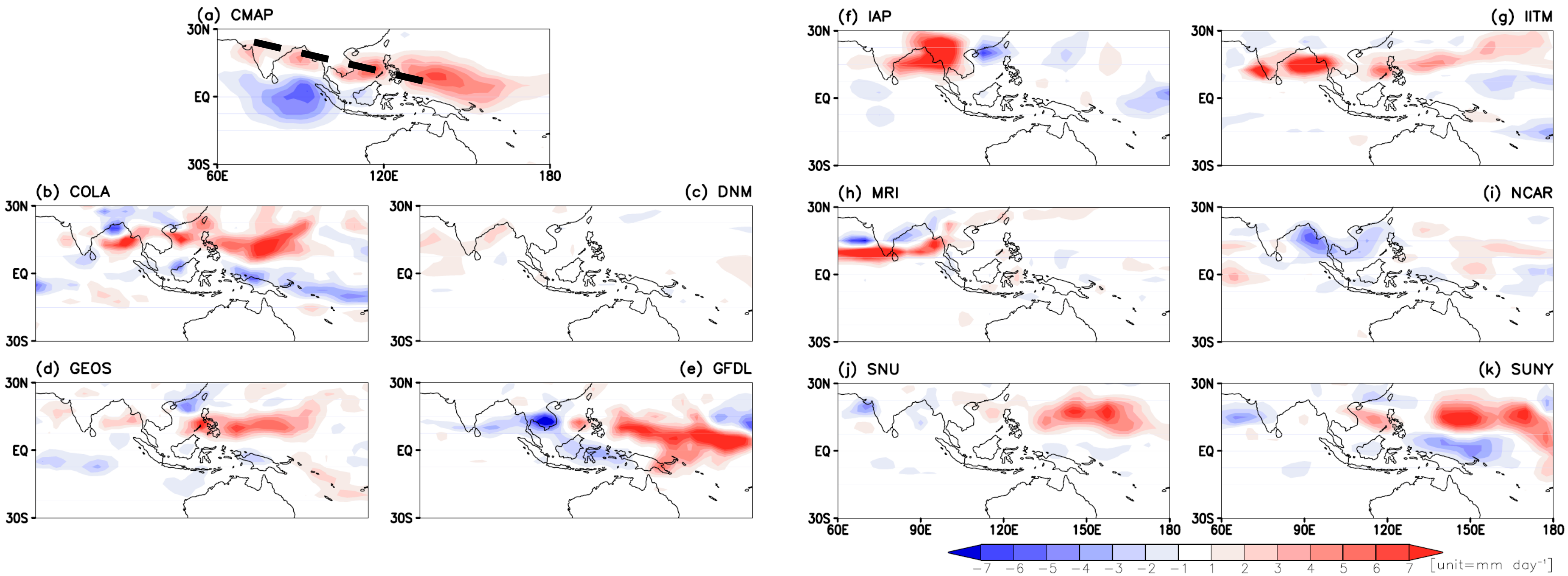

**Poleward - India**

**Eastward – W. Pacific**

**Quadra-pole**

**Poleward – W. Pacific**

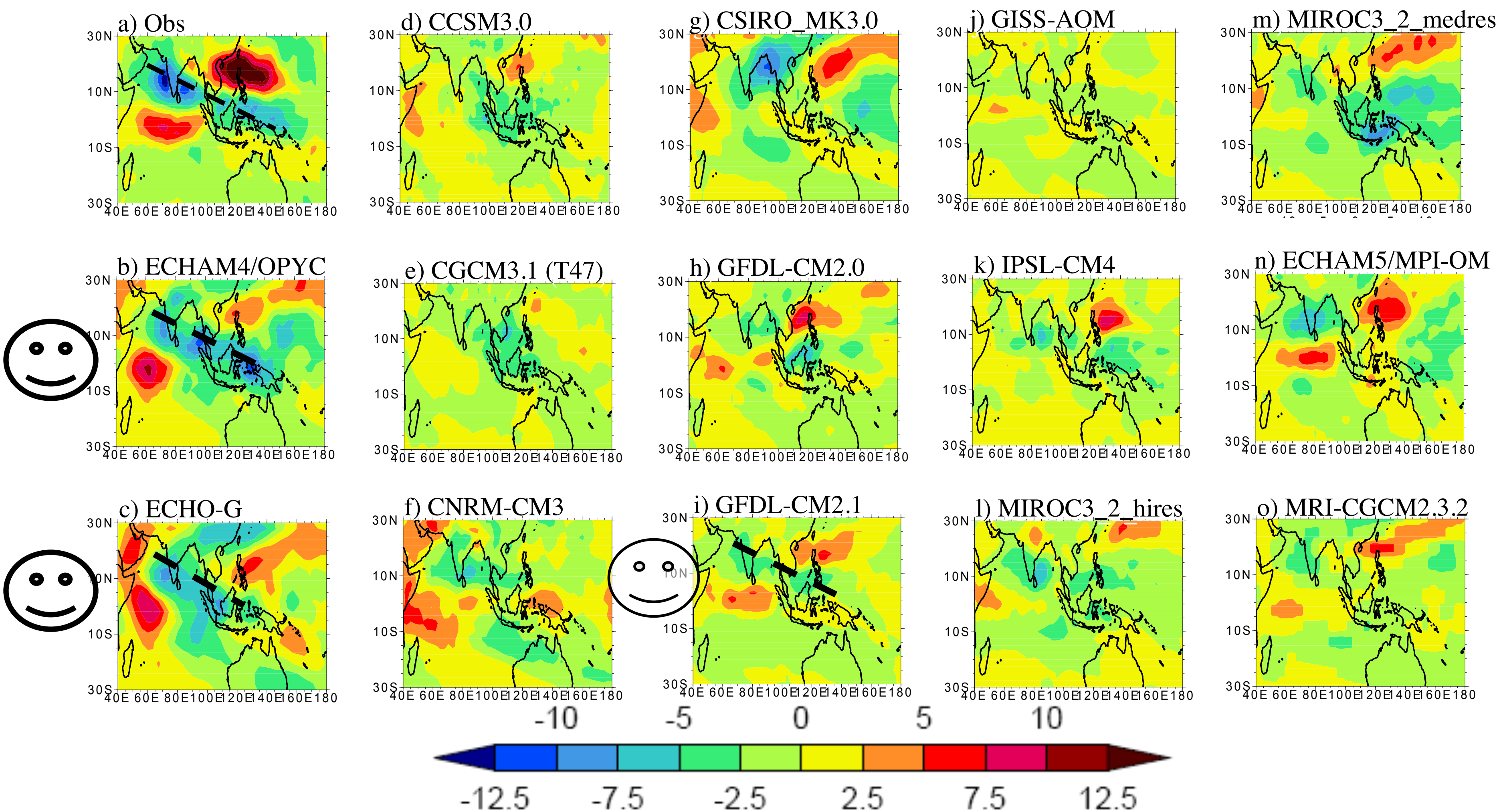
# Tilted rainband in AGCMs




**"Typically, AGCMs poorly represent the BSISV tilted rainband (Waliser et al. 2003, *Clim. Dynam*., 21, 423-446)"**

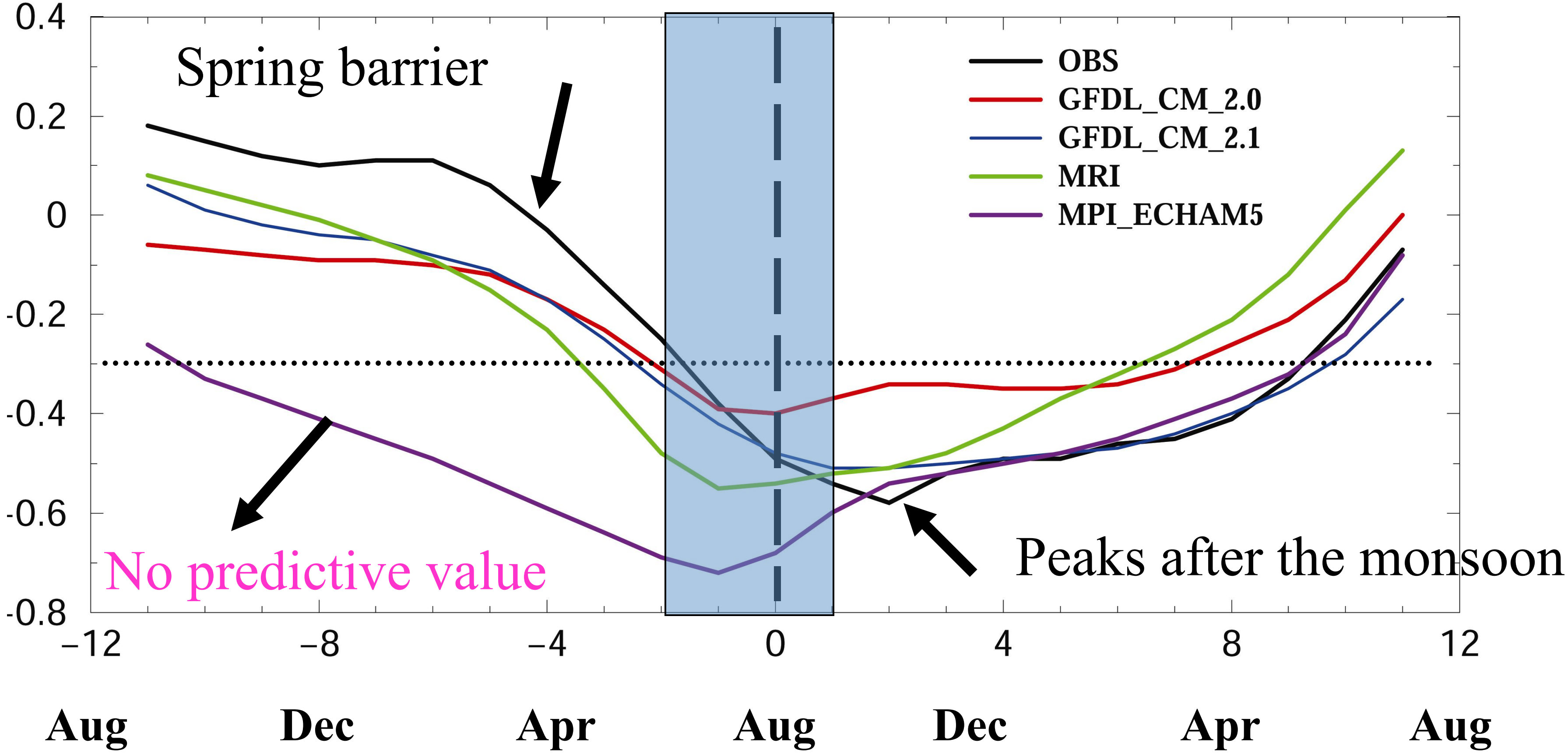
# BSISV in Coupled Models: The Tilted Rainband (Day 10)

**(Sperber and Annamalai 2007)**



# CMIP3 20c3m Integrations

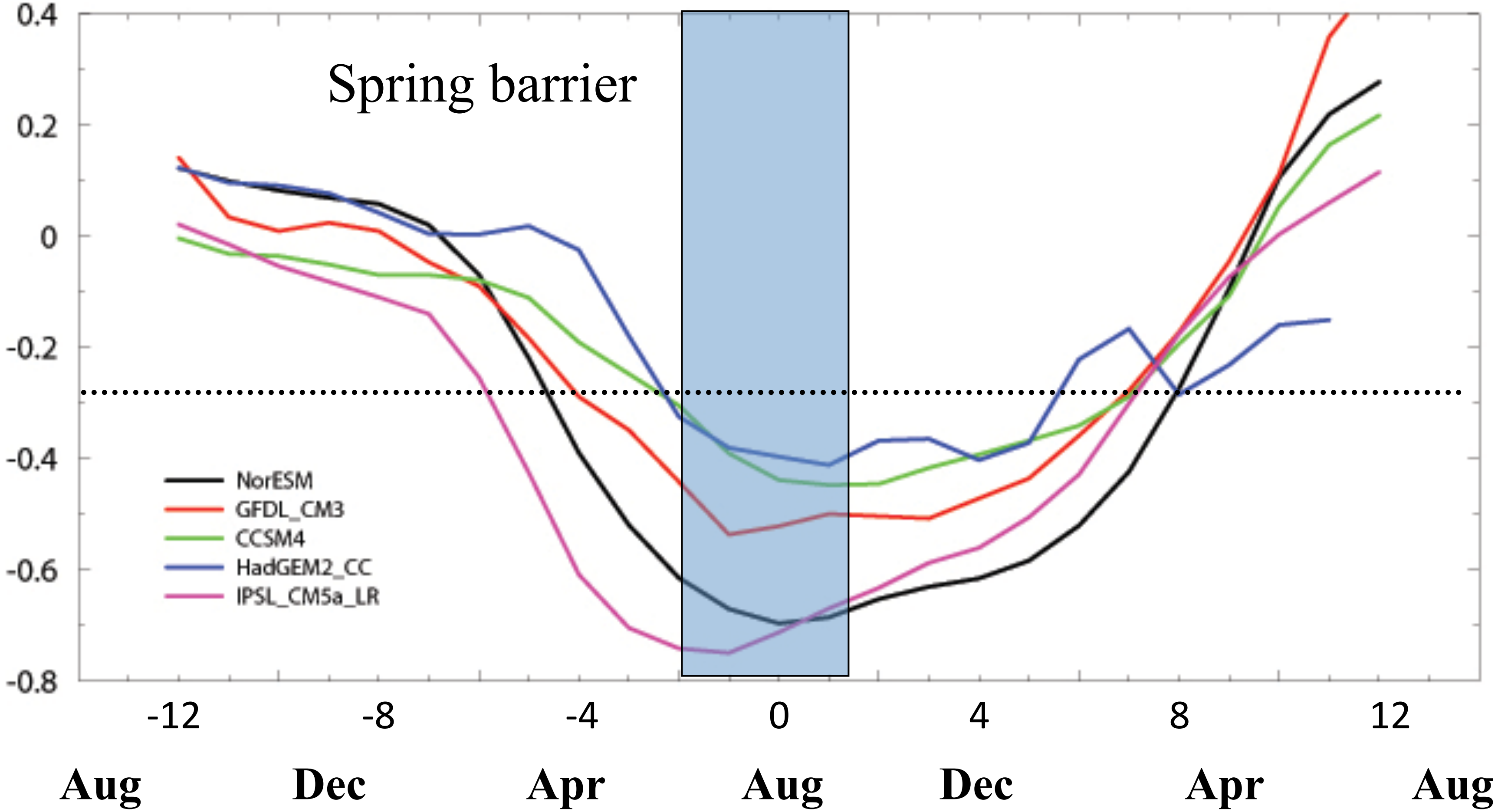
## Lead/lag relationship between AIR and NINO3.4 SST




**"except in CM_2.1 the phasing of the relationship is incorrect. However, the intensity of ENSO is too strong in GFDL_CM2.1"**

## CMIP5 20c3m Integrations

# Lead/lag relationship between AIR and NINO3.4 SST



# CMIP5 20c3m Integrations

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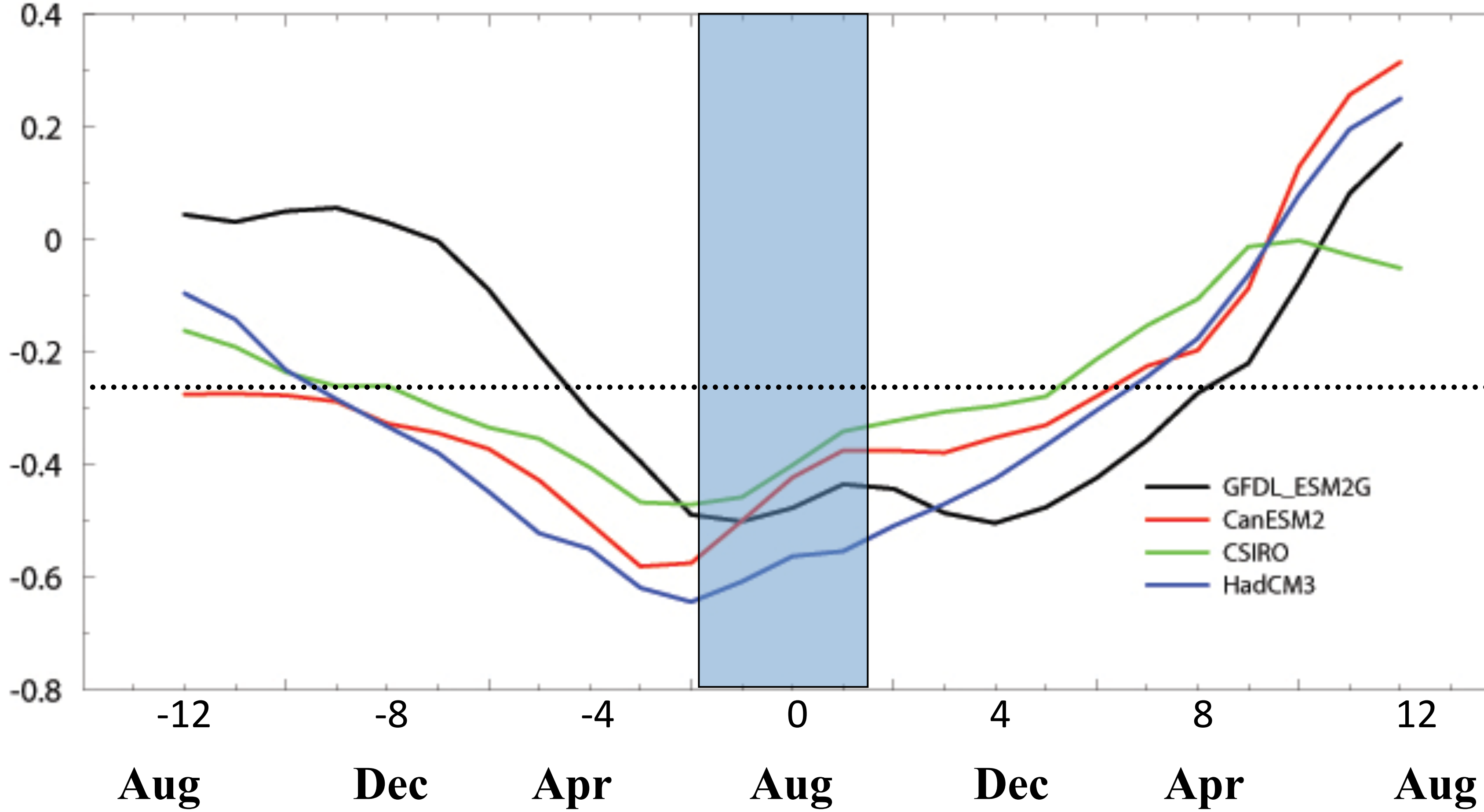
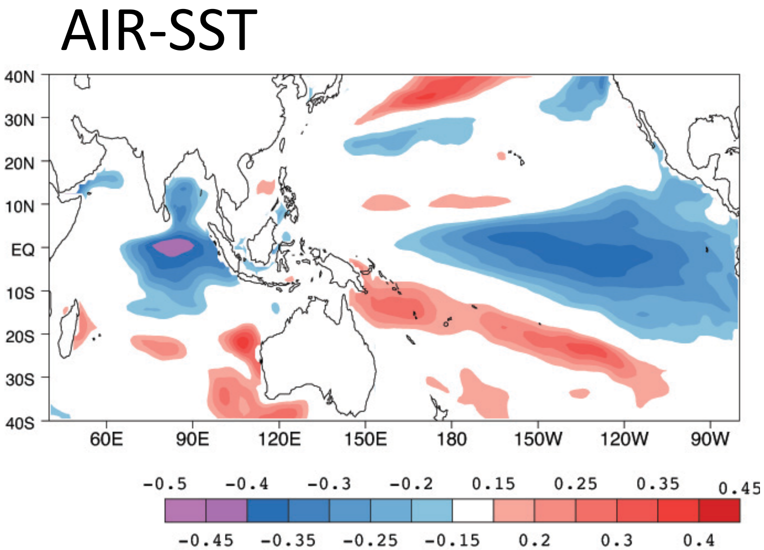
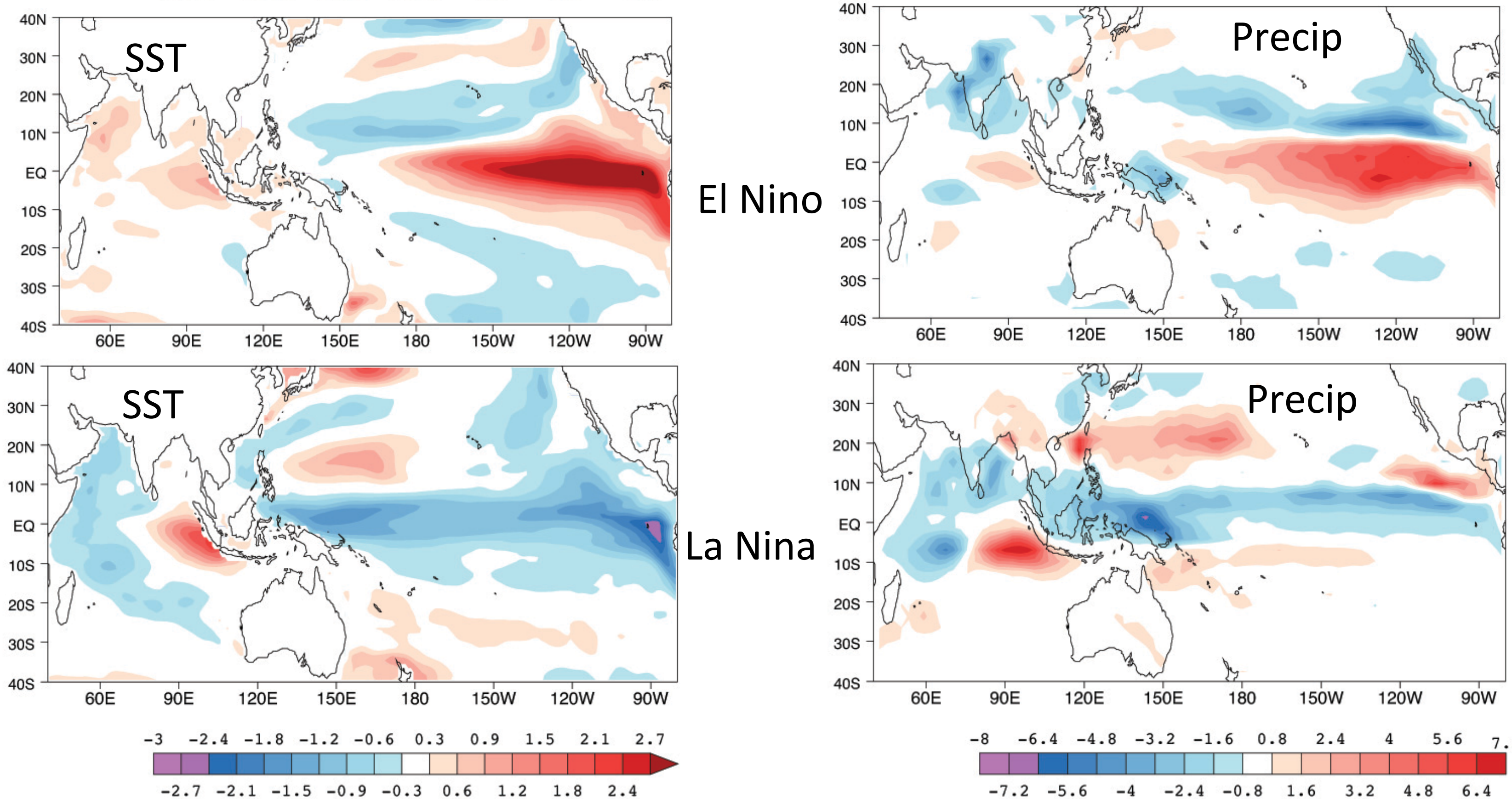


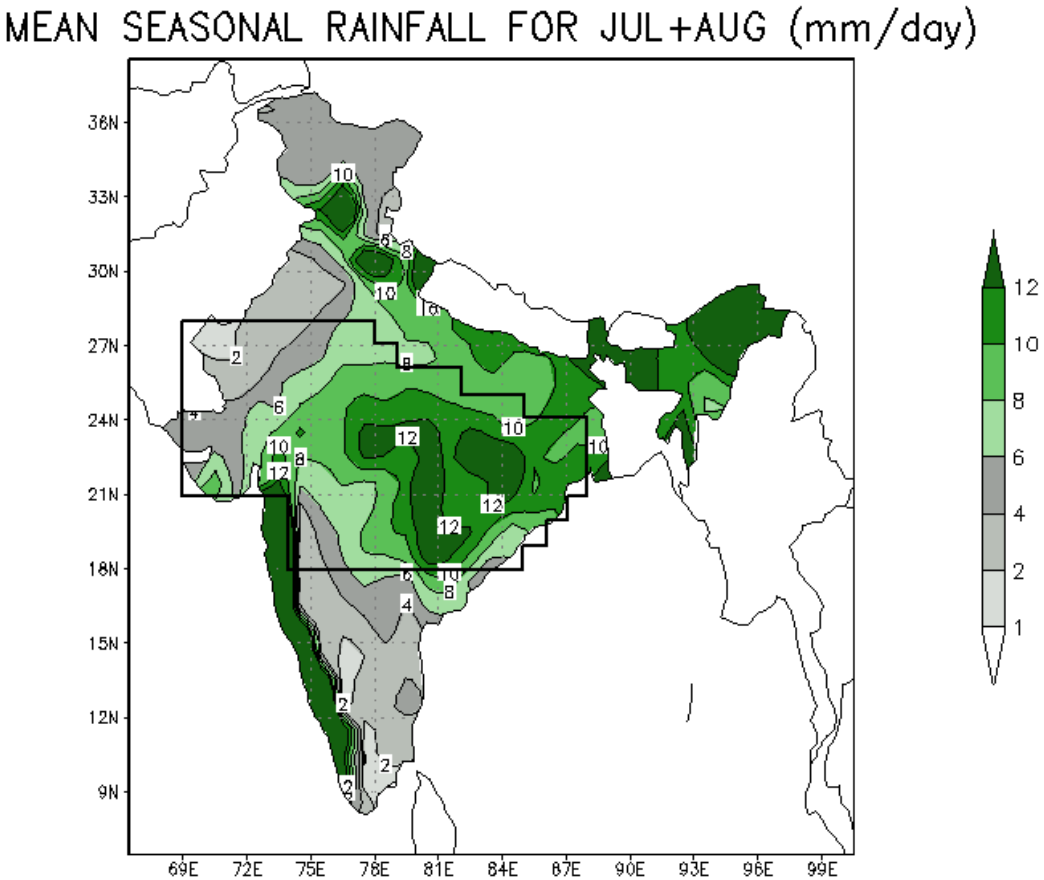

"correlations peak during late spring"

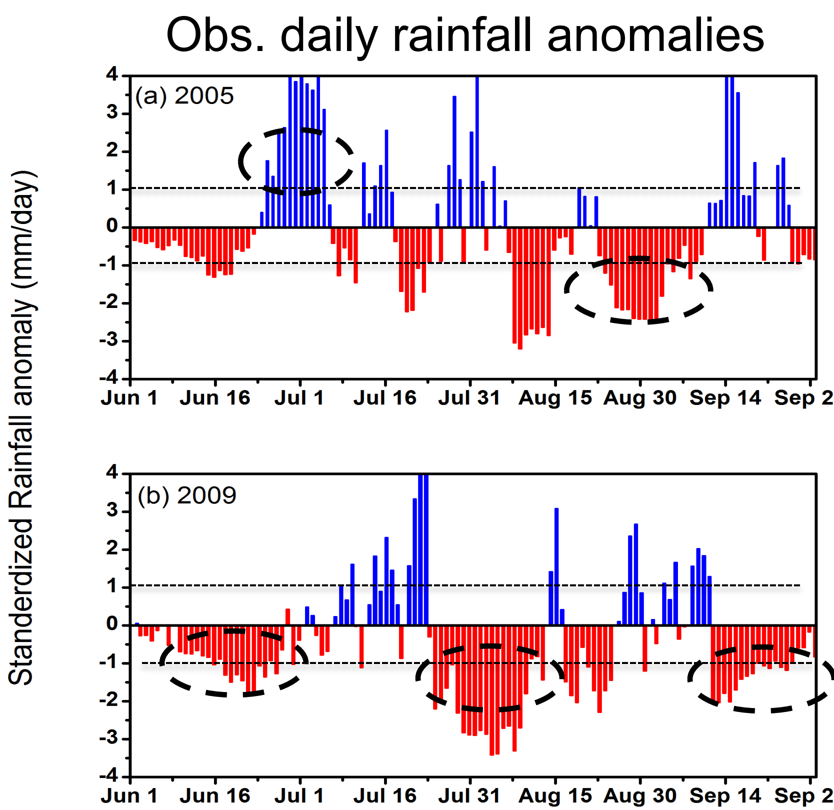



# MIROC – L500 Results

"systematic errors in regional SST"



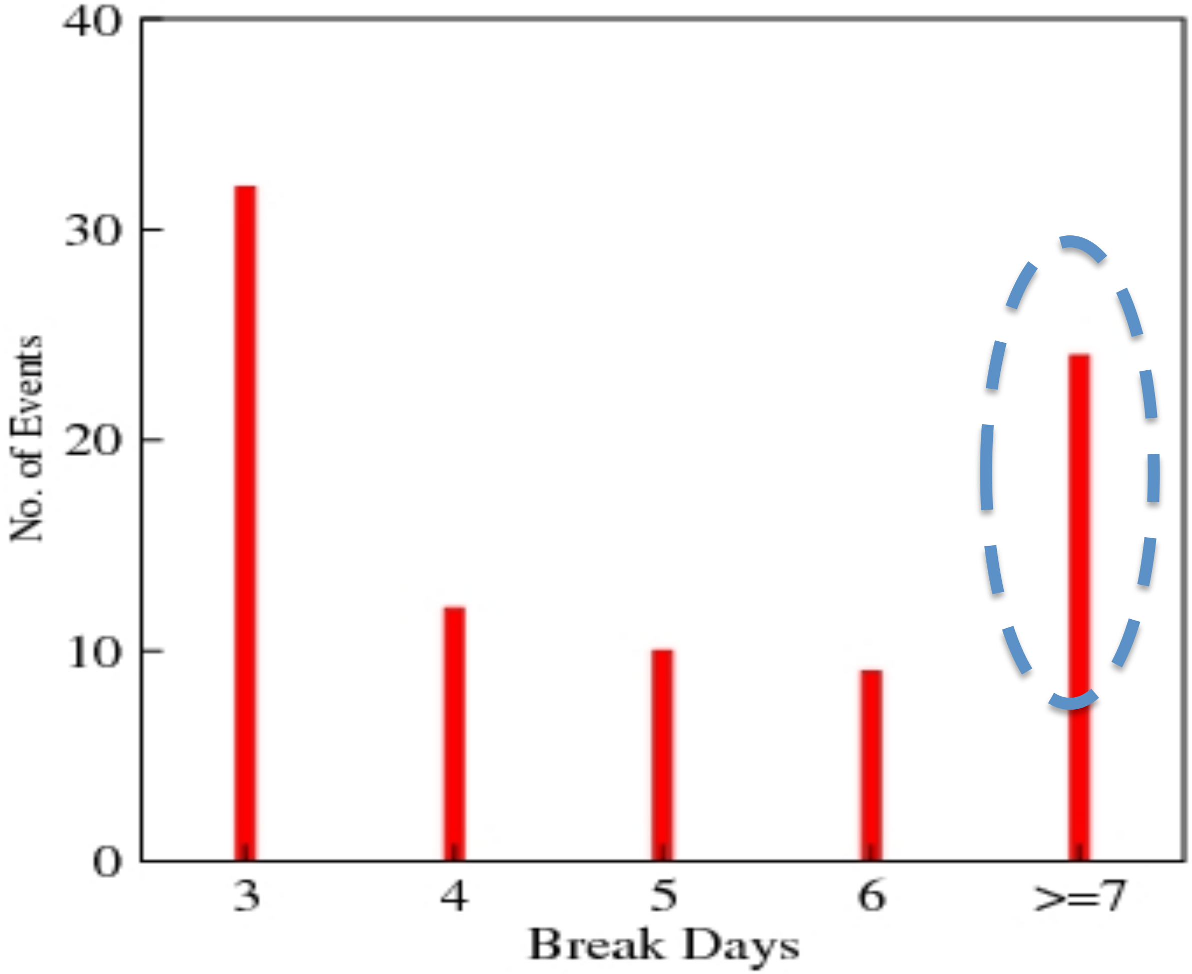



**-1σ for 7 days or more – extended break**

**+1σ for 7 days or more – extended active**

# Extended monsoon breaks over central India (1951-2009)

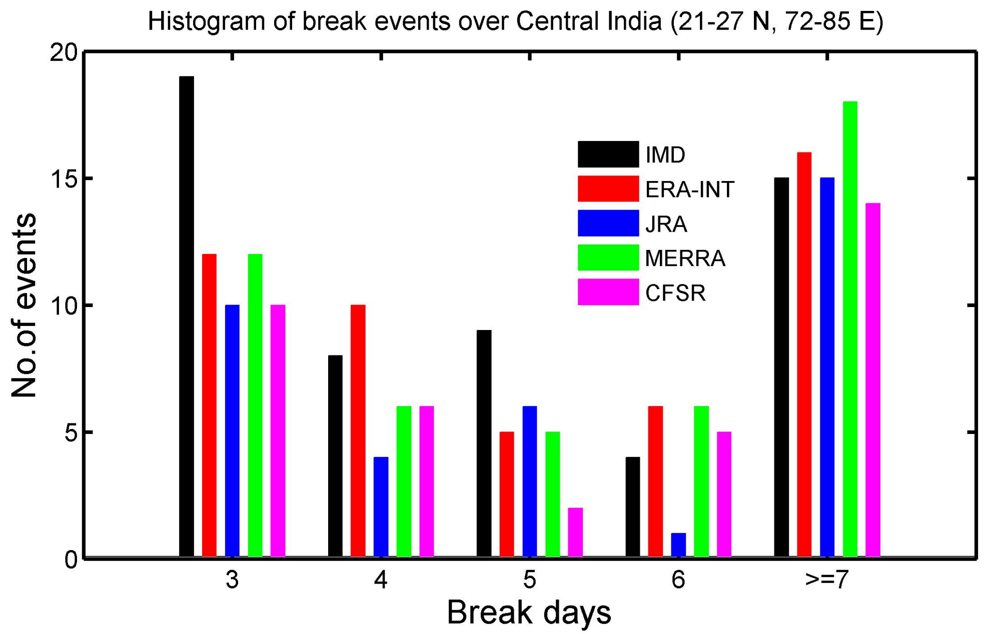



IMD 1°x1° gridded rainfall observations

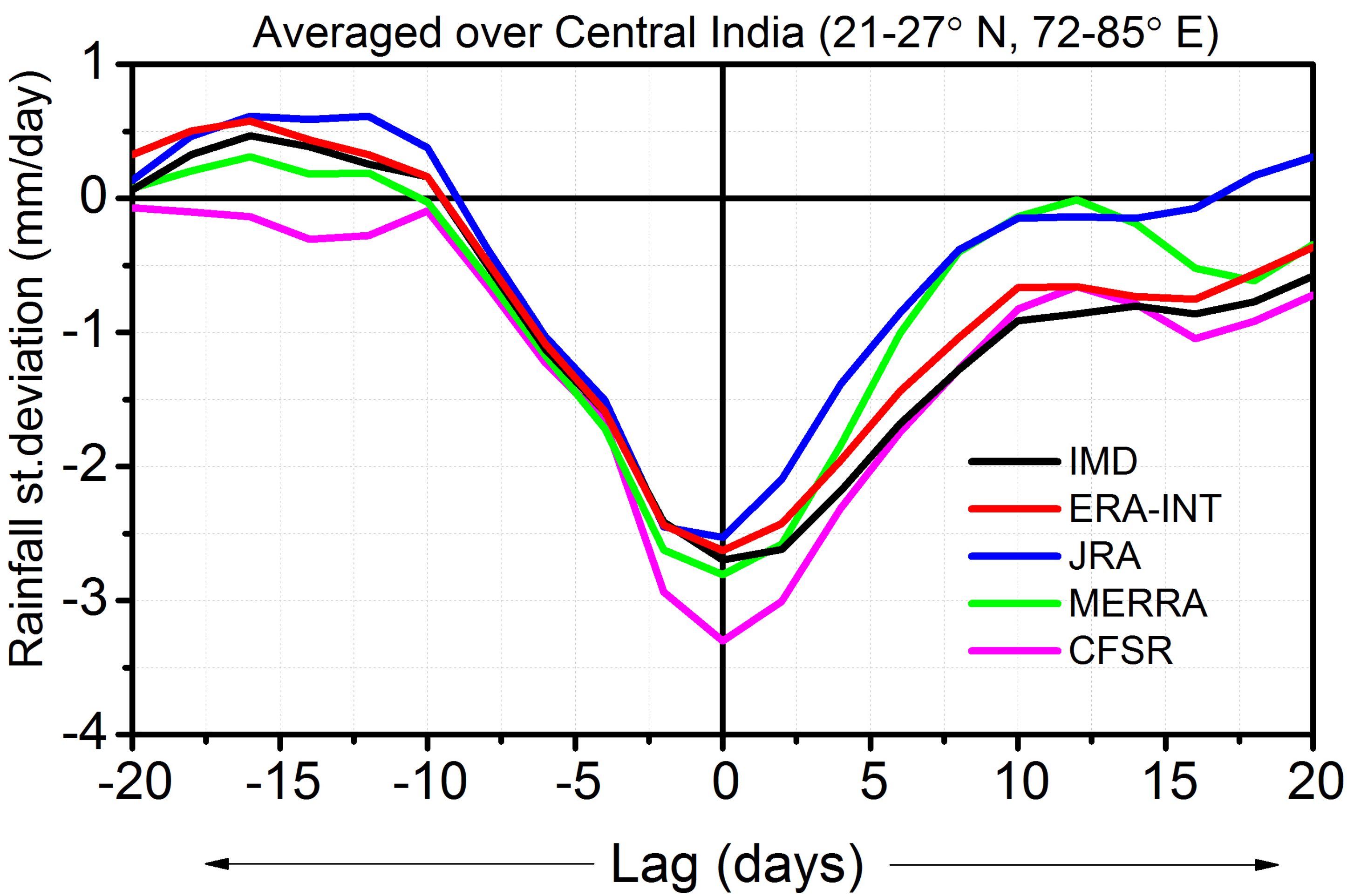
Rajeevan et al. (2006)

Individual year statistics – higher occurrences during El Nino
Space-time composites – MJO-like signal-
Extended breaks – nonlinear interaction between boundary forcing + internal dynamics

Prasanna and Annamalai (2012, JC)



Histogram of break events over Central India (21-27 N, 72-85 E)
No.of events
Break days
0
5
10
15
20
3
4
5
6
>=7
IMD
ERA-INT
JRA
MERRA
CFSR



Averaged over Central India (21-27° N, 72-85° E)
Rainfall st.deviation (mm/day)
1
0
-1
-2
-3
-4
-20
-15
-10
-5
0
5
10
15
20
Lag (days)
IMD
ERA-INT
JRA
MERRA
CFSR

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

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

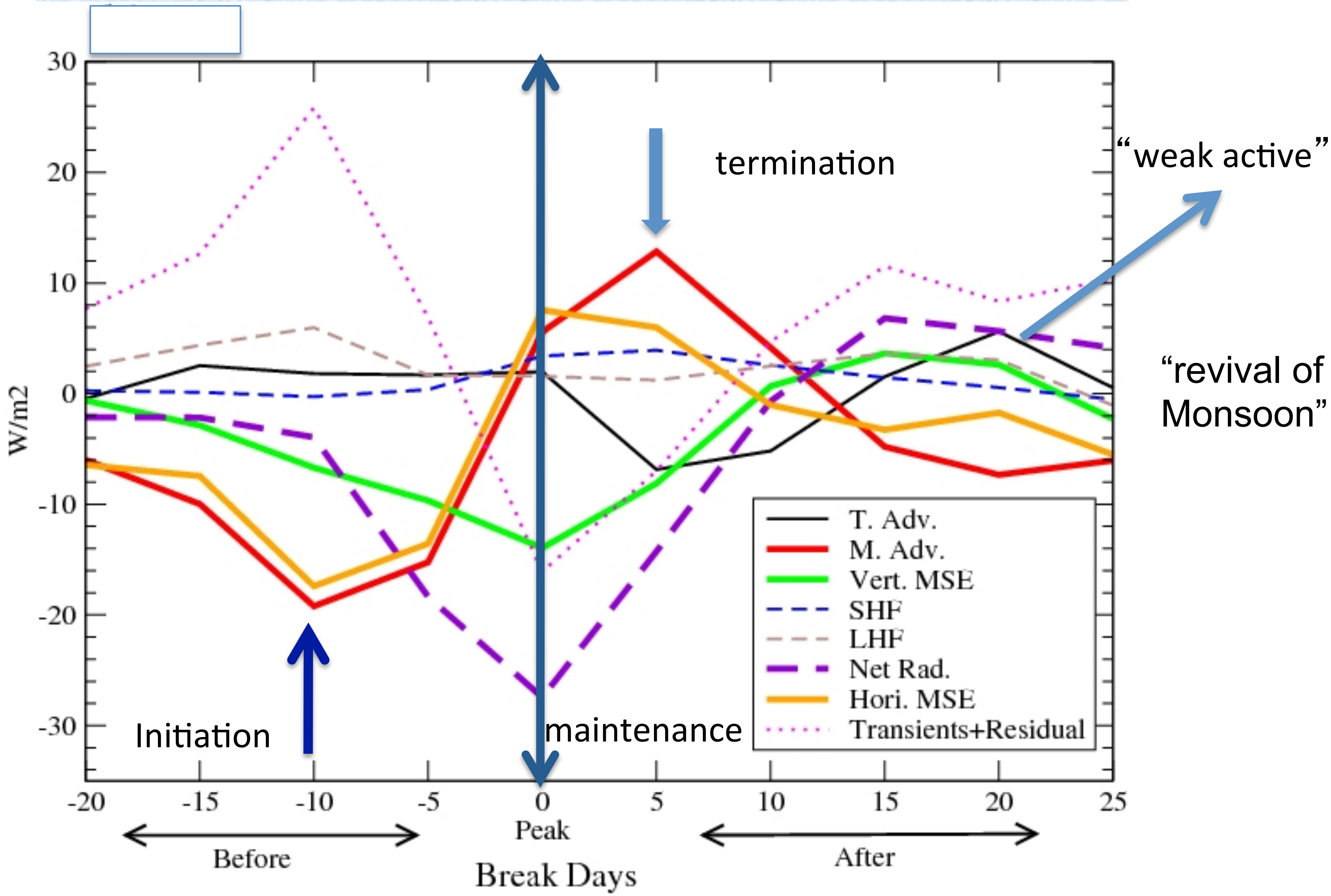
"storage" "adiabatic terms" "diabatic terms"

**diabatic and adiabatic terms feedbacks onto each other**

1. Deep tropics – above PBL – no horizontal T variations (WTG)
2. Entropy forcing: LH, SH, LW, SW, moisture variations
3. Physical parameterizations (cloud-radiation, convection, surface fluxes etc)

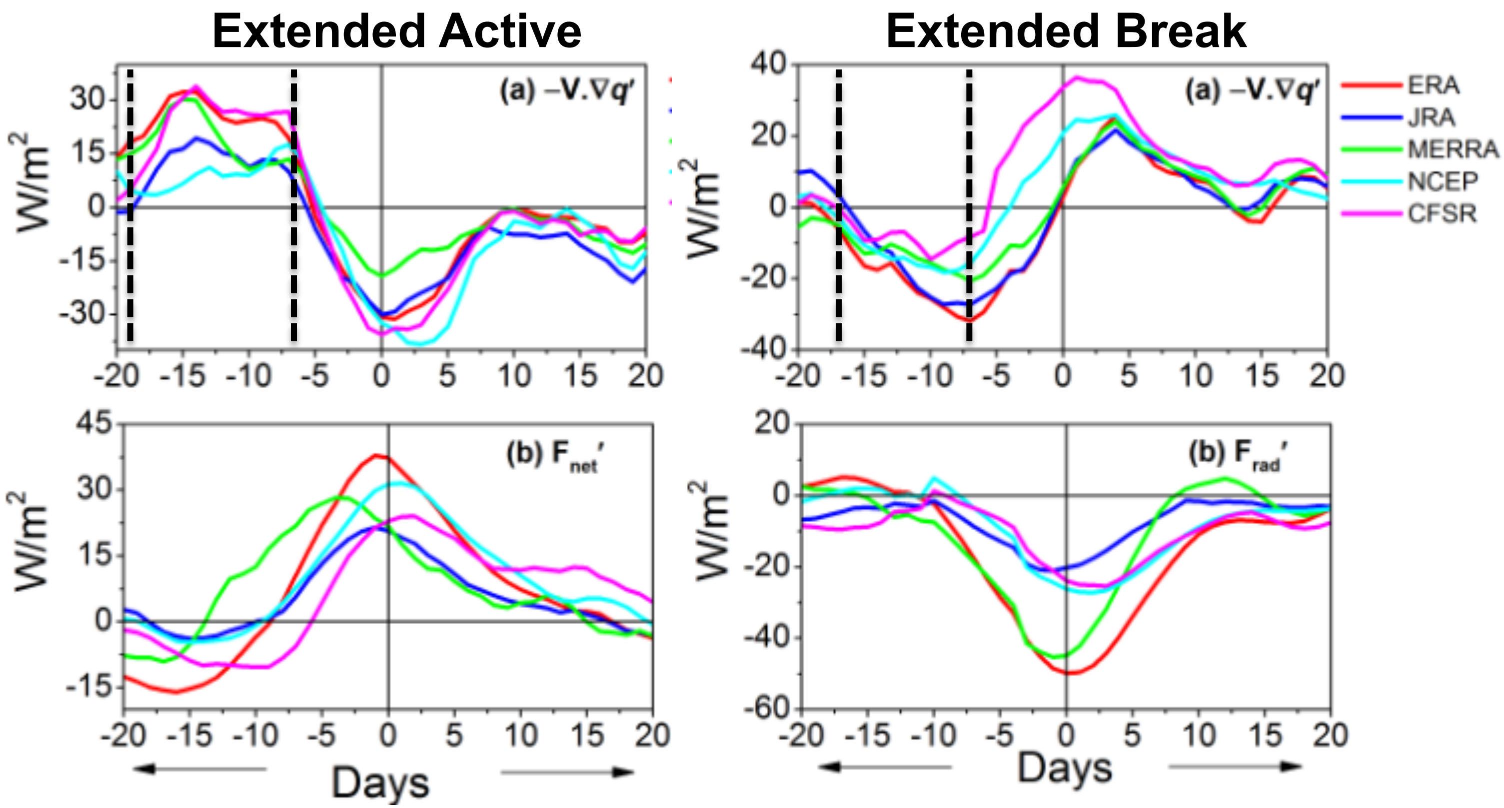
Neelin and Held 1987
Raymond et al. 2009
Bretherton et al. 2005
Neelin and Su 2005

# MSE budget terms – Central India (18-27N; 71-87E)




Dry adv → convection inhibition → LW cooling → descent/adiabatic warming

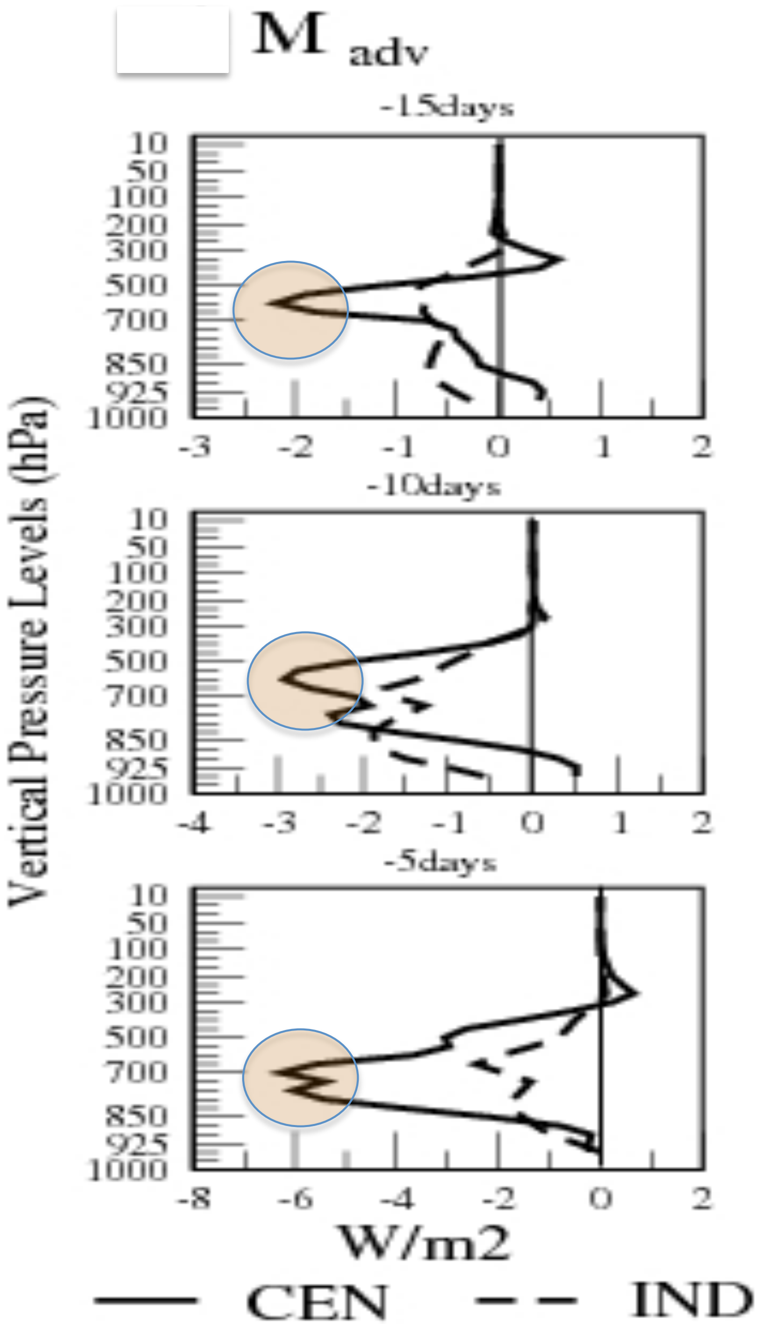
# Robust precursors – MSE budget over Central India from a suite of reanalyses




**Horizontal advection of moisture initiates extended active and break episodes**

Column radiative flux divergence maintains extended episodes

Prasanna and Annamalai (2012); Mohan and Annamalai (2016)




Dry air intrusion –

Convective inhibition layer

“deep convection sensitive to mid-troposphere moisture”

Bretherton et al. 2004;
Grabowski and Moncrieff (2004)

“moisture-convection feedback”

**Useful predictive information**

(**2002/2009 Case studies**)

# Summary for Case II

**Extended monsoon episodes**

MSE budget analysis identifies

$$-\langle \overline{V} \bullet \nabla m \rangle$$

initiation and termination

$$-\langle \overline{V} \bullet \nabla T \rangle \quad \langle LW \rangle$$

maintenance

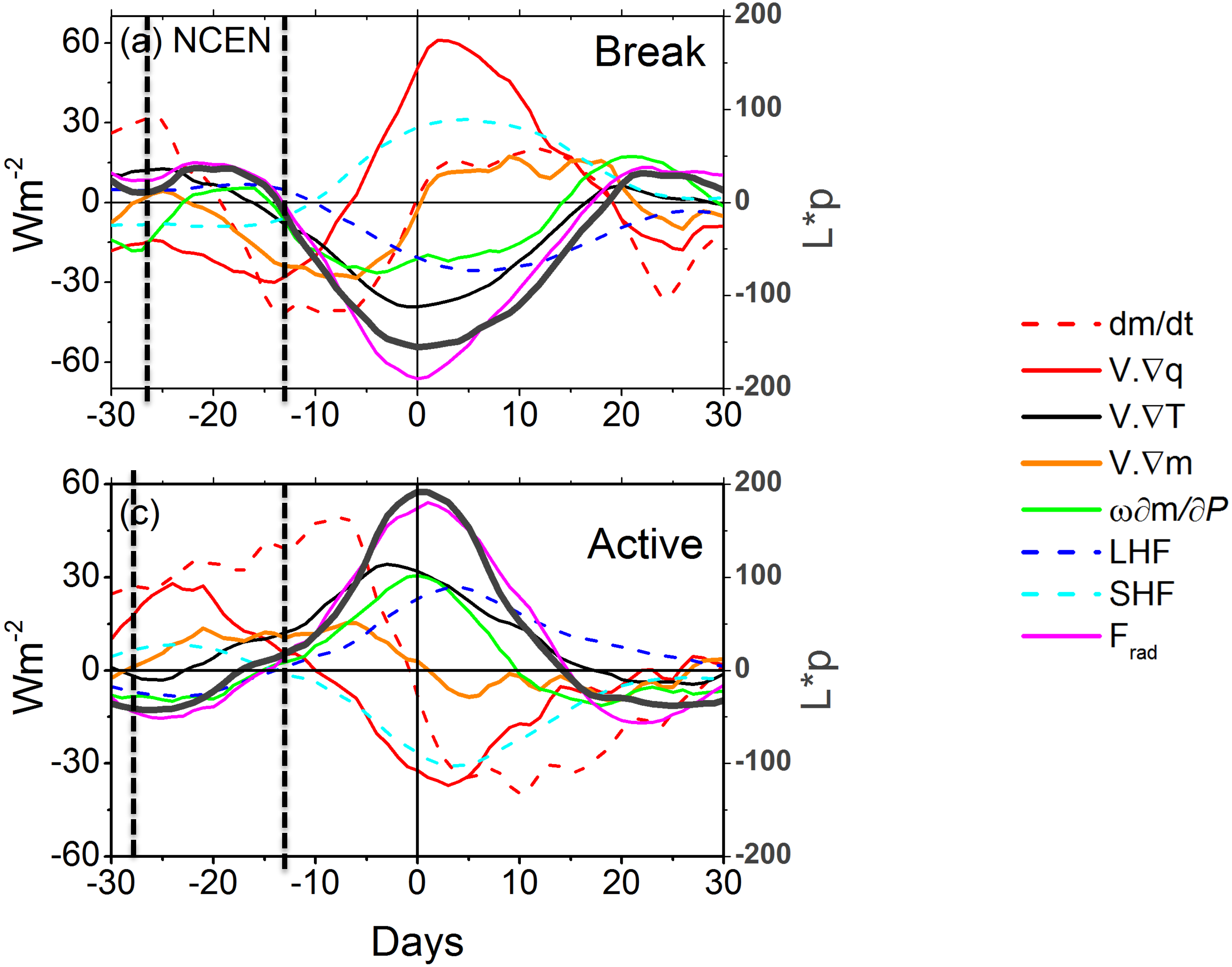
But.......large residuals – important moist and radiative processes missing

MSE is a useful diagnostic to identify leading moist and radiative processes deem responsible for rainfall anomalies over mean ascent regions

Applying this diagnostic to "all regional monsoon areas" within the

Asian-Australian monsoon domain (e.g., MC, Philippines, Sri Lanka, Burma etc)

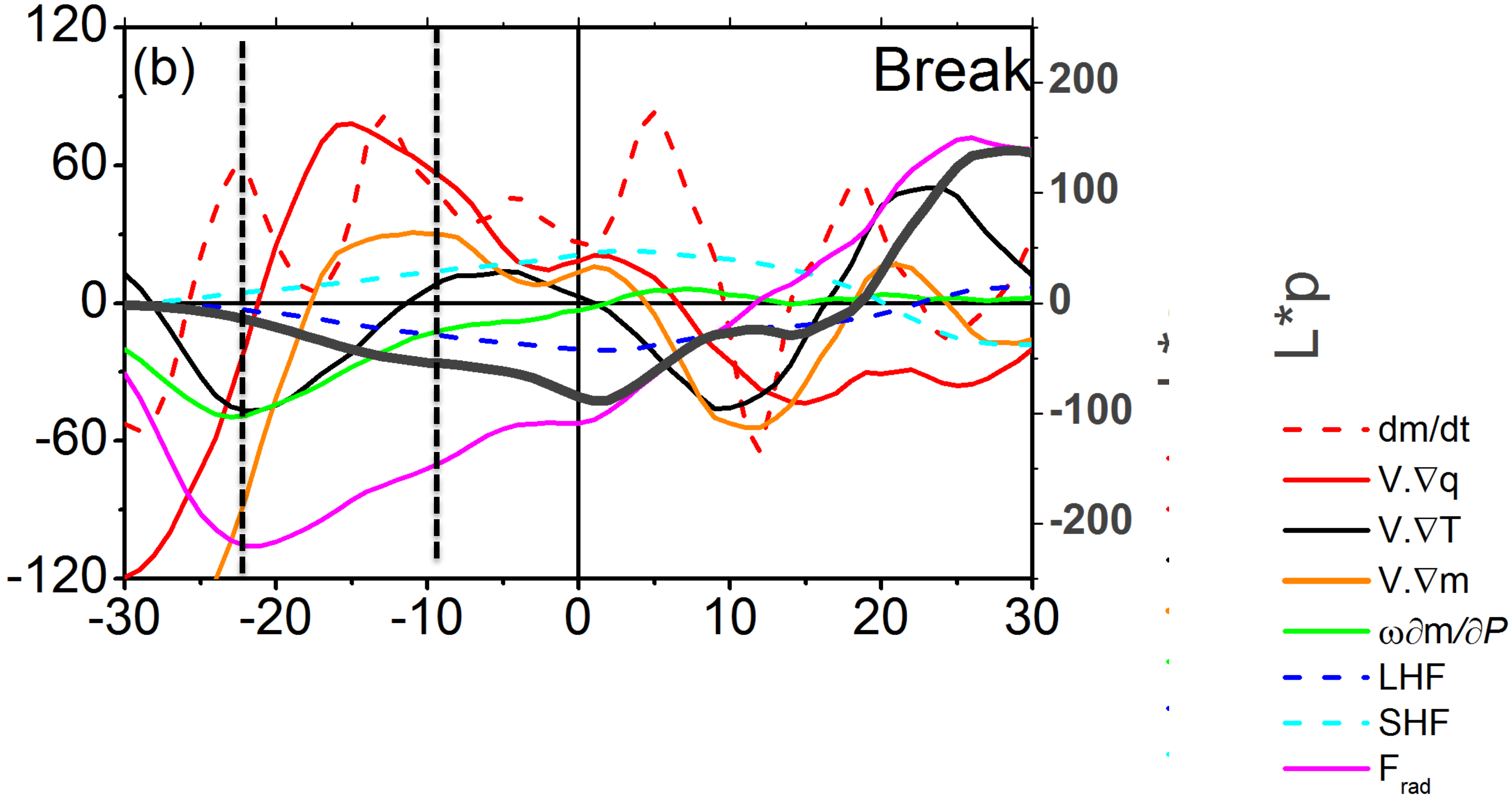
# MSE budget (composite)



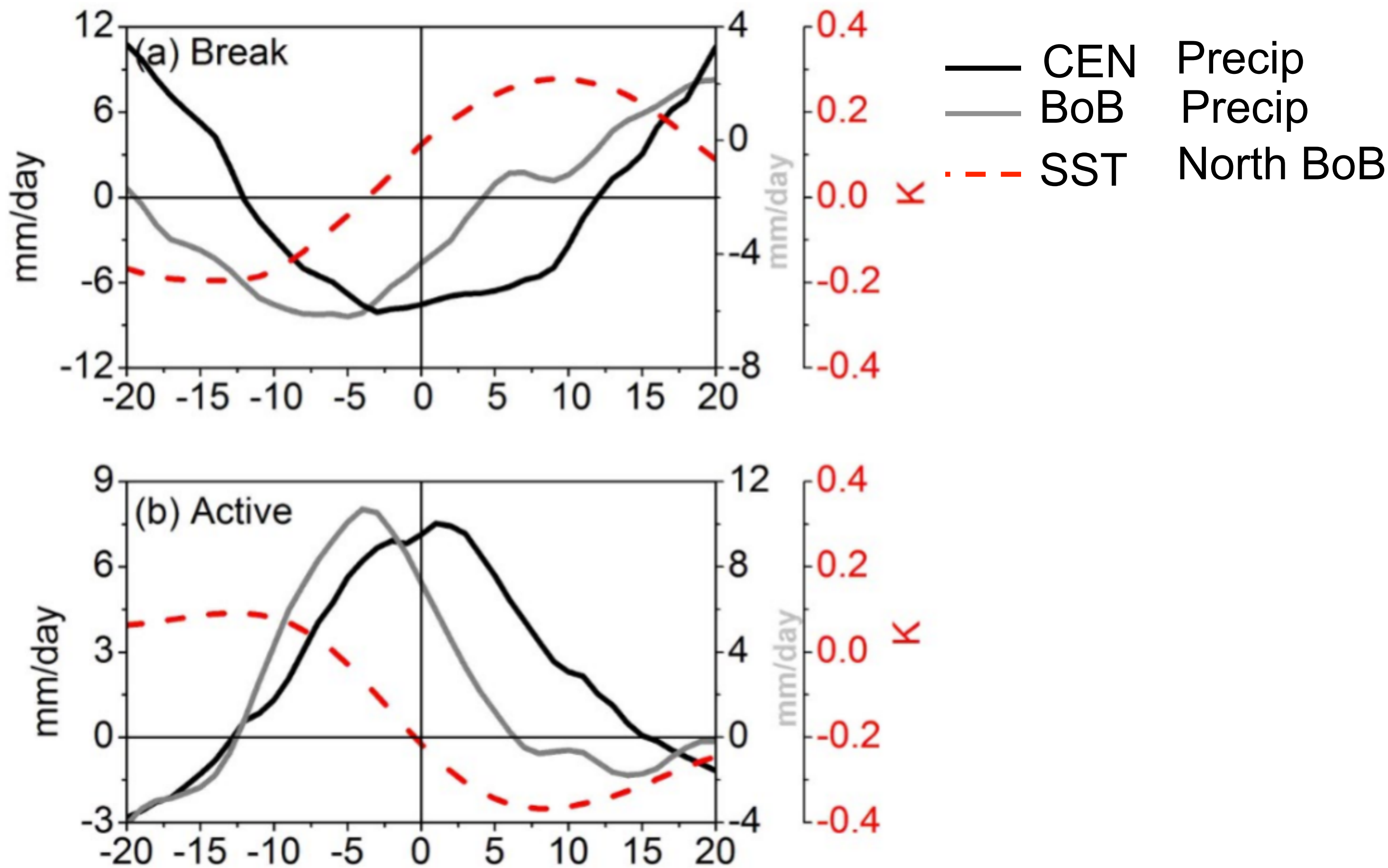

CFSv2 – contributions from horizontal Temperature advection are stronger

# MSE budget (false alarms)

Horizontal advection of “moistute” precedes break event!



# SST- rainfall associations




SST anomalies lead “local” precip anomalies over BoB that subsequently leads Precipitation anomalies over central India

**(Krishnamurti et al 1998; Sengupta et al 2002; Sengupta and Ravichandran 2001)**

## Mixed-layer heat budget equation

$$\frac{\partial(T_{ml})}{\partial t} = \frac{Q_{net} - Q}{p_0 C_p h} - V.\nabla T_{ml} - \frac{w_e(T_{ml} - T_d)}{h} + R$$

"storage"

"net surface heat flux"

horizontal advection

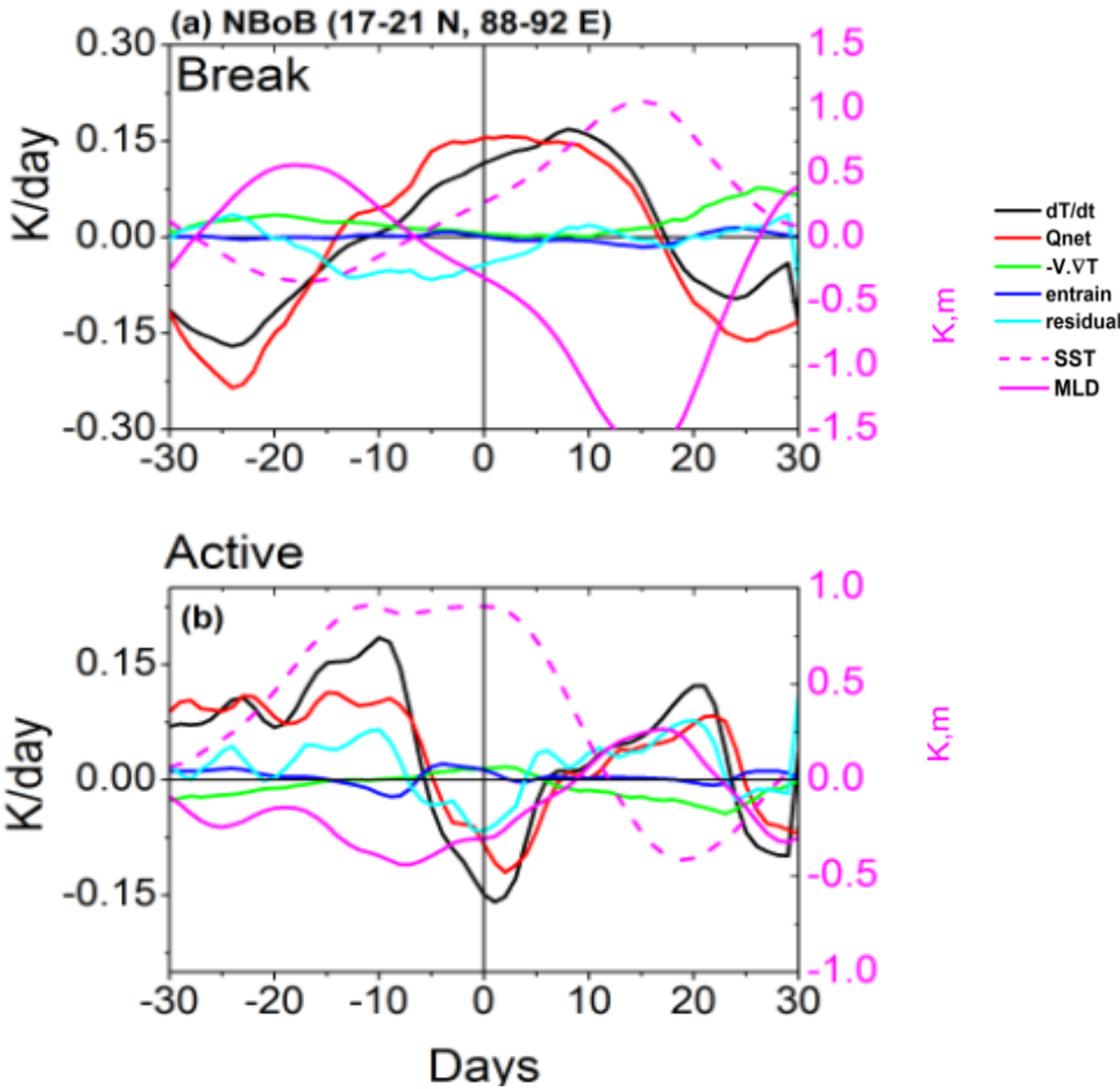
entrainment

**(adiabatic terms)**

**(diabatic term)**

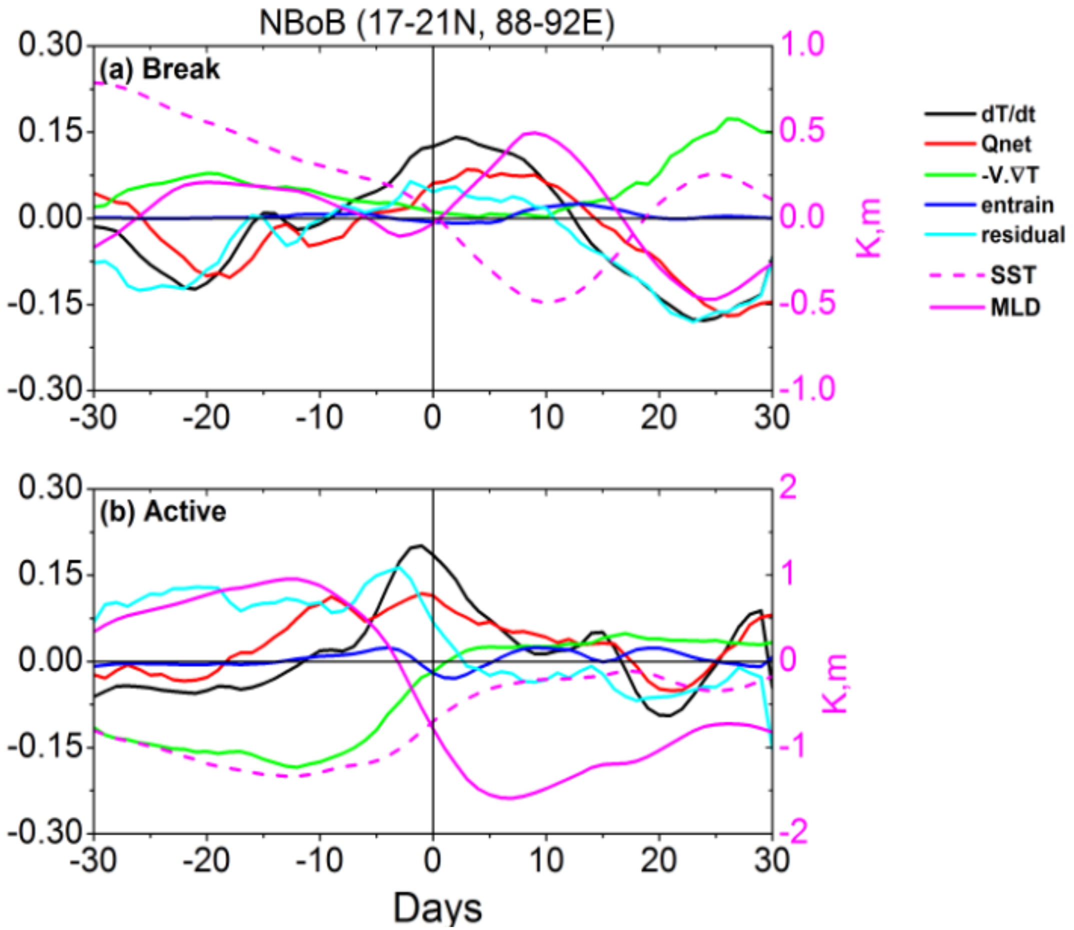
Sengupta and Ravichandran 2001; Sengupta et al (2002); Santoso et al. 2010; Huang et al 2010; Chi et al 2014;

# Mixed-layer heat budget equation (composite)




Net surface heat flux determines SST tendency consistent with observations

# Mixed-layer heat budget equation (false alarms)




SST anomalies do not provide a “clean” precursor signal

Representation of interaction between cumulus convection and circulation requires consideration of moisture and temperature that is represented by MSE, m, given by

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

The vertically integrated MSE tendency is approximately given by

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

Charging/ discharging

Horizontal advection

MSE export Vertical adv

fluxes

Cloud-radiative interaction

+ residuals

Neelin and Held 1987
Raymond et al. 2009
Maloney 2009

WTG approximation – temperature advection is negligible