Moist static energy budget diagnostics for monsoon research

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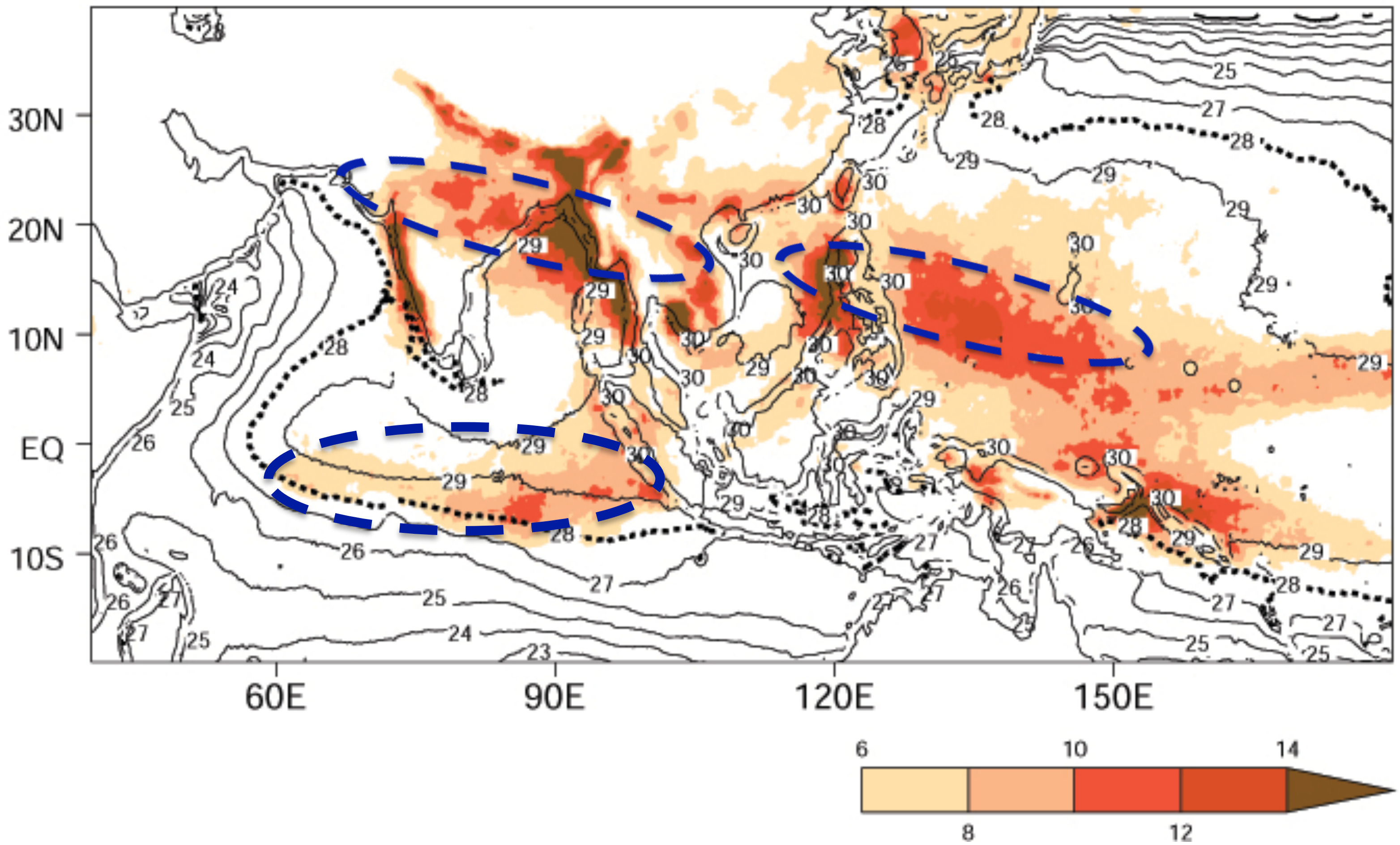
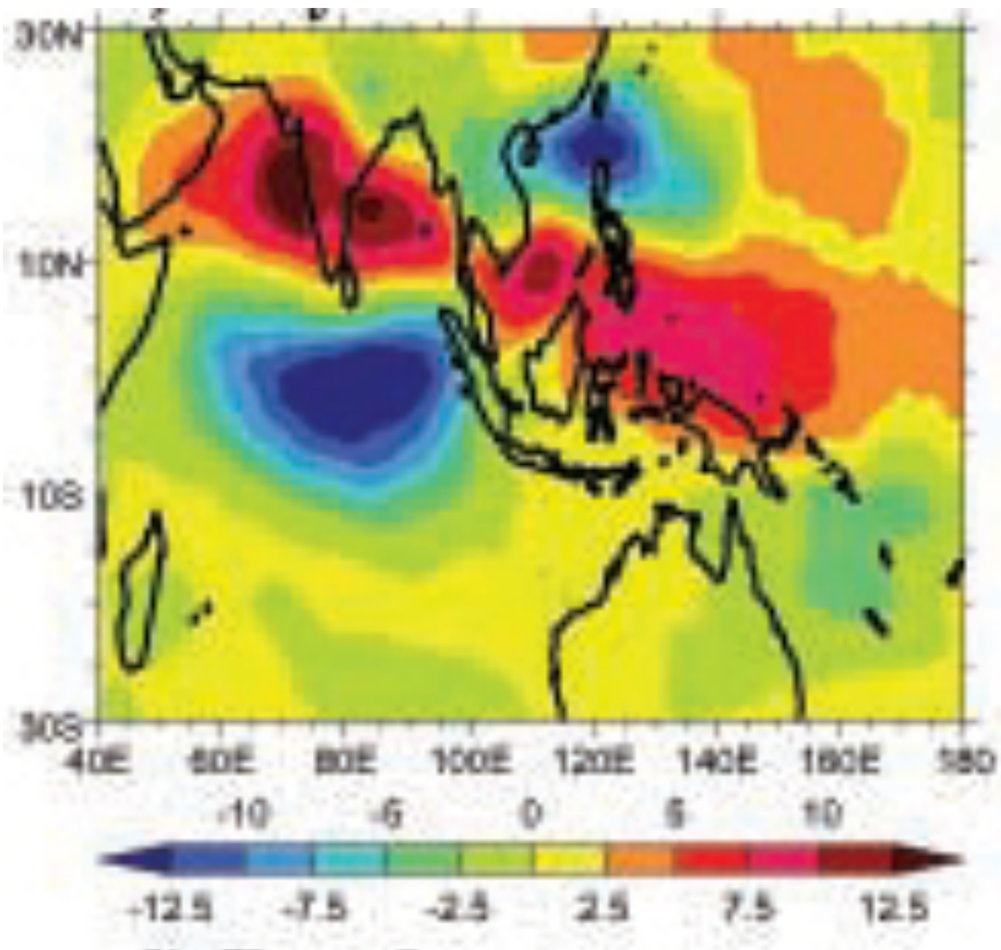
JJAS – Precipitation and SST Climatology



- Multiple regional rainfall maxima -
- EIO and SPCZ – still experience high precipitation (thermal equator at 20^{o}N)
- Central India rainfall – dynamical effects; Rain-shadow regions
- absolute ascent over a large domain

Observed Boreal Summer ISV



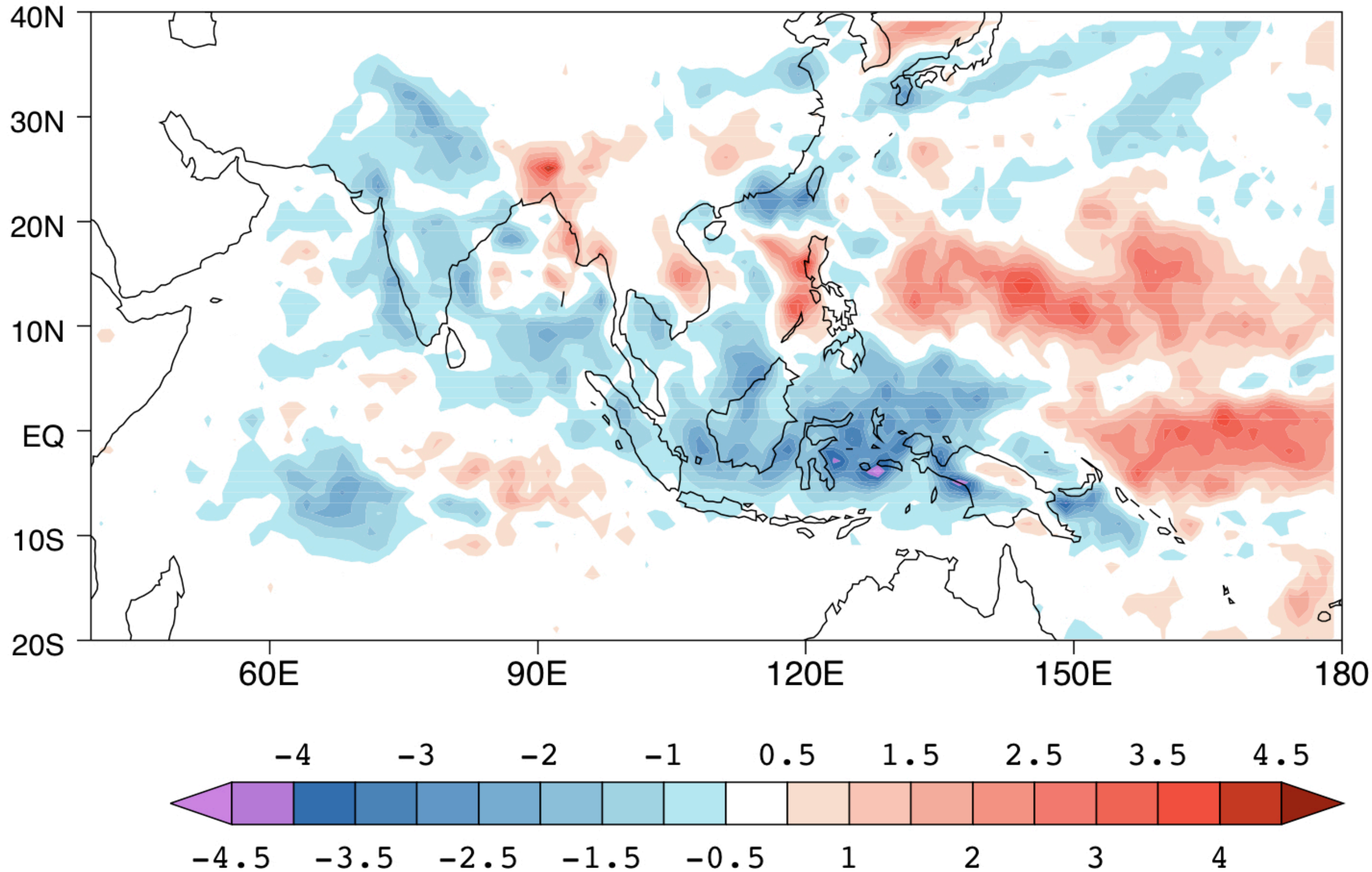
OLR anomalies W/m^2

"internal dynamics"

Annamalai and Sperber (2005, JAS)
Lau and Chan (1986, JAS)

"one-phase of the ISV"

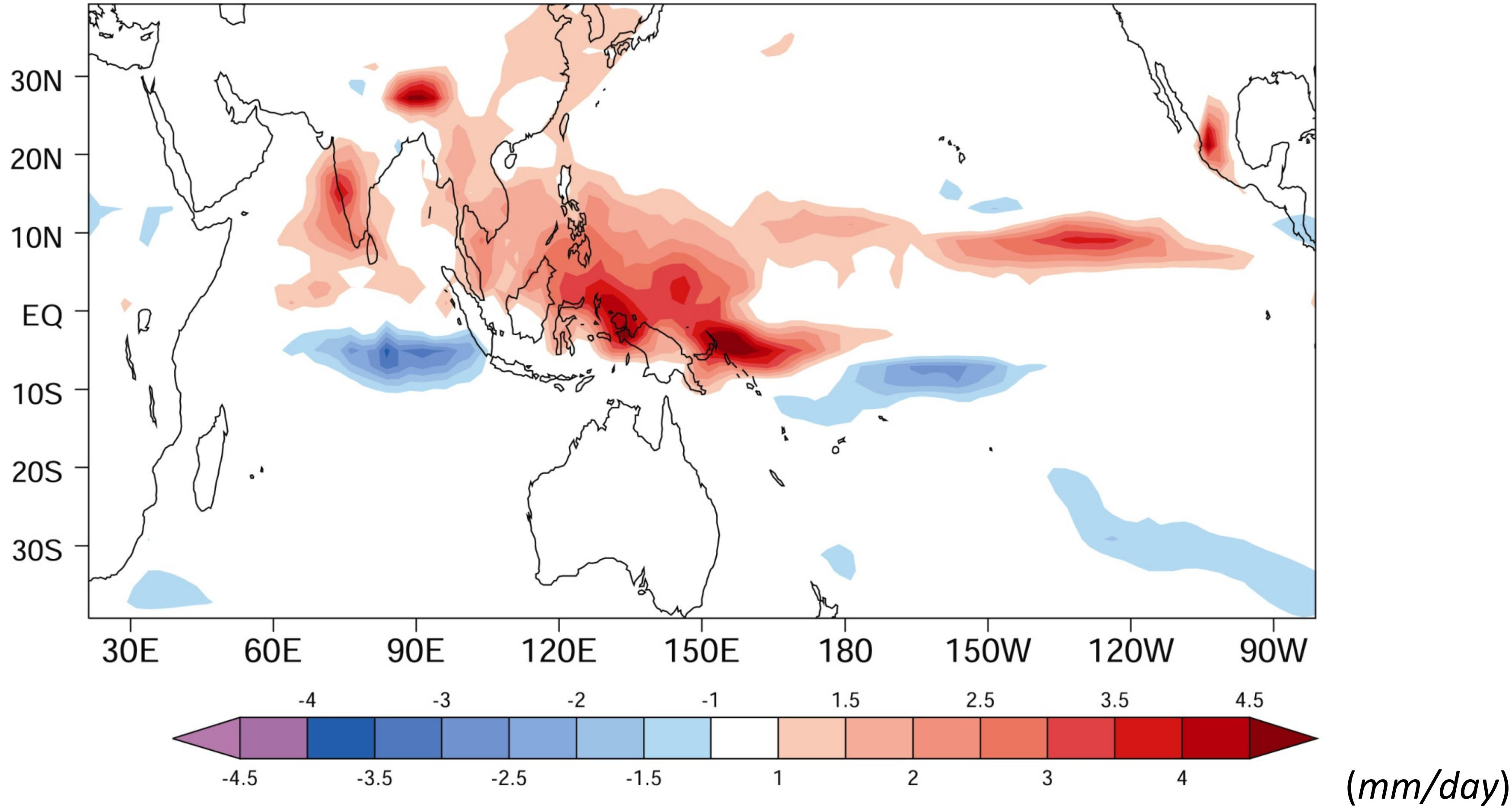
JJAS rainfall anomalies (2002/04/09) - TRMM



"Boundary forcing"

JJAS Precipitation response in CM_2.1

$4xCO_2$ *minus* 20c3m



Stowasser, Annamalai and Hafner (2009 J. Climate)

Overarching Hypothesis

Interaction between equatorial waves and moist physics

needs to be understood for attributing the causes for

precipitation anomalies over "mean ascent" regions

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

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

+ residuals

Charging/ discharging

Horizontal advection

MSE export Vertical adv

fluxes

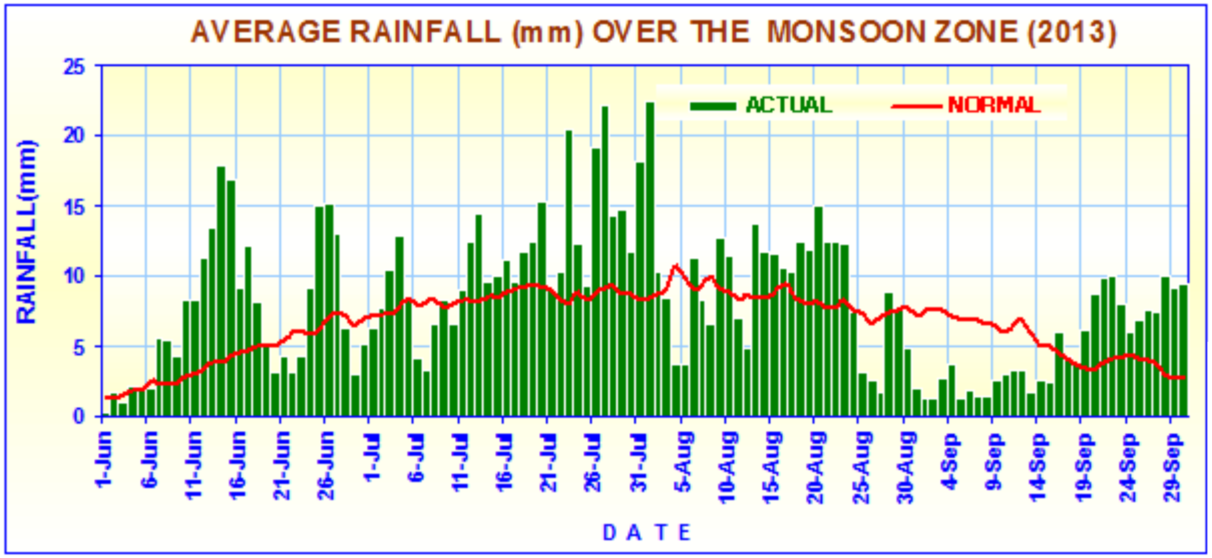
Cloud-radiative interaction

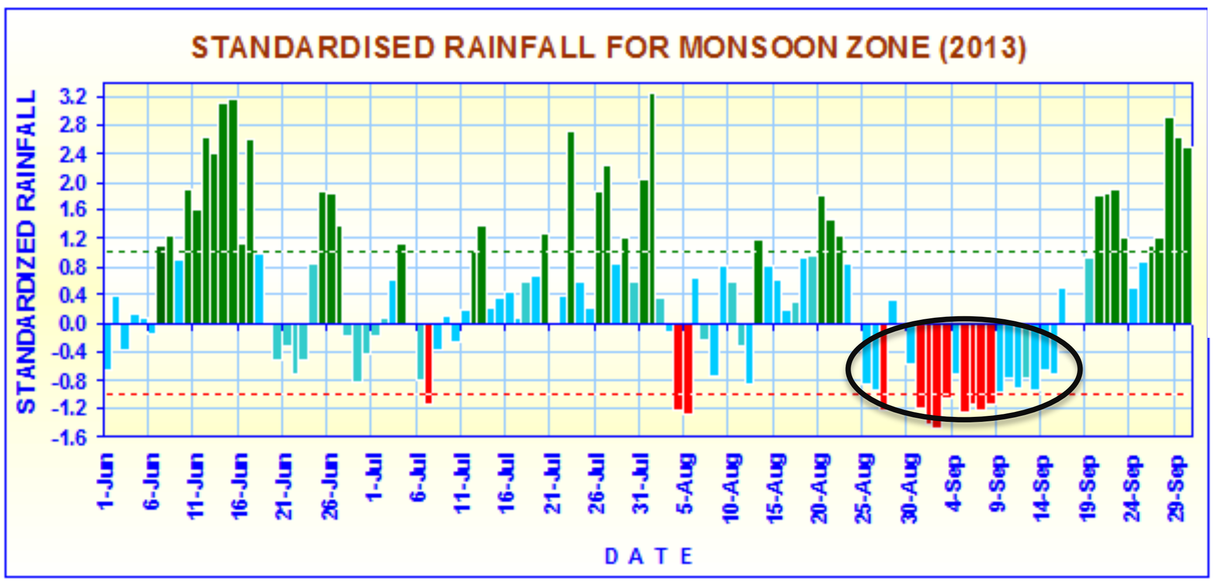
WTG approximation – temperature advection is negligible

MSE budget – Monsoon variability

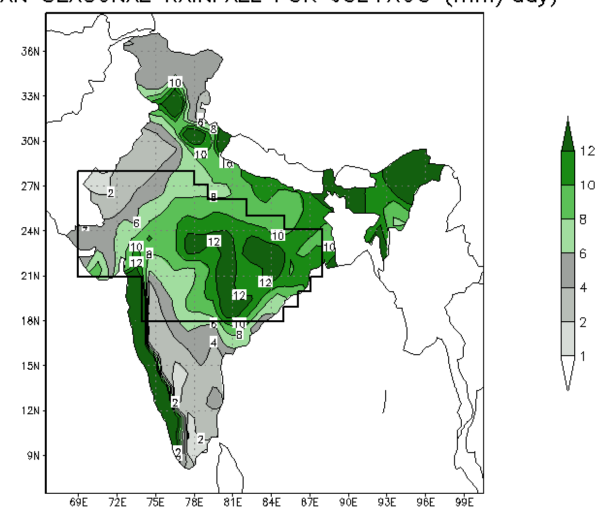
- Case I – Extended monsoon breaks over South Asia
- Case II – Drying tendency over South Asia (long-term trend in observed rainfall)
- Case III – Severe weak/strong monsoons (> 15% of the seasonal normal)
  Developing phase of ENSO

"dryness at different time scales"

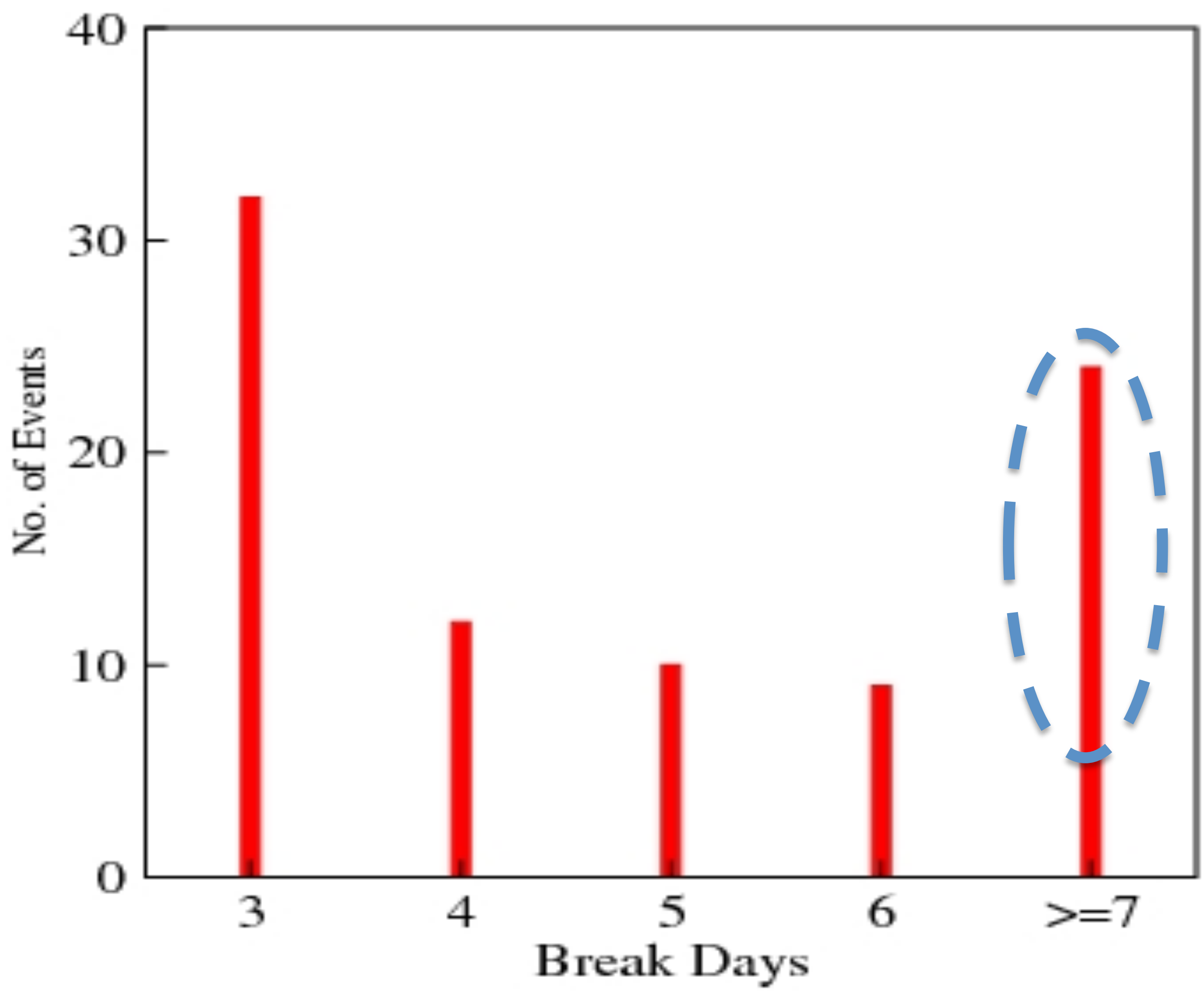




MEAN SEASONAL RAINFALL FOR JUL+AUG (mm/day)



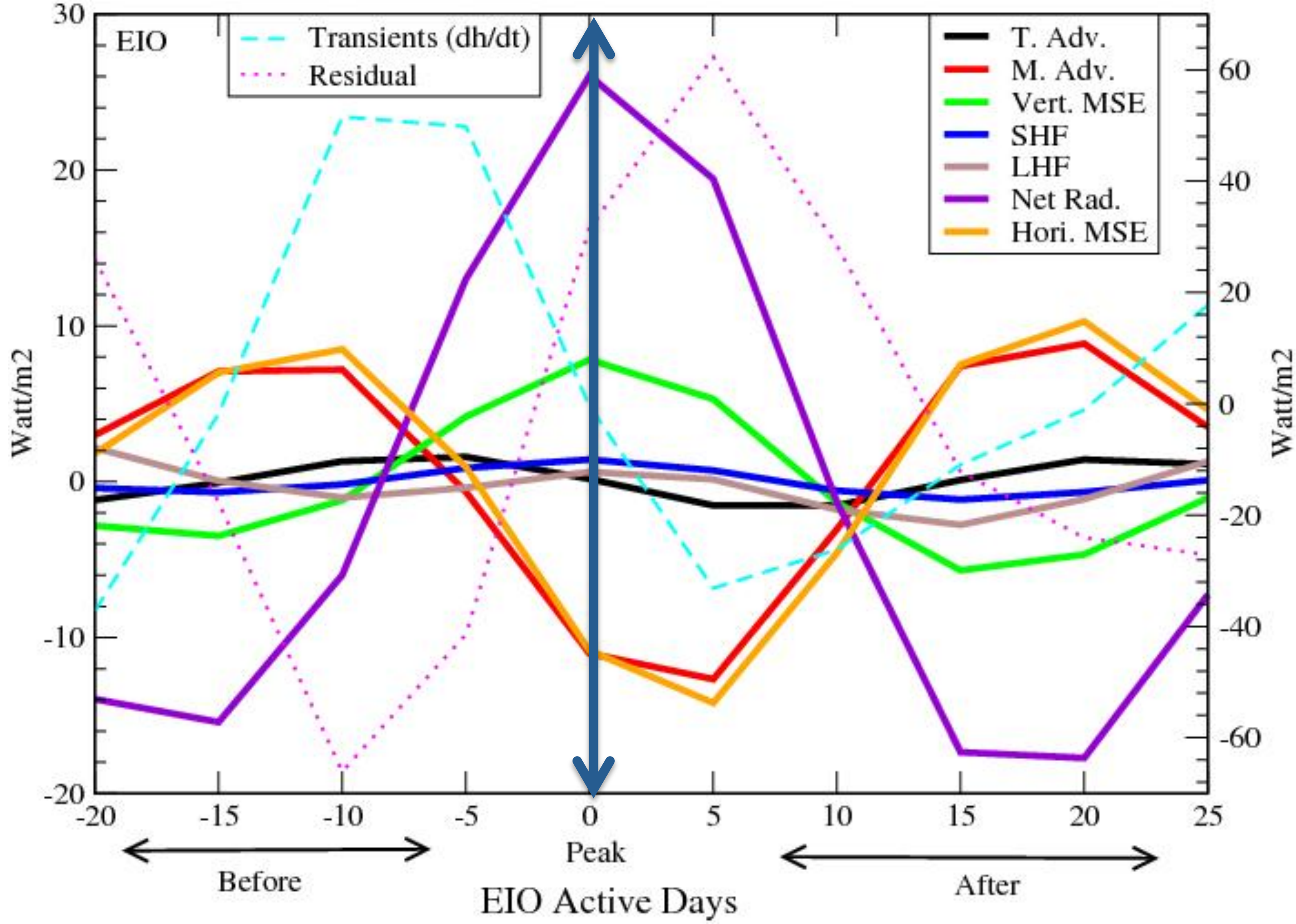
Extended monsoon breaks over central India (1951-2009)



IMD 1°x1° gridded rainfall observations

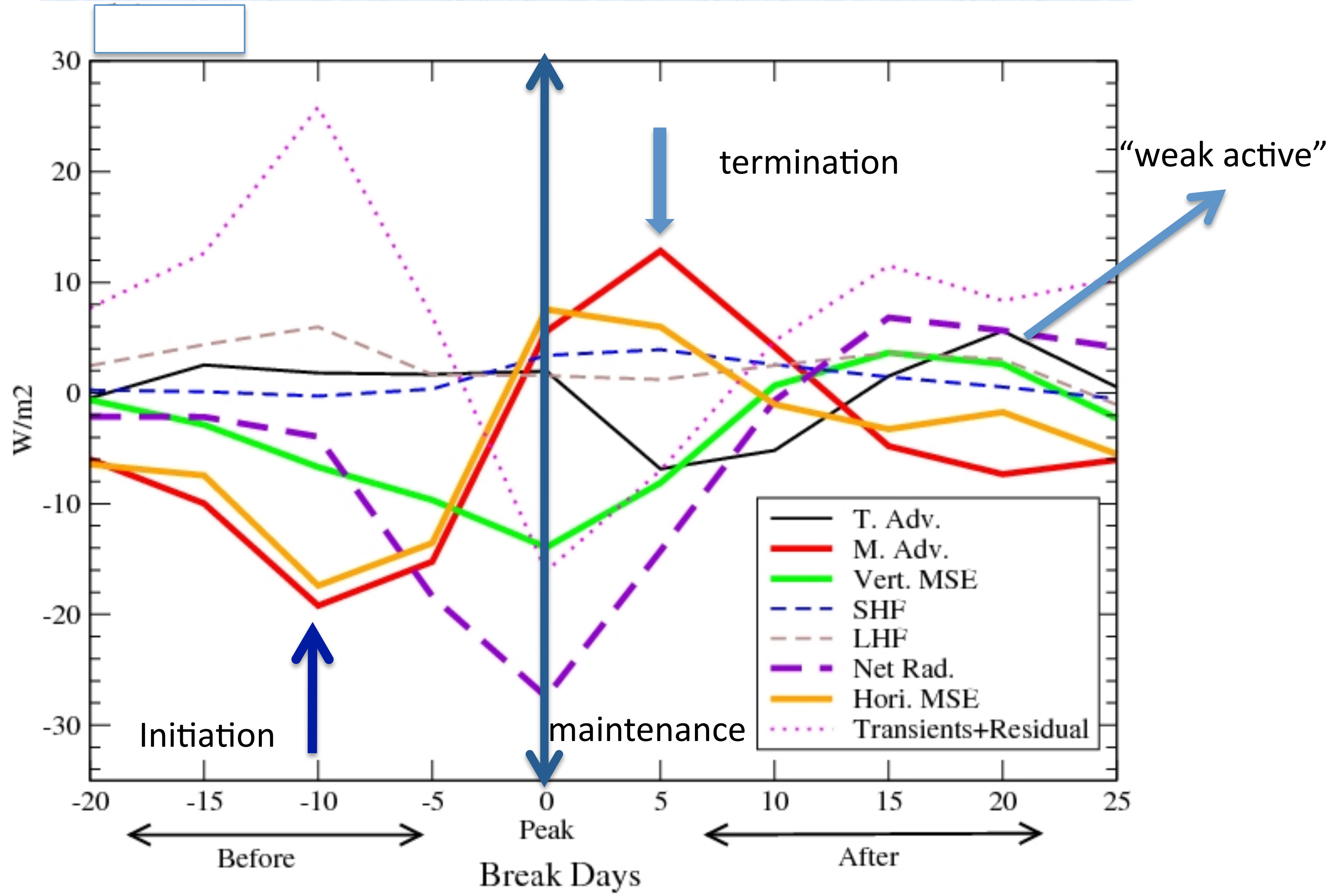
Prasanna and Annamalai (2012, JC)

MSE budget terms – Equatorial Indian Ocean



Differential radiative heating – anchors local Hadley circulation (Raymond 2005)

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



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

Summary for Case I

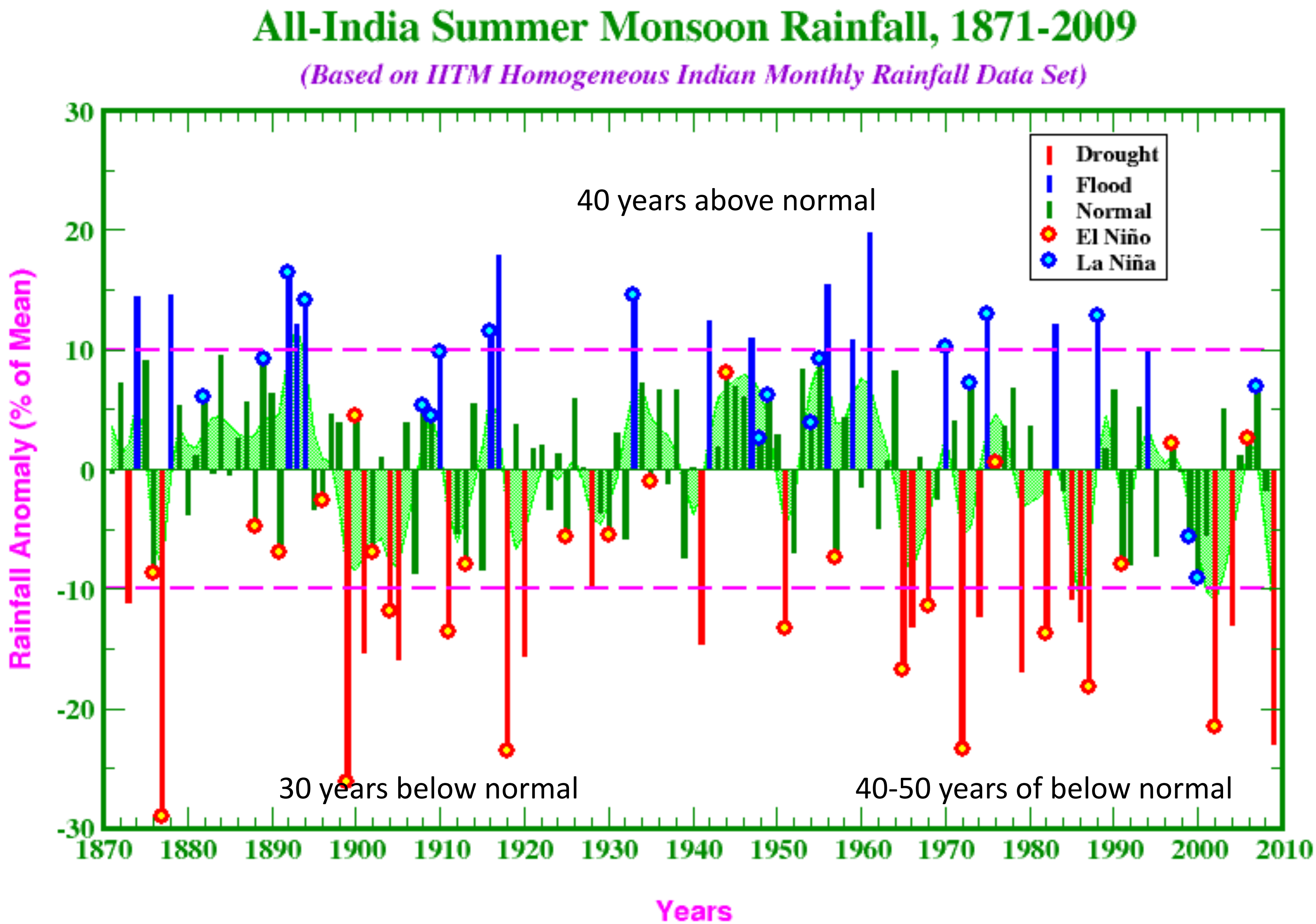
Extended monsoon breaks

MSE budget analysis identifies

$$-\left\langle \overline{V} \bullet \nabla m \right\rangle \qquad \qquad \left\langle LW \right\rangle$$

initiation and termination maintenance

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

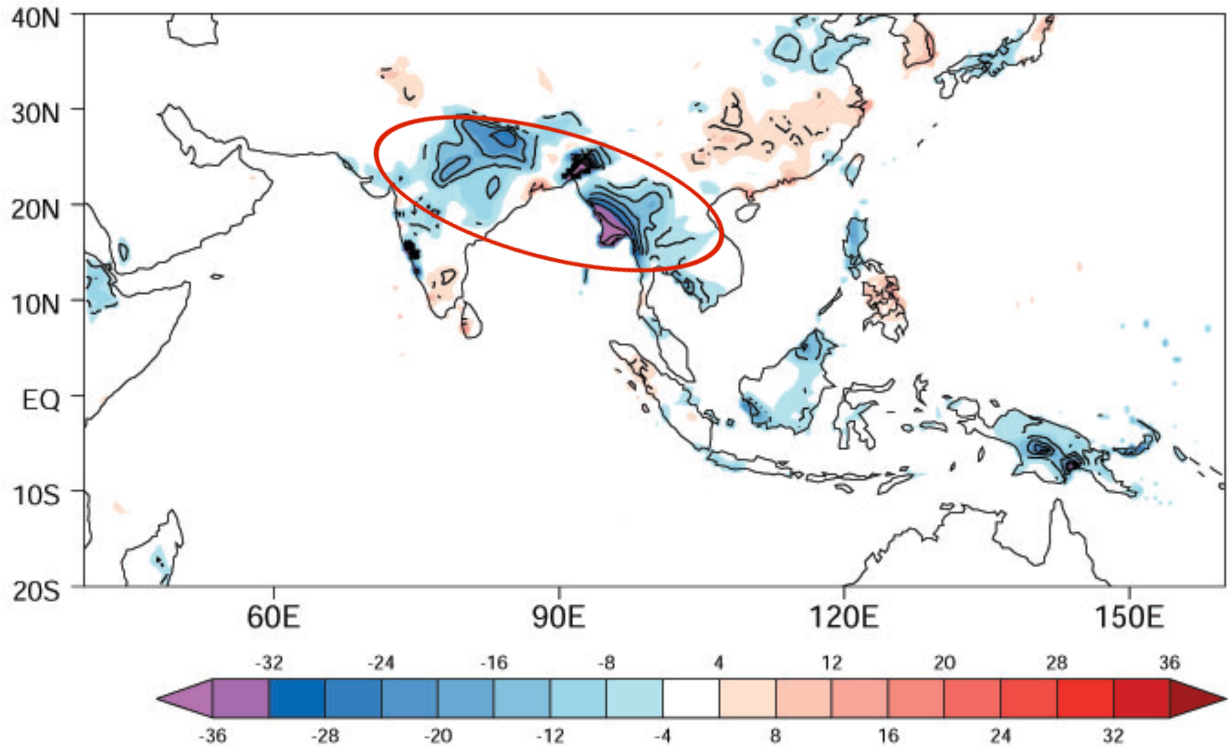


"since 1994….in a given year monsoon rainfall over India has not exceeded 10% above normal" but such incidents have occurred in the past too -

2 La Nina years – below normal rainfall

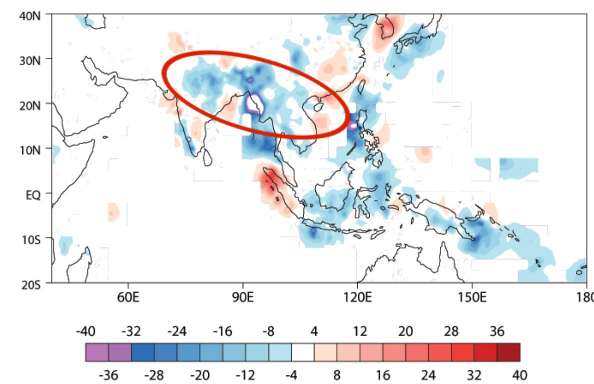
Linear trend in monsoon rainfall

CRU product

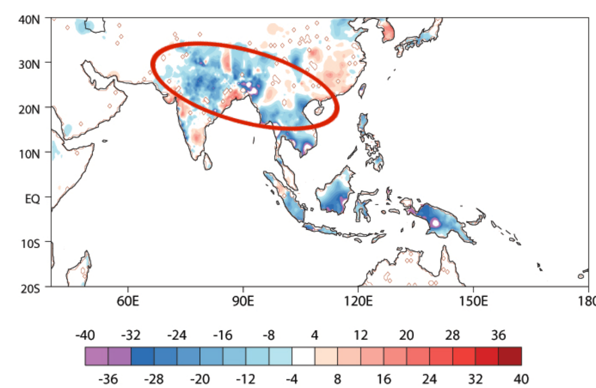


"spatial coherency – amplitude differs"

Delaware product

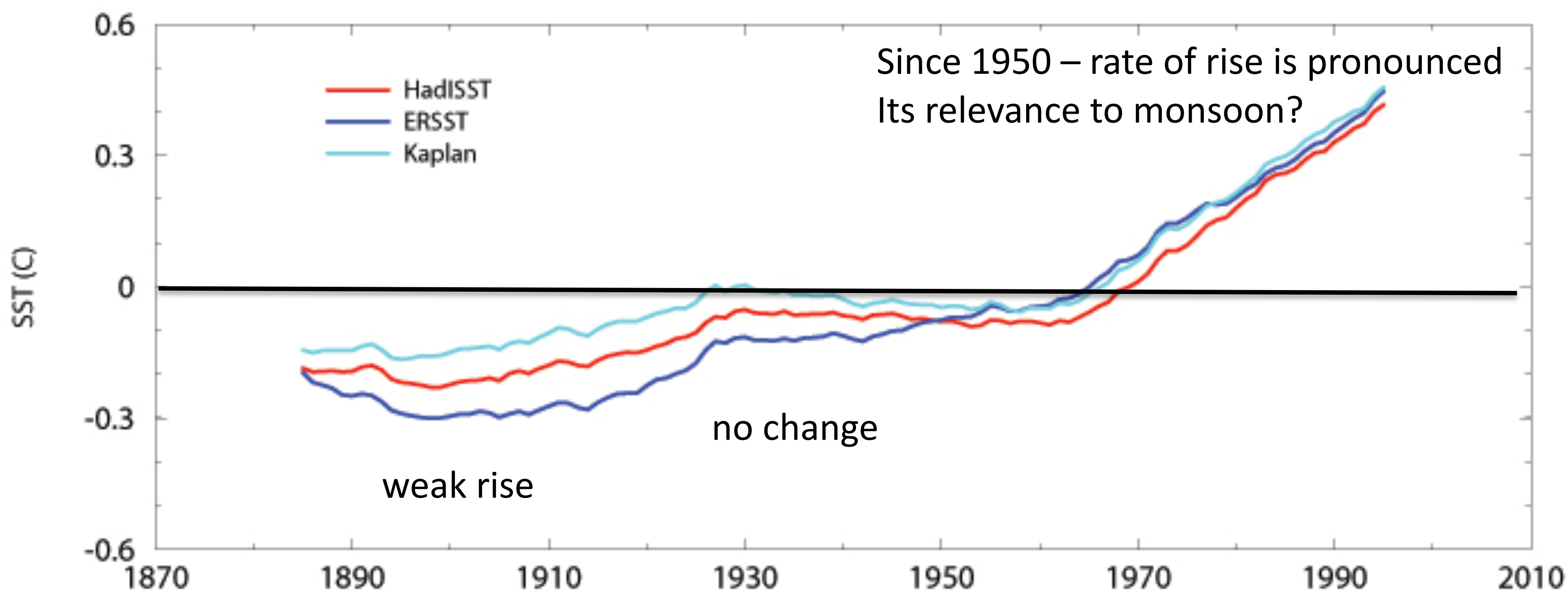


PREC/Land (NOAA)

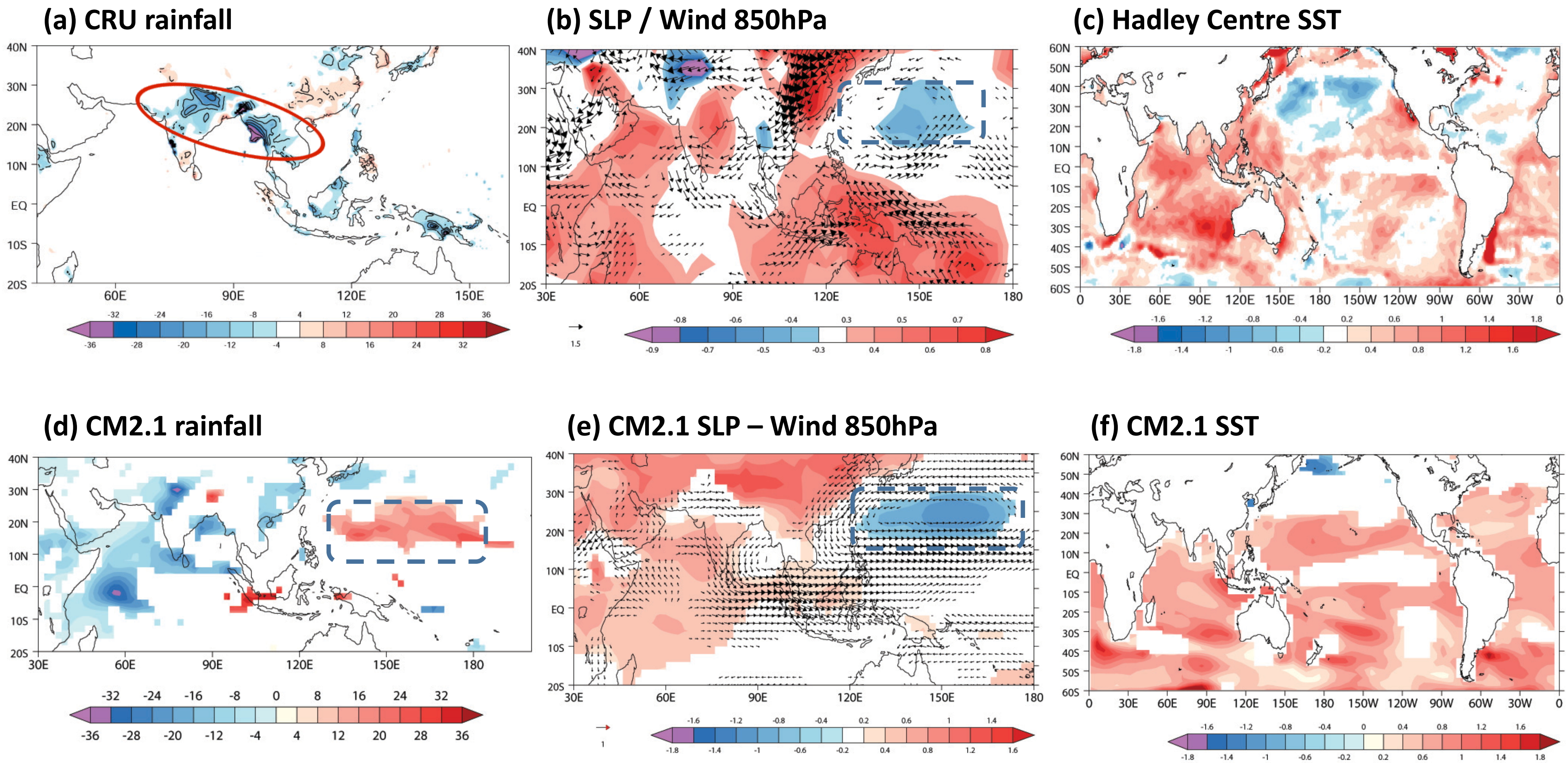


Black carbon aerosols – Ramanathan and Colleagues (Scripps/NCAR)
Sulphur aerosols – Ramasamy and Colleagues (GFDL)

SST averaged over the tropical Indian Ocean – West Pacific



Significant SST rise (above natural variability) since ~ 1950s



SST rise – shifts the monsoon circulation

more rainfall over tropical west Pacific

less rainfall over South Asia

Working Hypothesis

SST trend shifts the monsoon circulation – promotes more rainfall

over the tropical western Pacific - subsequent descent through Rossby waves and

dry air intrusion aid in the weakening of rainfall over South Asia

Annamalai et al. (2013, J. Climate)

Numerical experiments performed

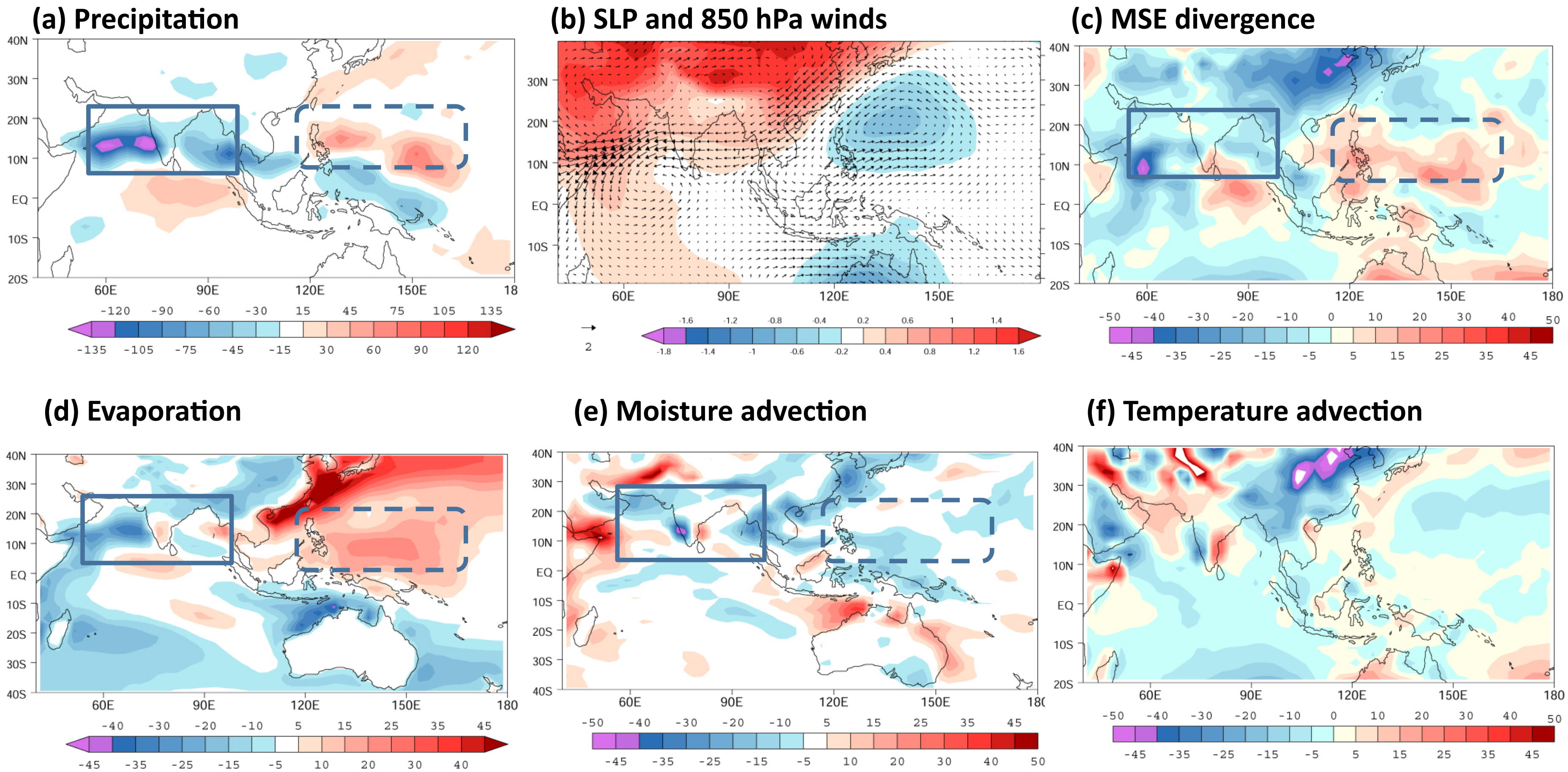
Monthly observed SST trend (1949 – 2000) superimposed on clim. SST – 5 members

1. Tropical oceans (GFDL – AM2.1) – results are shown

2. Tropical Indo-Pacific warm pool (GFDL - AM2.1)

3. Tropical west Pacific only (GFDL – AM2.1)

4. Linear barolcinic model (steady-state solutions) – to identify Rossby wave dynamics



Linear trend simulated by AM2.1

Dry, cool air penetrates South Asia

Summary

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

- MSE budget residuals – observational constraints over Monsoon regions

- Model improvement – need 3-d moisture and radiation observations

Additional slides

Any precursors in moist and radiative processes?

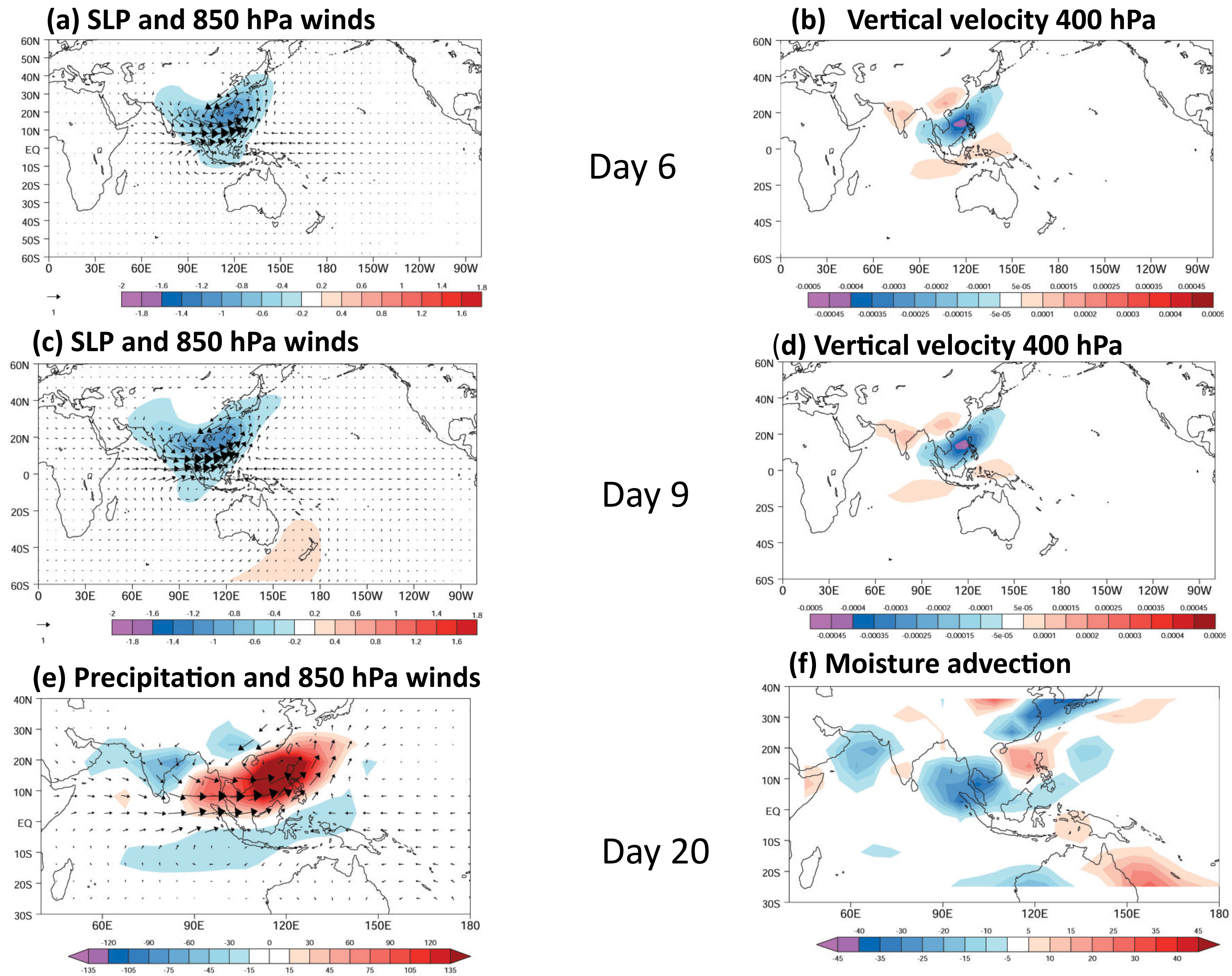
- **ERA-Interim (1989-2010) -**
- **For composite and individual cases, apply MSE budget**

Budget estimated over (i) central India

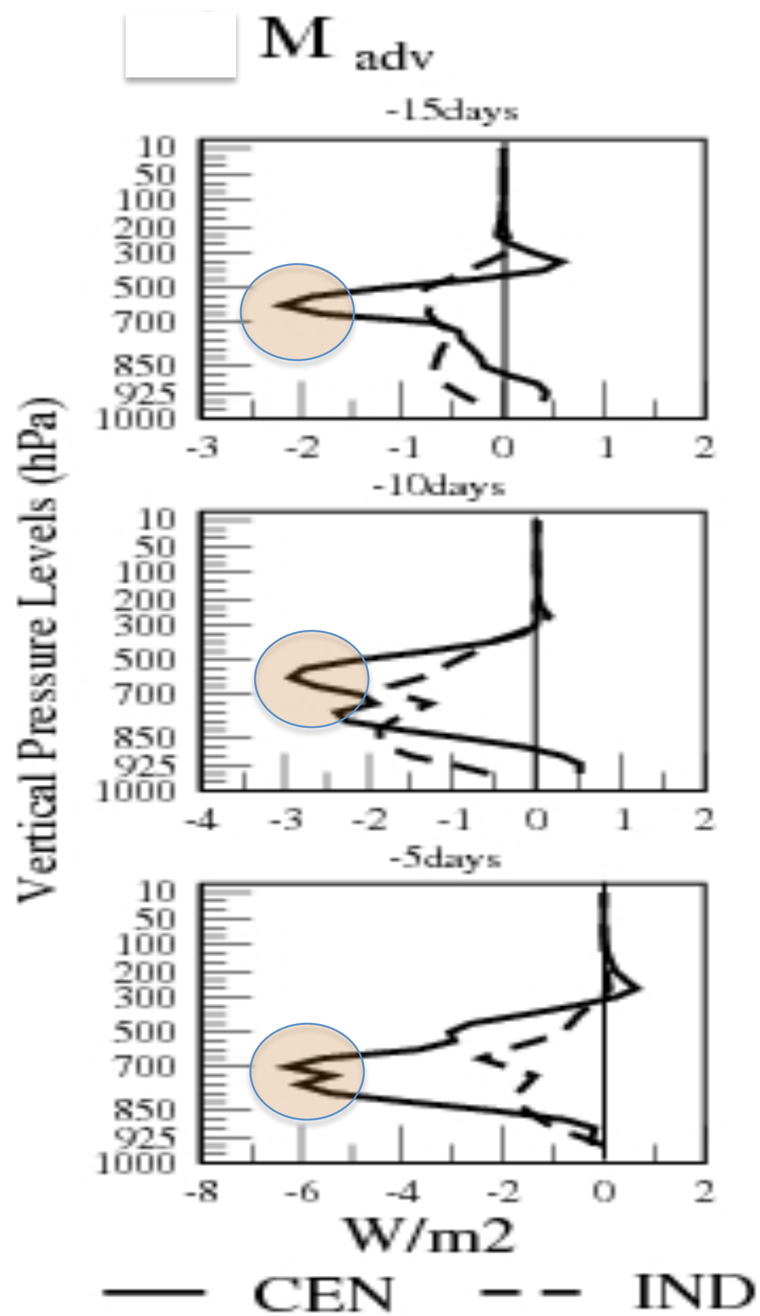
(ii) Eastern equatorial IO

(iii) Tropical western Pacific

Regional circulation anomalies forced by (ii) and (iii) are important



Rossby wave interpretation



Dry air intrusion –

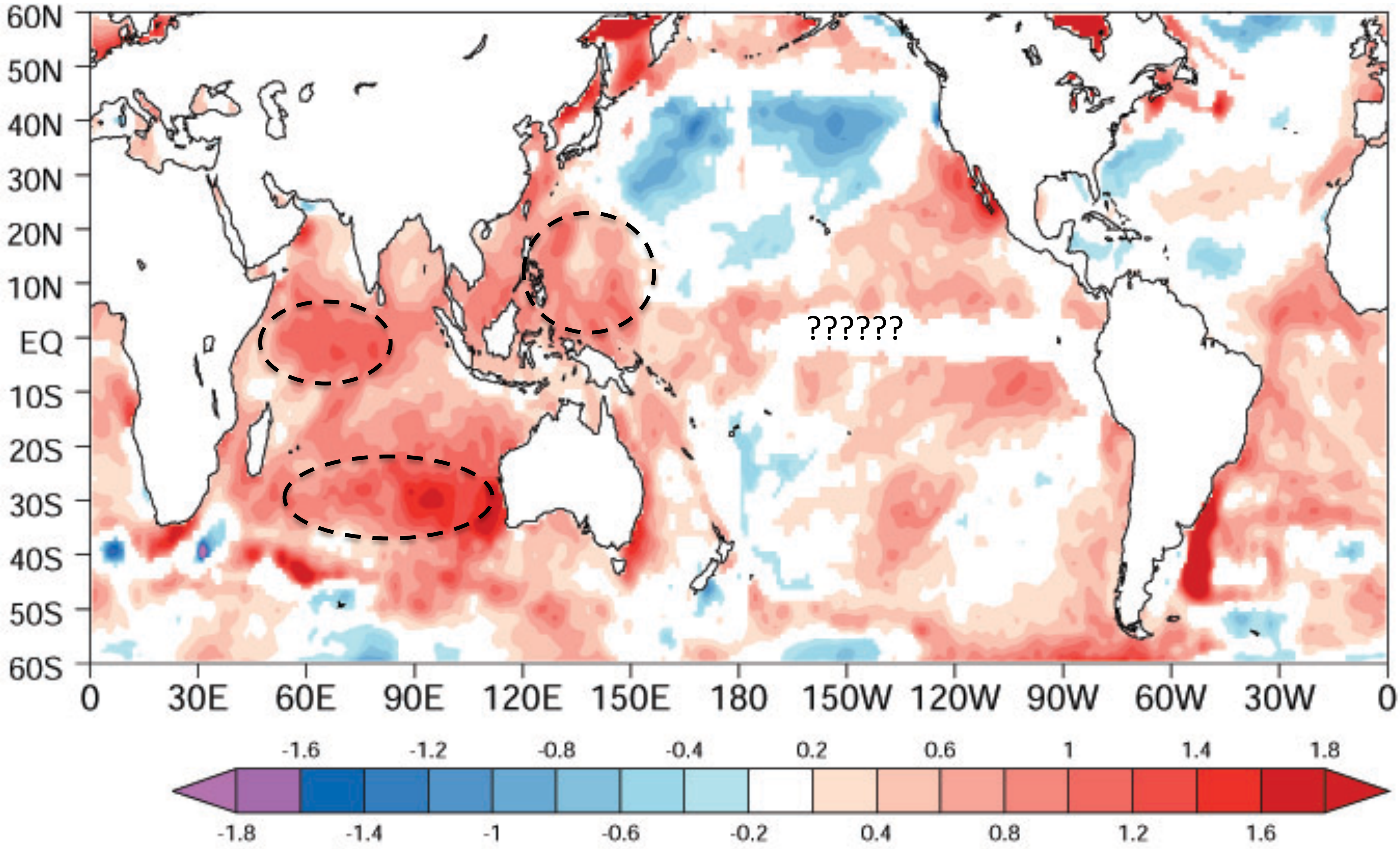
Convective inhibition layer

"deep convection sensitive to mid-troposphere moisture"

Useful predictive information

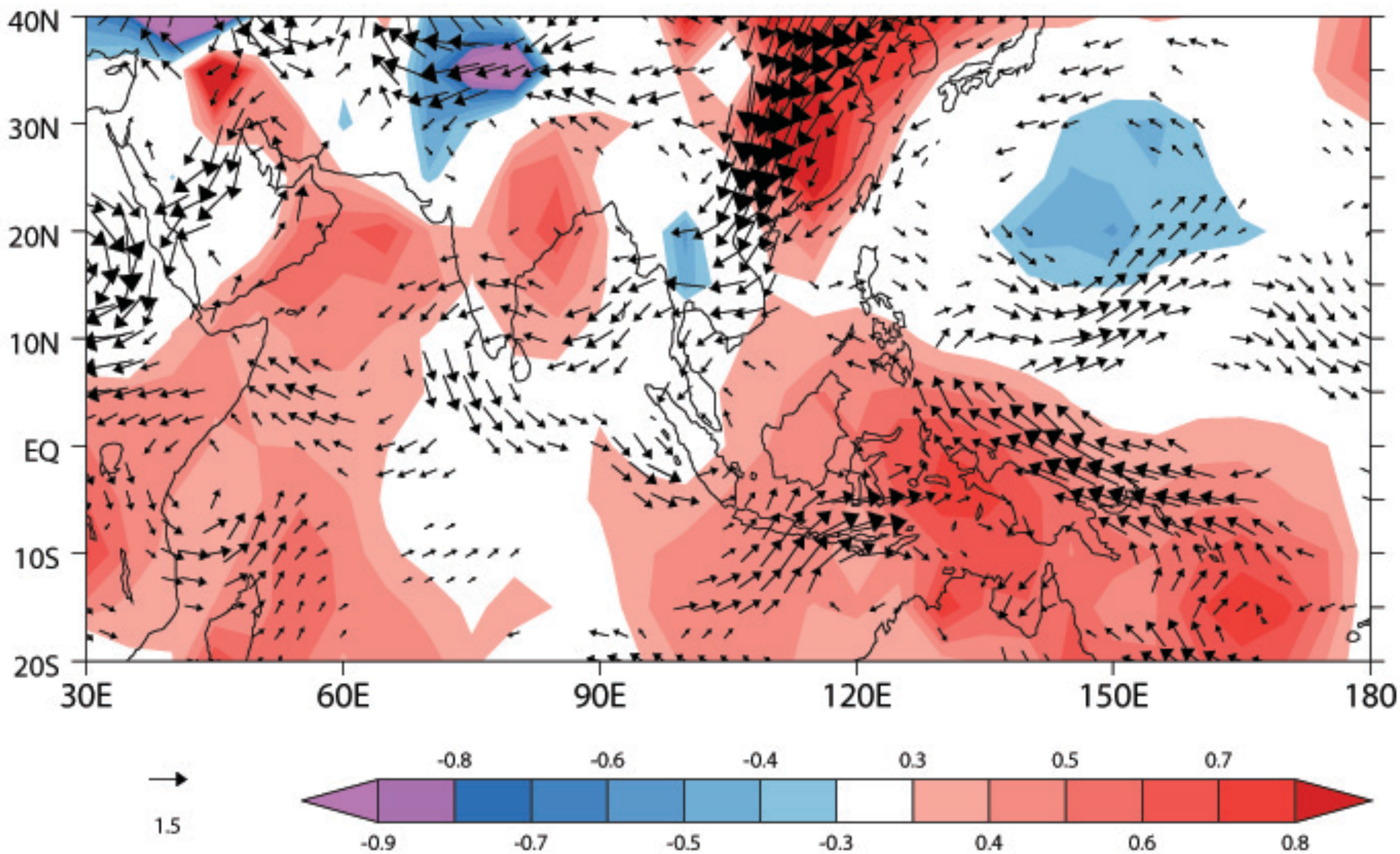
(**2002/2009 Case studies**)

JJAS SST linear trend



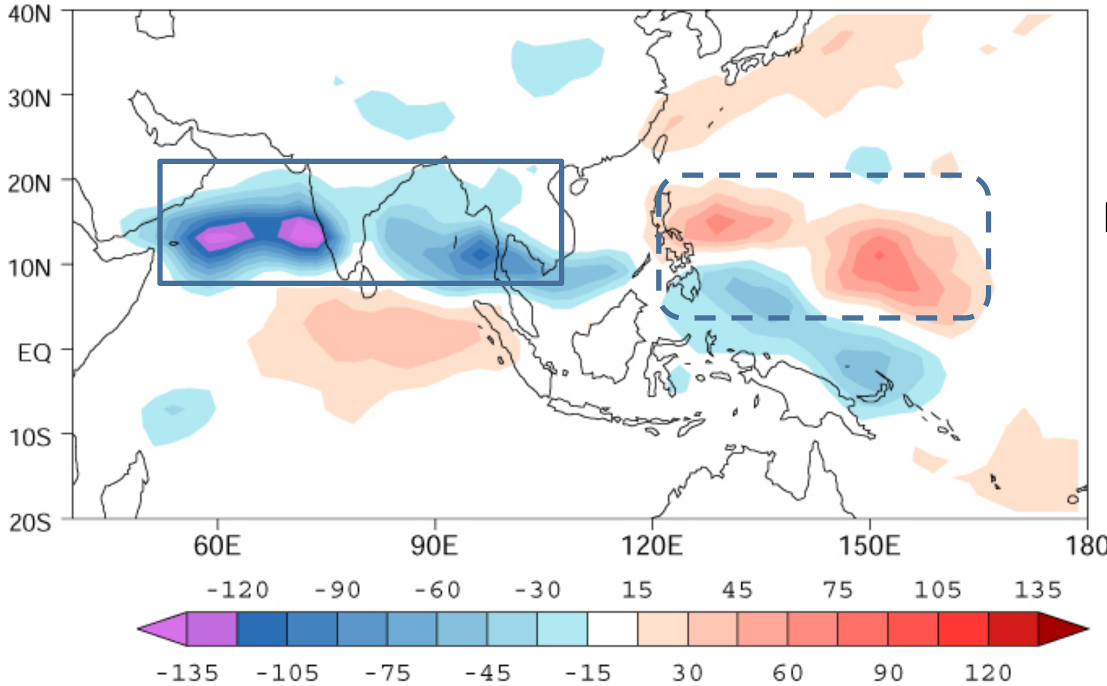
SST rise over climatological low rainfall regions – any changes in evaporation – obs??

SLP (shading) and 850 hPa wind – linear trend 1949-2005



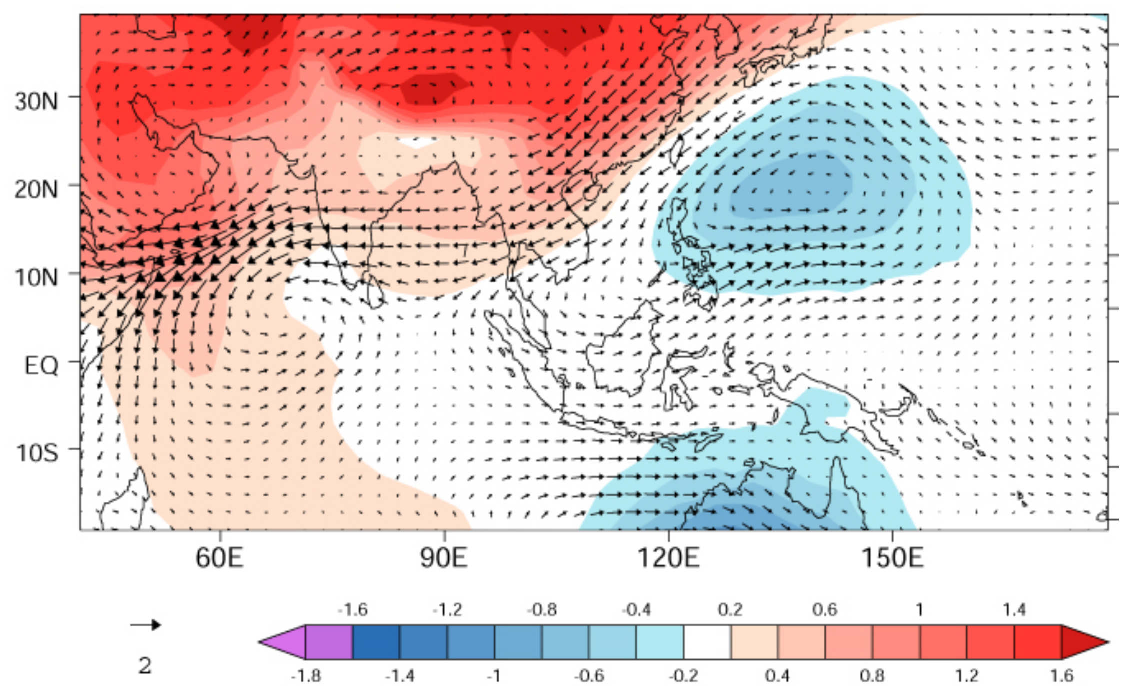
monsoon trough over India weakens" SLP deepens over the tropical western Pacific – "Australian and Mascarene High – intensify – cross-equatorial flow over the western Pacific is strengthened - cyclonic vorticity (regional circulation changes)

" Despite SST rise, atmosphere over the tropical Indian Ocean has not yet responded"



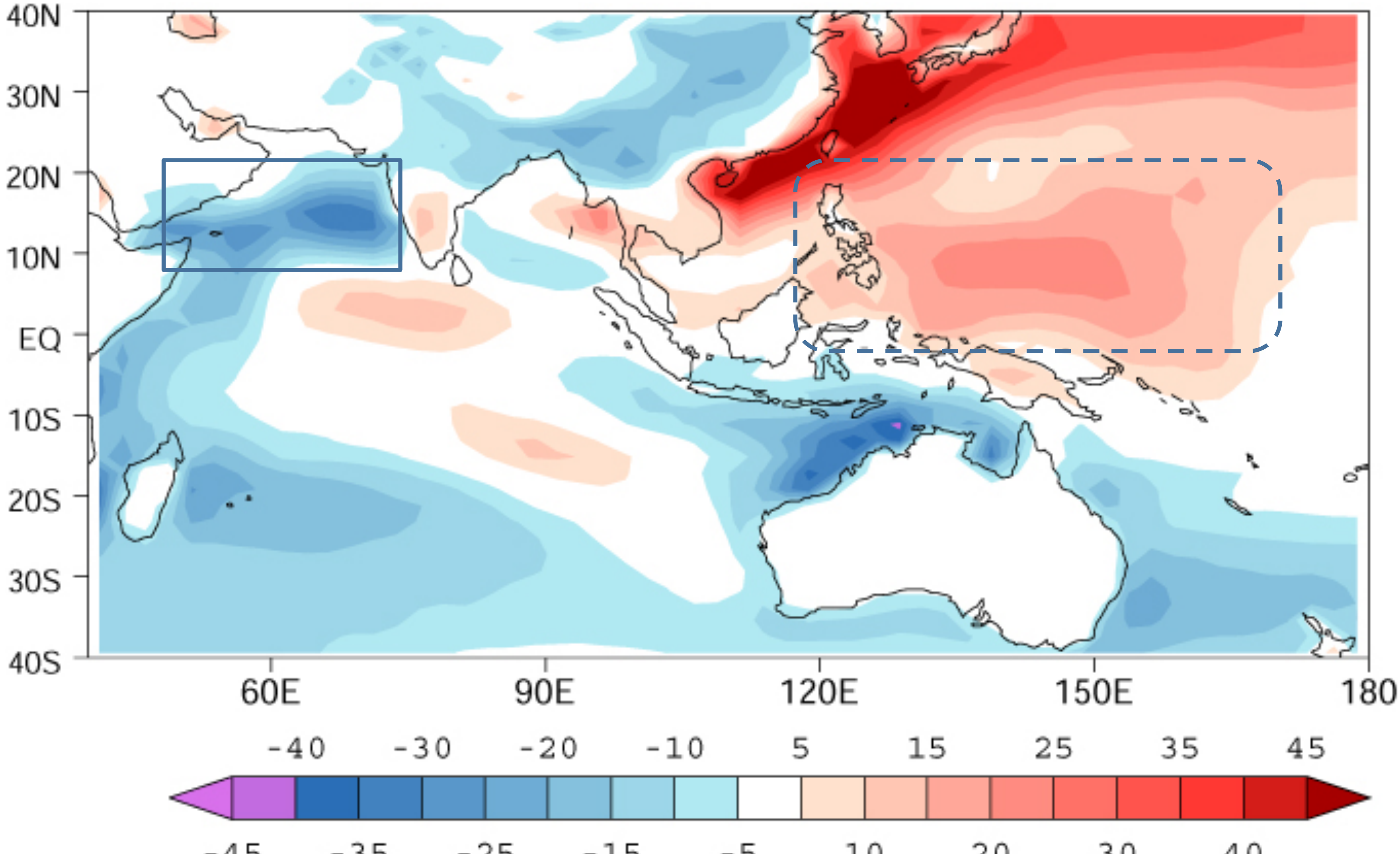
Rainfall linear trend (AM21 simulated)

SLP (shaded) and 850 hPa wind

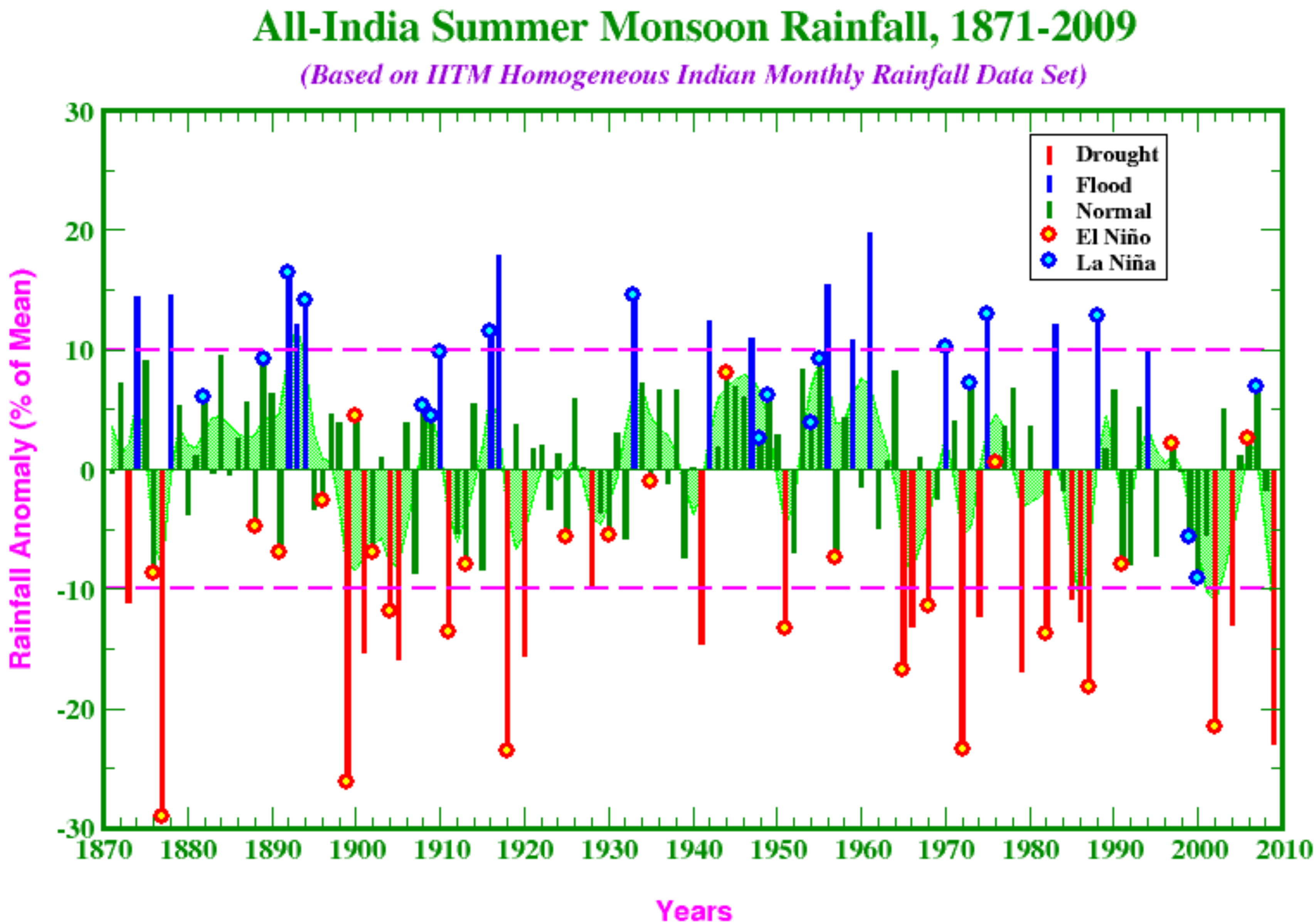


“Australian high – not consistent with reanalysis products”

Evaporation trend – simulated by AM2.1

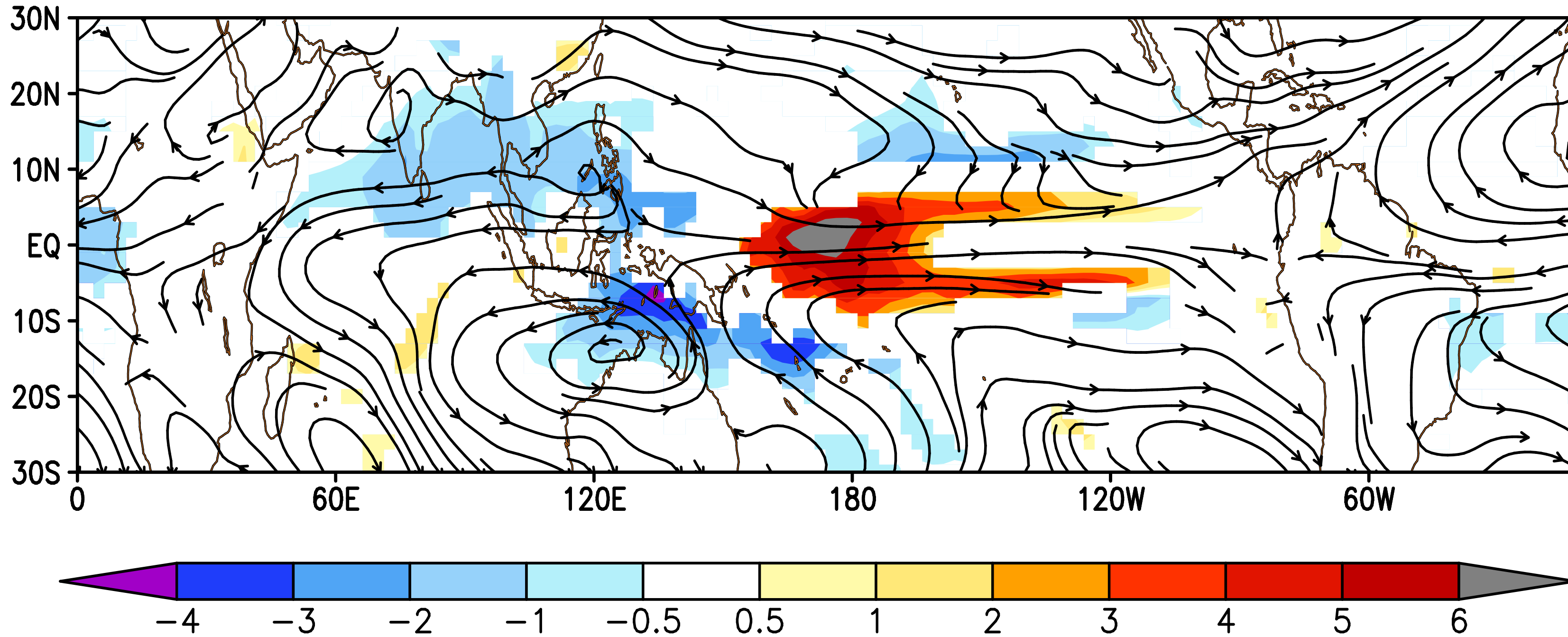


"Evaporation decrease along the cross-equatorial flow is due to wind anomalies despite SST rise is prescribed in the model experiment"



Severe weak monsoon years – associated with El Nino

May averaged CM2.1 composite of anomalous 850 hPa stream line and rainfall



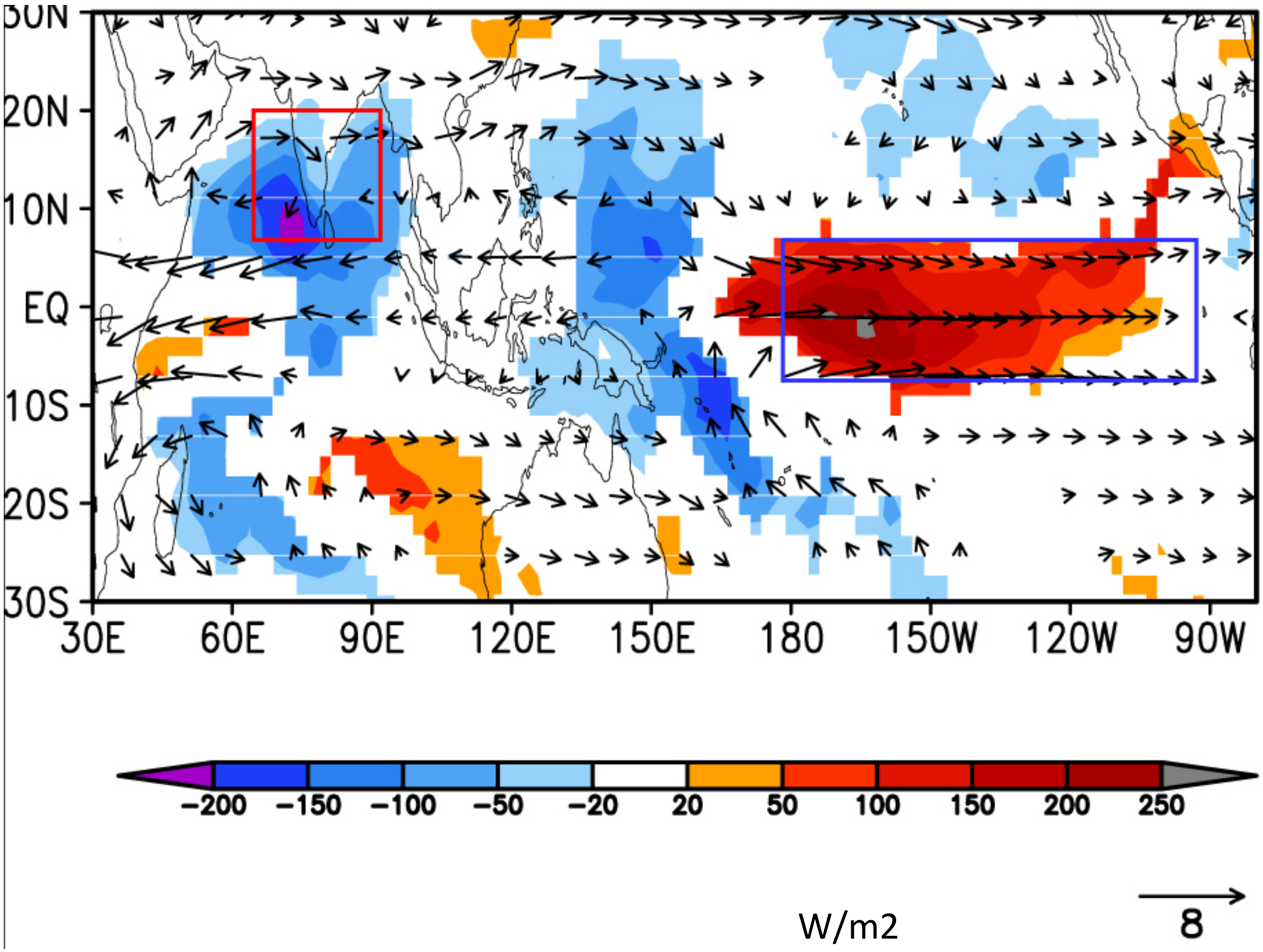
Severe weak monsoons over south Asia co-occurred with developing phase of El Nino

NIO – anticyclonic vorticity – within 2-3 days of SST forcing – rainfall after about 20 days

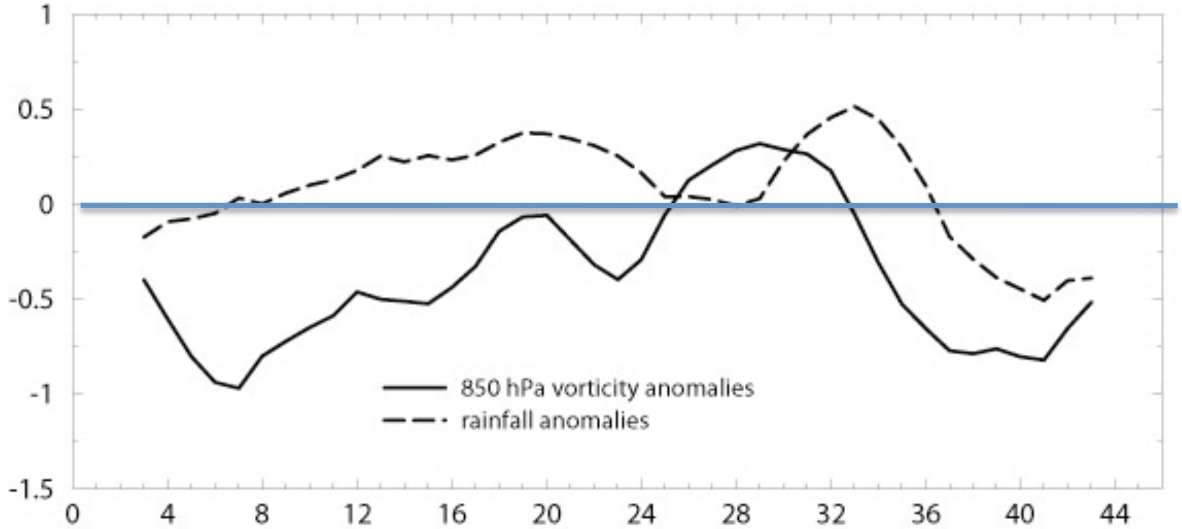
Dry air advection from north is instrumental in initiating the dryness

Pillai and Annamalai (2012, J. Atmos. Sci.)

May rainfall and 850 hPa wind response to El Nino SST forcing



AM2.1 solutions – Forced with CM2.1 composite SST anomalies (El Nino)

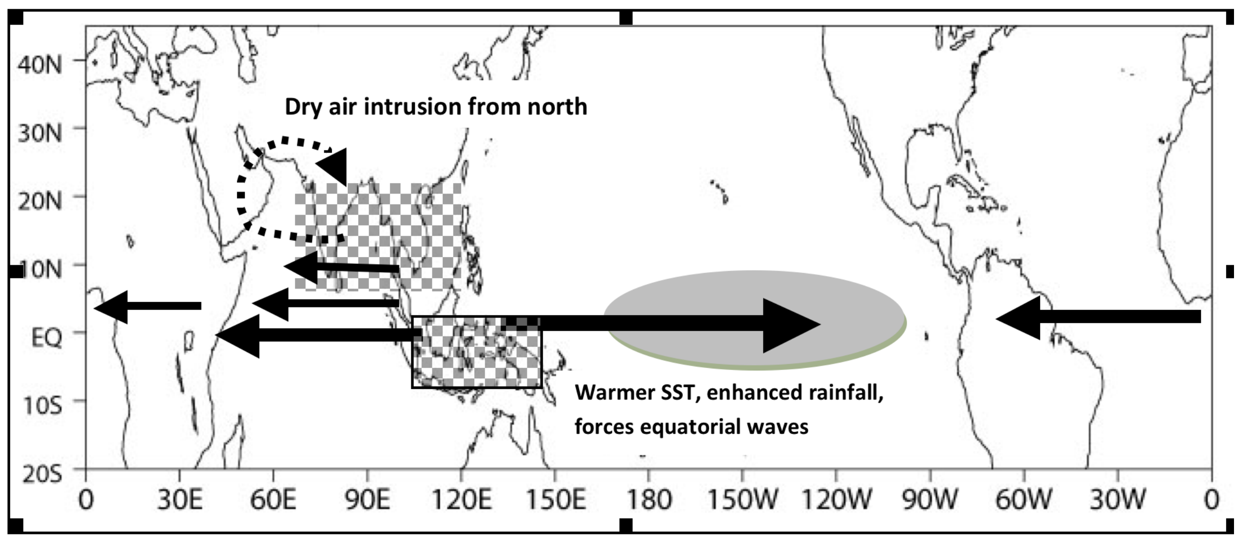


Days from 15 March

Rainfall over S. Asia

850 hPa Vorticity

(west of rainfall maximum)



Summary – Case II

“dry advection leads rainfall anomalies – long lead time – useful for prediction”