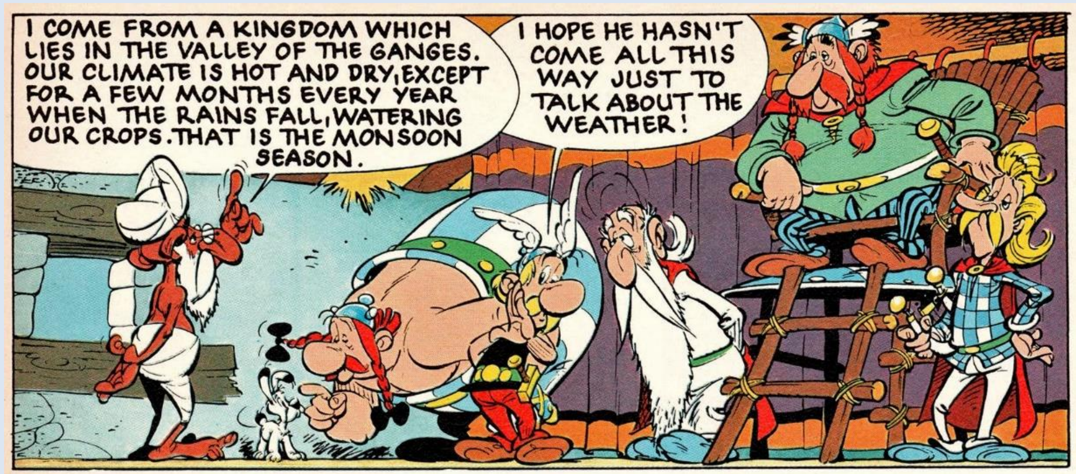
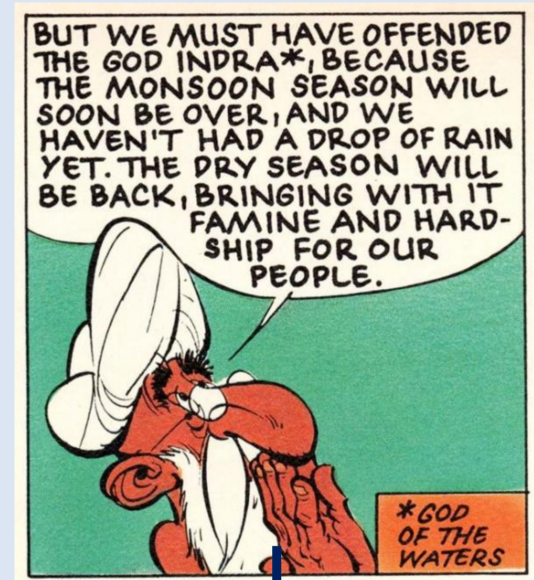
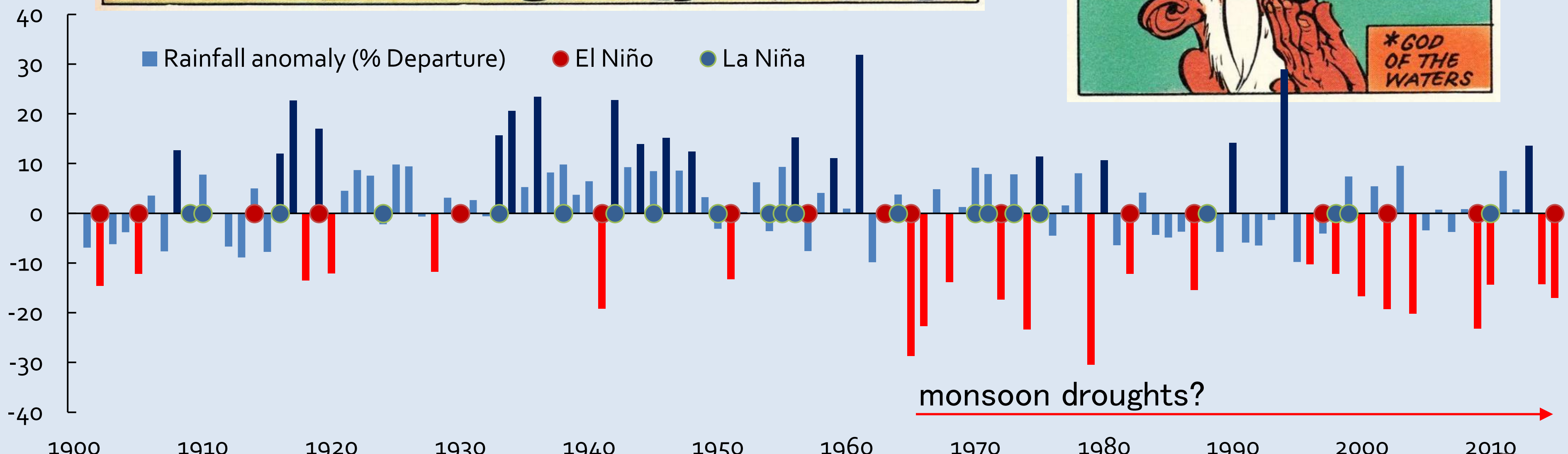
Interaction of Asian Monsoon and global oceans
—in a changing climate







Roxy Mathew Koll
Indian Institute of Tropical Meteorology, Pune

Interaction of Asian Monsoon and global oceans

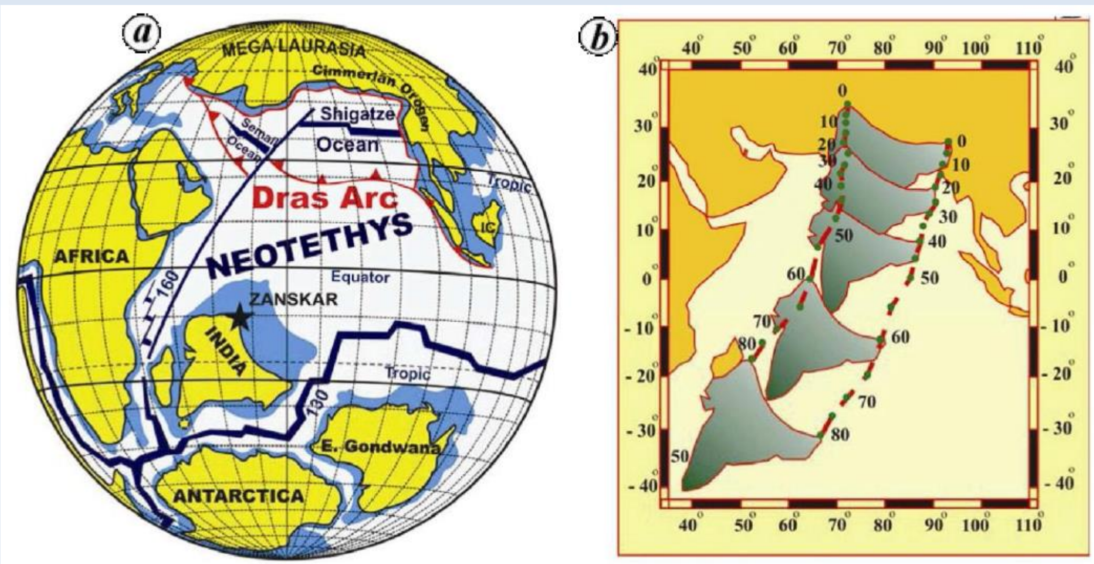
1. **Past: A bit of Monsoon history**

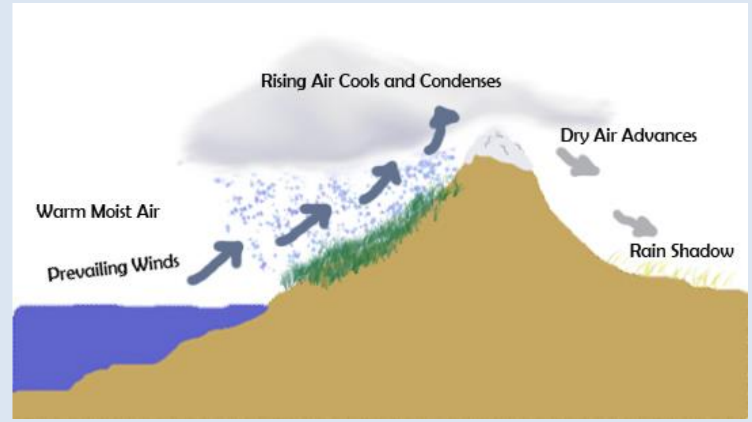
2. **Present: The Monsoon we know/live**
   - Role of Ocean on the Monsoon
     - Interannual variability of the Monsoon – ENSO, IOD, etc.
     - Intraseasonal variability of the Monsoon
     - SST–convection relationship

3. **Trends/Future: Changing Oceans and the Monsoon**
   - Changing ENSO–Monsoon interactions
   - Indian Ocean warming
   - Atlantic warming
   - Interplay between the tropical oceans

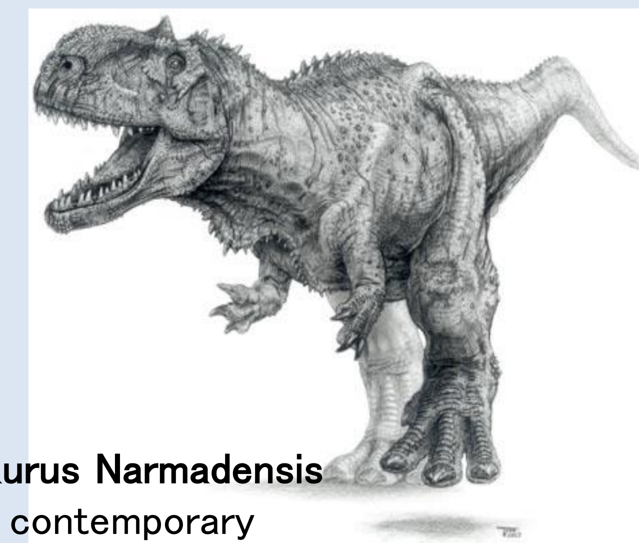
4. **Monsoon Modeling**

Plate tectonics – factors leading to modern monsoon





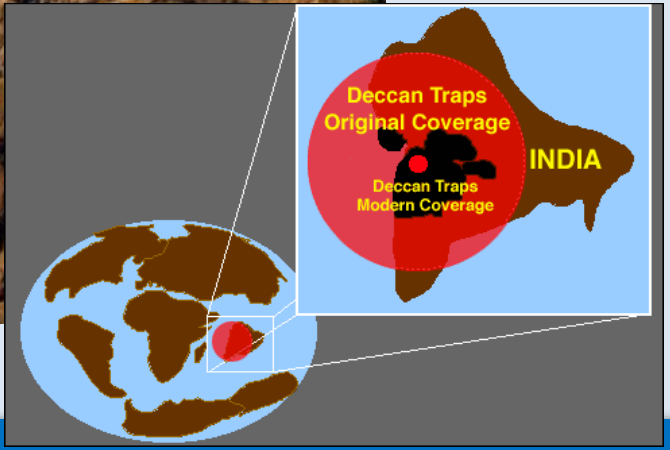
Indian plate motion: rate of ~ 15cm/yr
– collided with Eurasia c.20–30 Mya.
Tethys evolved into the present day Indian Ocean



Rajasaurus Narmadensis
–T.rex contemporary

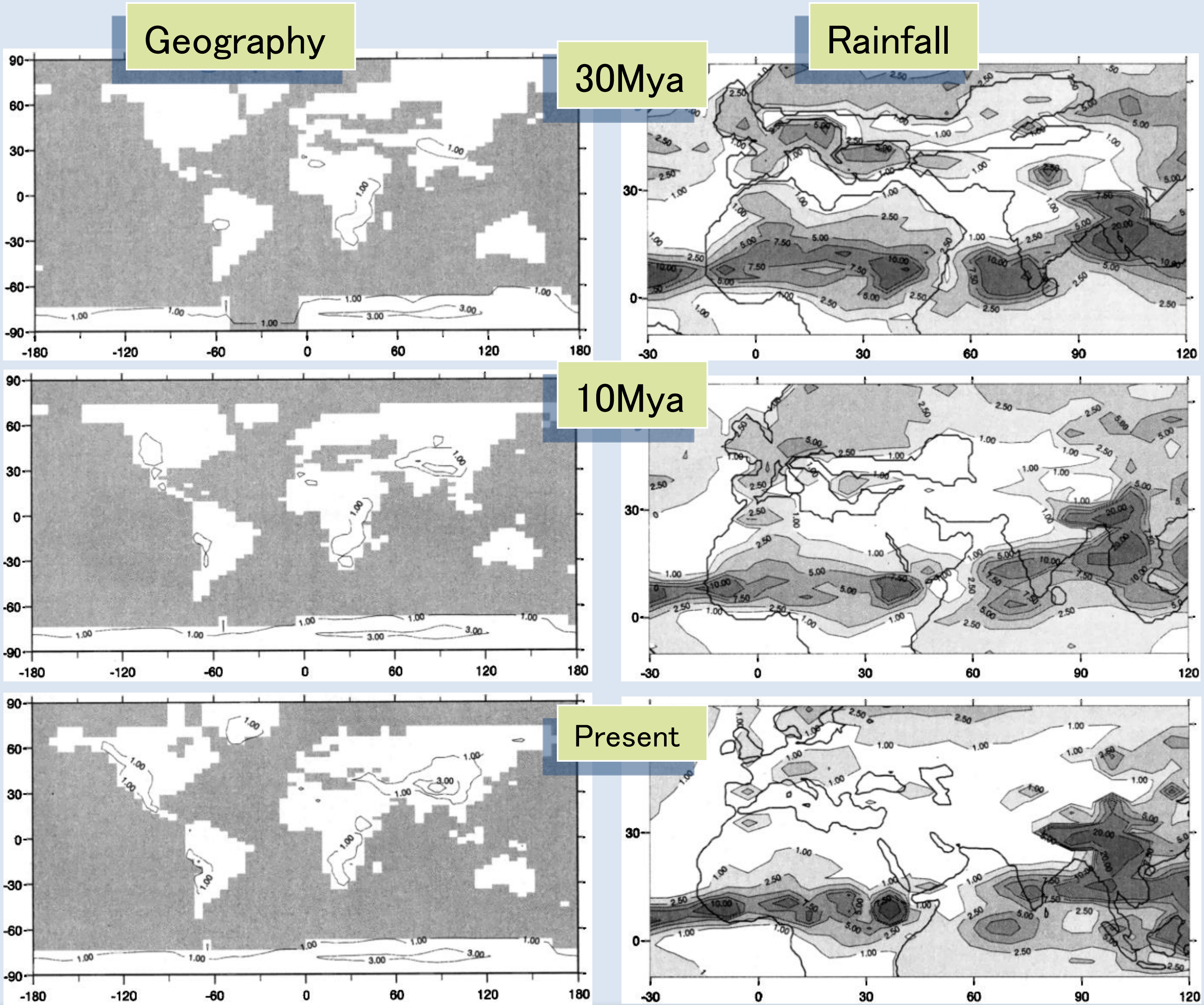
Copley et al. *JGR*, 2010; Jain *Curr.Sci.*, 2014

Remnants of Deccan Volcanism



History of Monsoon, 30Mya

Rise of the Himalayas and strengthening of the monsoon



The Himalaya–Tibetan plateau uplift during late Tertiary strengthened the Asian Monsoon.

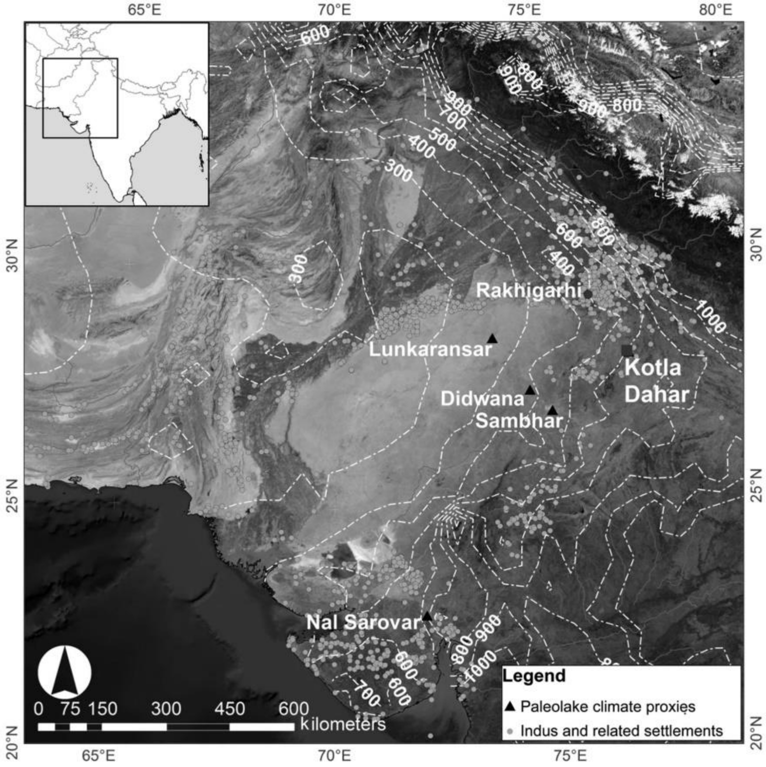
Confinement of African monsoon to a thin band, expanding the subtropical desert is also seen.

Role of Orography:

1. Upward deflection of large scale horizontal flow by orography
2. Uplifted moist air will expand, cool and condense – forming clouds

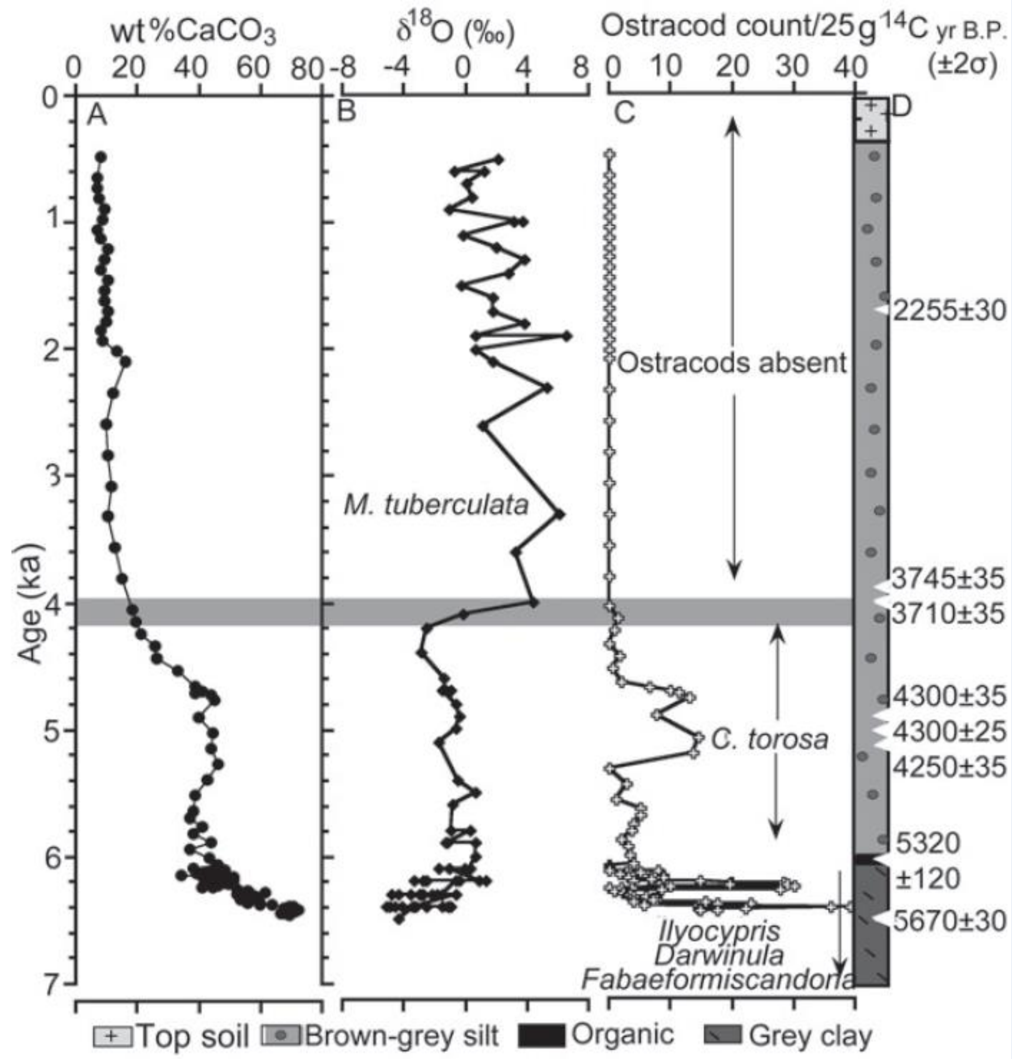
Fluteau et al. *JGR*, 1999

Monsoon weakening in NW and collapse of Indus Valley

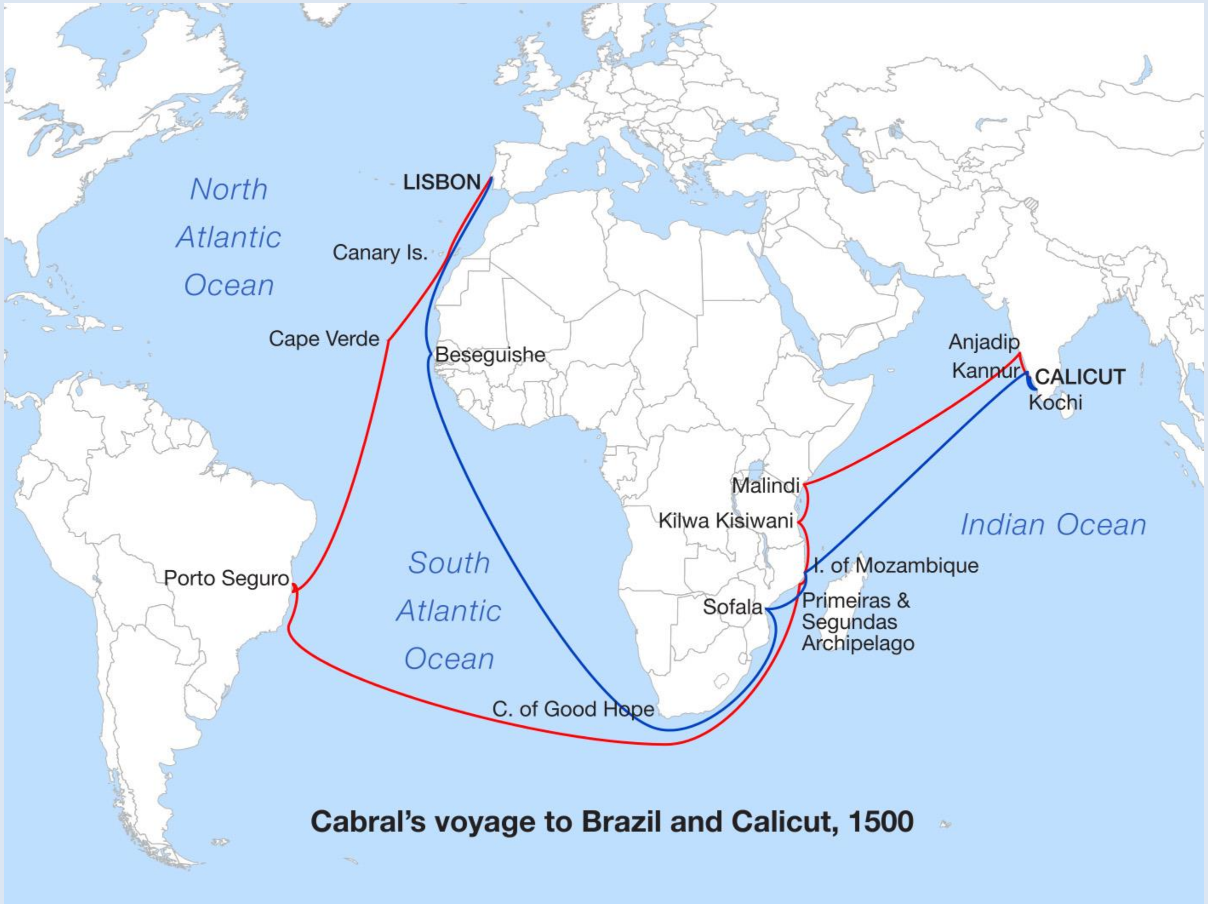


Variation in the timing and intensity of the monsoon affects lake-water Oxygen isotope and alters relative hydrologic balance between evaporation and precipitation in the lake.

Presence/absence of ostracods confirms this.



Trade Winds – History Changers!



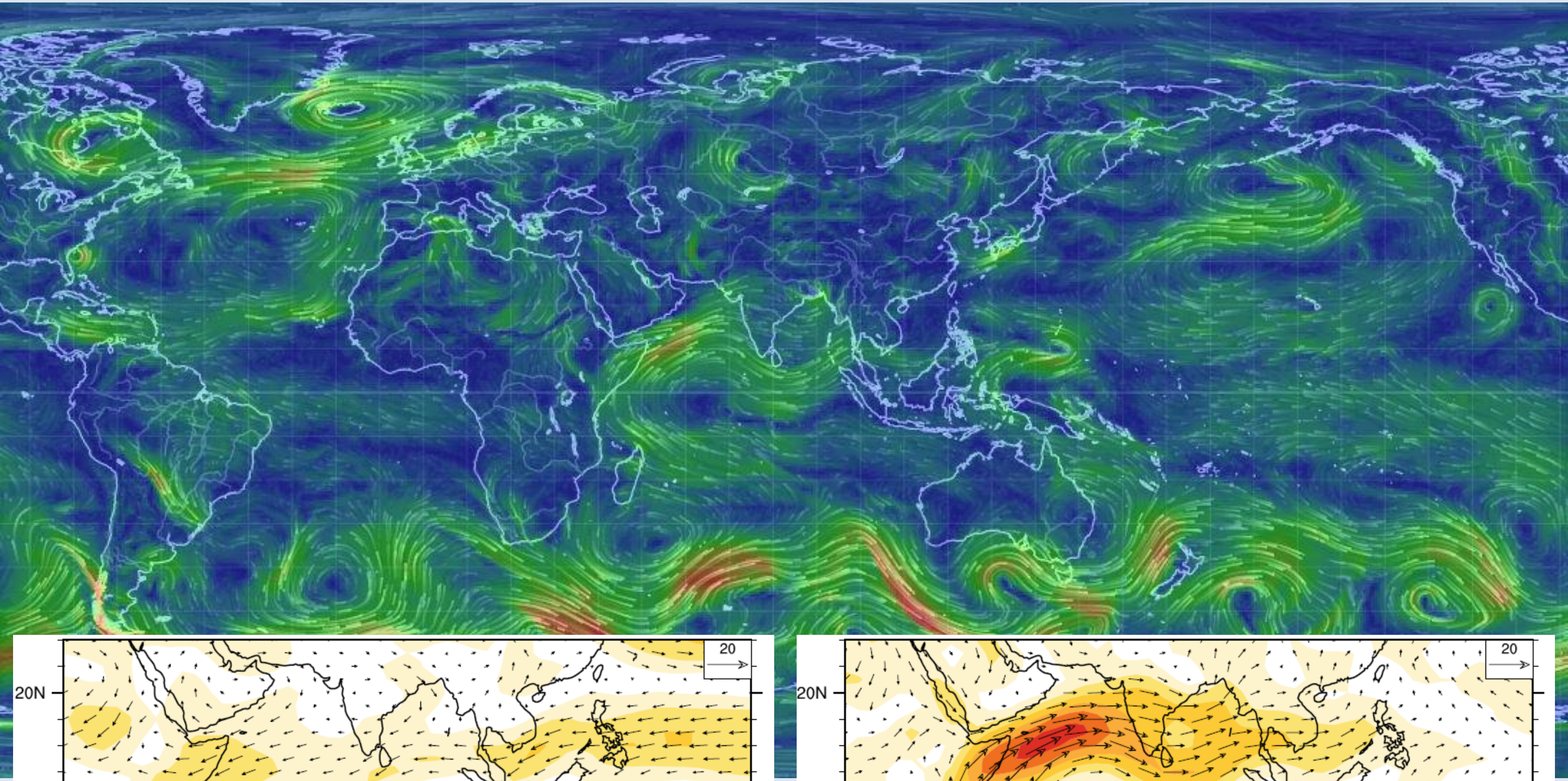
Using the trade wind secret, Indian/Asian and Arabian traders were able to dominate the lucrative market by concealing the true source of their cargoes for centuries.

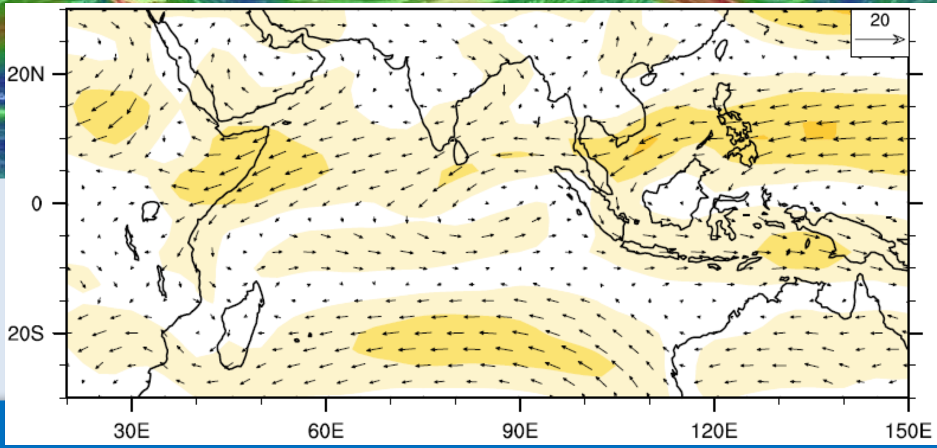
Mediterranean sailors from Egypt and Europe were fearful of open-sea sailing and their ships hugged the coastlines

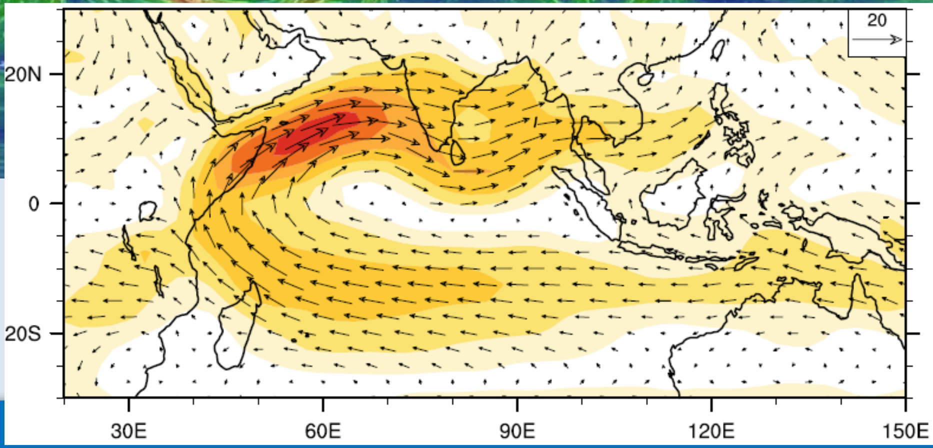
– until 1st century BC when a stranded sailor revealed the secret to Egyptian Officials.

Monsoon, manifested by Winds

Trade Winds

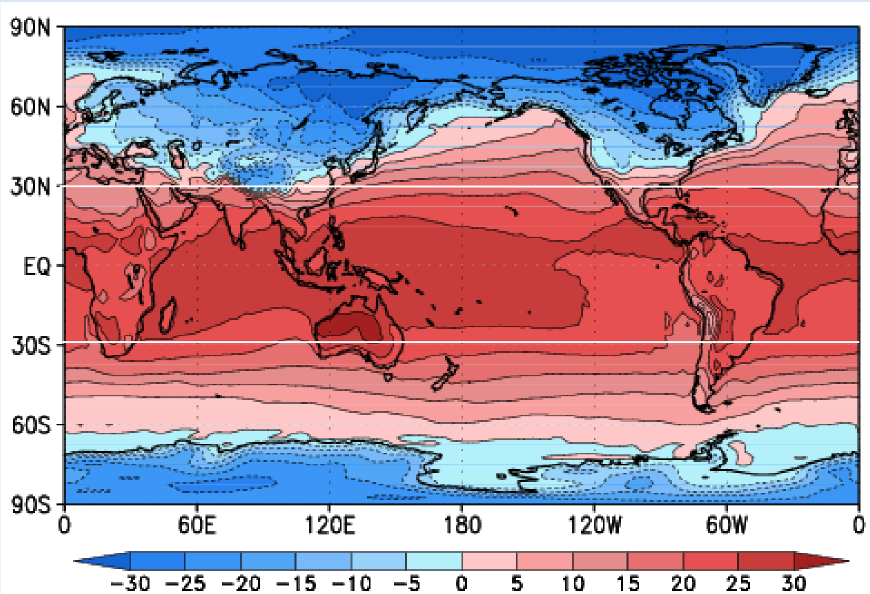






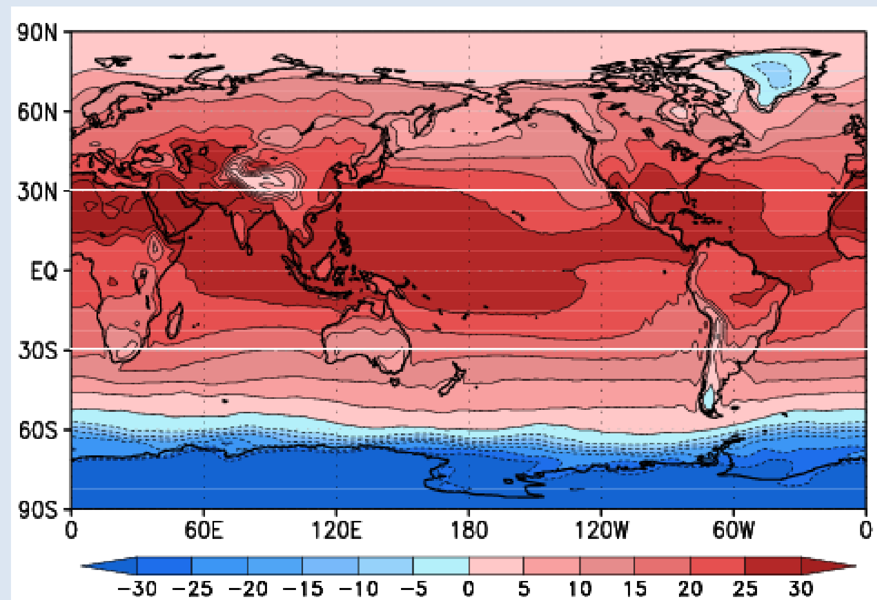
Monsoon, manifested by Surface Temperatures

Seasonal migration of solar insolation



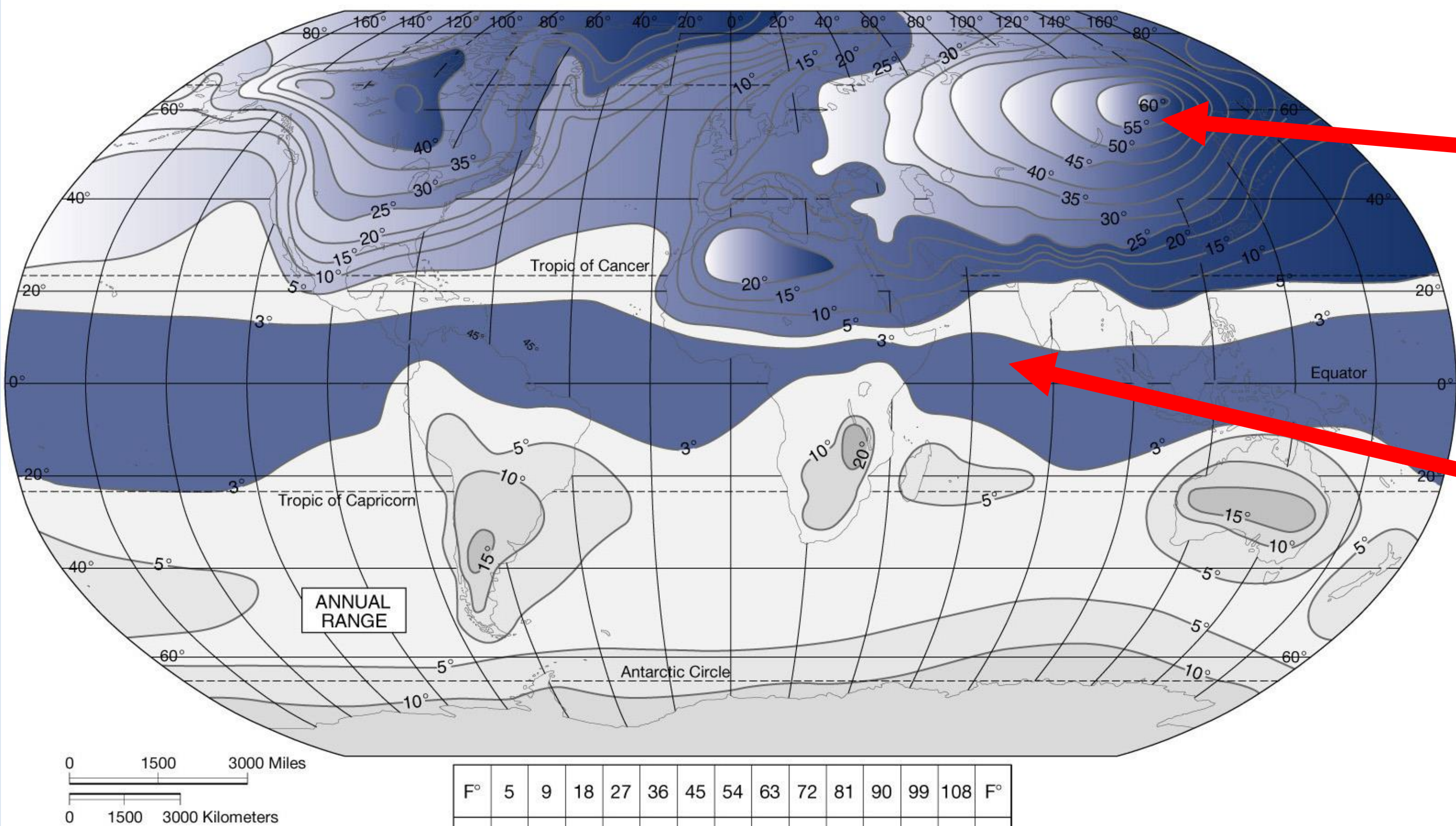
January

July



Monsoon, manifested by Thermal Contrast

Land and sea warms at different rates, sp.heat capacity



F°	5	9	18	27	36	45	54	63	72	81	90	99	108	F°
C°	3	5	10	15	20	25	30	35	40	45	50	55	60	C°

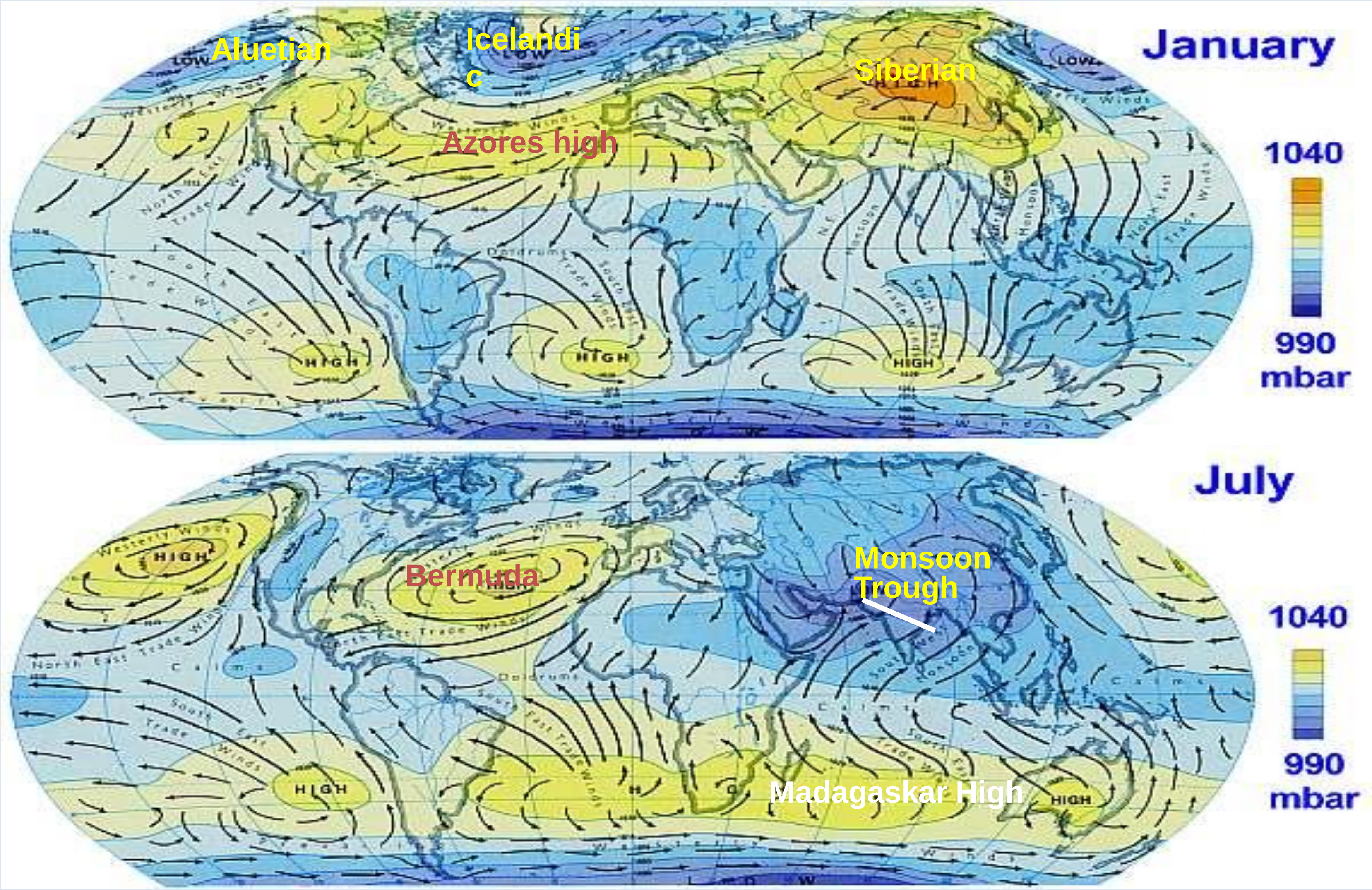
(c)

Tibetan plateau: range of 60° C

Ocean: range of 3 to 5° C

Monsoon, manifested by Pressure Gradient

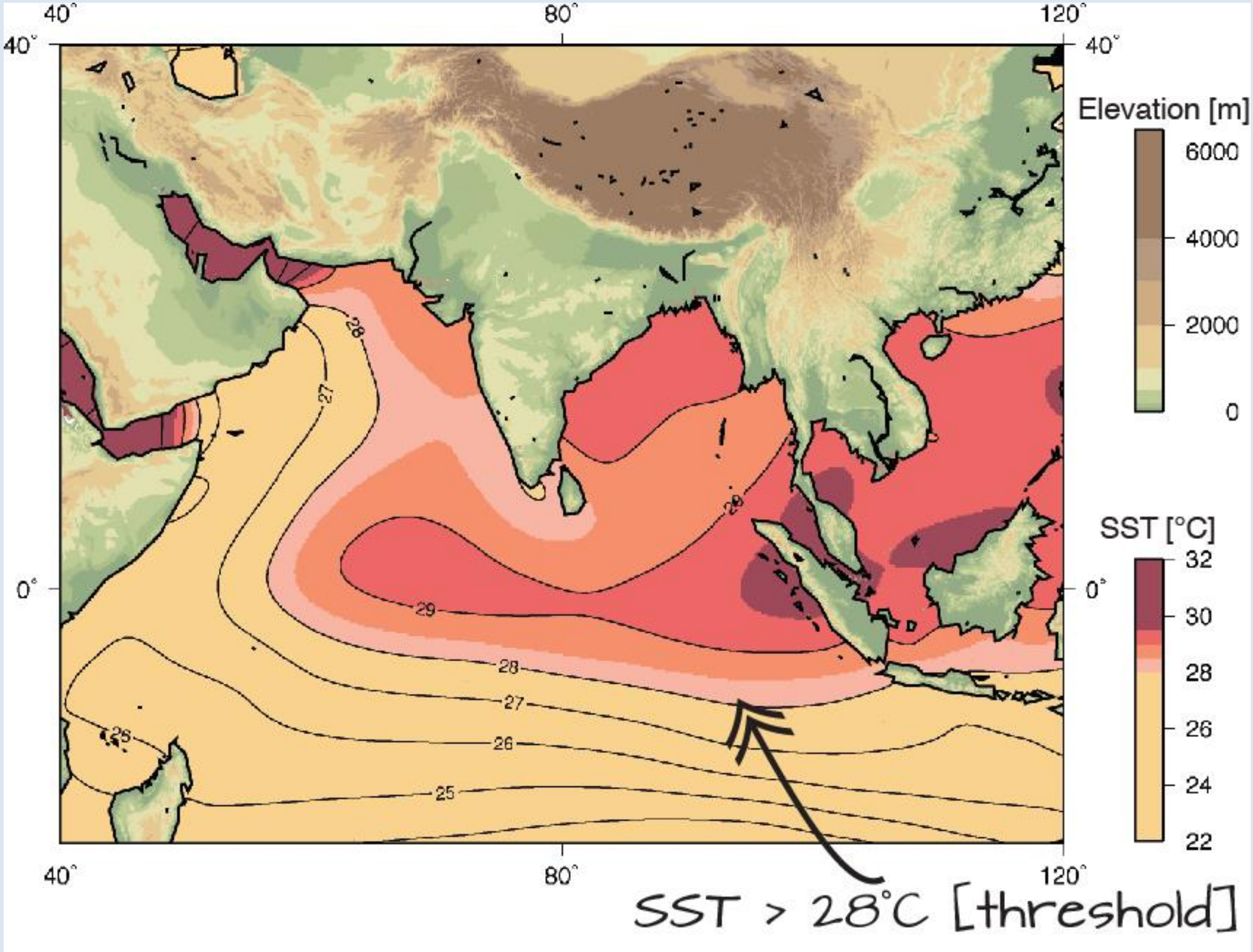
Monsoon Trough and 120° shift in wind direction



Madagascar–Mascarene High/Anticyclone and Monsoon Trough

Monsoon, manifested by conducive SST

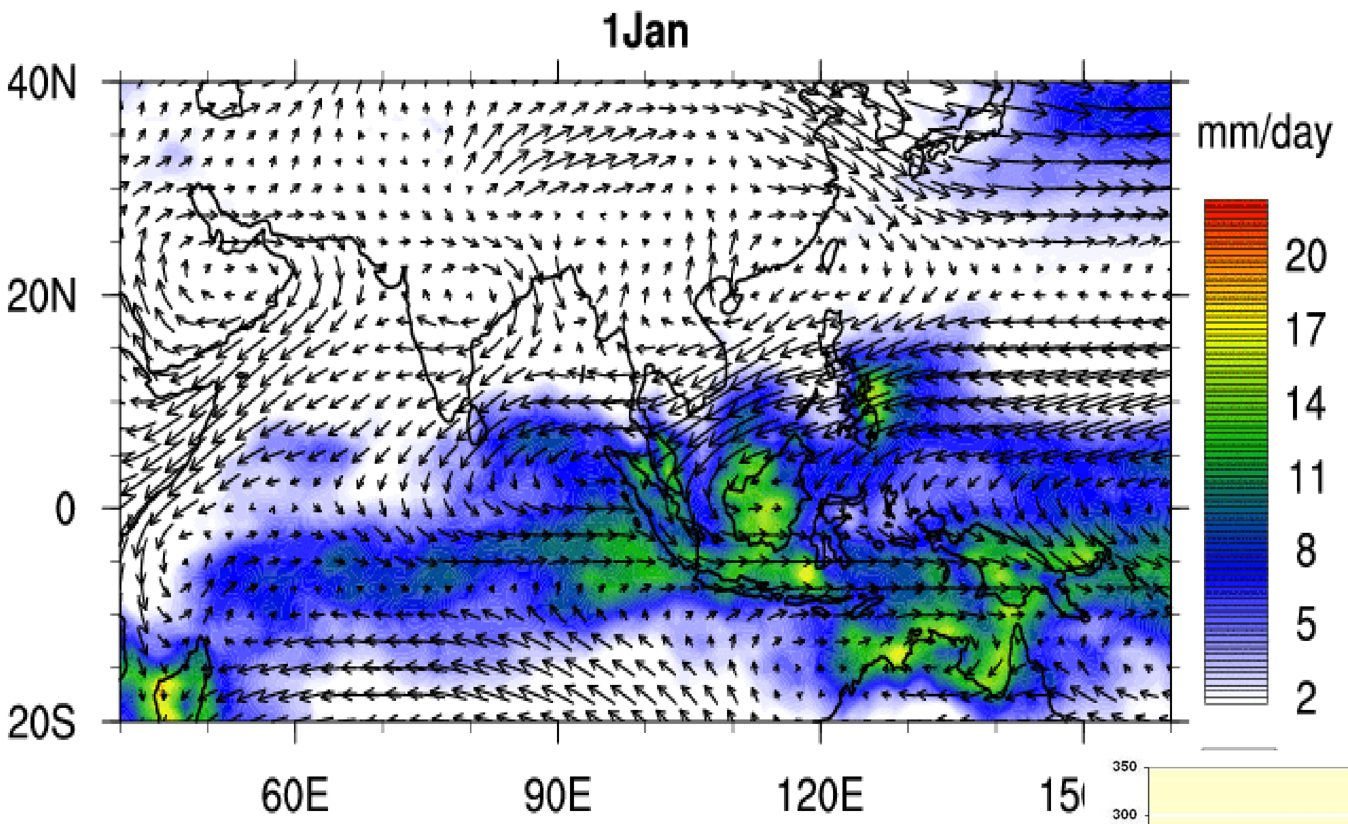
SST > 28C conducive for enhanced convective activity

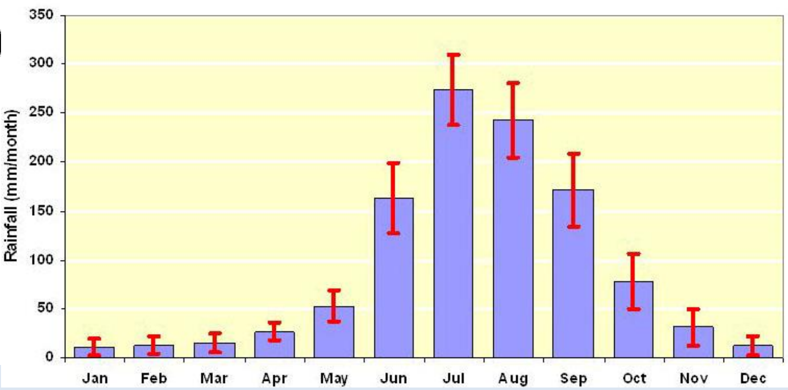


Gadgil et al., *Nature*, 1984; Roxy, *Climate Dynamics*, 2013

Monsoon, manifested by Rainfall

Seasonal Migration of Tropical Convergence Zone (TCZ)





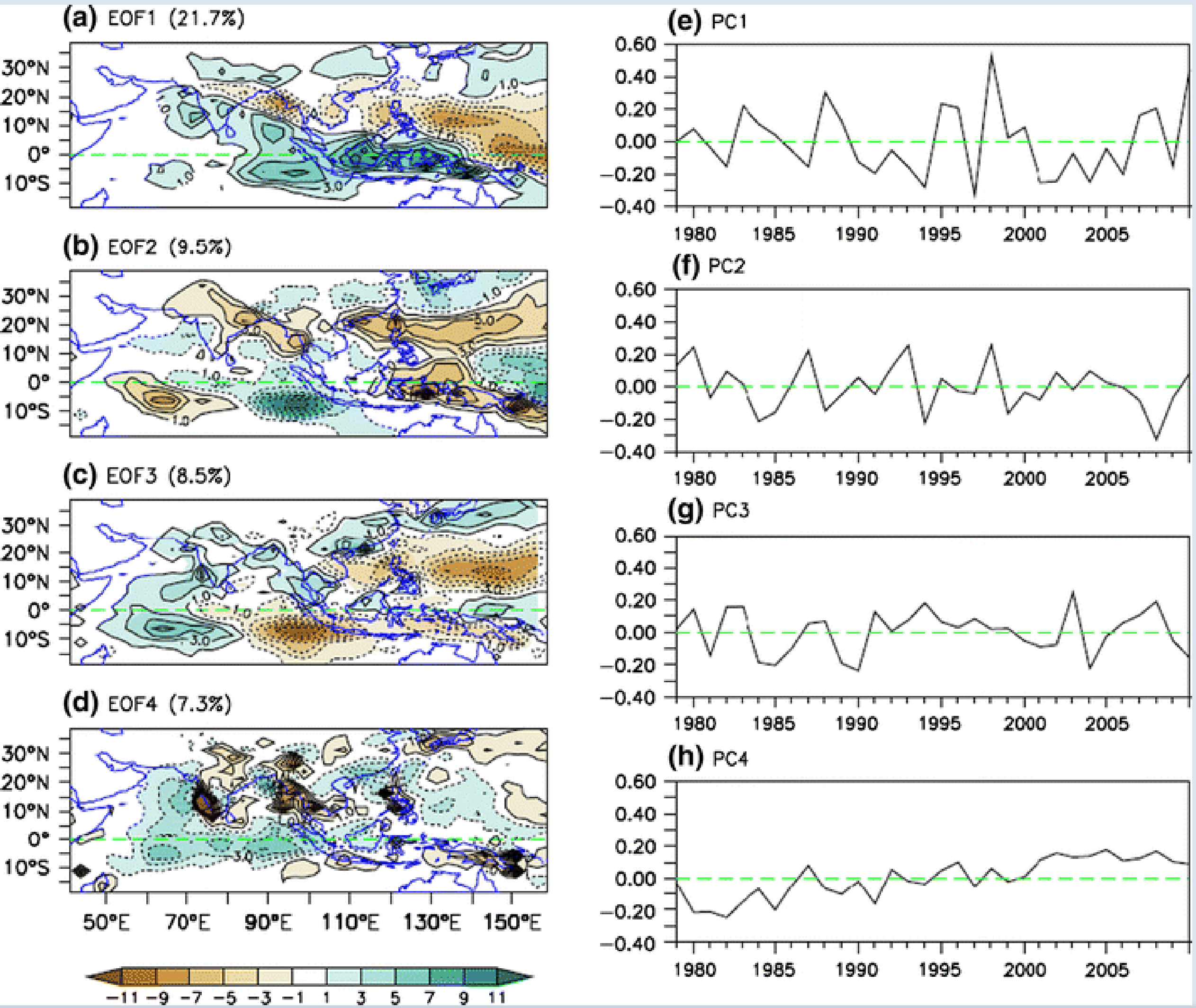
Annual evolution of daily mean Winds at 850 hPa and Precipitation

Interannual Variability of the Monsoon

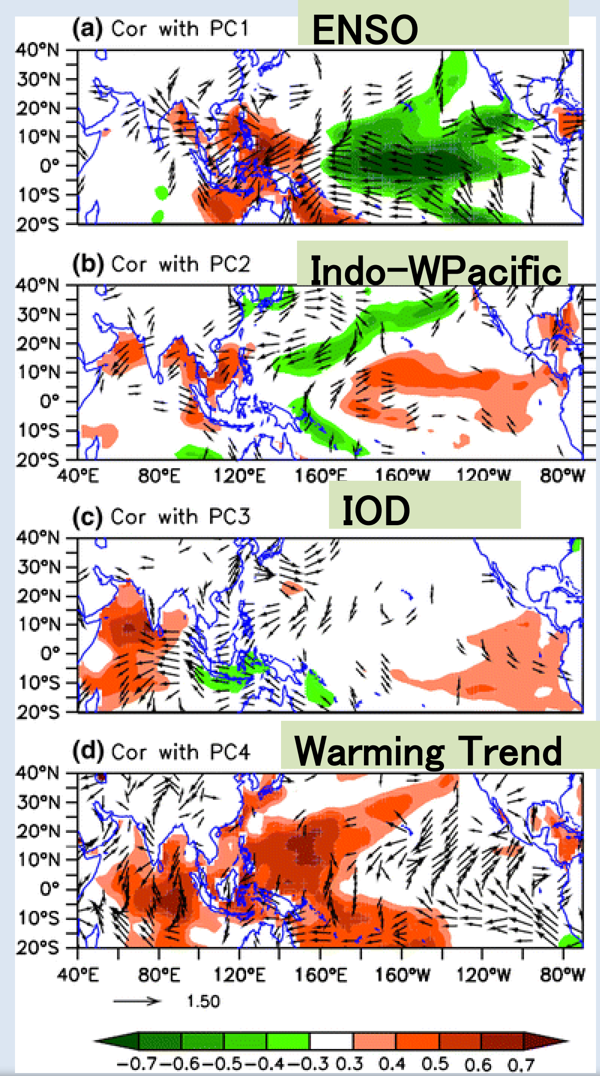
predictable mode analysis

ocean-atmospheric processes – 47% of total variance

EOFs and corresponding PCs of precipitation



Correlation of SST with PC

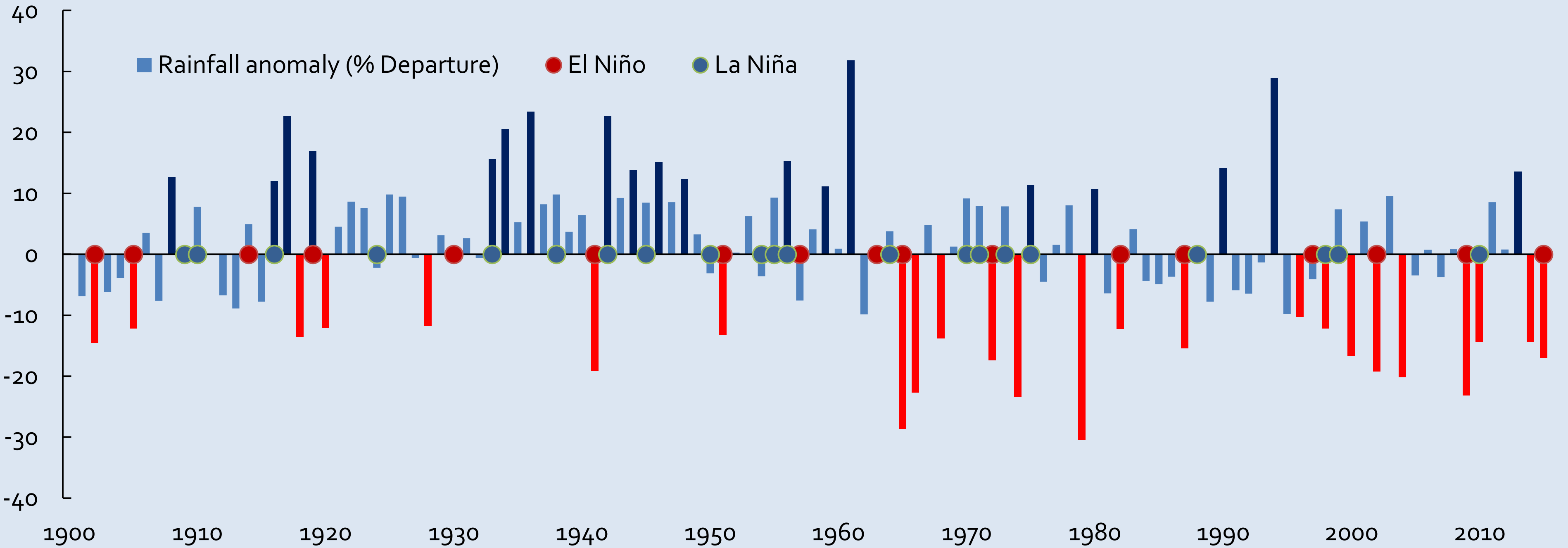


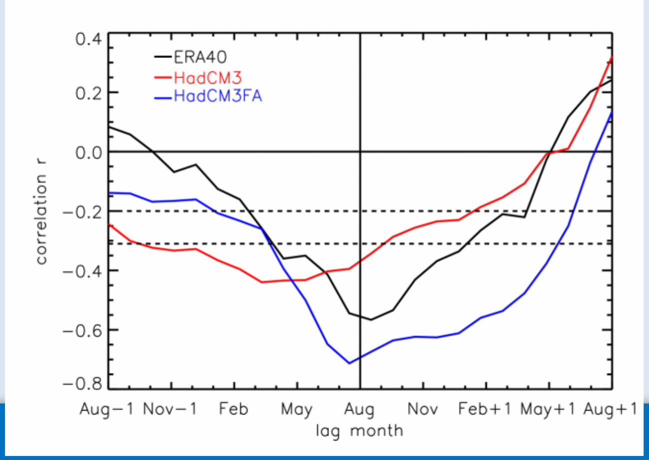
Wang, Lee, et al., *Climate Dynamics*, 2015; Krishna kumar et al., *GRL*, 2005

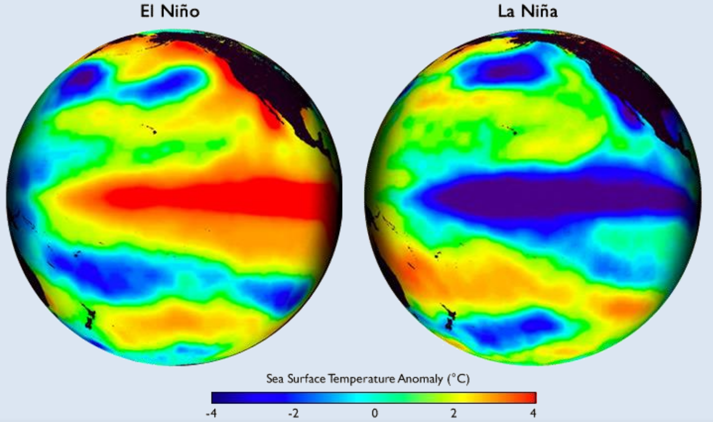
Interannual Variability of the Monsoon – ENSO

El Niño Southern Oscillation (ENSO) is a major driver

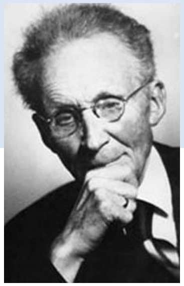
Generally, weak monsoon coincides with El Nino and strong monsoon with La Nina.

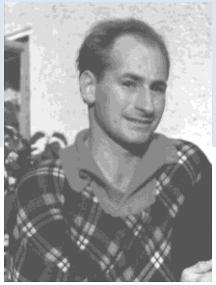


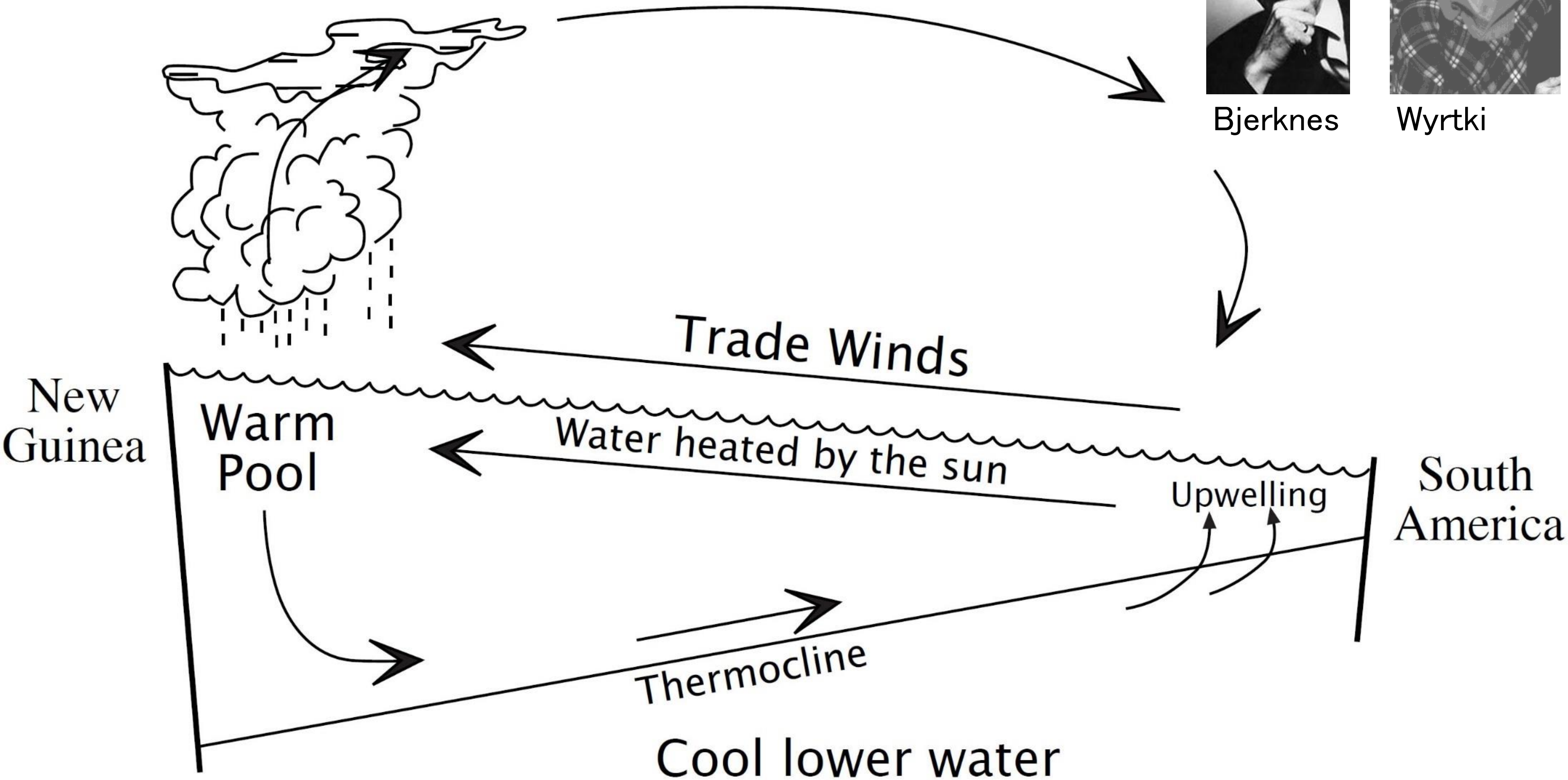




ENSO – neutral conditions – Bjerknes feedback

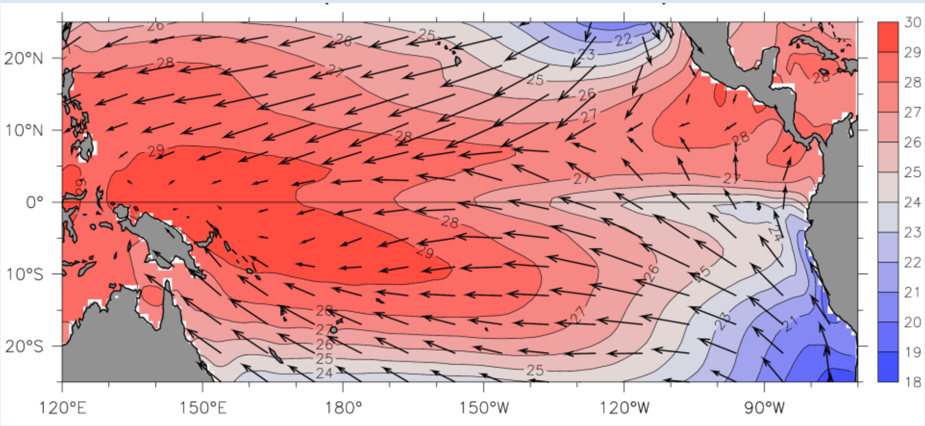

Bjerknes

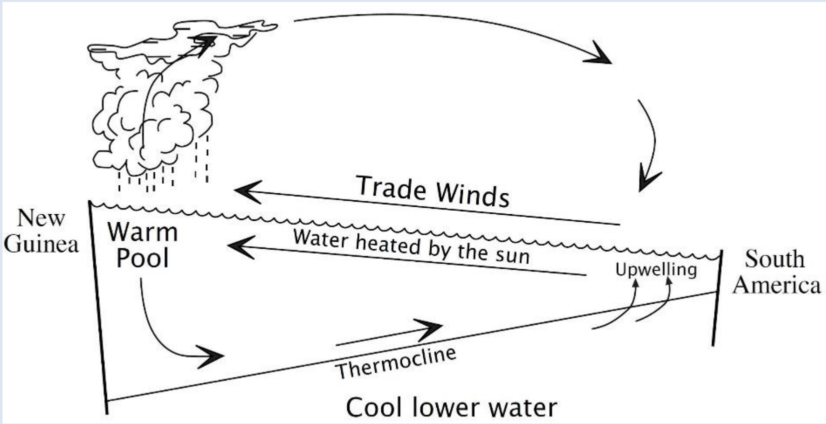

Wyrtki



Interannual Variability of the Monsoon – ENSO

ENSO – neutral conditions – Bjerknes feedback





- Strong east-west asymmetry over the equatorial Pacific: Walker circulation (with easterly winds at the surface) in the atmosphere and a 5degC SST contrast between west warm pool and east cold tongue.

- Under easterly winds, surface ocean currents flow poleward a few degrees away from the equator following the Ekman dynamics -> upwells water into the surface layer on the equator.

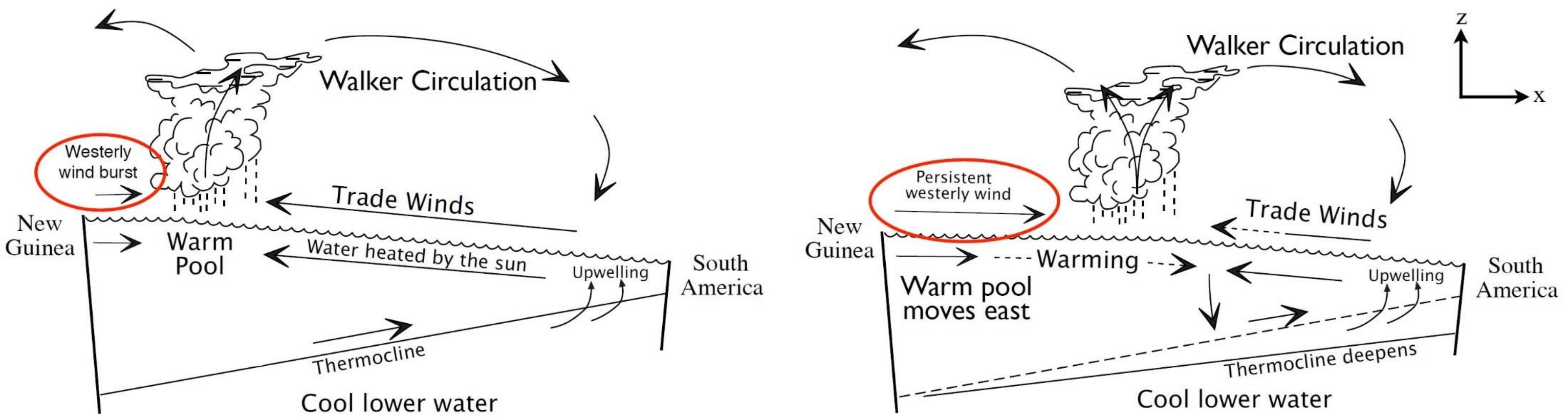
- If the thermocline is close to surface, this equatorial upwelling brings cold thermocline water into the mixed layer, causing an SST cooling. On the equator where the Coriolis force vanishes, surface currents flow in the wind direction, resulting in the westward South Equatorial Current (SEC). The equatorial upwelling and the SEC shoals the thermocline in the east and deepens it in the west.

- On the other hand, the eastward SST cooling limits deep convection to the west and maintains a pressure gradient that drives the easterly winds along the equator. This circular argument indicates that ocean-atmosphere interaction is at a state of positive feedback.

Bjerknes, 1969; Wrytki, 1975; Figures – William Kessler

Interannual Variability of the Monsoon – ENSO

Bjerknes feedback – positive feedbacks couple thermocline slope, SST, zonal winds



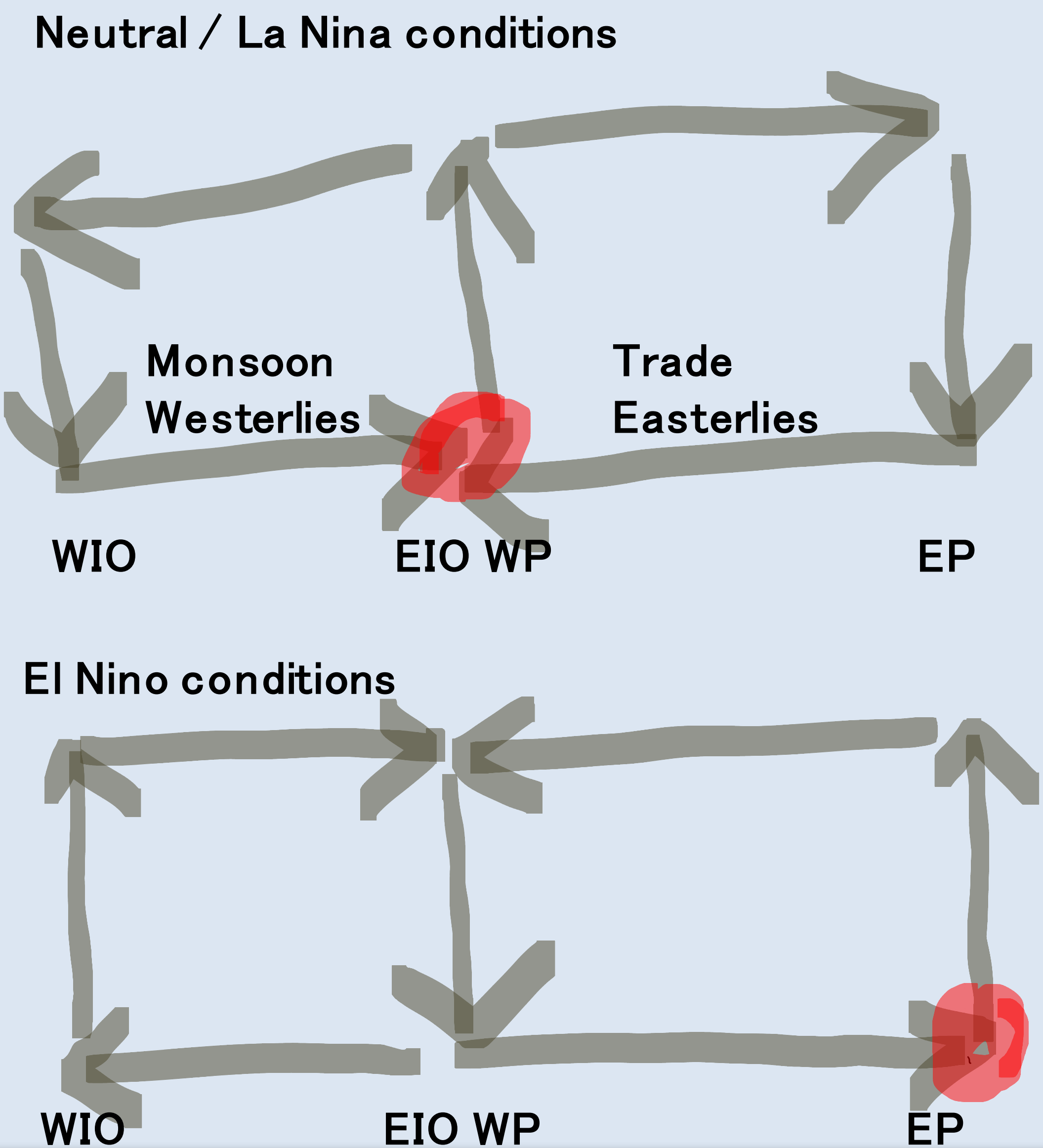
The background appears stable, but because it is maintained by positive feedbacks, weakening any element weakens the entire system (Bjerknes 1966).

An example is westerly winds in the west originating in the MJO. Though these may be transient, they can result in longer-standing disruption of the background, and a coupled chain reaction leading to El Niño.

While trades and upwelling may continue in the east, events in the west can deepen the thermocline in the east, warming SST remotely there (Wyrtki 1975).

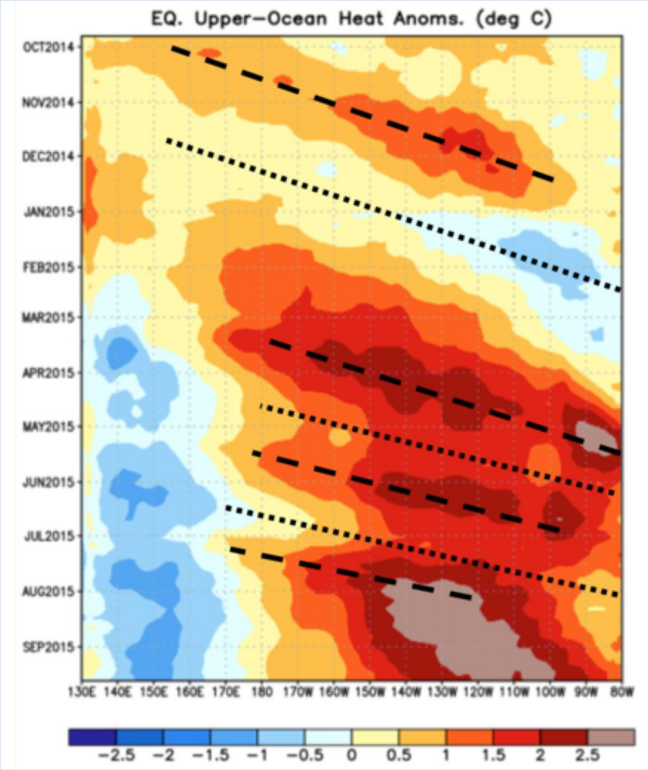
More about westerly wind bursts: Chen et al. *Nature Geoscience*, 2015

Walker Circulation

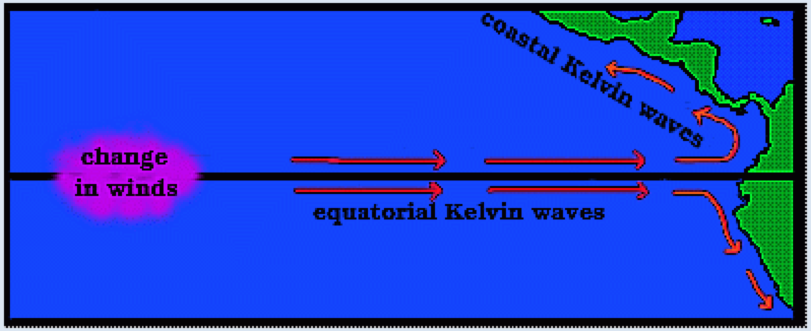


Gilbert Walker

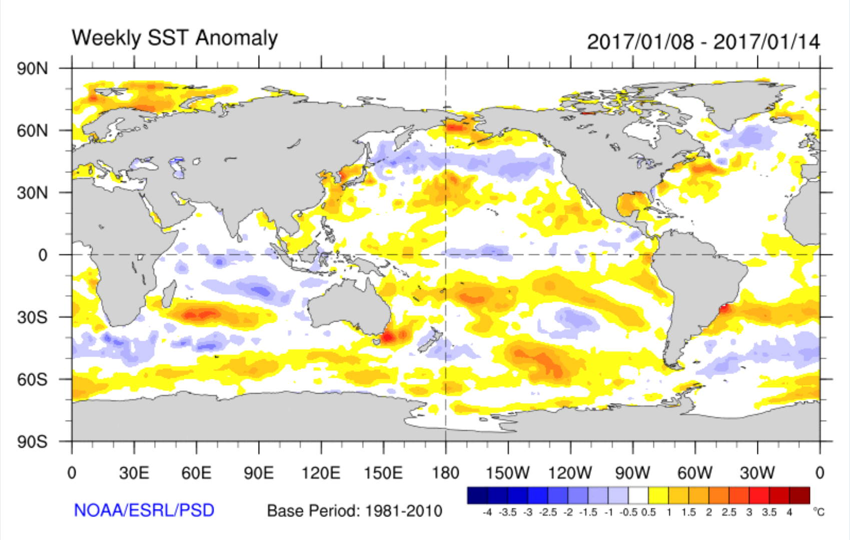
Kelvin Waves



Downwelling phase: The thick warm layer sloshes east, pushing down the thermocline as it goes, thus we call this a "downwelling" wave. The thermocline is the boundary between the warmer, near surface mixed layer and colder deeper water. Because of this downward push as the wave travels eastward, it is harder for the colder, deeper water to affect the surface so near-surface temperatures are often above average. This will often (not always) warm the surface temperatures and plant the seeds for an El Niño.

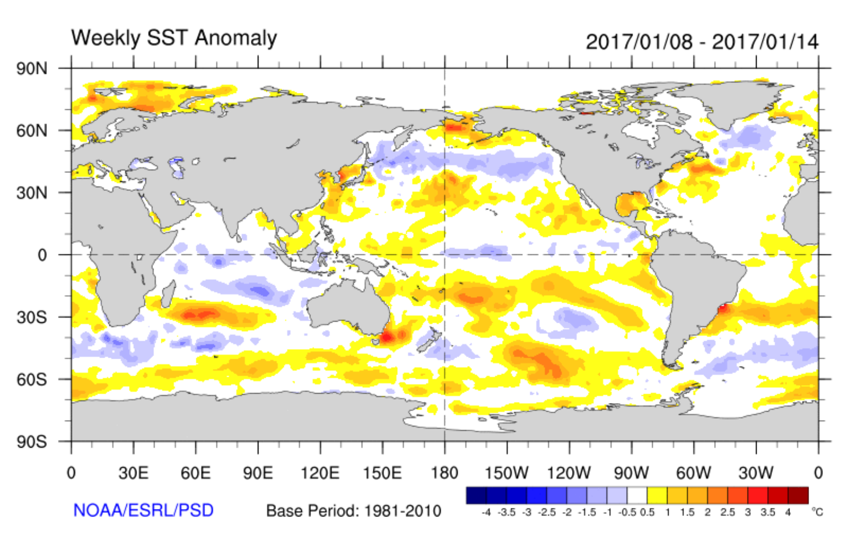


El Niños are "usually" followed by La Niñas



Interannual Variability of the Monsoon – ENSO

El Niños are "usually" followed by La Niñas



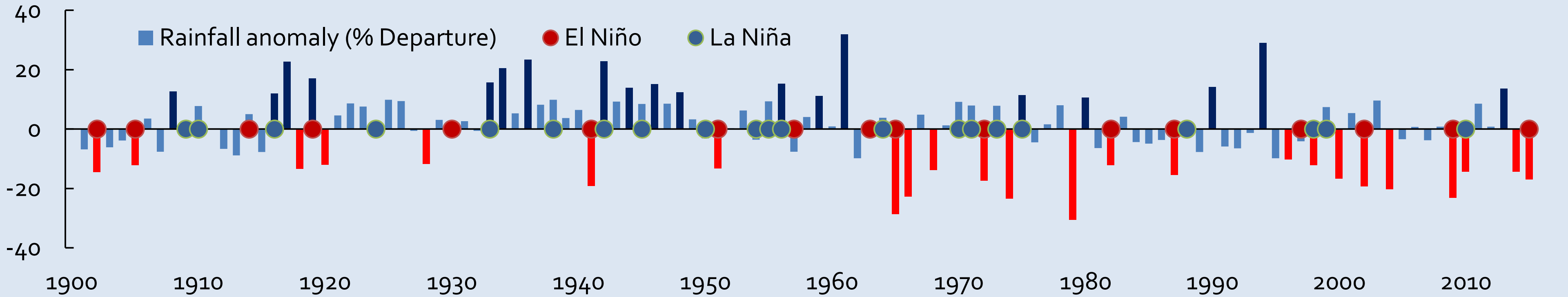
Low-level westerly wind anomalies, not only trigger eastward-moving oceanic Kelvin waves at the equator, but also westward-moving waves just north and south of the equator (called Rossby waves). While Kelvin waves are pushing warm water east, these Rossby waves move cooler subsurface water toward the west. They then bounce off the western side of the tropical Pacific (around Indonesia) and have a return trip, traveling eastward near the equator.

On their eastward trip, these waves also promote cooler water, and can neutralize or reverse El Niño around 6 months after the westerly wind bursts. This cool pulse interrupts the positive feedback mechanism responsible for the growth of an El Niño, ending El Niño and promoting La Niña development.

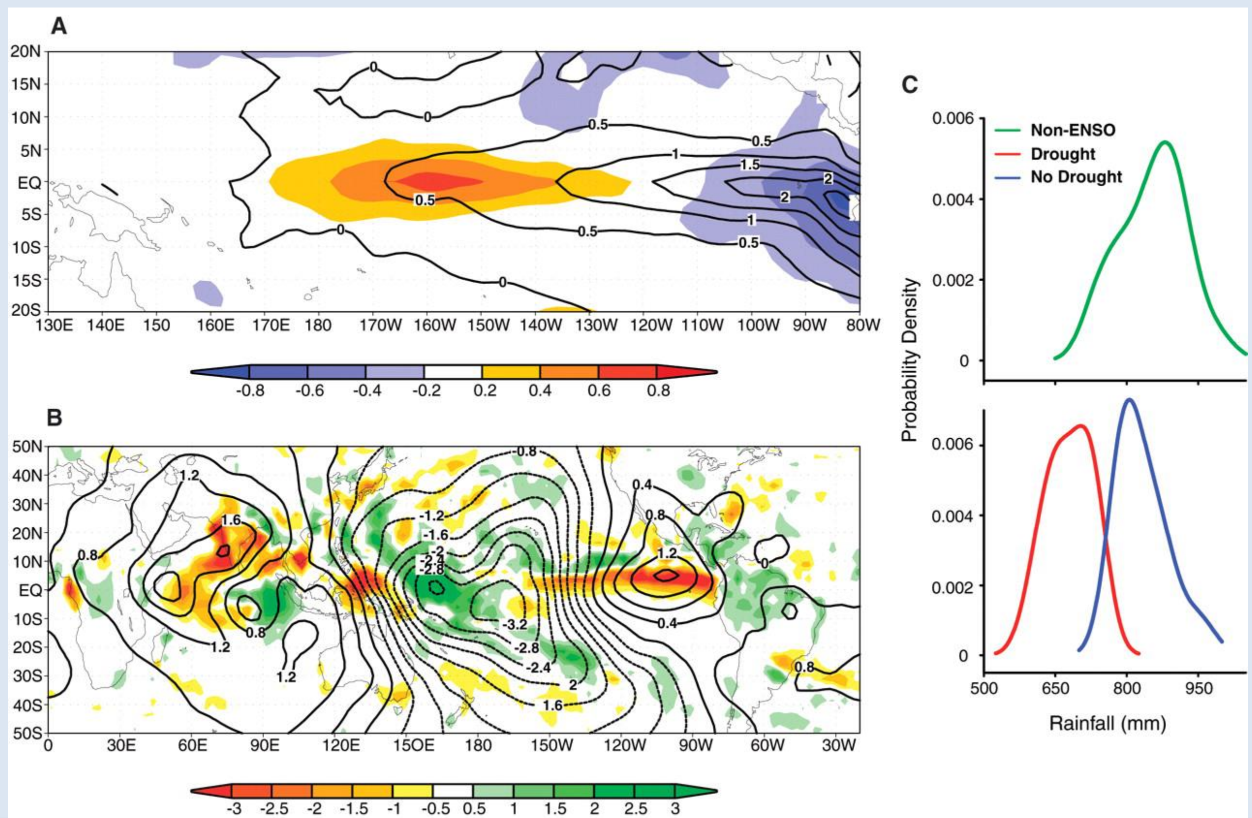
Since stronger El Niño events often involve stronger westerly wind anomalies, these events tend to trigger stronger Rossby waves and stronger tendencies for El Niño to decay and possibly reverse after peaking at the end of a calendar year.

Interannual Variability of the Monsoon – ENSO

but not all El Niño years are drought years – 50%



Other flavors of El Nino?
Other tropical oceans?
Or… does monsoon has its own identity?



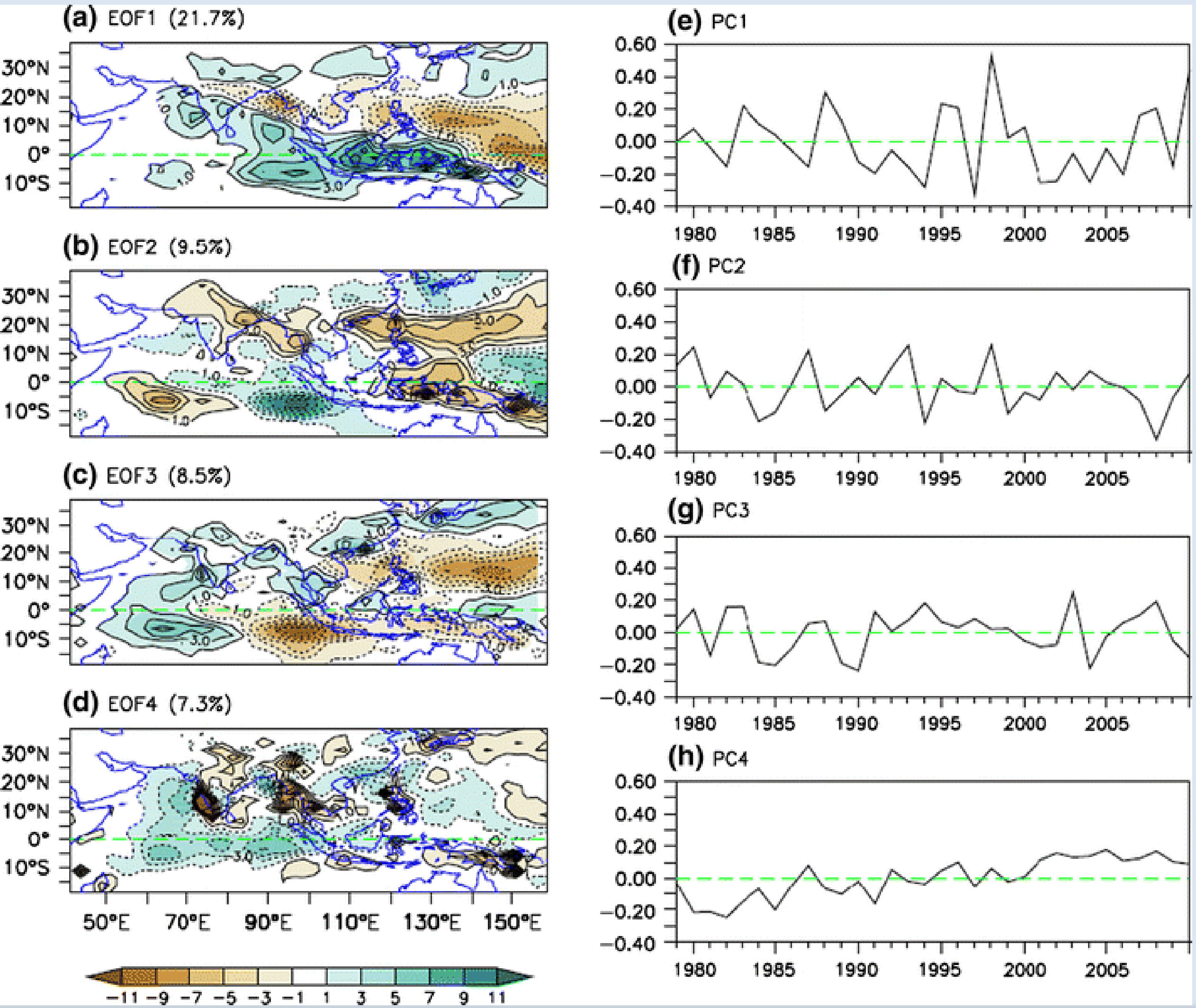
Krishna Kumar et al., *Science* 2006; Ashok et al., *JGR* 2007

Interannual Variability of the Monsoon

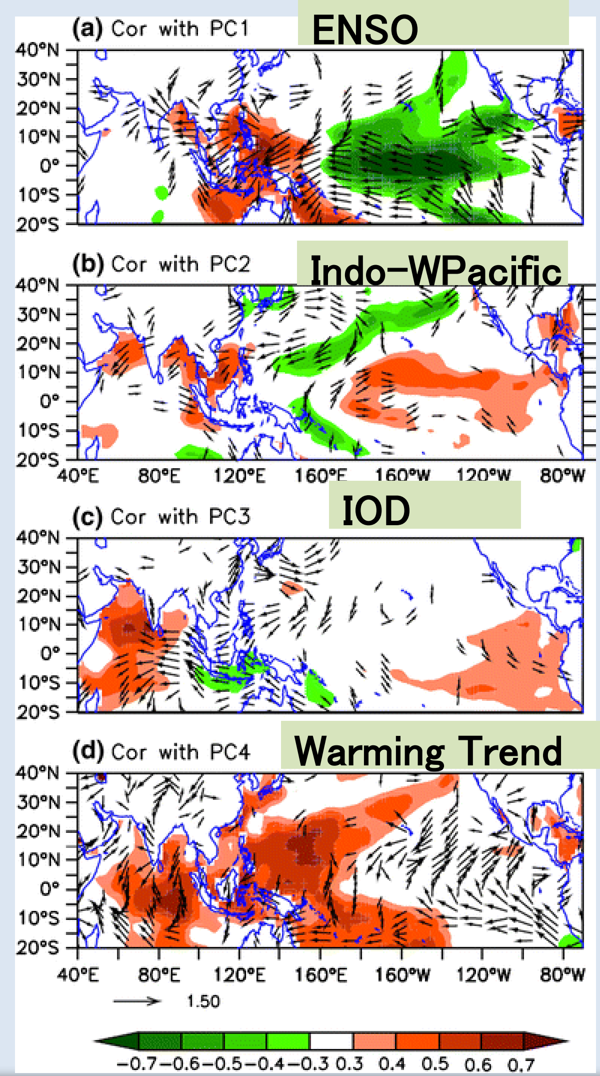
predictable mode analysis

ocean-atmospheric processes – 47% of total variance

EOFs and corresponding PCs of precipitation



Correlation of SST with PC



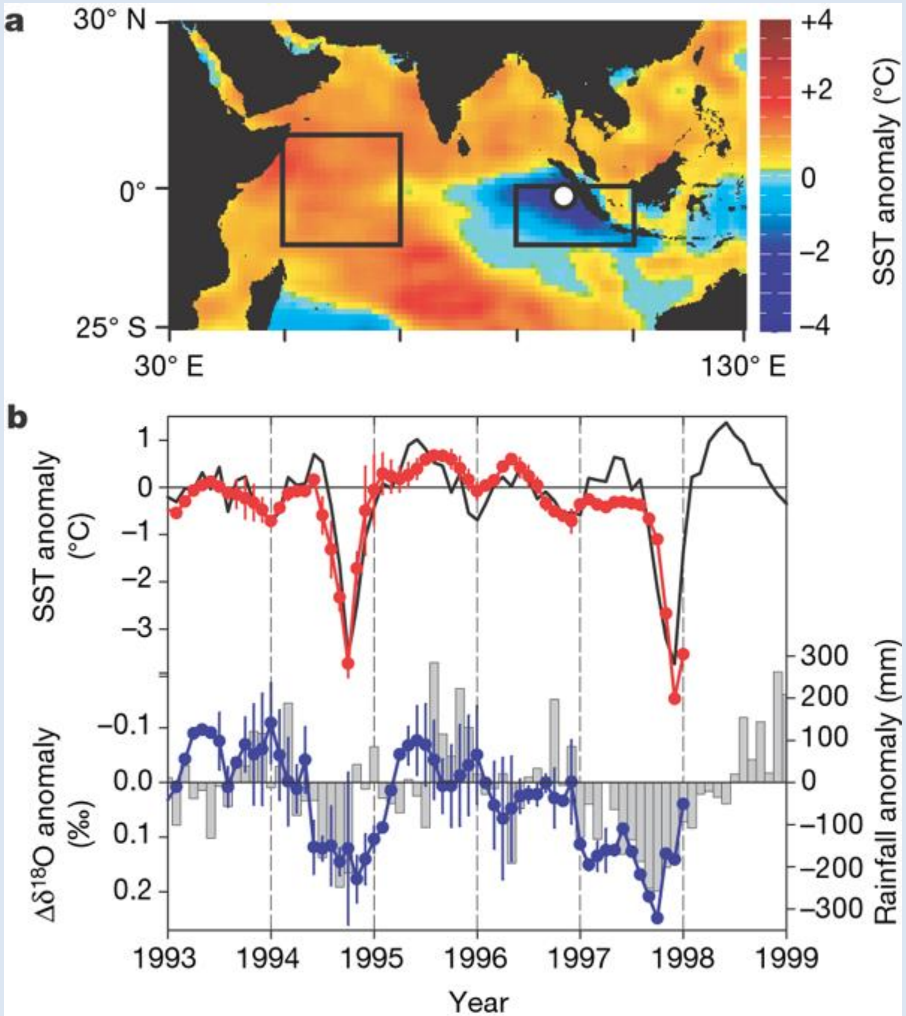
Wang, Lee, et al., *Climate Dynamics*, 2015

Interannual Variability of the Monsoon – IOD

Indian Ocean Dipole (IOD)

aka Indian Ocean Zonal Mode (IOZM)

aka the controversial mode



DIPOLES, TEMPERATURE GRADIENTS, AND TROPICAL CLIMATE ANOMALIES

BY STEFAN HASTENRATH

An examination into misleading terminology.

Comment on "Dipoles, Temperature Gradients, and Tropical Climate Anomalies"

—RAGHU MURTUGUDDE AND
ANTONIO J. BUSALACCHI
Earth System Science Interdisciplinary Center,
University of Maryland, College Park,
College Park, Maryland

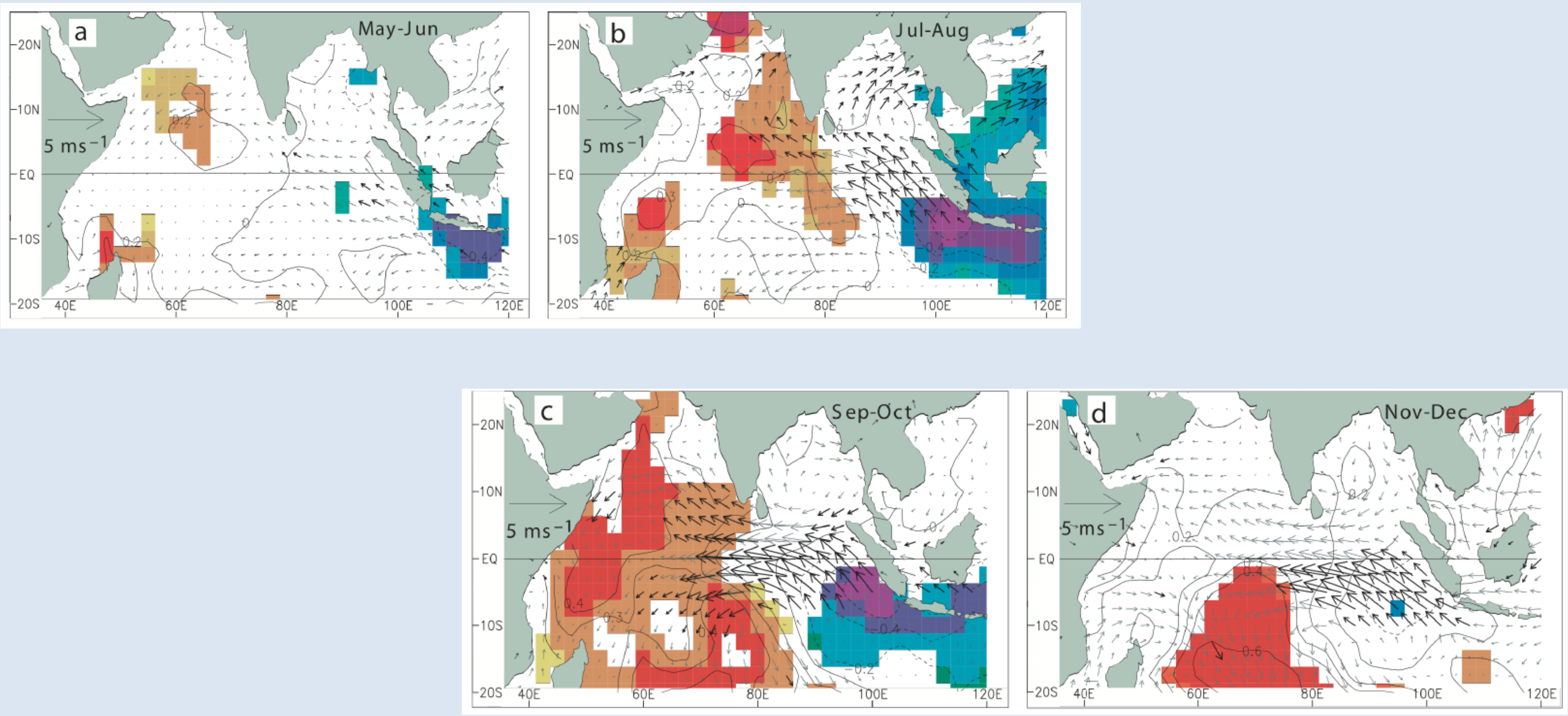
—JULIAN P. MCCREARY JR.
International Pacific Research Center,
University of Hawaii, at Manoa, Honolulu, Hawaii

Murtugudde et al., *Korean Met. Soc.* 1998; Saji et al. and Webster et al., *Nature*, 1999.

Interannual Variability of the Monsoon – IOD

IOD enhances local meridional circulation – monsoon rains

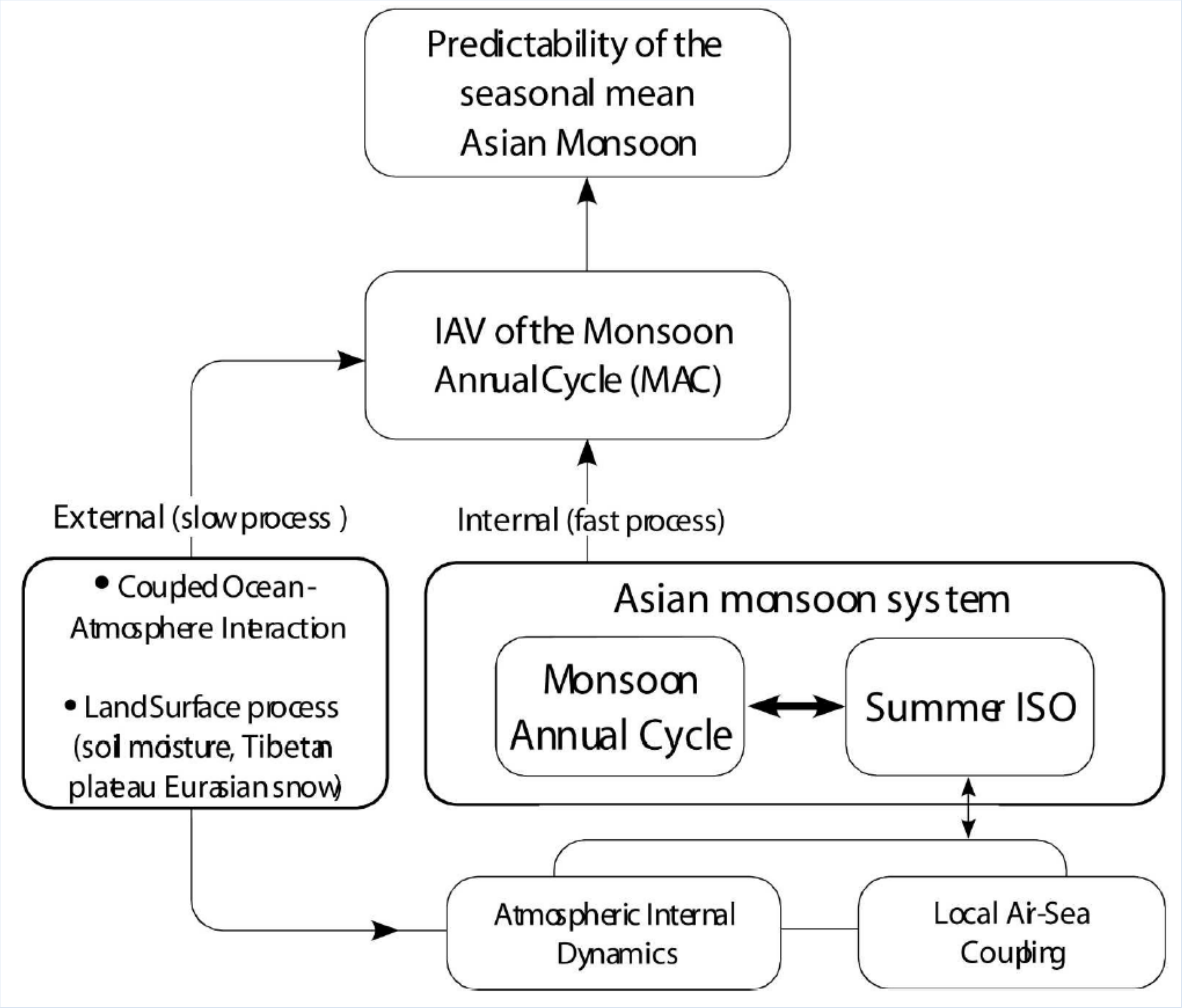
Temporal evolution of IOD ->



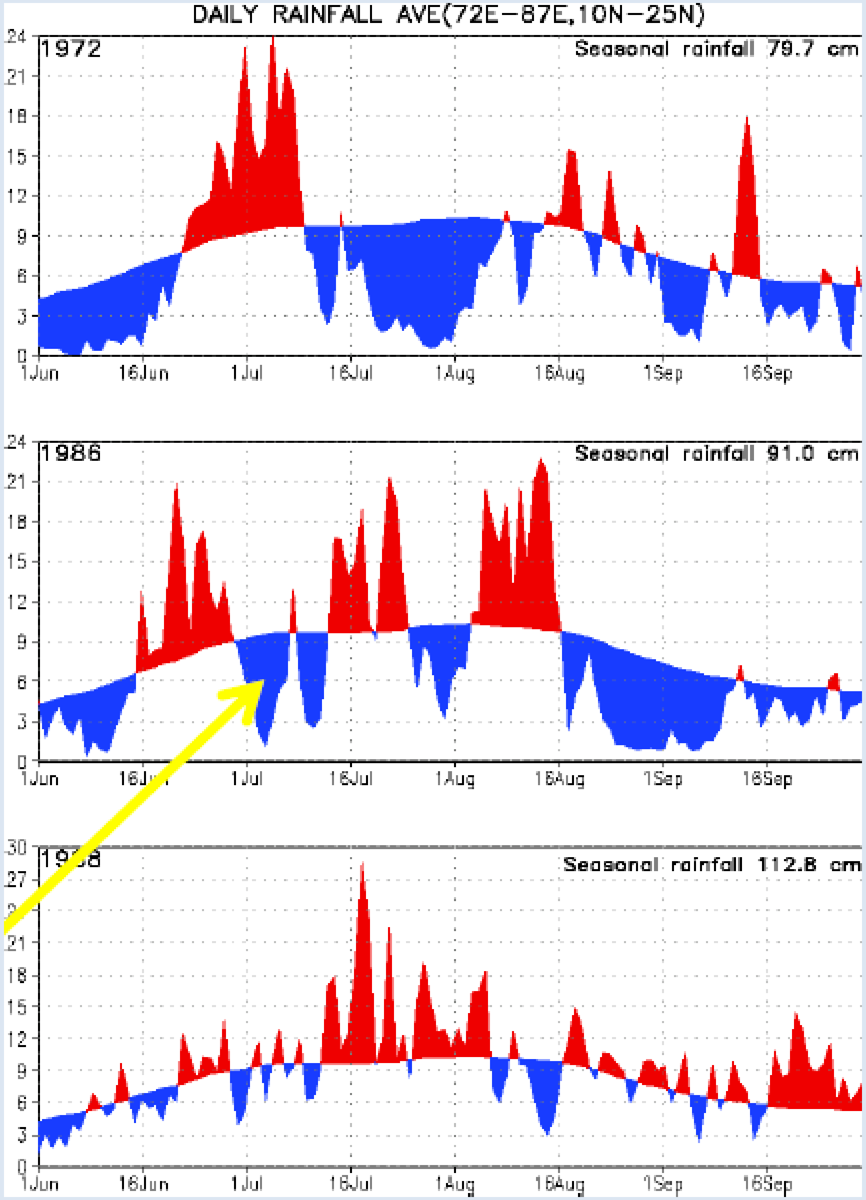
Ashok et al., *GRL* 2001; Figures: Boschat, *PhD Thesis* 2012

Interannual Variability of the Monsoon

Internal variability?



Intraseasonal variability of the Monsoon



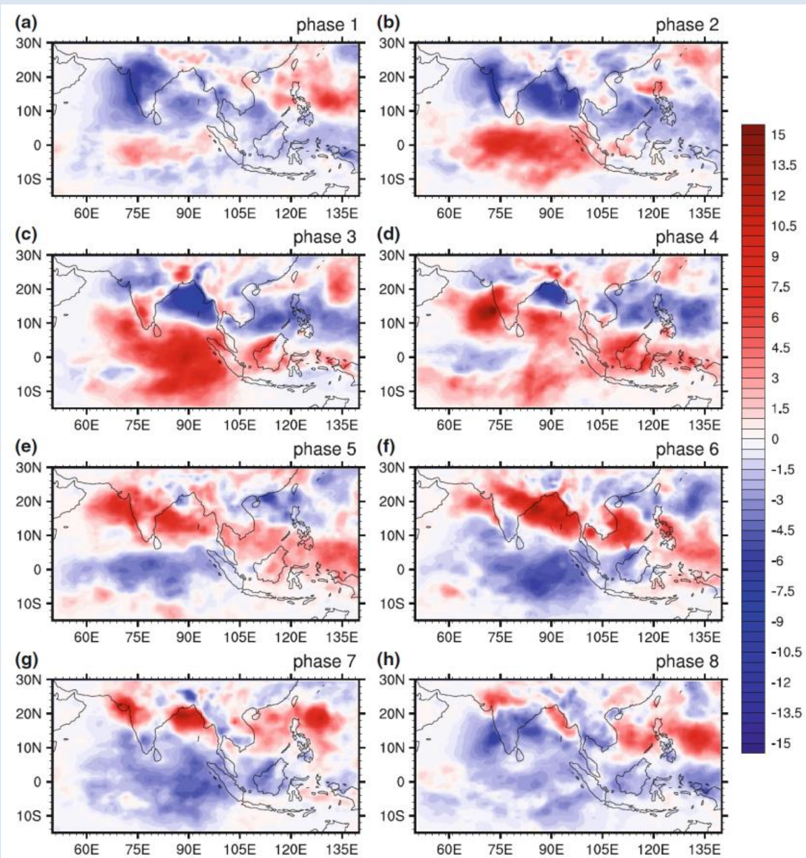
Monsoon is characterized by large amplitude intraseasonal oscillations (ISO) –active and break spells of rain.

They represent a very large signal and hence potentially predictable

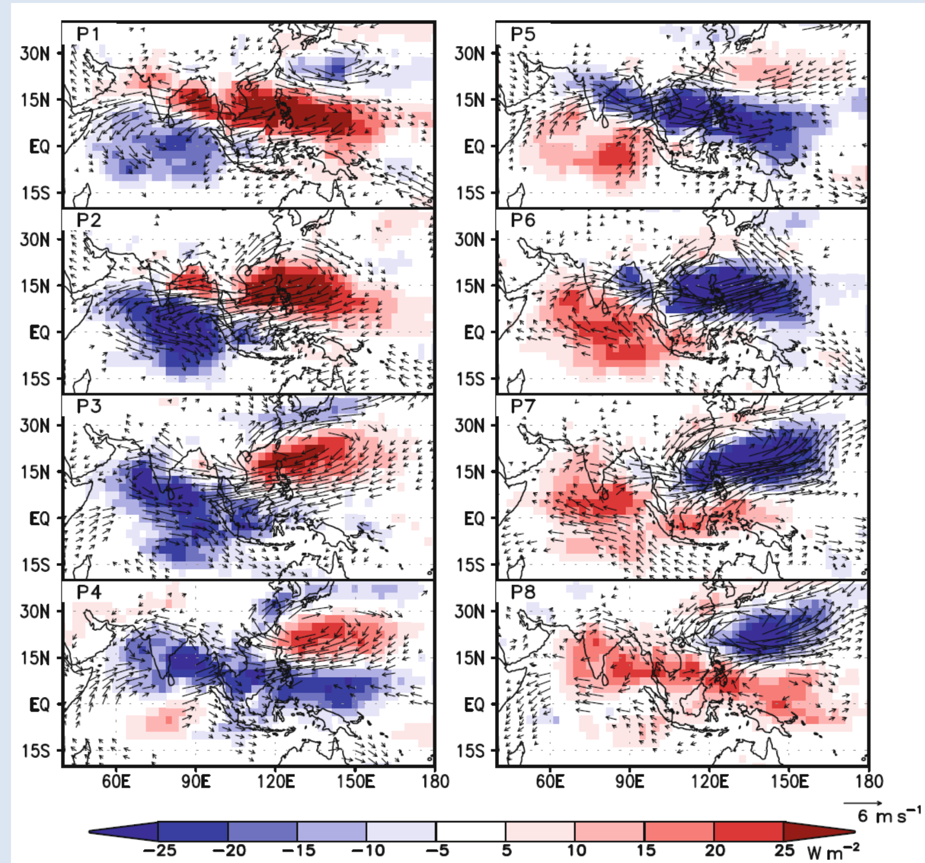
Intraseasonal variability of the Monsoon

— MISO, BSISO… different names… MJO??

MISO: Monsoon Intraseasonal Oscillation
e.g. Suhas et al. 2013 – Rainfall anomalies



BSISO: Boreal Summer Intraseasonal Oscillation
e.g. Lee et al. 2013 – OLR/Wind (850 hPa) anom.

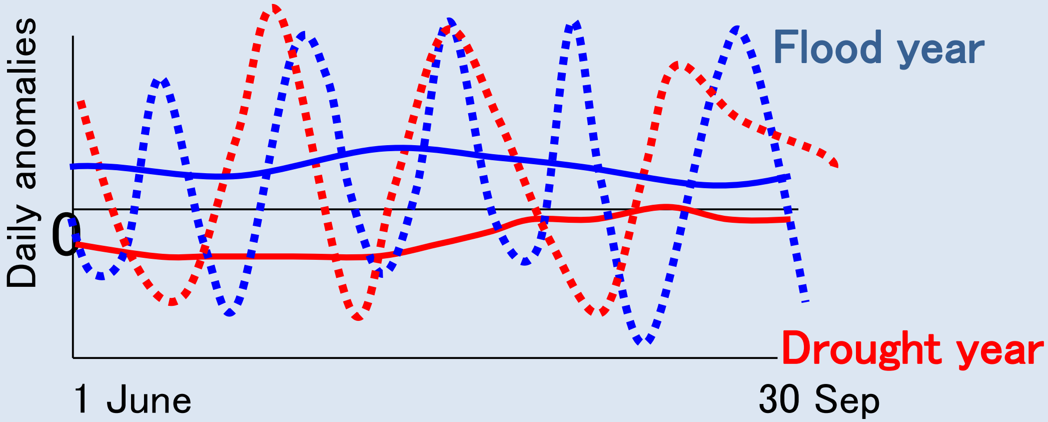


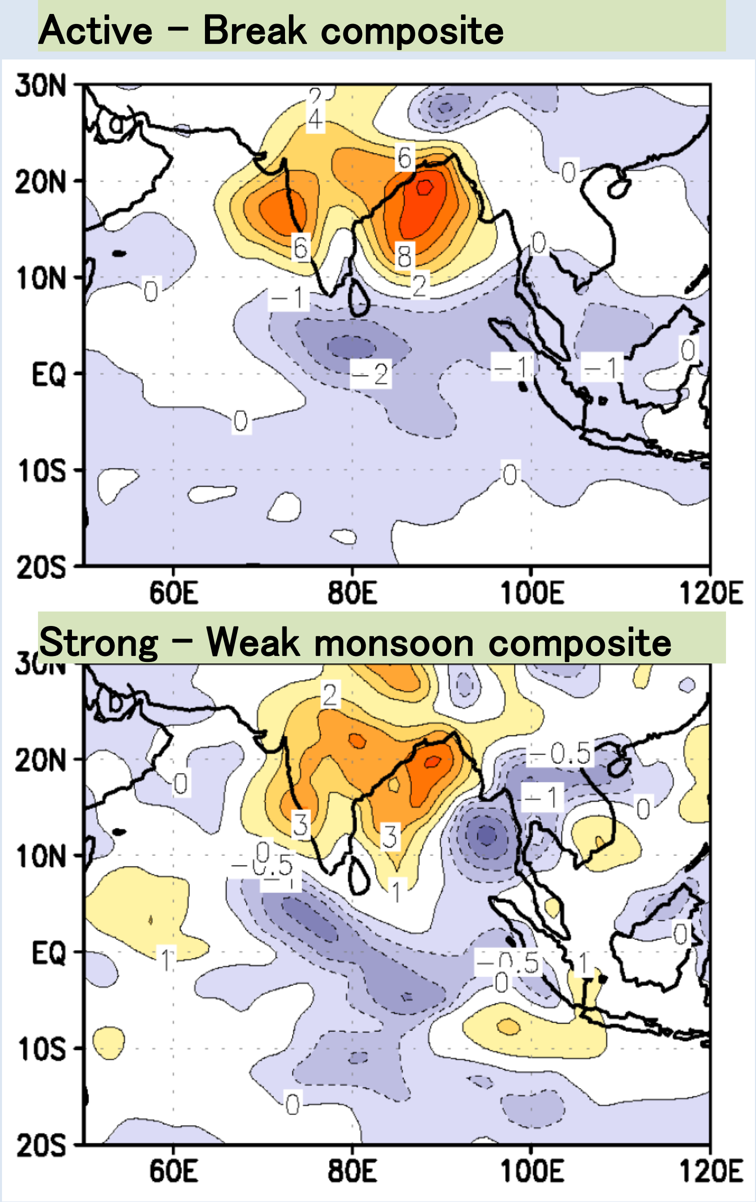
1. **Northward propagation**
2. **Ocean-atmosphere coupled interaction**
3. **Arabian Sea – Bay of Bengal – South China Sea**

Intraseasonal variability of the Monsoon

— contribution to the seasonal mean

Higher frequency of occurrence of active conditions would result in stronger than normal seasonal mean, and vice-versa.



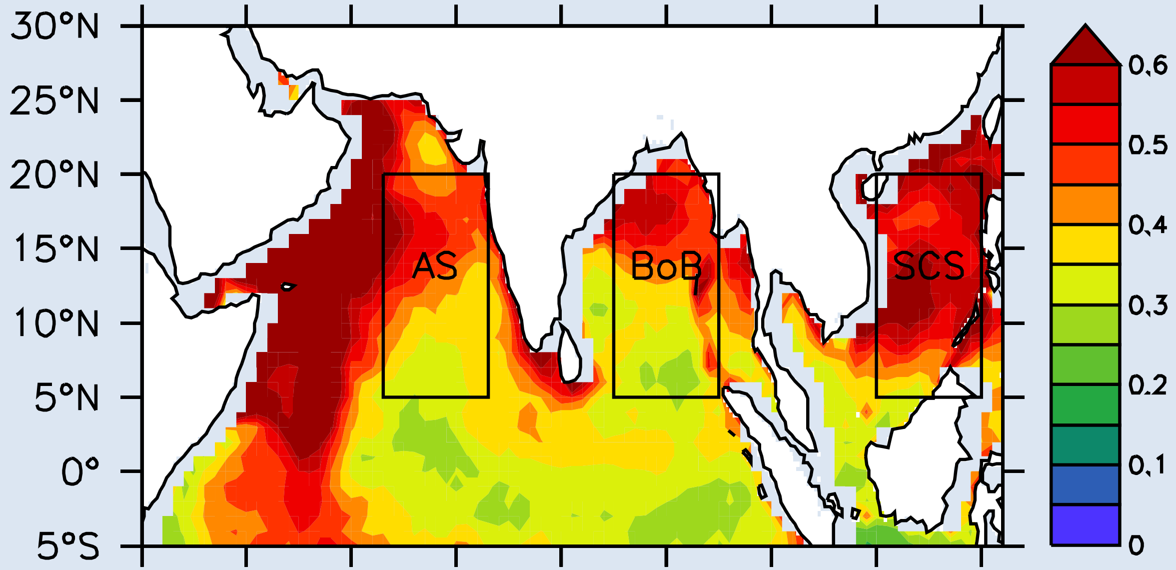


Spatial structure of the summer ISOs have certain similarity with that of the summer seasonal mean.

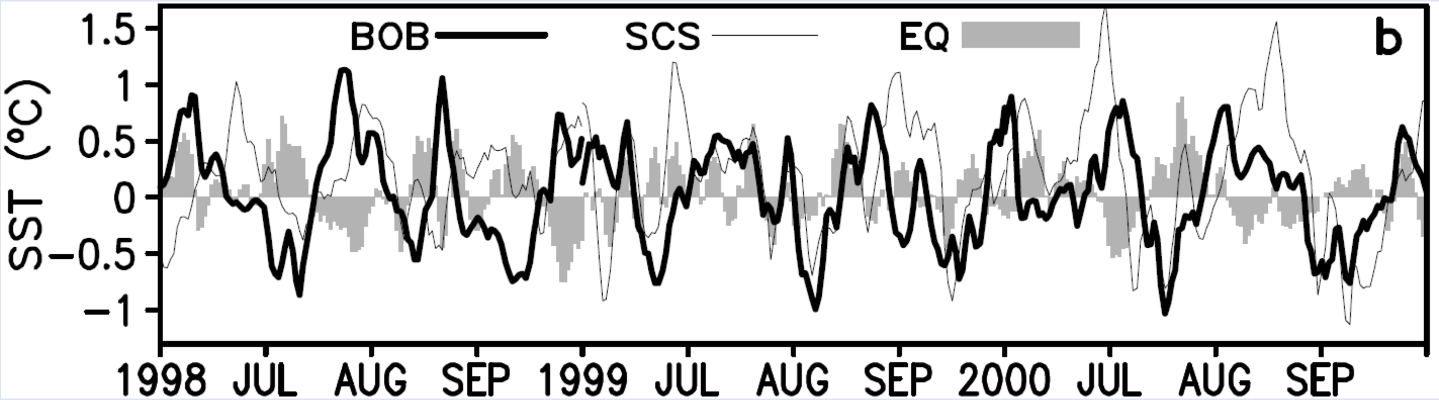
Intraseasonal variability of the Monsoon

— SST variability over the monsoon basins

SST variability during summer



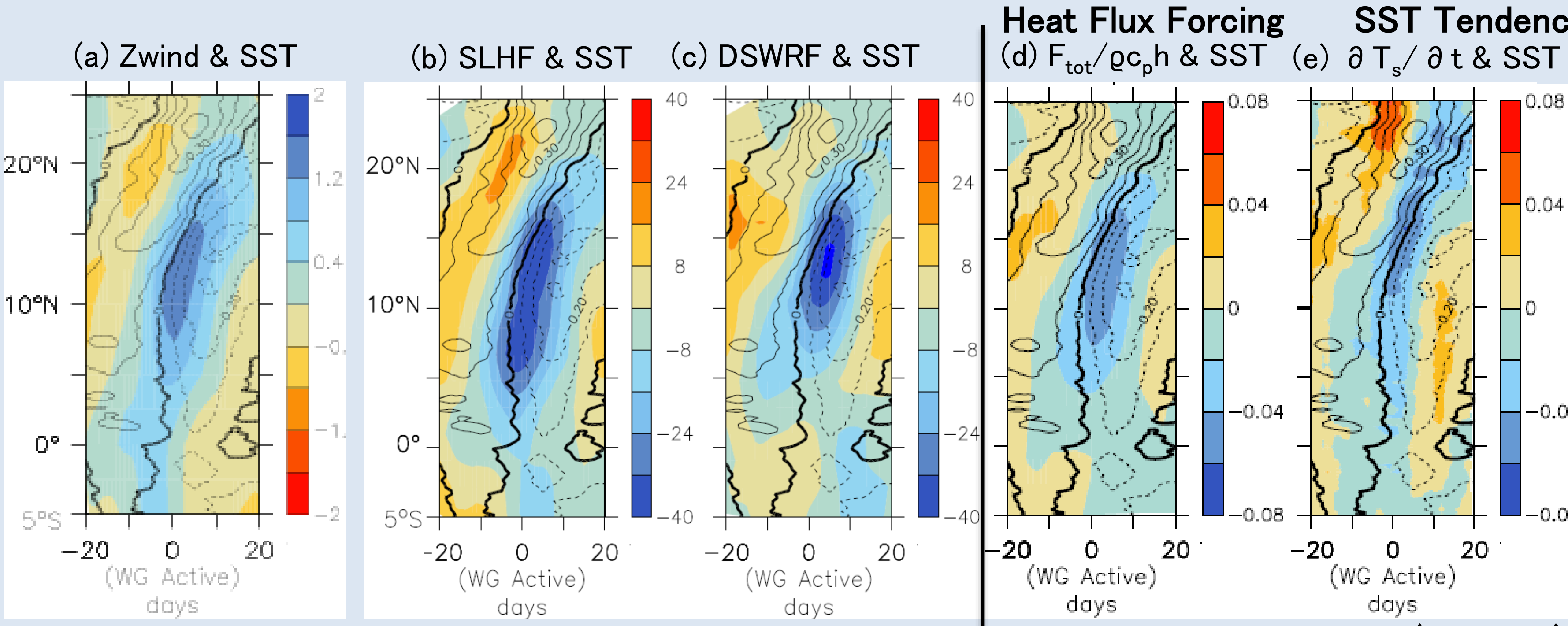
SST & heat flux anomalies associated with monsoon ISV are observed over a large domain, Arabian Sea -> Bay of Bengal -> South China Sea -> w. North Pacific



Intraseasonal variability of the Monsoon

— Source of SST variability

Intraseasonal SST over monsoon basins: driven by **Latent heat flux** (LHF is dominant due to stronger winds) and **Shortwave flux** (SWF) anomalies.



Arabian Sea (60–70E)

SST tendency equation:
$$\frac{\partial T_s}{\partial t} = \frac{F_{tot}}{\rho c_p * MLD}$$

Quantitatively:

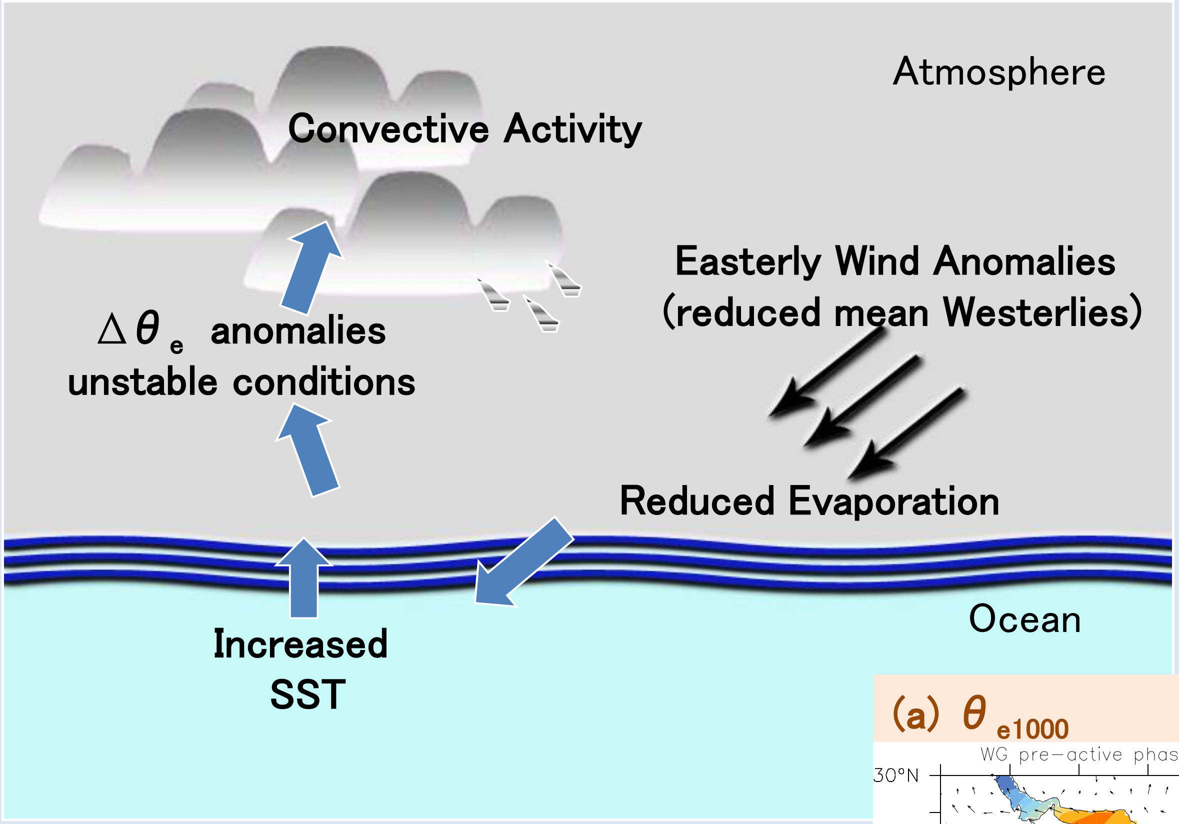
F_{tot} of 50 Wm^{-2}, MLD of 40 m, standard ϱ & c_p => $F_{tot}/\varrho c_{p*}MLD = 0.025^{\circ}C\ day^{-1}$

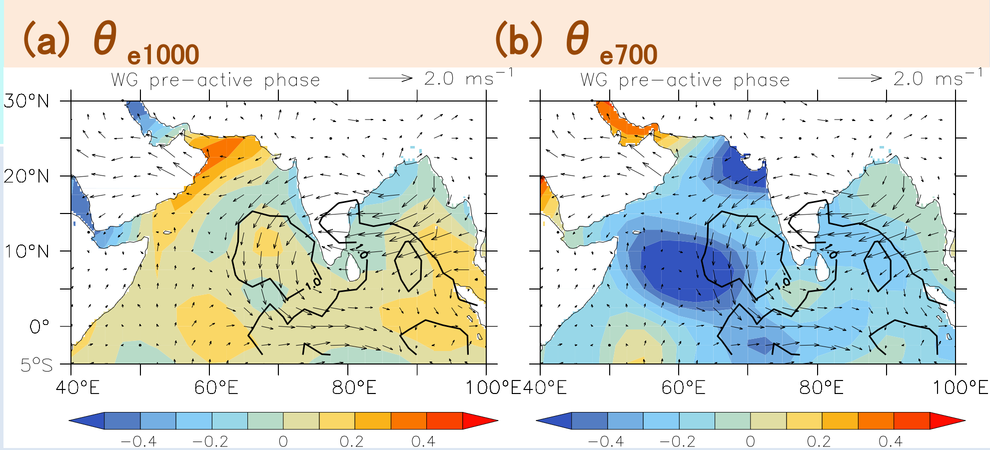
SST change of 0.8°C in 40 days => $\partial T_s/\partial t = 0.02^{\circ}C\ day^{-1}$

Hendon & Glick 1997; Vecchi and Harrison 2002; Fu et al. 2008; Roxy and Tanimoto 2007

Intraseasonal variability of the Monsoon

— Role of SST variability on the Monsoon ISV





positive SST anomalies

⇒ destabilize lower atmospheric column

⇒ convective activity

Intraseasonal variability of the Monsoon

— Mixed layer is important

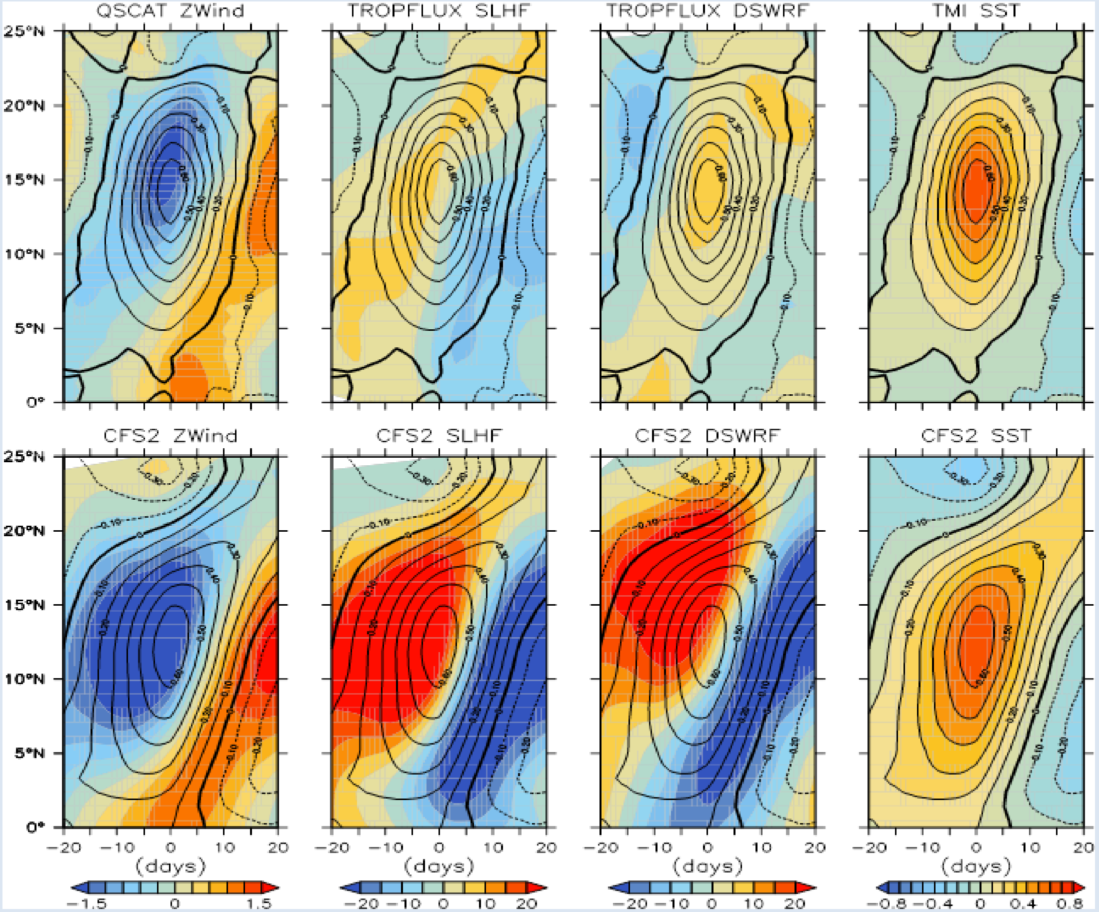
$$\frac{\partial T_s}{\partial t} = \frac{F_{tot}}{\rho c_p * \mathbf{MLD}}$$

Comparison of observed and model (CFSv2) ISV

ISV is overestimated in the model. Where is it coming from?

Flux Contribution => SST Tendency
The increased SST anomalies in the model are **comparable** to the simulated net surface flux anomalies, For 30 W m^{-2} (30m MLD), dT = 0.025C day^{-1}.

Wind Contribution => LHF
Using the bulk aerodynamic equations, an overestimation of 1ms^{-1} of wind speed is **comparable** to an increase of 14 W m^{-2} of latent heat flux anomalies, in the model.



Flux Contribution => SST Tendency

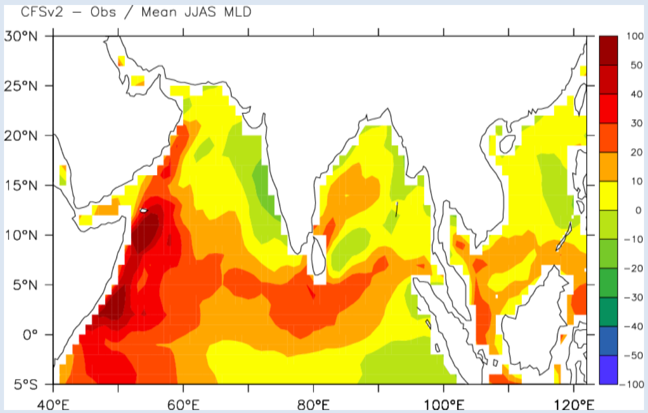
Wind Contribution => LHF

Roxy et al., *Climate Dynamics* 2013

Intraseasonal variability of the Monsoon

— Mixed layer is important

JJAS MLD Diff. [CFSv2 - Boyer]



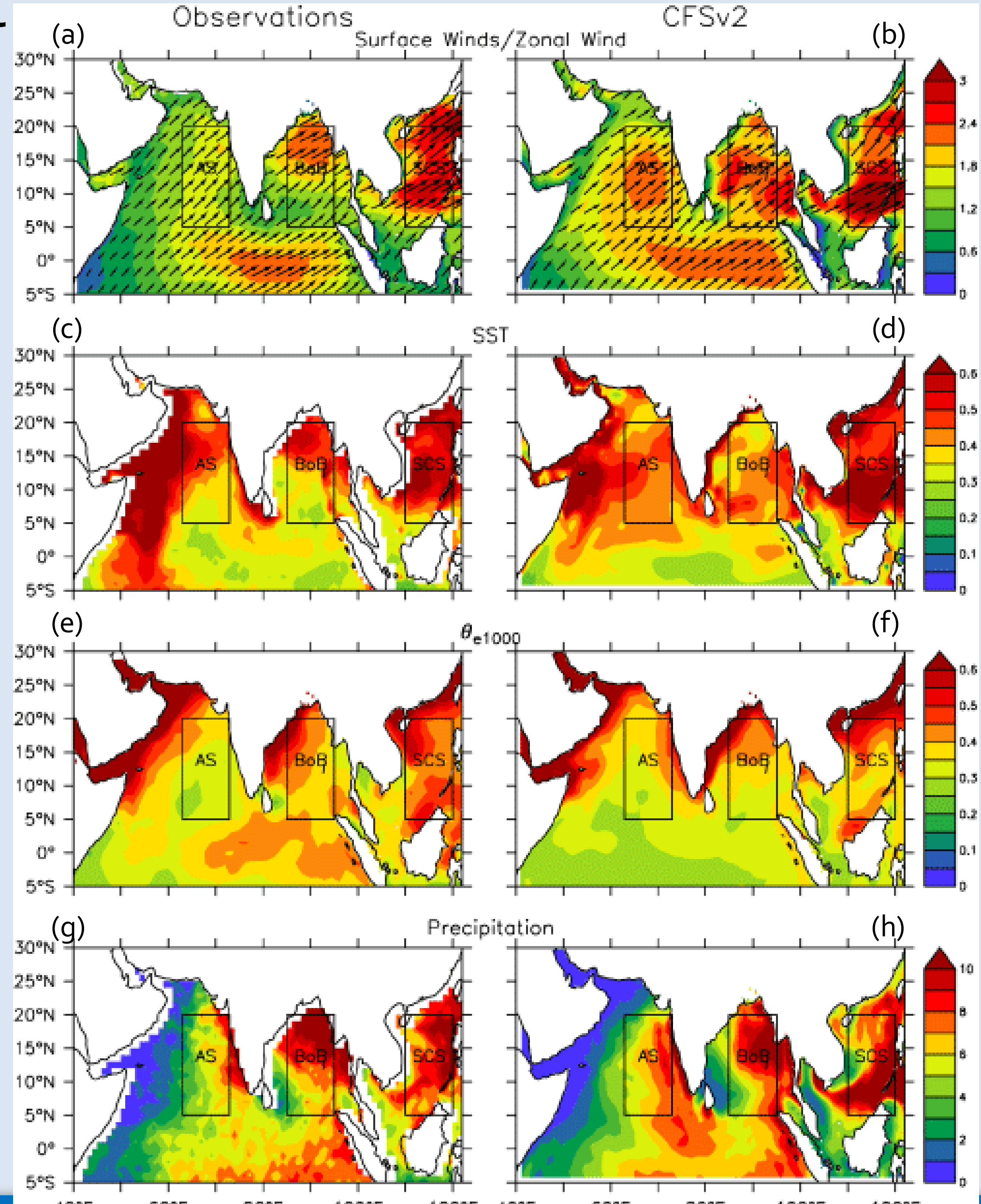
Biases in ISV of SST correlated with biases in ISV of MLD

For the same magnitude of fluxes, change in SST is different:

Shallow MLD –> ISV amplified

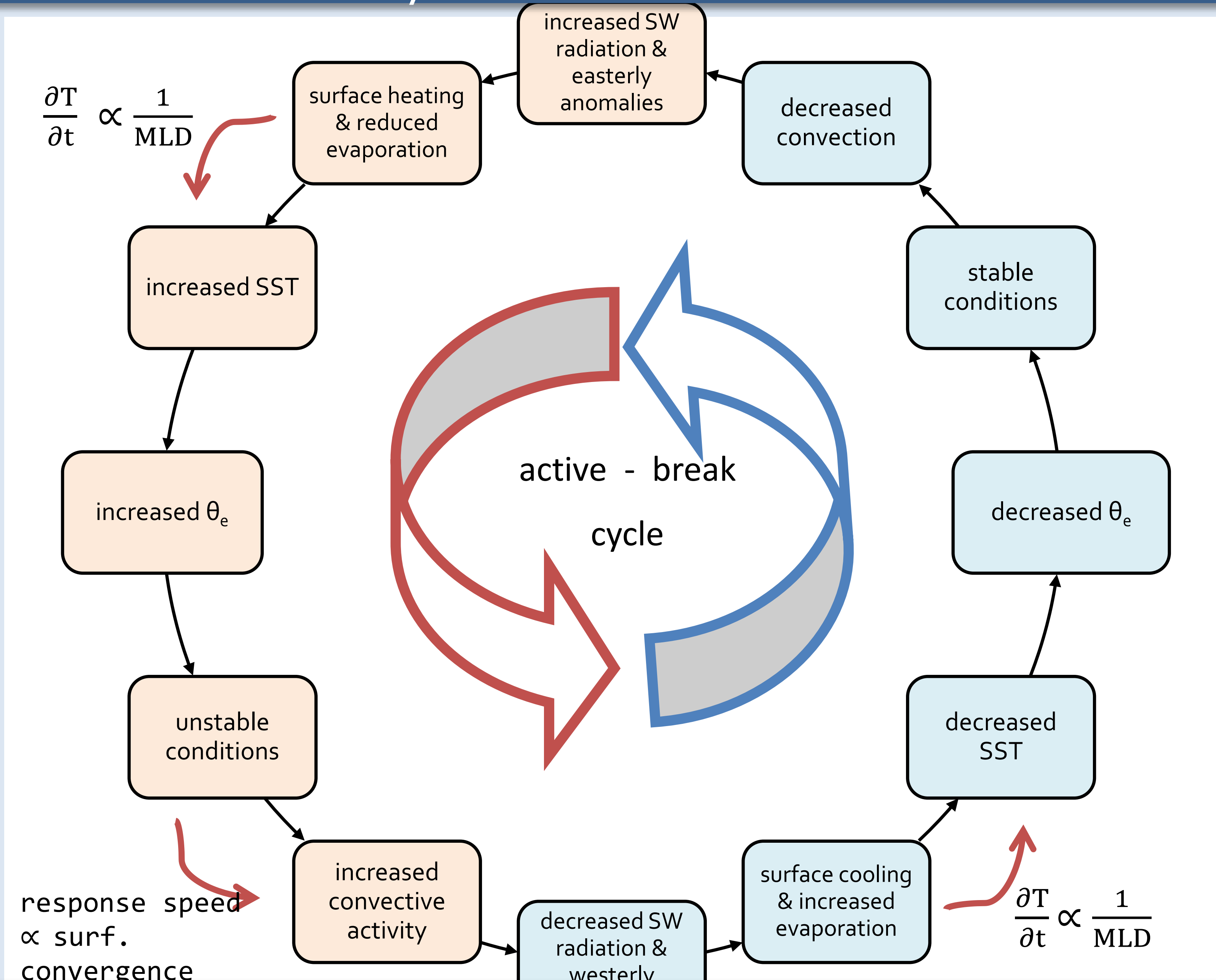
Deep MLD –> ISV weakened

r = **0.5**, significant at 95% levels



Roxy et al., *Climate Dynamics* 2013

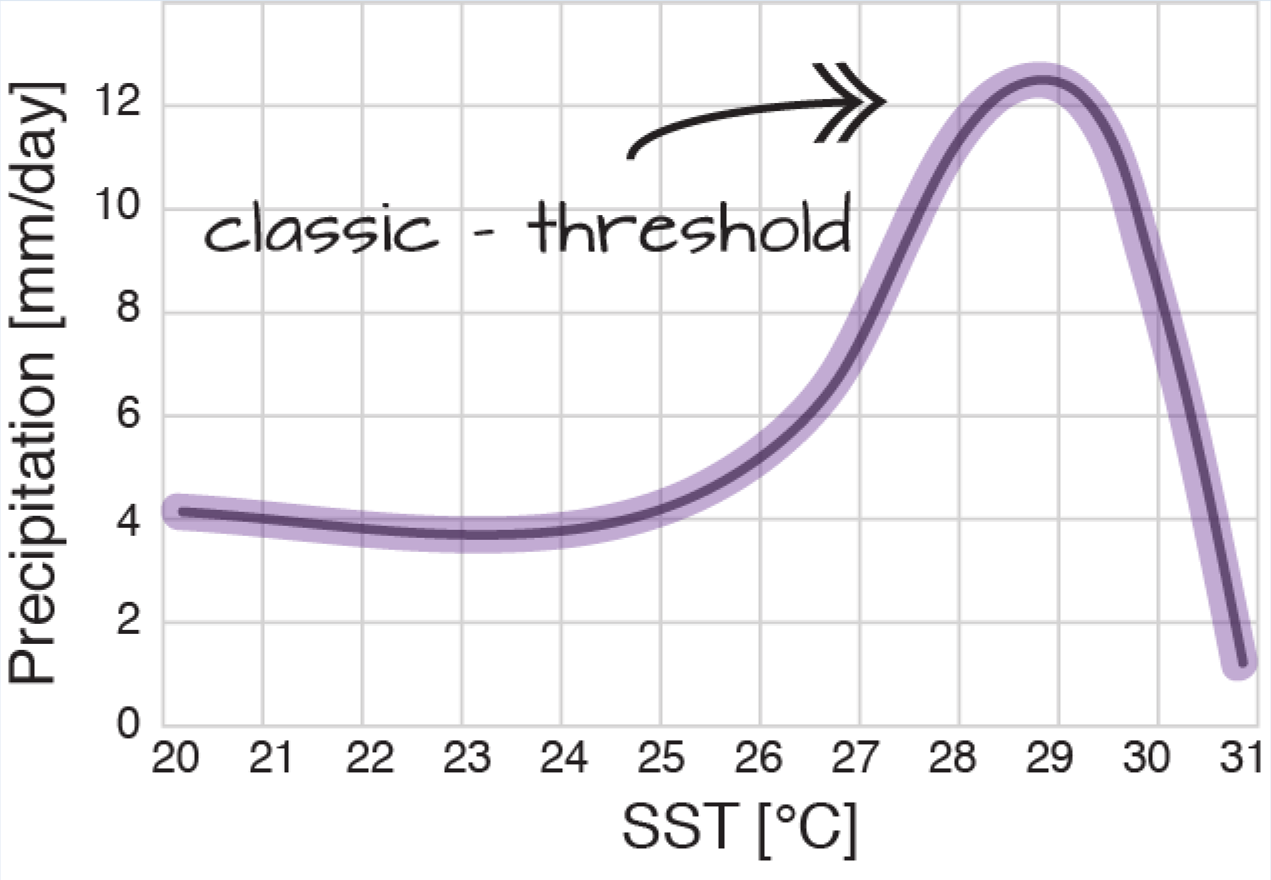
Intraseasonal variability of the Monsoon



Roxy et al., *Climate Dynamics* 2013

SST- precipitation relationship

— Lower and Upper Threshold for convection?



SSTs above **26 ℃** conducive for increased convection
Are SSTs important for convection, beyond **28.5 ℃ ?**

Gadgil et al., *Nature*, 1984; Waliser et al., *J. Climate*, 1993

SST- precipitation relationship

— Earlier studies: Upper Threshold and CAPE

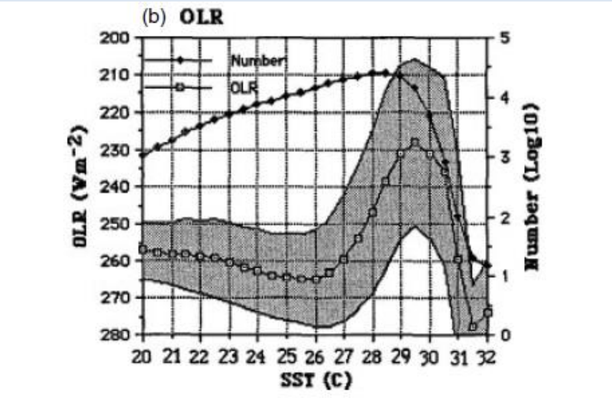


Figure 1. SST–convection relation in the global tropics (reproduced from Waliser *et al.*, 1993) for monthly values in 2° × 2° latitude–longitude squares of global tropics 25°S to 25°N for the period 1975–1985: (a) SST and HRC and (b) SST and OLR. The right ver-

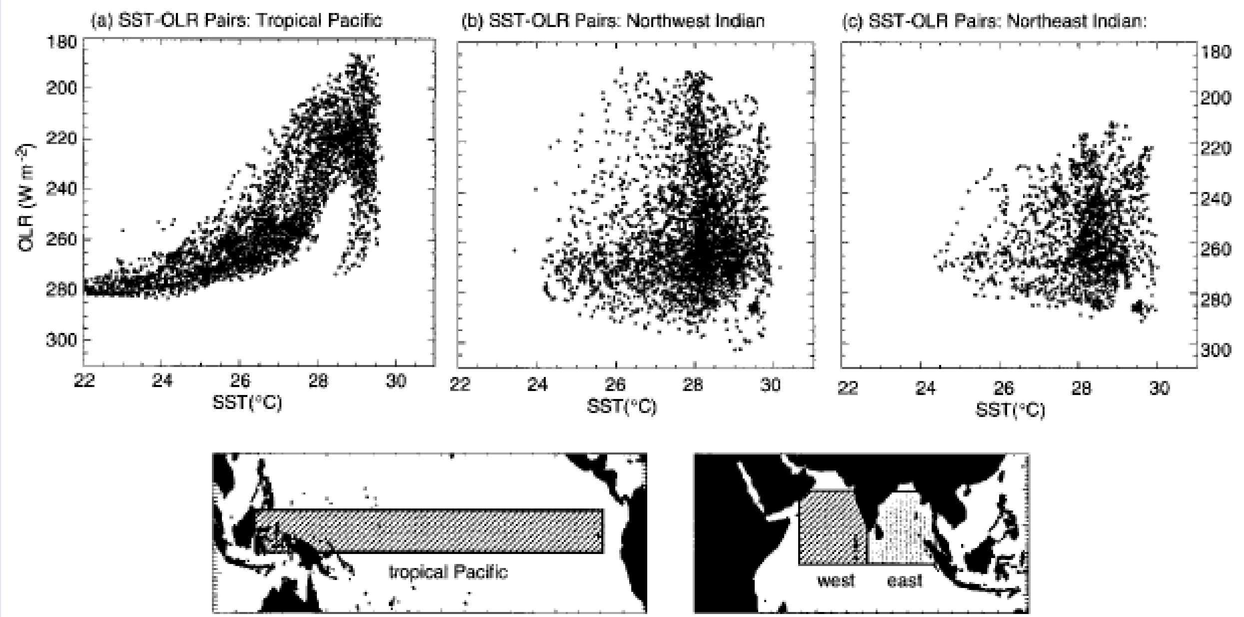


FIG. 3. OLR–SST (W m^{-2} and °C with ordinate scale reversed) pairs for (a) the tropical Pacific Ocean in the region 5°S–5°N, 120°E–90°W, (b) the northern Indian Ocean for the region equator–20°N, 55°–80°E, and (c) the northern Indian Ocean, equator–20°N, 80°–100°E. The geographical areas are depicted by the areas within the shaded boxes on map panel. Mean monthly values are plotted for Mar, Apr, and May for all points in the boxes. Data are from 1972–89.

Earlier studies: Precipitation increases monotonously at SSTs beyond **26 ℃**, but limited to: **Upper threshold of 28 – 29℃**

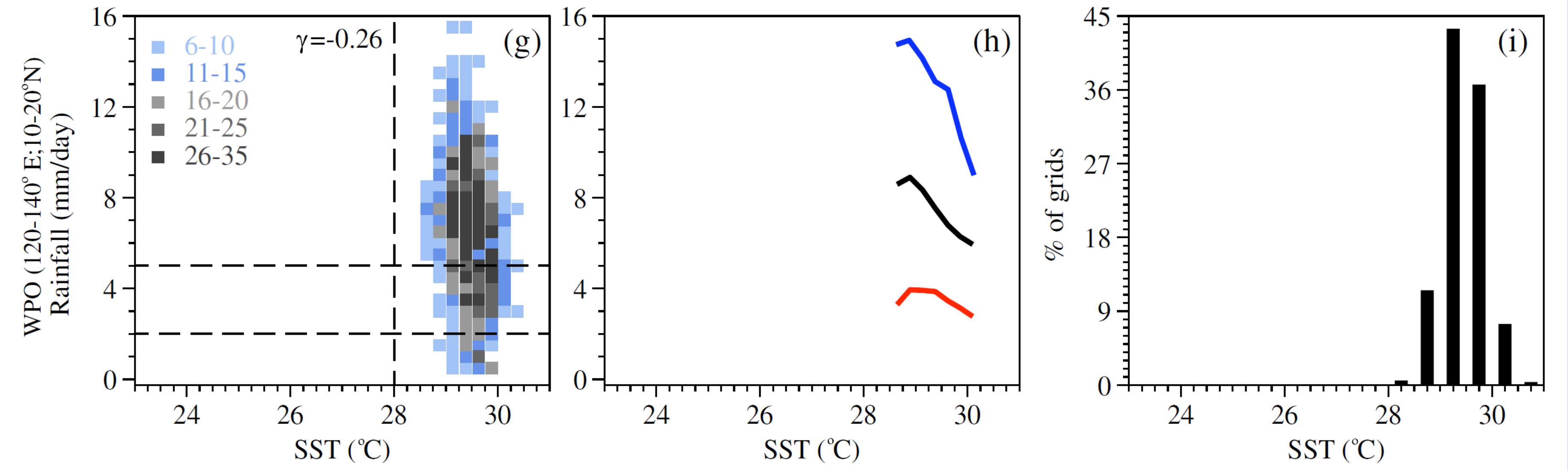
Explanation given: Precipitation tends to occur where positive convective available potential energy (CAPE) exists

-> the occurrence of deep convection will tend to squelch CAPE?

Gadgil et al. 1984; Waliser et al. 1993; Loschnigg and Webster 2000; Bhat et al. 1996

SST- precipitation relationship

— negative relationship over west Pacific, at SSTs > 29°C?



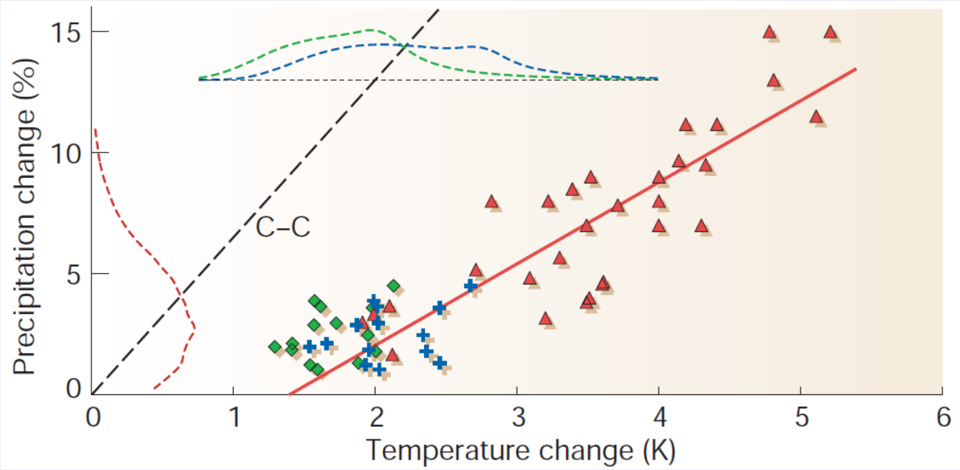
Rajendran et al., *J. Earth System Science*, 2012

SST- precipitation relationship

Clausius-Clapeyron

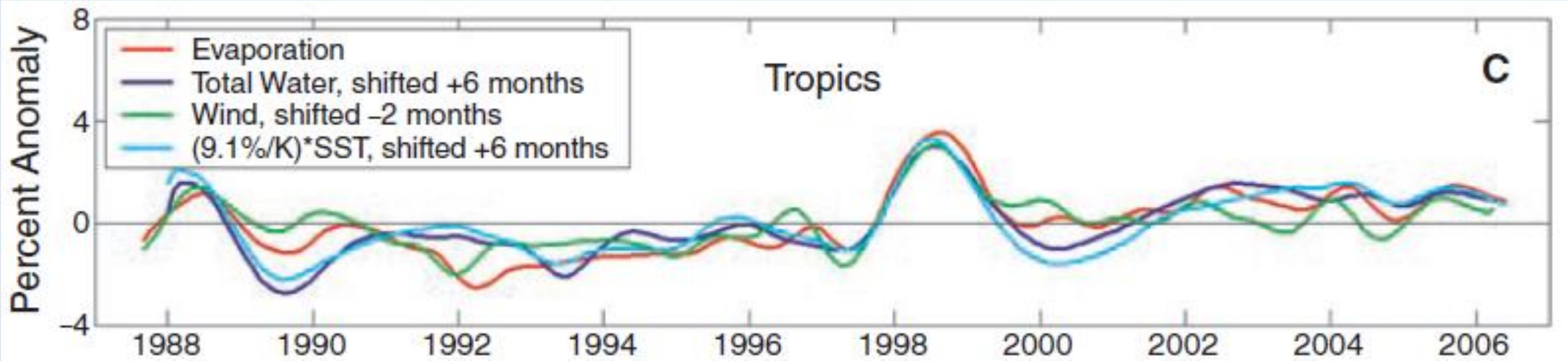
— moisture increases with increasing temperature

The Clausius–Clapeyron relation implies that specific humidity and hence atmospheric moisture would increase roughly exponentially with temperature – 7%/°C – substantially smaller than the sensitivity change documented.



C–C also controls how "wet gets wetter, and dry gets drier".

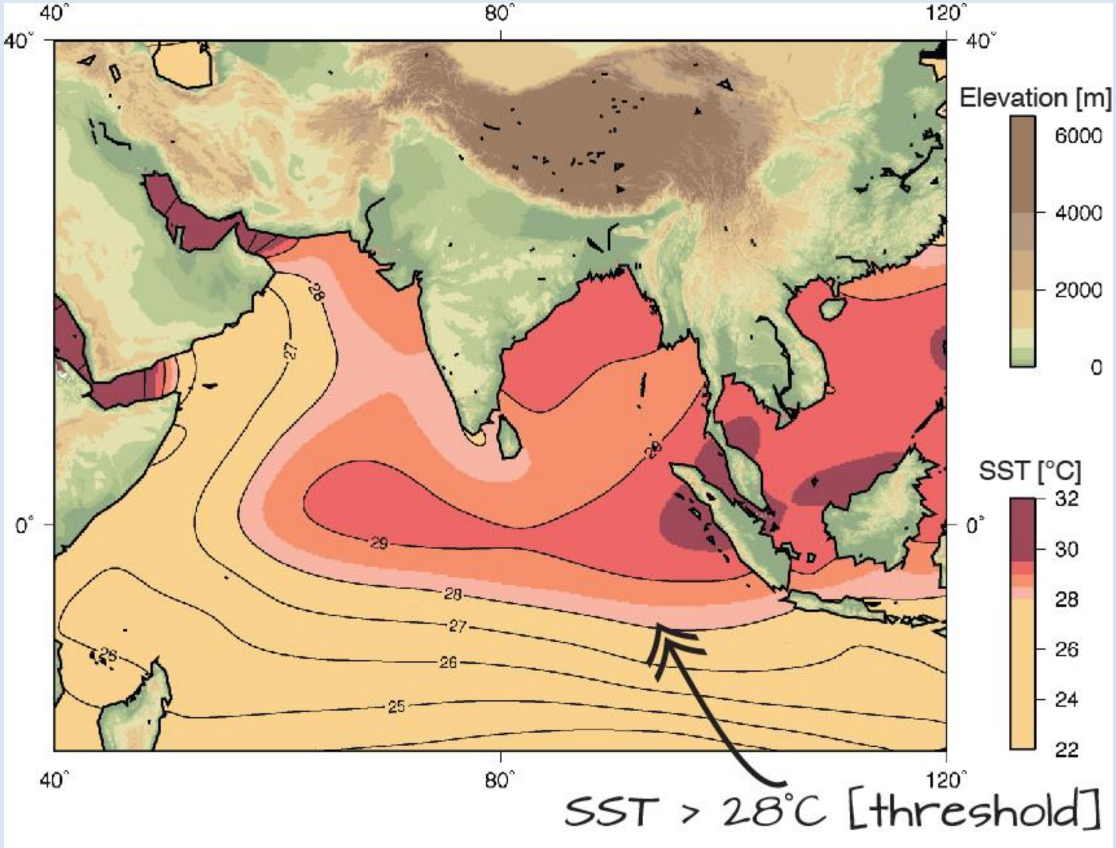
Observations suggest that precipitation and total atmospheric water have increased at about the same rate over past 2 decades.
–> **with SST, moisture has increased**
–> **with moisture, rainfall has increased**



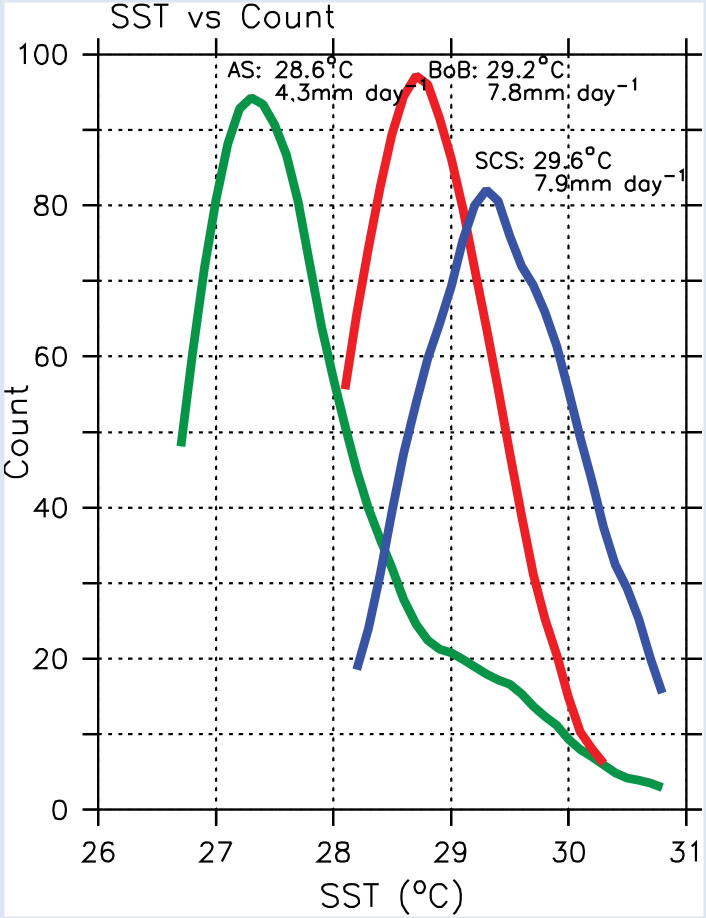
Allan and Ingram, *Nature,* 2002; Allan and Soden, *Science,* 2006; Wentz et al., *Science,* 2007

SST- precipitation relationship

— Does high SSTs have an active role on Monsoon?



SSTs averaged over the open basins

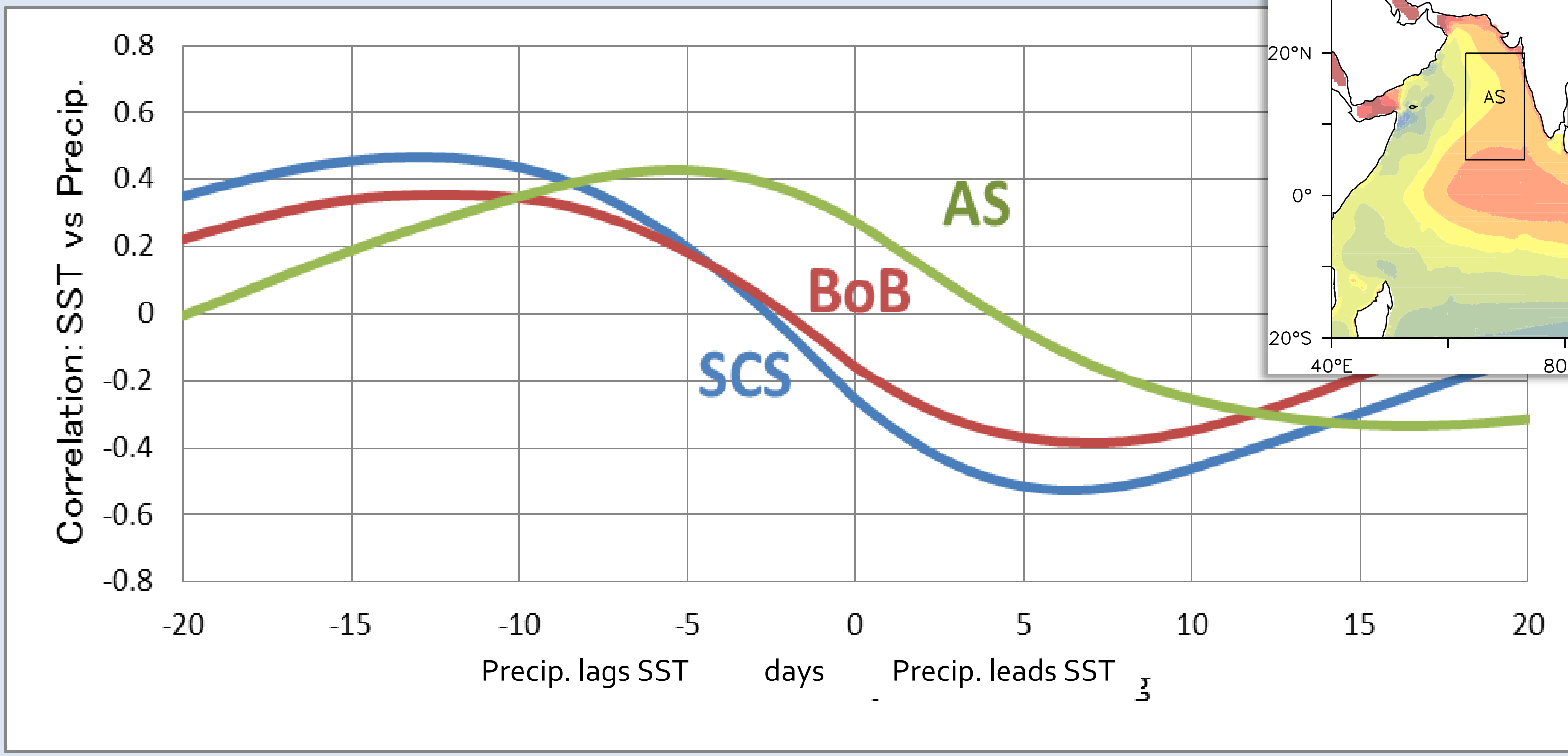


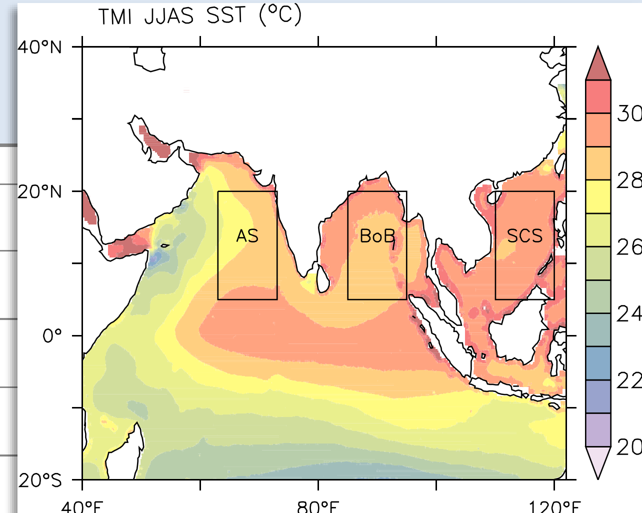
mean SSTs are above 28.5°C

SST- precipitation relationship

— it's a lead-lag relationship!

The SST–precipitation relationship have different **lead–lags** over the Arabian Sea and the Bay of Bengal/South China Sea

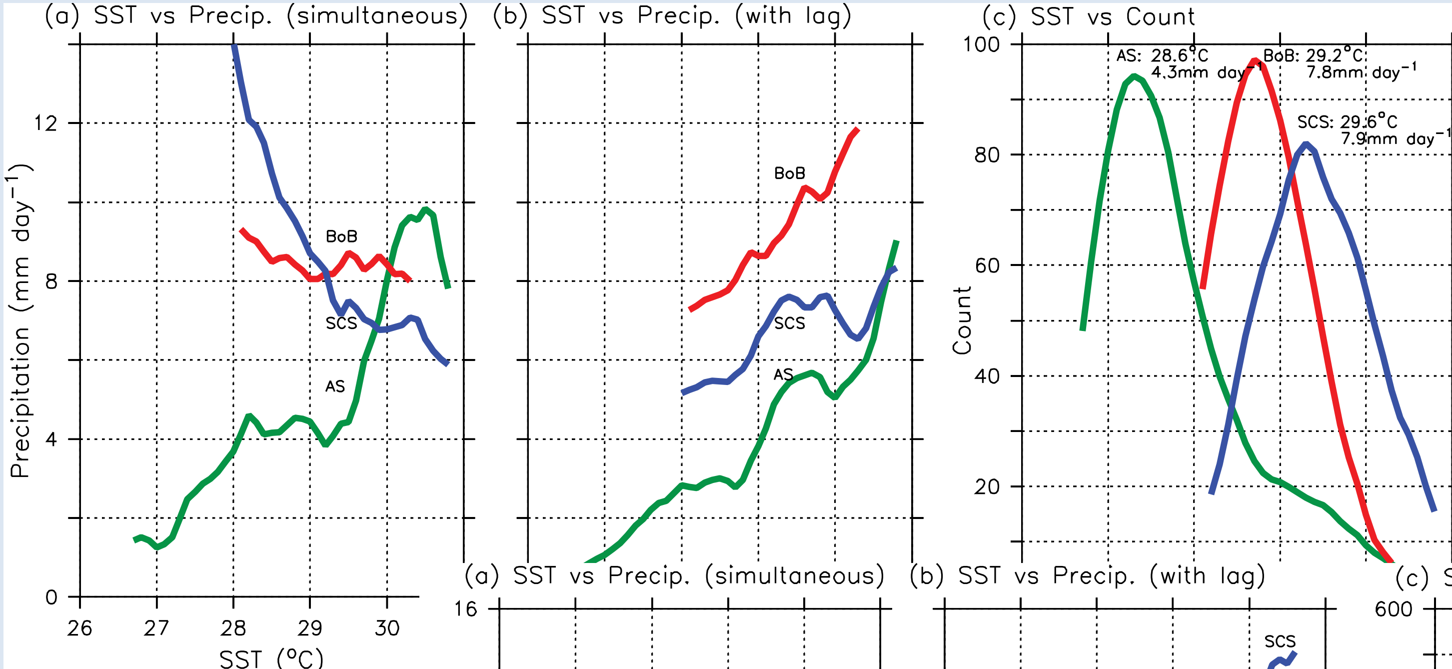




The magnitude of the correlation refers to the intensity of the driving force, and the corresponding lag (lead) time denotes how quickly the atmosphere responds to the SST anomalies and vice versa.

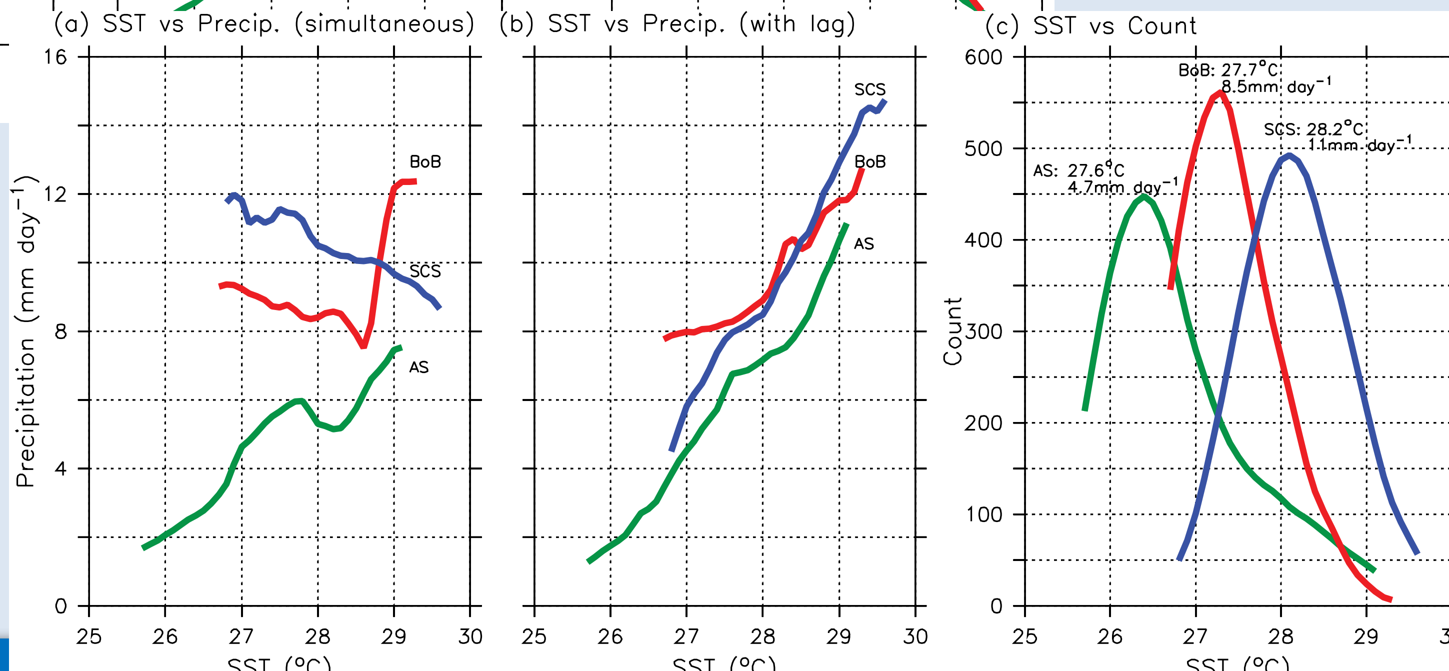
SST- precipitation relationship

lags considered, 1°C rise in SST -> 2 mm/day in rainfall



Observations

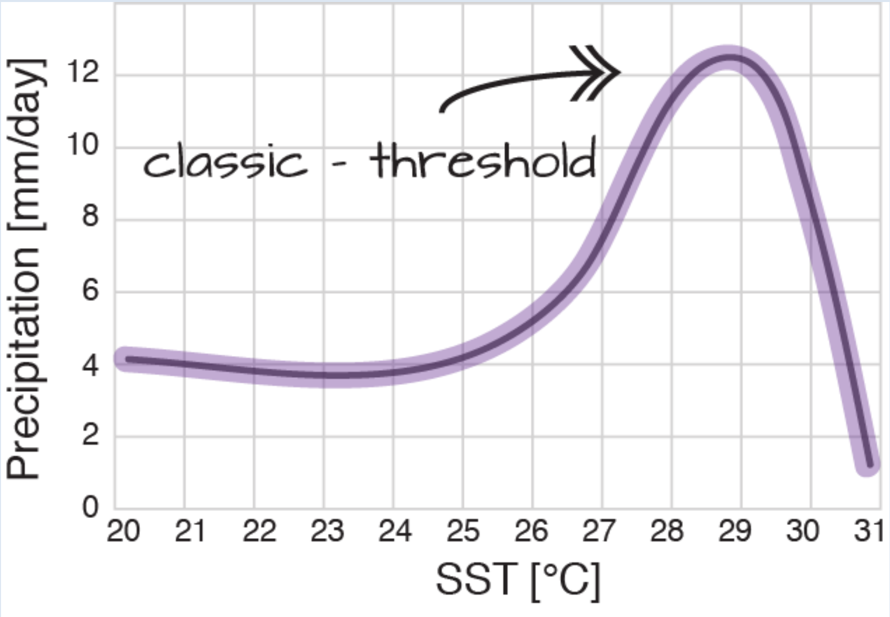
Model Simulations

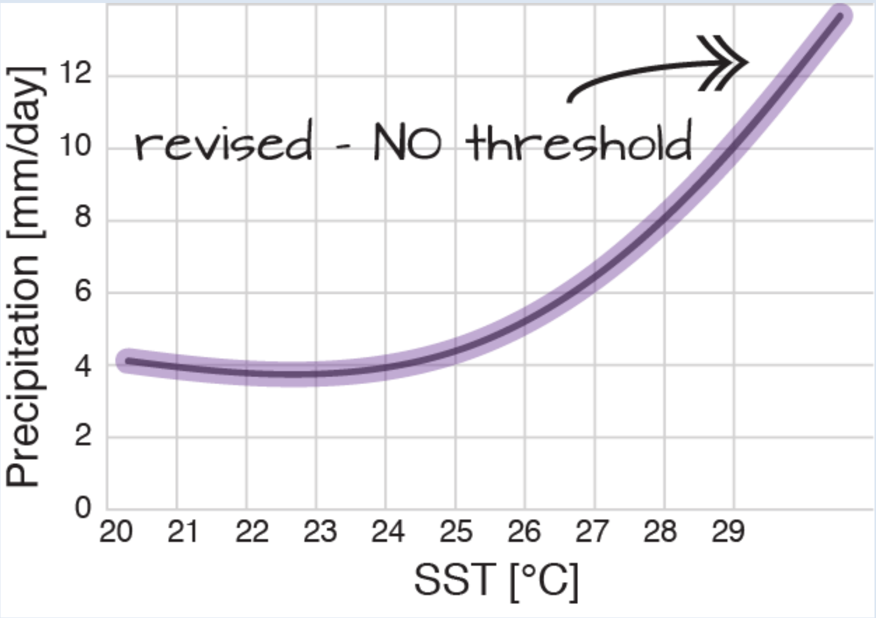


Roxy, *Climate Dynamics* 2014

SST- precipitation relationship

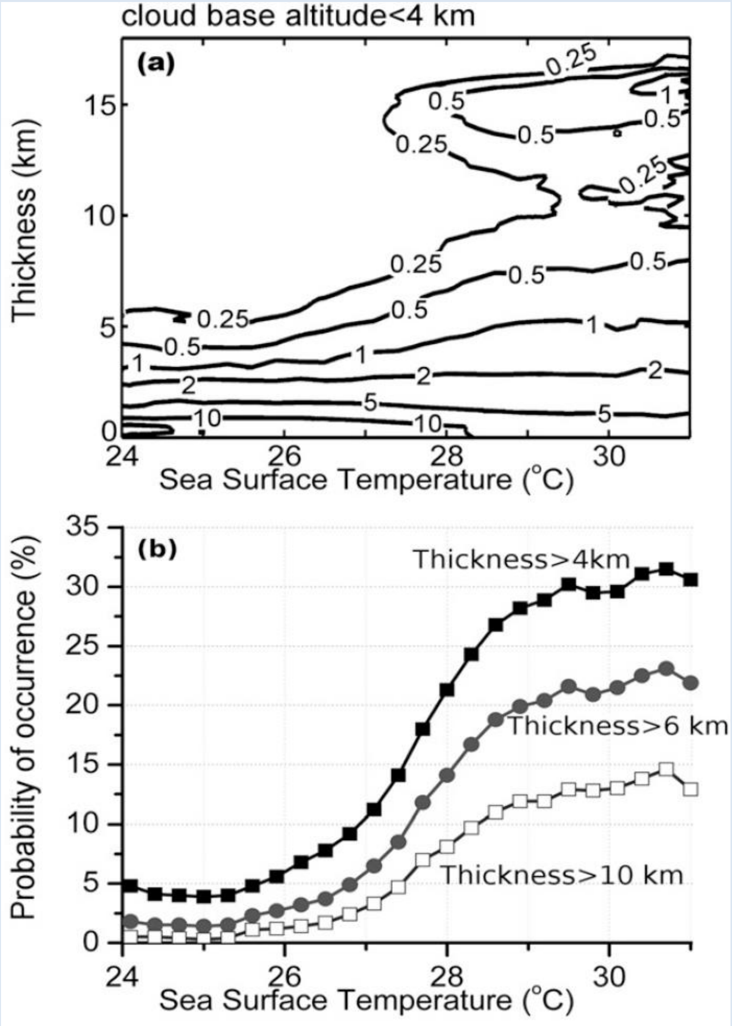
lags considered, 1°C rise in SST -> 2 mm/day in rainfall

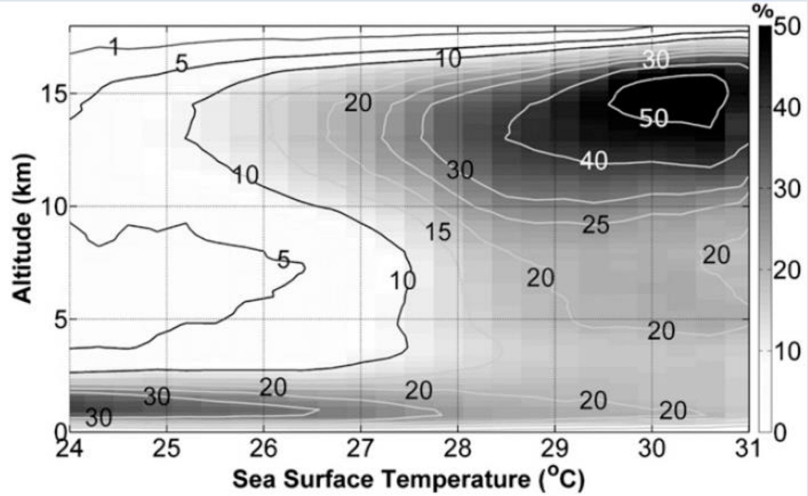




SST- precipitation relationship

Cloud vertical distribution and thickness grows with increased SST (CloudSat and CALIPSO)

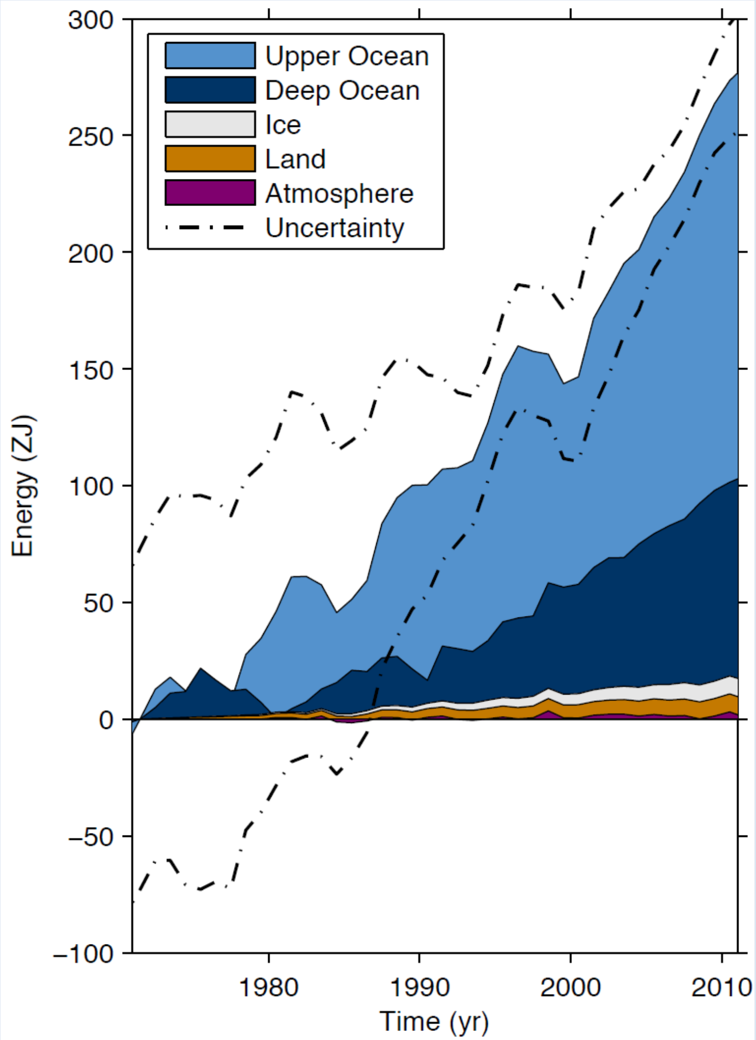




Nair and Rajeev, *J.Climate*, 2013

Climate Change and the Monsoon – Tropical Ocean warming

Heat gain is uneven among earth system components — Ocean gaining more than 90% of the heat



Oceans are a big deep reservoir of a liquid with high heat capacity.

Almost all (more than 90%) of Earth's heat gain goes into the oceans.
Rate is 8 x 10^{21} J/yr, or 2.5 x 10^{14} J/sec.

≈ 4 Hiroshima atomic bomb detonation per second
(1 detonation = 6.3 x 10^{13} Joules
So, about 2 billion atomic bombs since 1998)

Atmospheric heat gain is an especially small part of the total.

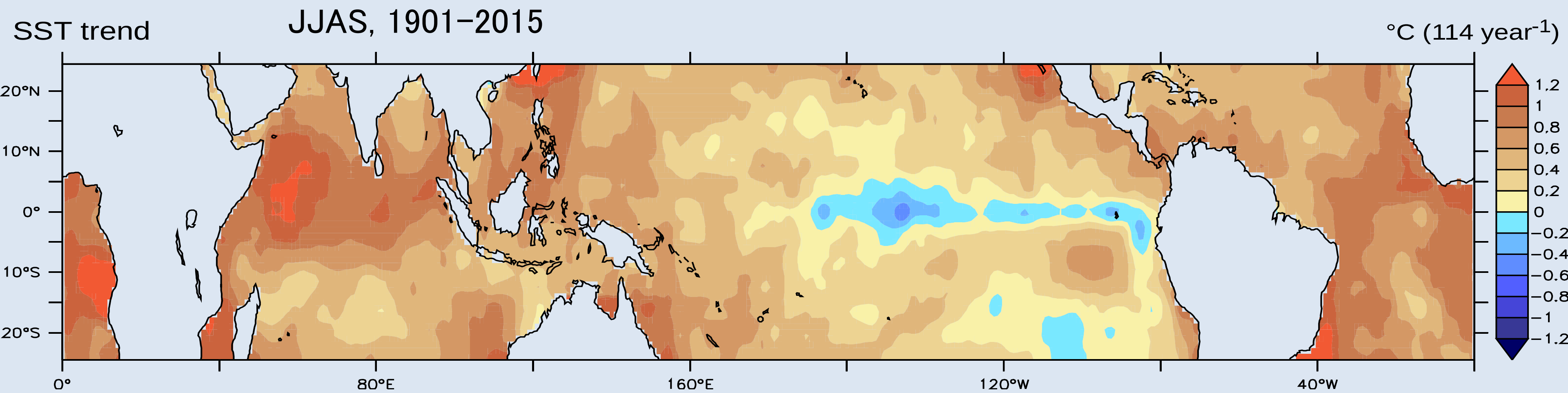
Atmosphere + Land + Ice accounts for less than 10% of the heat gain.

Church et al., *GRL*, 20111; Nuccitelli et al., *Phys.Lett.*, 2012; IPCC, *AR5*, 2013

Climate Change and the Monsoon – Tropical Ocean warming

Heat gain in the ocean is also uneven

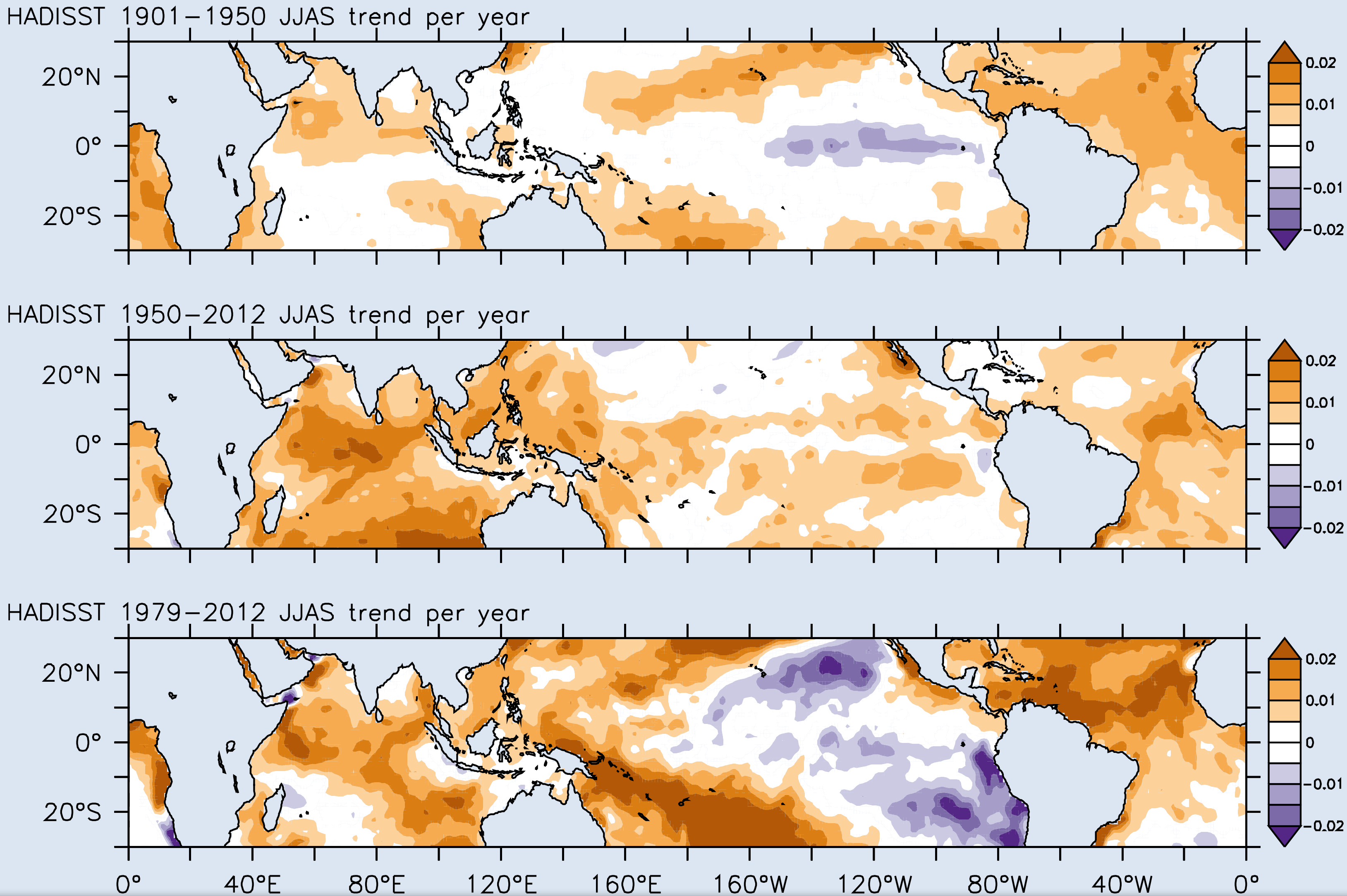
— Indian and Atlantic Oceans have warmed up



Roxy et al., *J.Climate*, 2014

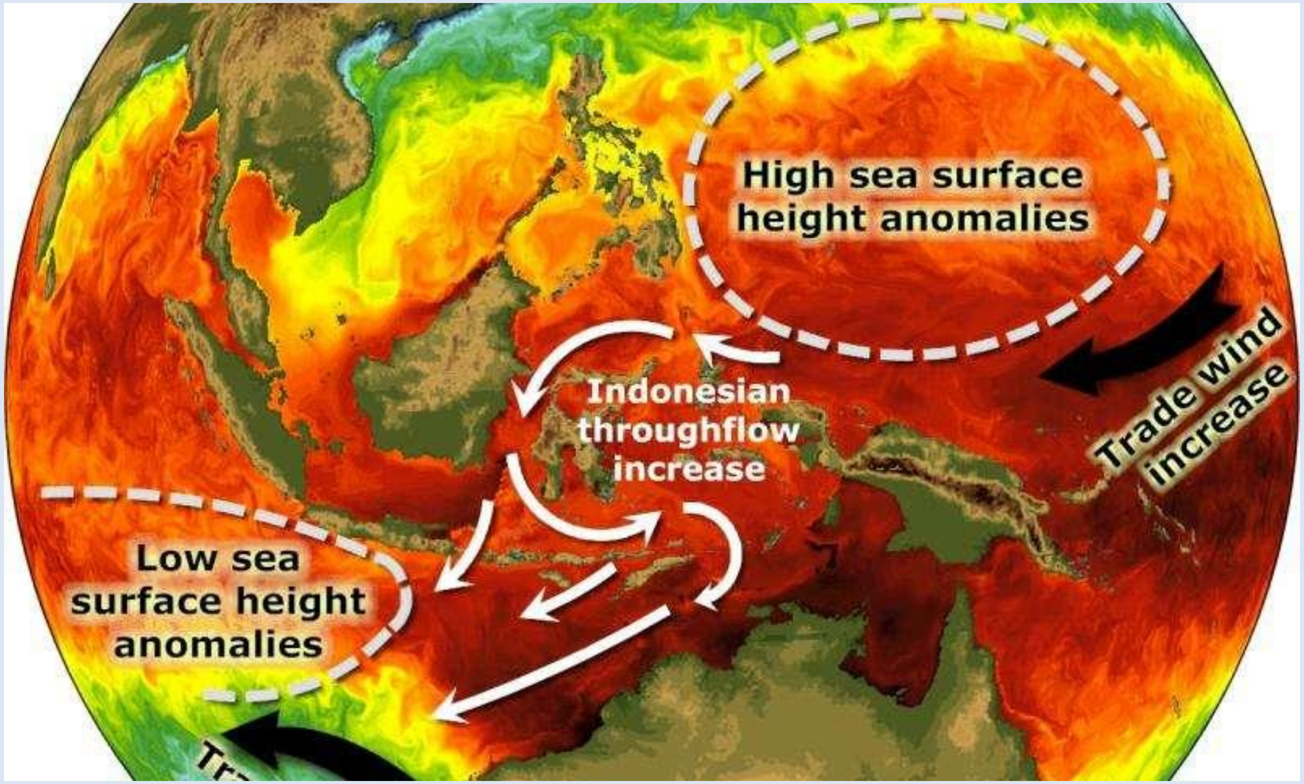
Climate Change and the Monsoon – Tropical Ocean warming

Surface warming uneven through different periods
— monotonous warming in the Indian and Atlantic Oceans



Climate Change and the Monsoon – Tropical Ocean warming

Subsurface warming in the Indian Ocean
— Increased heat transport from the Pacific to Indian Ocean



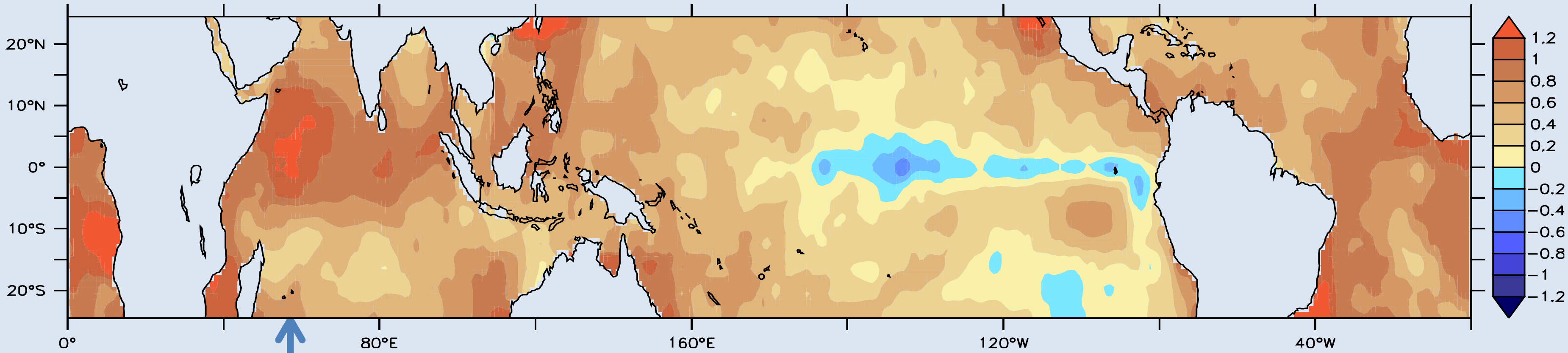
Indian Ocean heat content has increased abruptly, which accounts for more than 70% of the global ocean heat gain in the upper 700 m during the past decade.

Lee et al. *Nature Geosciences*, 2015

Climate Change and the Monsoon – Tropical Ocean warming

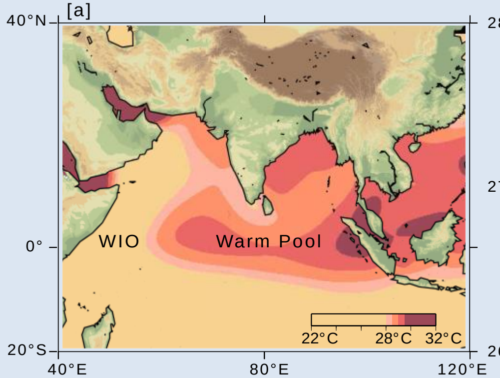
— western Indian Ocean warmed up to 1.2°C

SST trend

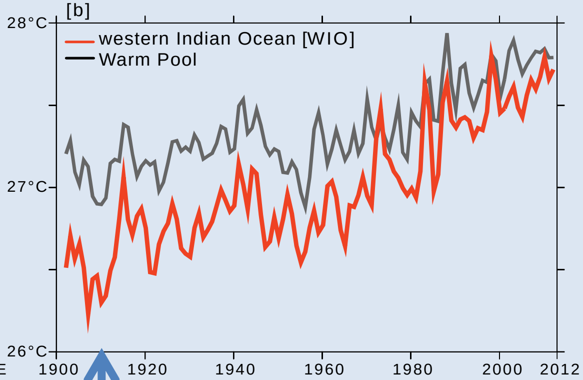


Basin-wide warming, with significant warming over western Indian Ocean.

SST Climatology

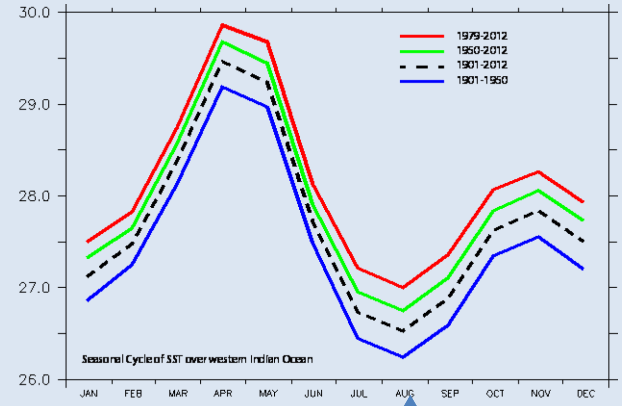


Time-series [1901–2012]



Monotonous **warming over west nullifies zonal SST gradient**

Changes in SST seasonal cycle



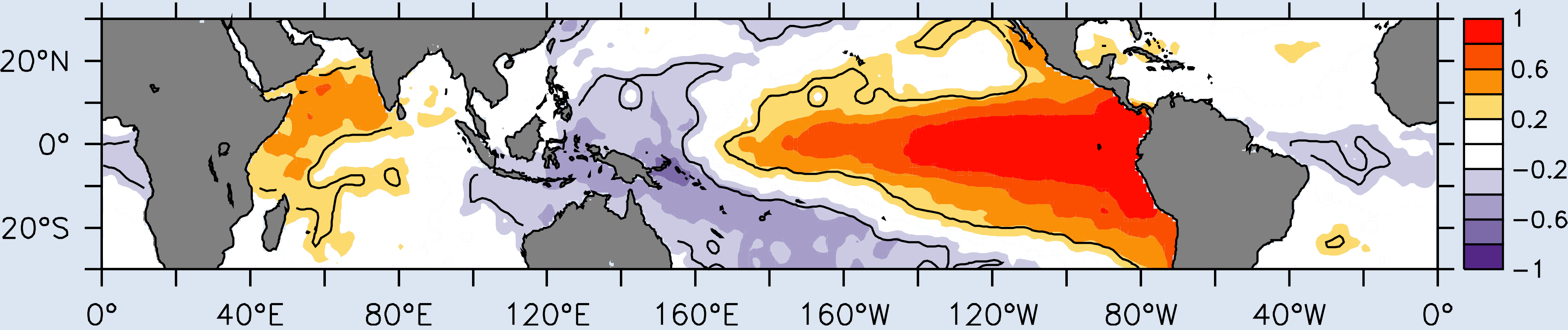
SST change largest in summer

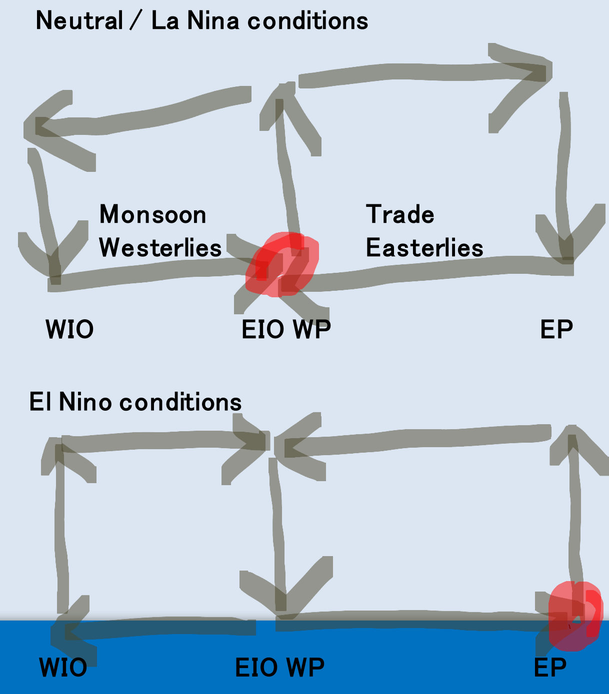
Roxy et al., *J.Climate*, 2014

Climate Change and the Monsoon – Tropical Ocean warming

WIO: Pacific-Indian Ocean teleconnection during summer — Walker Circulation

(a) Correlation: east Pacific SSTa vs Global SSTa, June-Sept mean

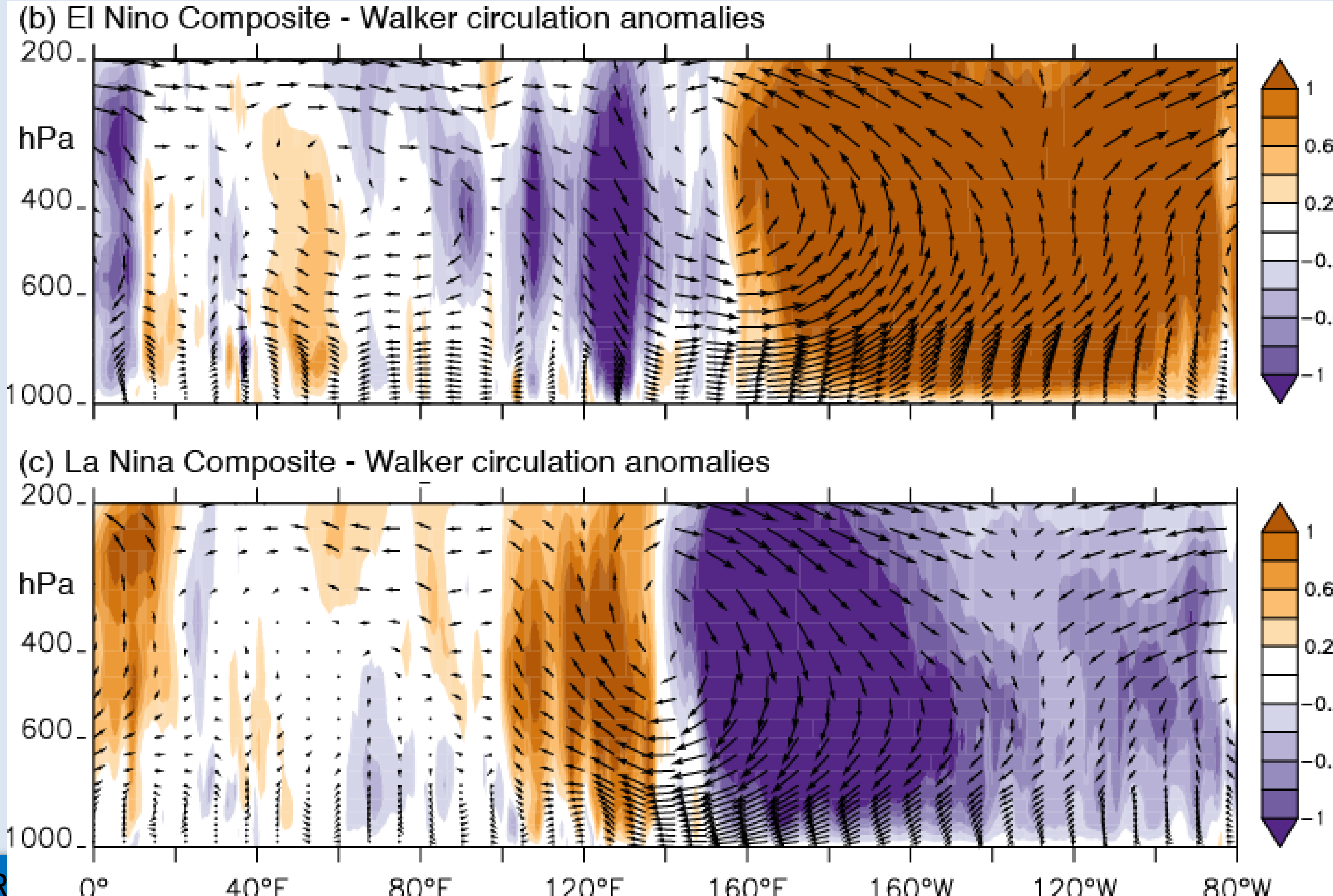




Roxy et al., *J.Climate*, 2014

Climate Change and the Monsoon – Tropical Ocean warming

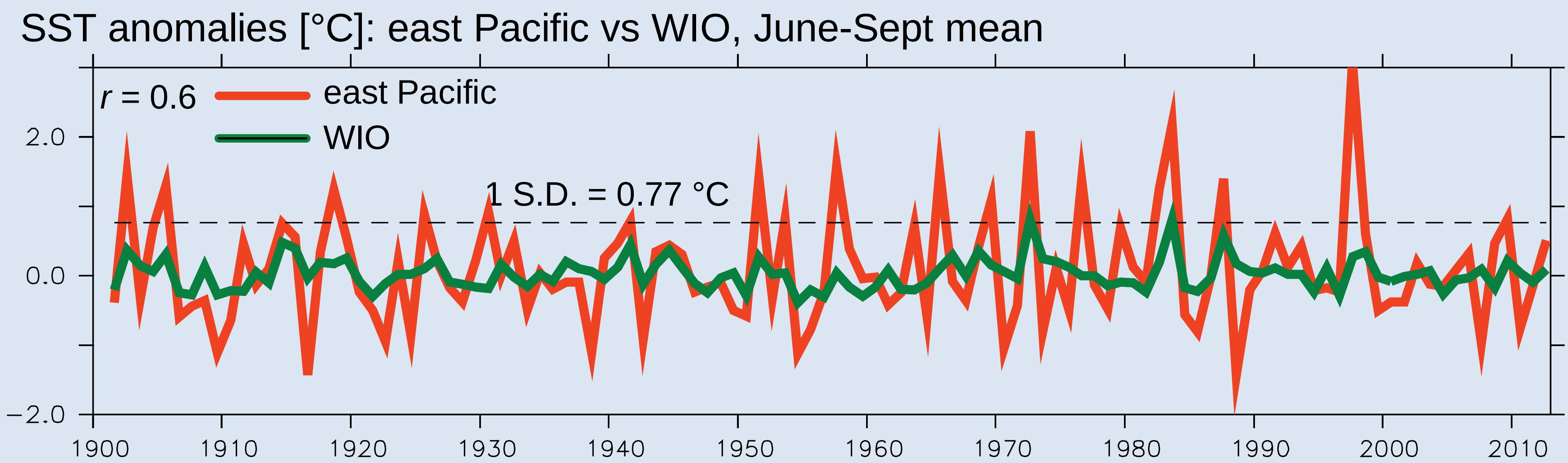
Asymmetry in ENSO forcing: Influence of El Niño > La Niña



Climate Change and the Monsoon – Tropical Ocean warming

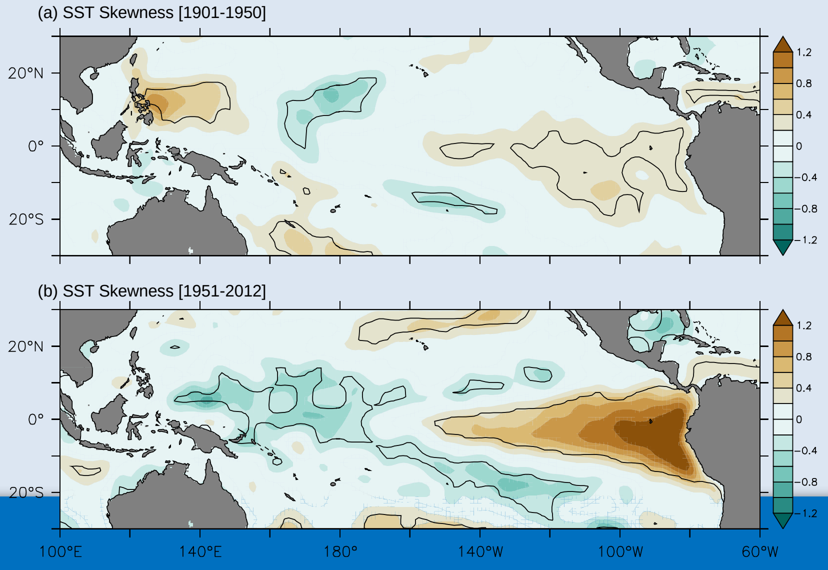
Skewness in ENSO forcing:

Increase in Frequency and Magnitude of El Niños



Detrended anomalies show increase in frequency and strength of El Niños. The warm events over Indian Ocean also has increased. Occasionally, they cross the El Niño criteria (1 S.D. = 0.77 degC).

Positive skewness over east Pacific in recent decades >>

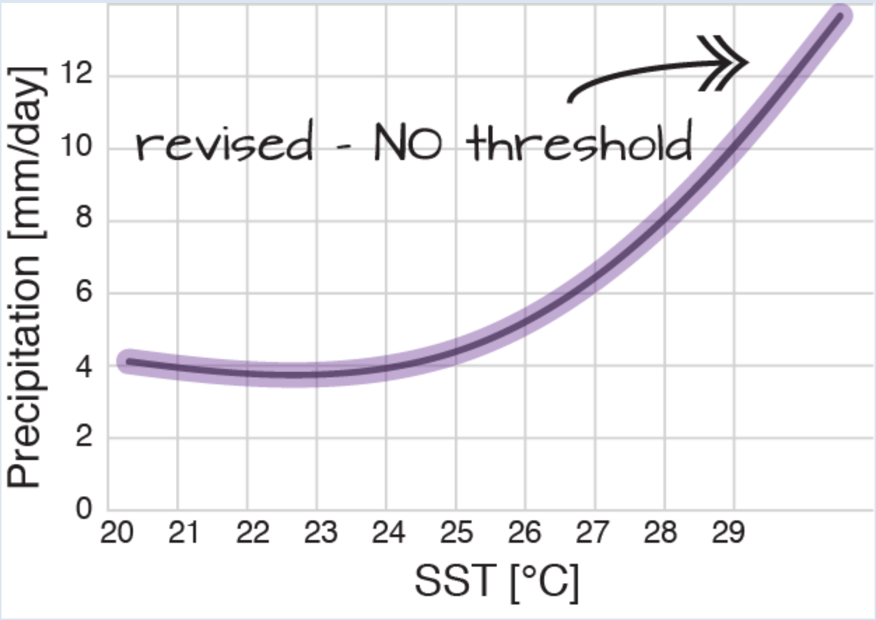


Roxy et al., *J.Climate*, 2014

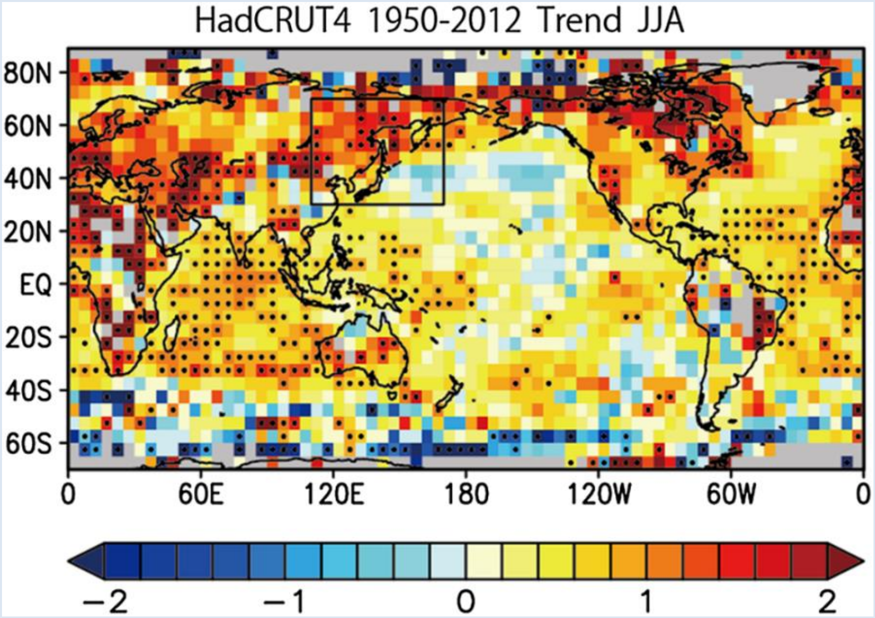
Climate Change and the Monsoon – Tropical Ocean warming

Ideally, Increased ocean warming = more rainfall
Increased land-sea contrast = more rainfall

Increased ocean warming



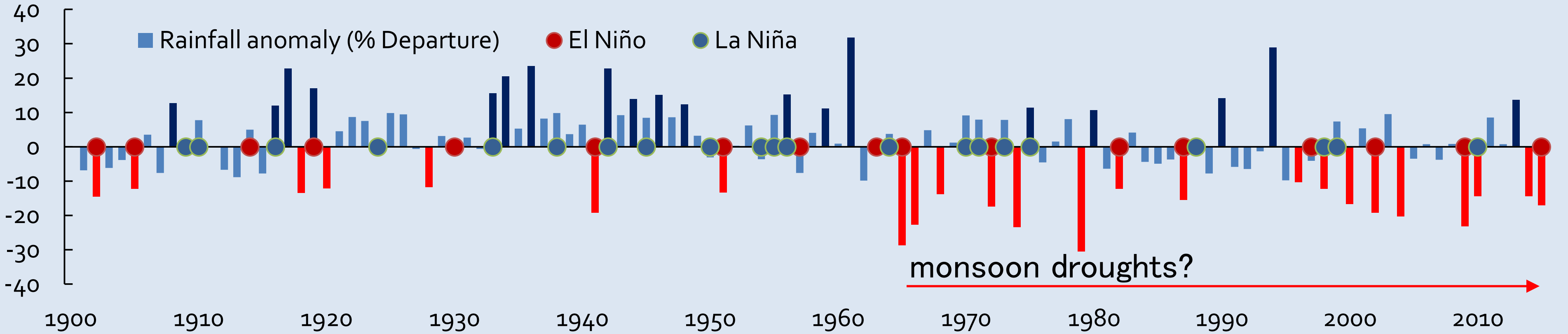
Increased land–sea thermal contrast



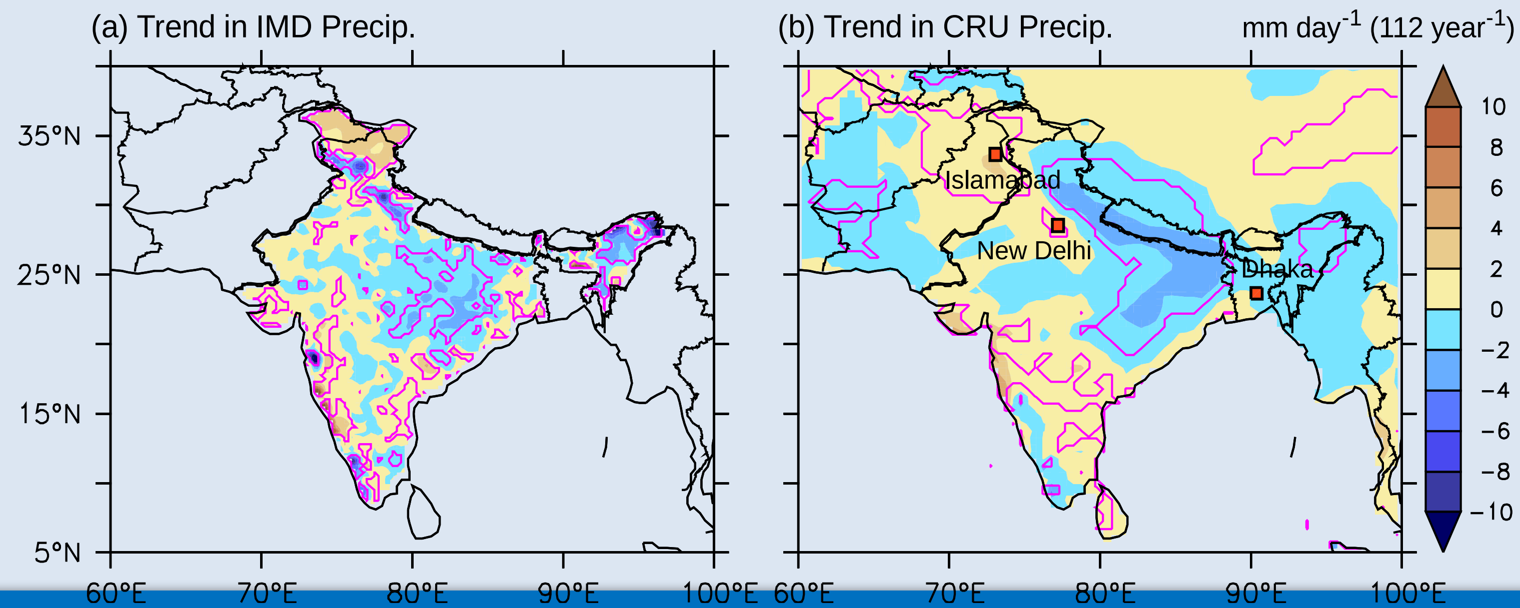
Annamalai and Turner, *Nature Climate Change* 2012

Climate Change and the Monsoon – Tropical Ocean warming

but it's a weak South Asian Monsoon



Decreasing trend in precipitation from Pakistan through central India to Bangladesh.
Significant over central Indian subcontinent (horse-shoe pattern)

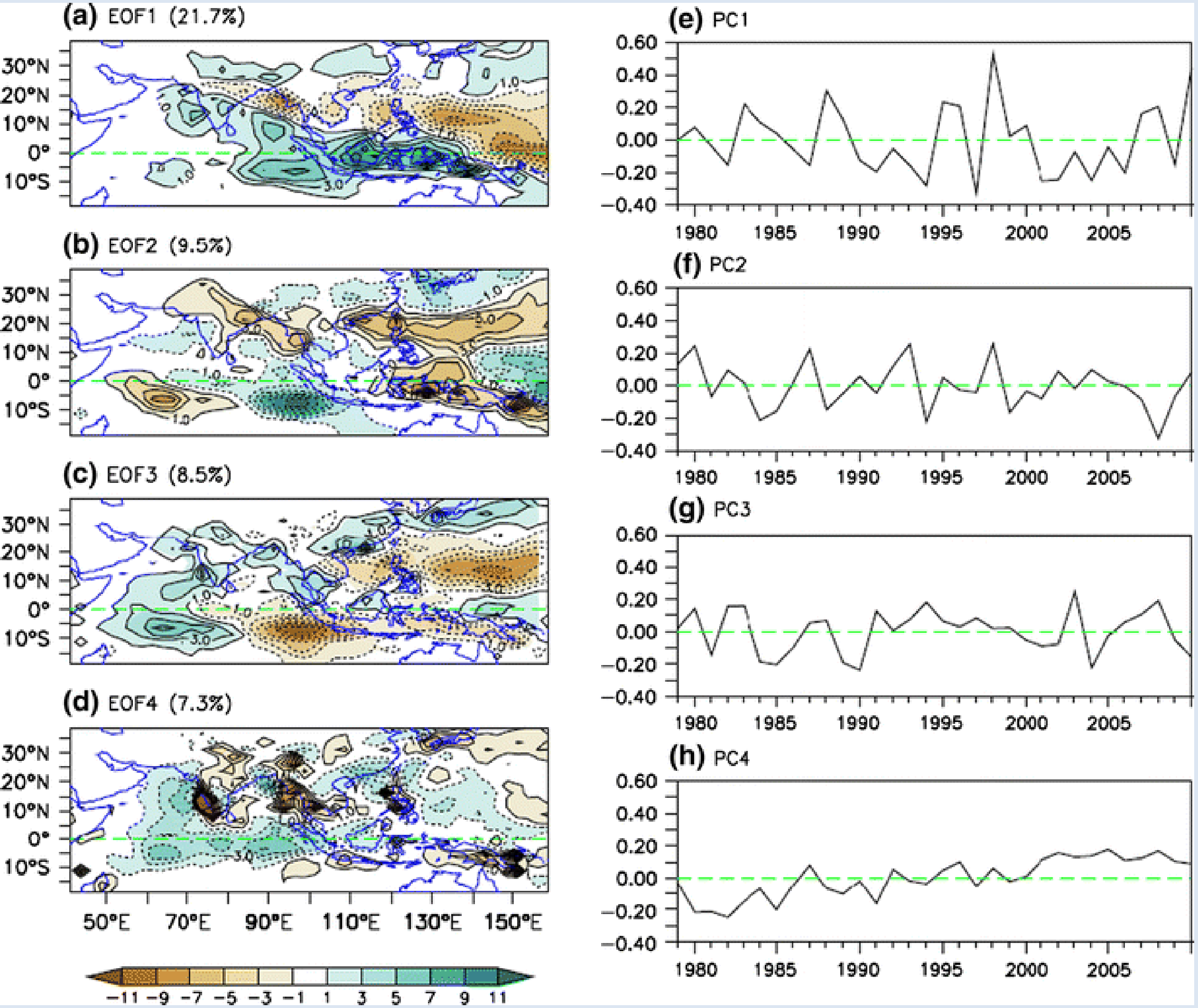


Guhathakurta and Rajeevan, *IJOC*, 2008; Roxy et al., *Nature Communications*, 2015

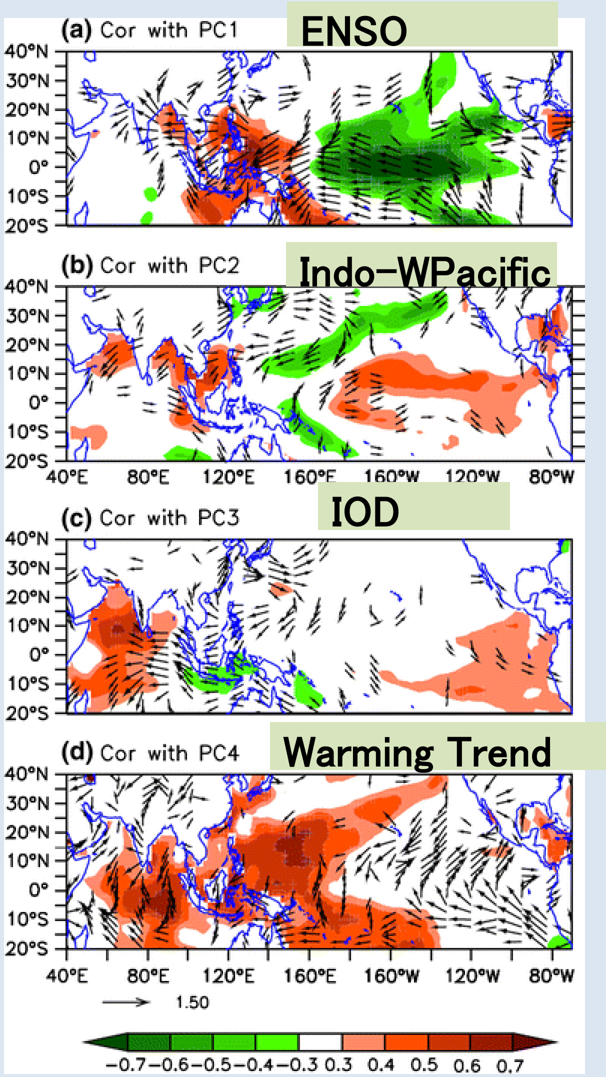
Climate Change and the Monsoon – Tropical Ocean warming

EOF4 corresponds to ocean warming trend

EOFs and corresponding PCs of precipitation



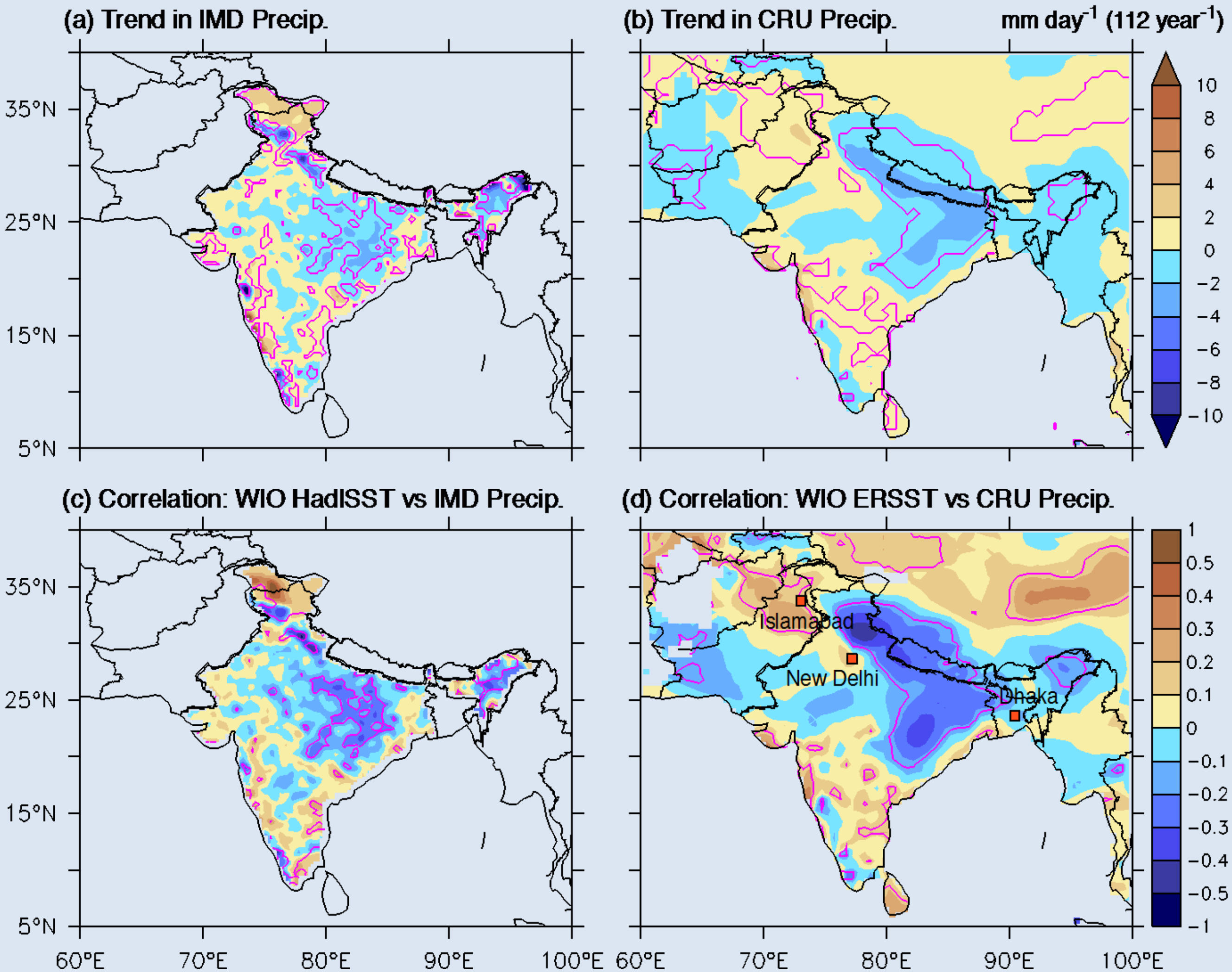
Correlation of SST with PC



Wang, Lee, et al., *Climate Dynamics*, 2015; Annamalai et al., *J. Climate* 2012

Climate Change and the Monsoon – Tropical Ocean warming

Indian Ocean warming well correlated with weak Precip.



(a) & (b)
Decreasing trend in precipitation from Pakistan through central India to Bangladesh. Significant over central Indian subcontinent (horse-shoe pattern)

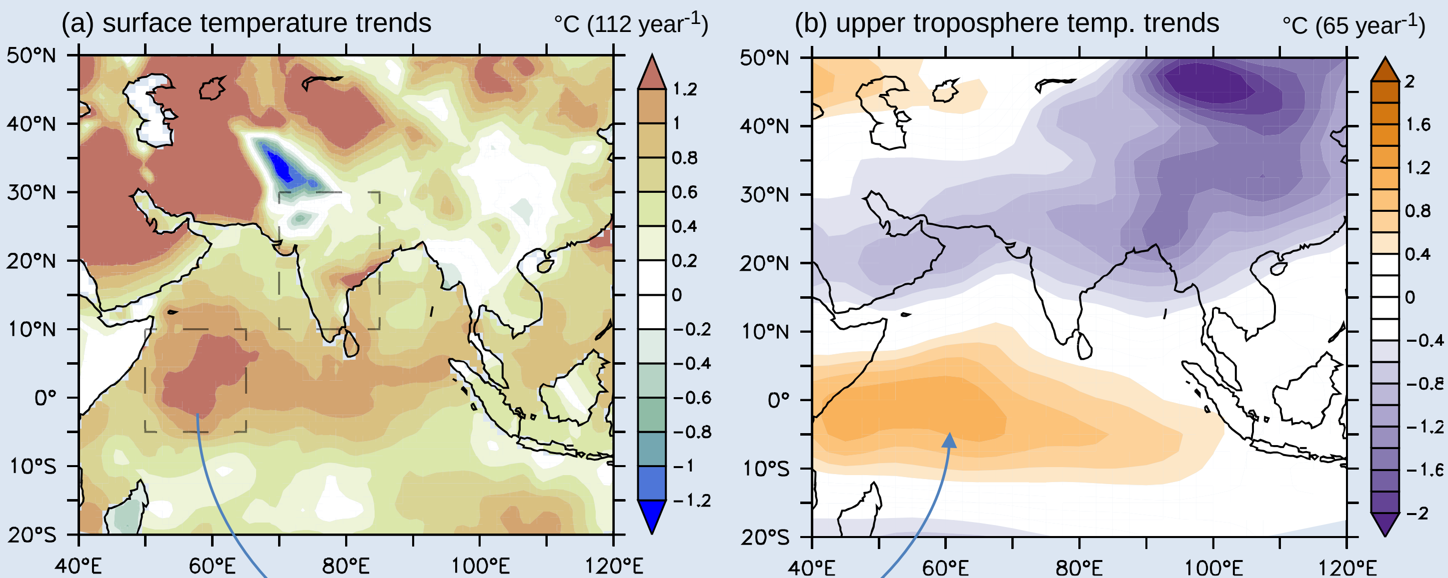
(c) & (d)
Trend and correlation with western Indian Ocean warming has similar patterns!

Roxy et al., *Nature Communications*, 2015

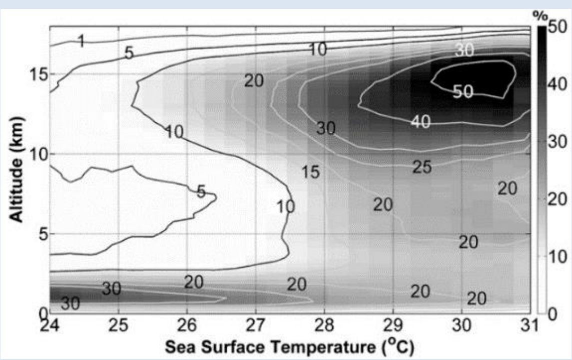
Climate Change and the Monsoon – Tropical Ocean warming

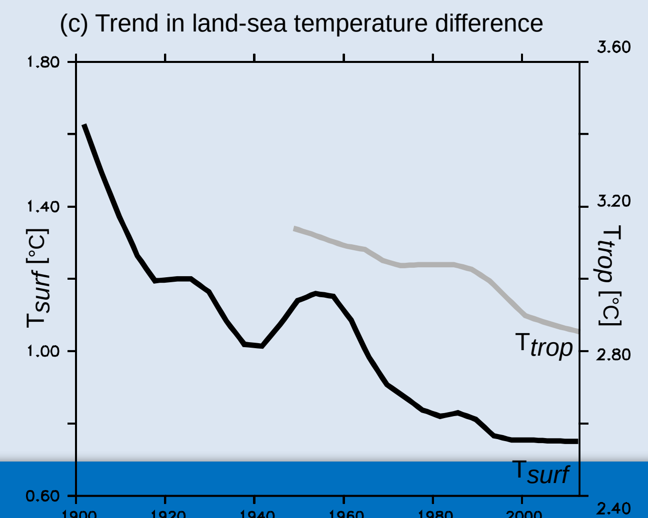
Land-sea thermal contrast over South Asian domain

Indian Ocean-large warming, Subcontinent-suppressed warming



Increased SST results in intense vertical development of convection

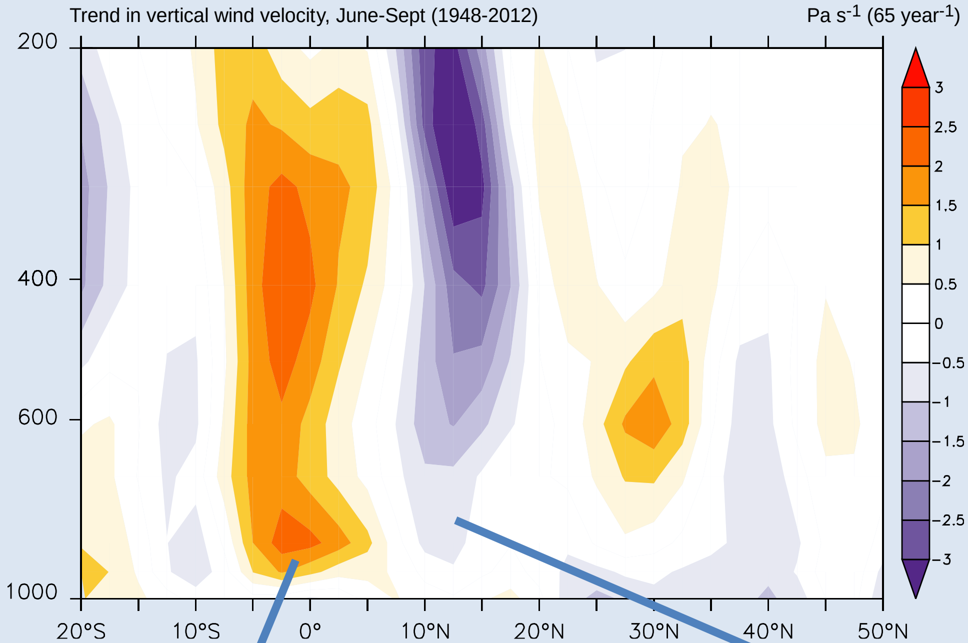


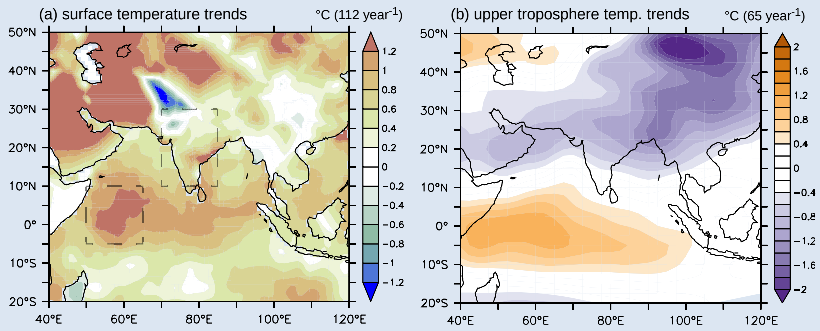


Climate Change and the Monsoon – Tropical Ocean warming

Weakening local Hadley circulation: Convection enhanced over ocean and suppressed over land

Observations: trend in vertical velocity (1948–2012)





WIO warming extends the warm pool, and increases ocean convection

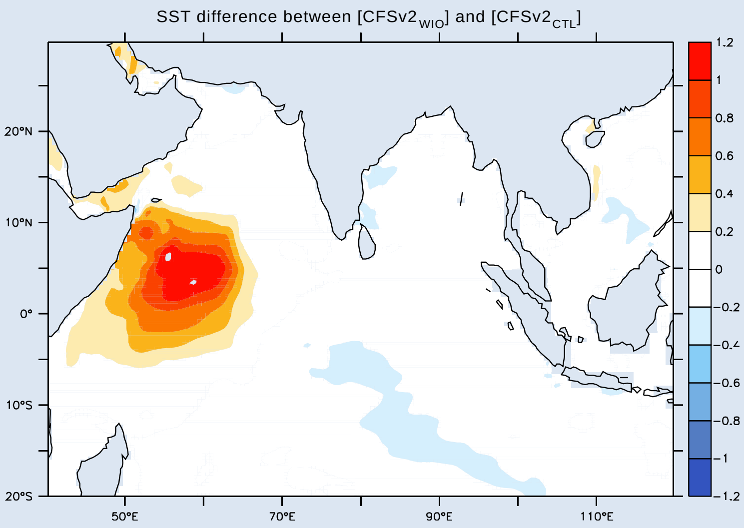
Large scale upward motion over the Indian ocean (10S–10N), extending up to the upper troposphere and favoring intense local convection.

Compensated by subsidence of air over the subcontinent (10–20N), inhibiting convection over the landmass and drying the region.

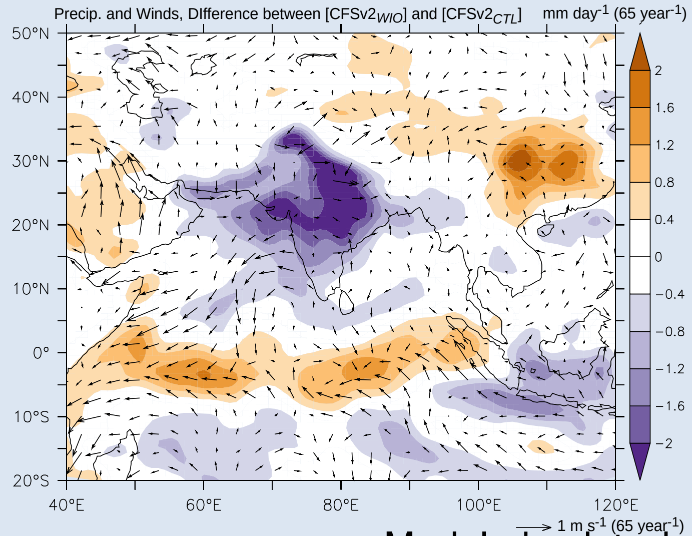
Roxy et al., *Nature Communications*, 2015

Weakened Monsoon precip/winds due to warming
Model simulations with Indian Ocean warming

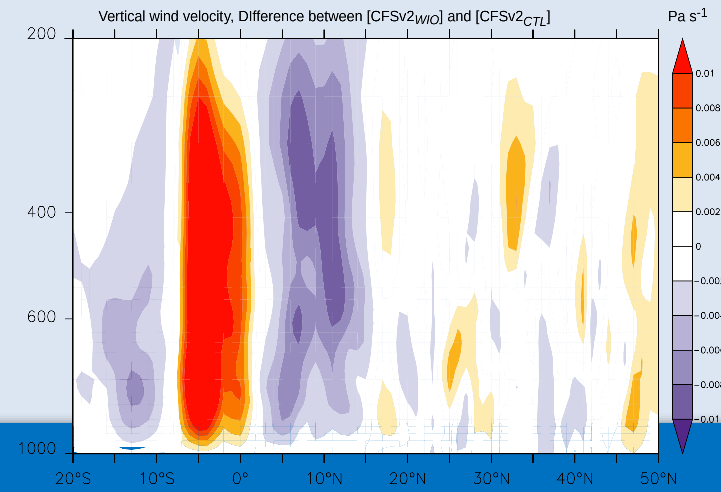
Model simulated warming of WIO



Model simulated response to warming



Model simulated vertical velocity in response to Indian Ocean warming



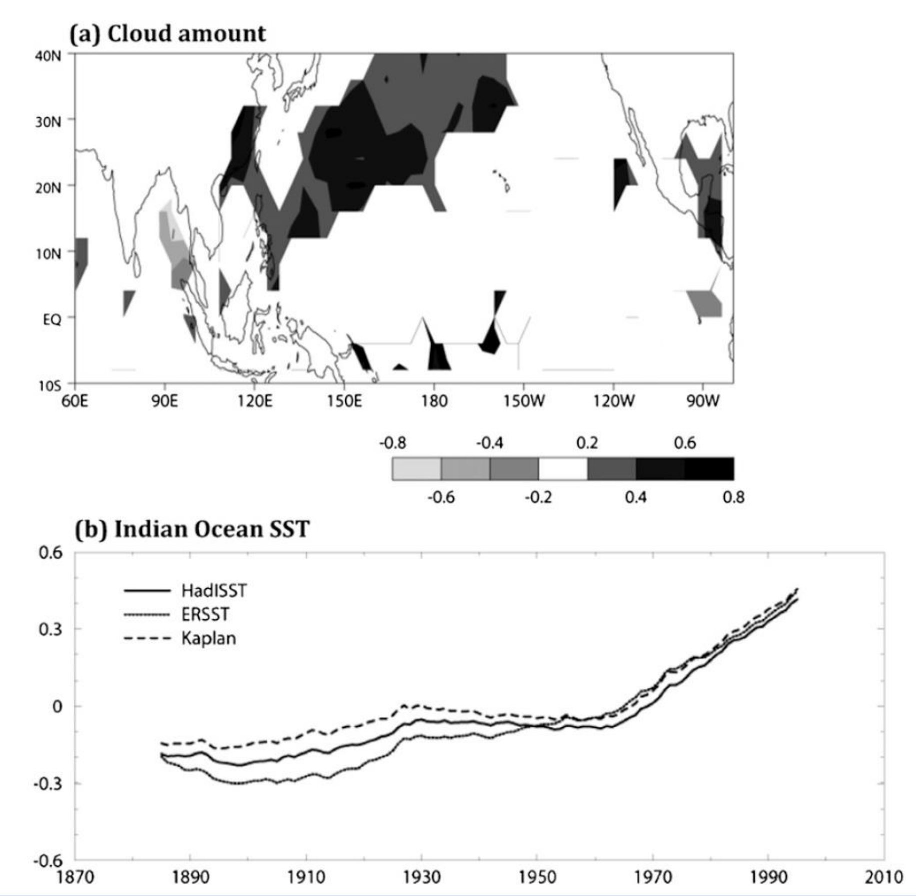
Competition between ocean and land rainfall:
SST warming extends the warm pool, increases ocean rainfall
…but results in decreased rainfall over the subcontinent
– horseshoe pattern in model simulations with increased IO warming

Roxy et al., *Nature Communications*, 2015

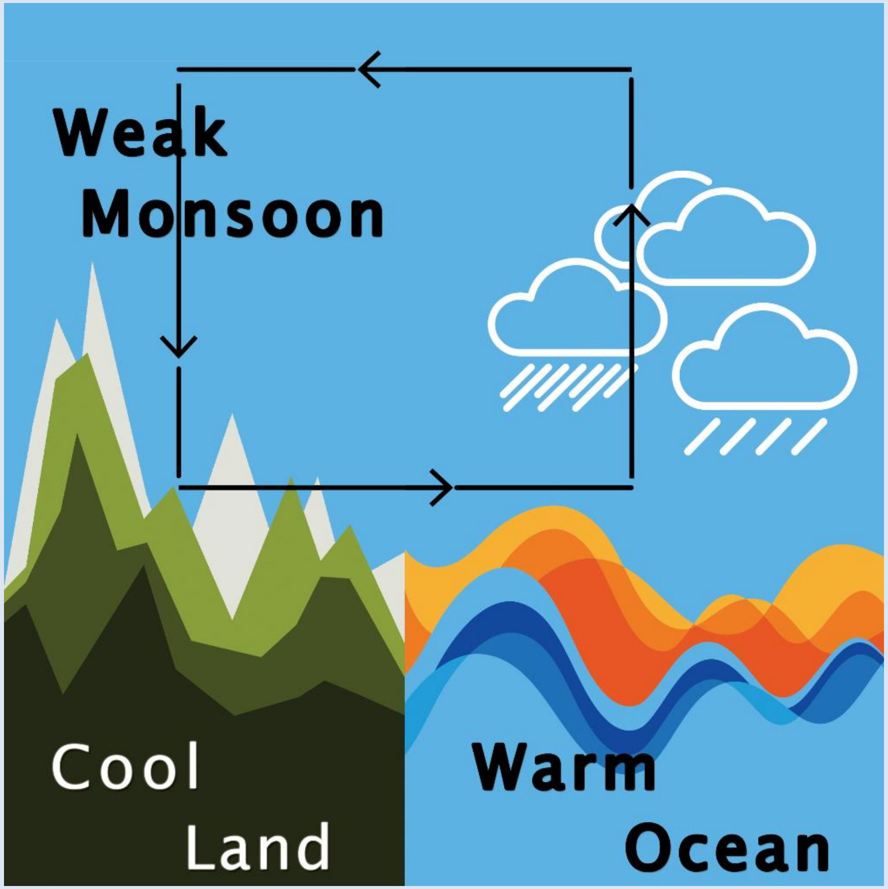
Climate Change and the Monsoon – Tropical Ocean warming

Other Mechanisms

Rise in Indo-Pacific SST increases tropical western Pacific monsoon rainfall, which incites a Rossby wave that forces descending air to the west, drying South Asia.



Climate Change and the Monsoon – Tropical Ocean warming

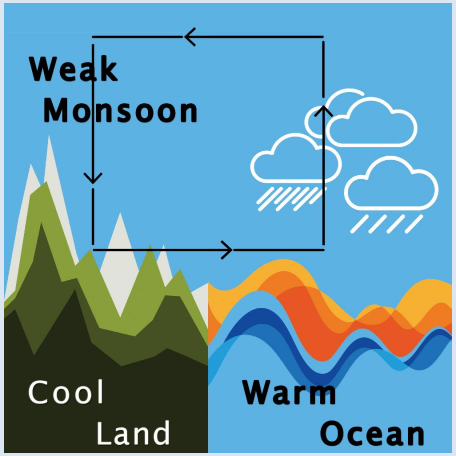


Future?
CMIP5 future projections suggest further warming of the Indian Ocean. Will the monsoon decrease further?

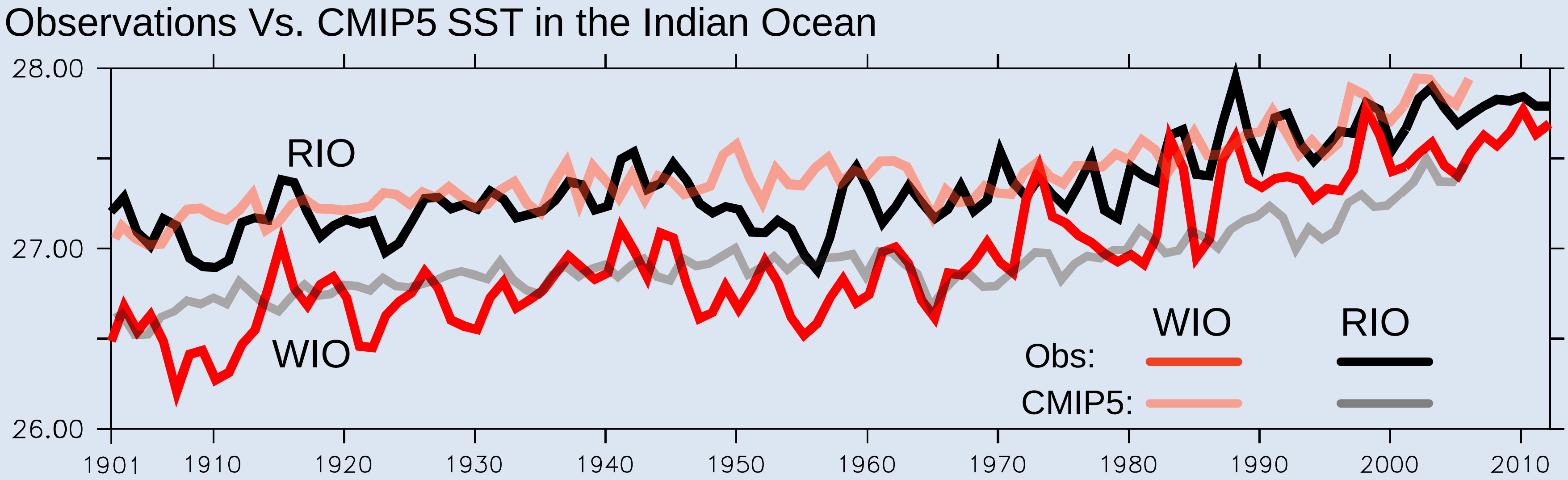
These future projections also suggest increasing monsoon rainfall (Sharmila et al 2015).

However it is to be noted that these models fail to reproduce the present day monsoon (Sabeerali et al 2014, Saha et al 2014)

Climate Change and the Monsoon – Tropical Ocean warming

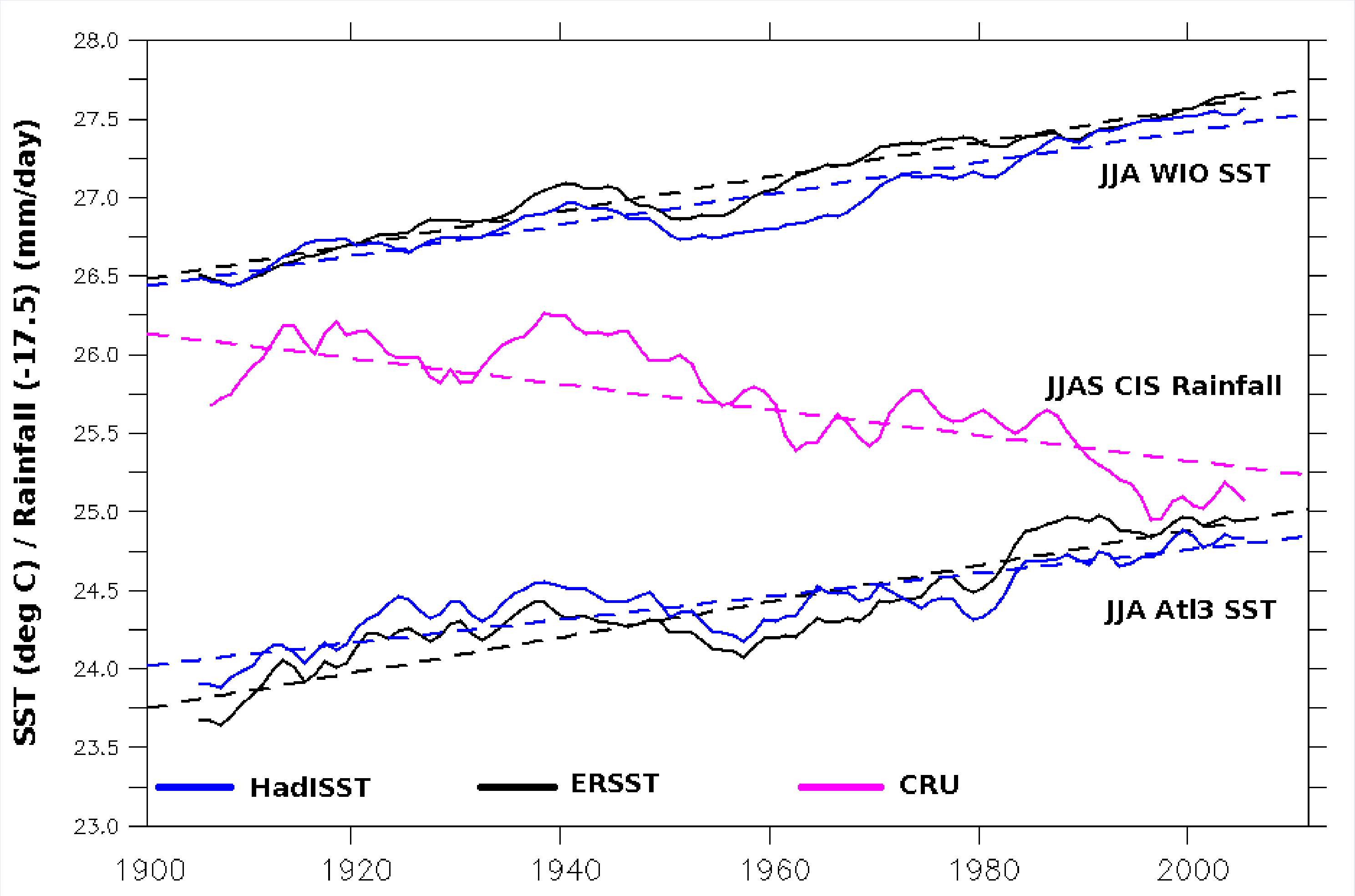


CMIP5 models fail to reproduce the Indian Ocean SSTs
–bias in thermocline/equatorial dynamics?



Climate Change and the Monsoon – Tropical Ocean warming

Does the Atlantic warming has a role?



Pottapinjara et al.

Climate Change and the Monsoon – Tropical Ocean warming

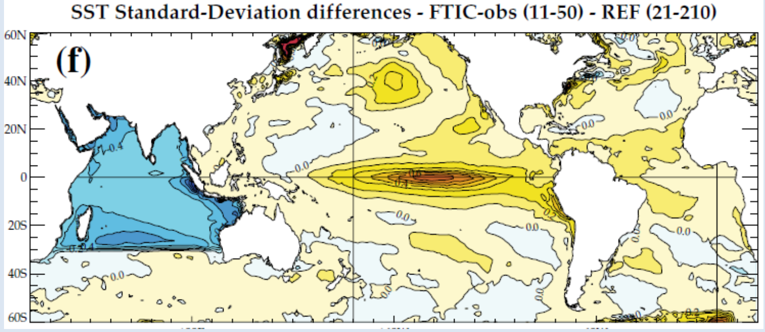
Indian Ocean warming may dampen the El Niño

Table 1 Summary of the numerical experiments with their main characteristics, including length, nudging domain and SST climatology used for the nudging in the Indian or Atlantic oceans decoupled experiments

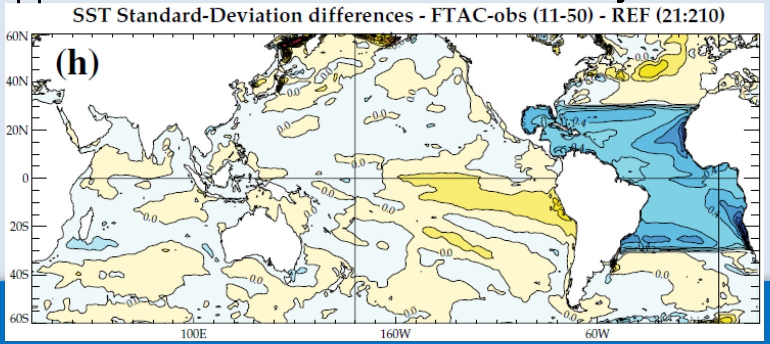
Name	REF	FTIC	FTIC-obs	FTAC	FTAC-obs
Correction area	None	Indian Ocean 30°E–120°E 25°S–30°N	Indian Ocean 30°E–120°E 25°S–30°N	Atlantic Ocean 100°W–20°E 25°S–25°N	Atlantic Ocean 100°W–20°E 25°S–25°N
Smoothing area	None	30°S–25°S	30°S–25°S	30°S–25°S 25°N–30°N	30°S–25°S 25°N–30°N
SST data	None	REF	AVHRR	REF	AVHRR
Time duration (year)	210	110	50	110	50

Suppressing the Indian Ocean SST variability increased the ENSO strength.

Suppressed Indian Ocean variability

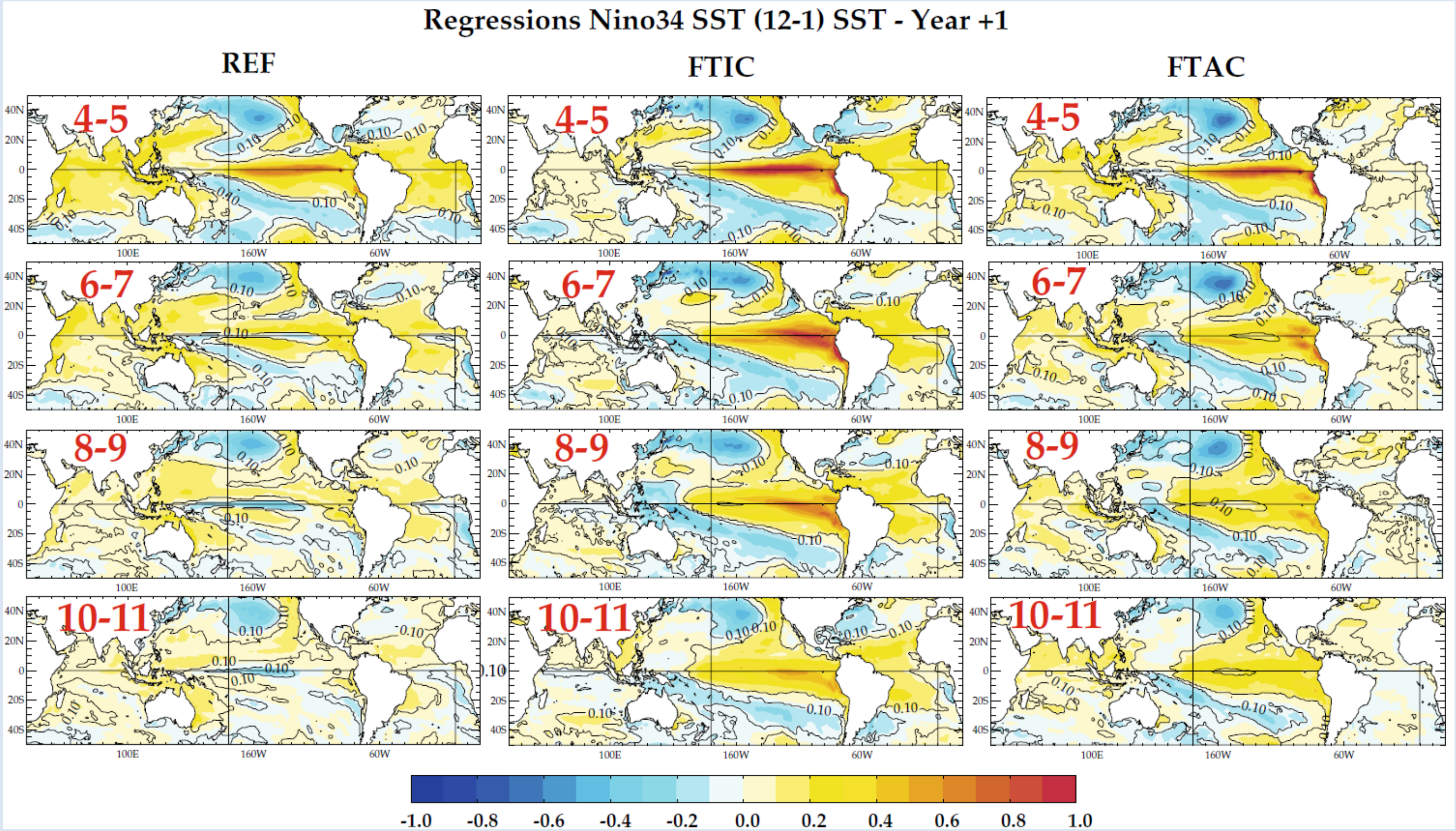


Suppressed Atlantic Ocean variability



Climate Change and the Monsoon – Tropical Ocean warming

Indian Ocean warming may shorten the El Niño cycle



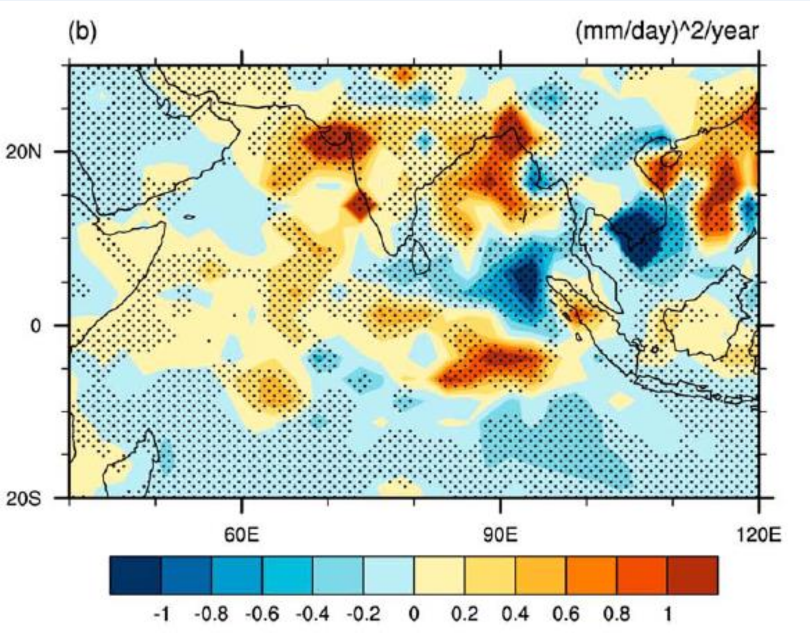
Suppressing the Indian Ocean SST variability increased the El Niño decaying period. i.e. increased Indian Ocean SST variability kills an El Niño at an earlier state.

Involve modulations of the surface winds in the western equatorial Pacific, which trigger eastward-propagating oceanic Kelvin waves responsible for the turnabout of ENSO (through changes in the thermocline).

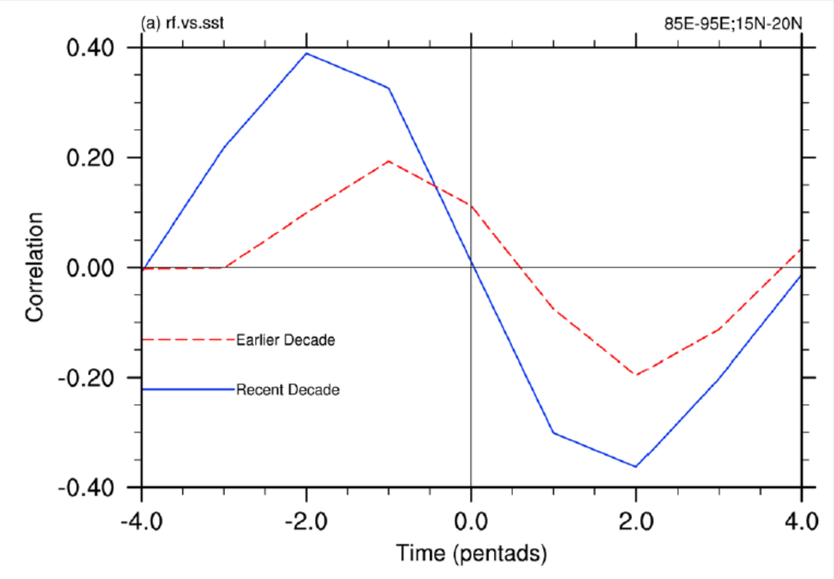
Climate Change and the Monsoon – Tropical Ocean warming

Increased variance in ISO
and changes in ocean-atmosphere interaction

Trend in MISO variance, 1979–2010



Changes in SST–precipitation relationship



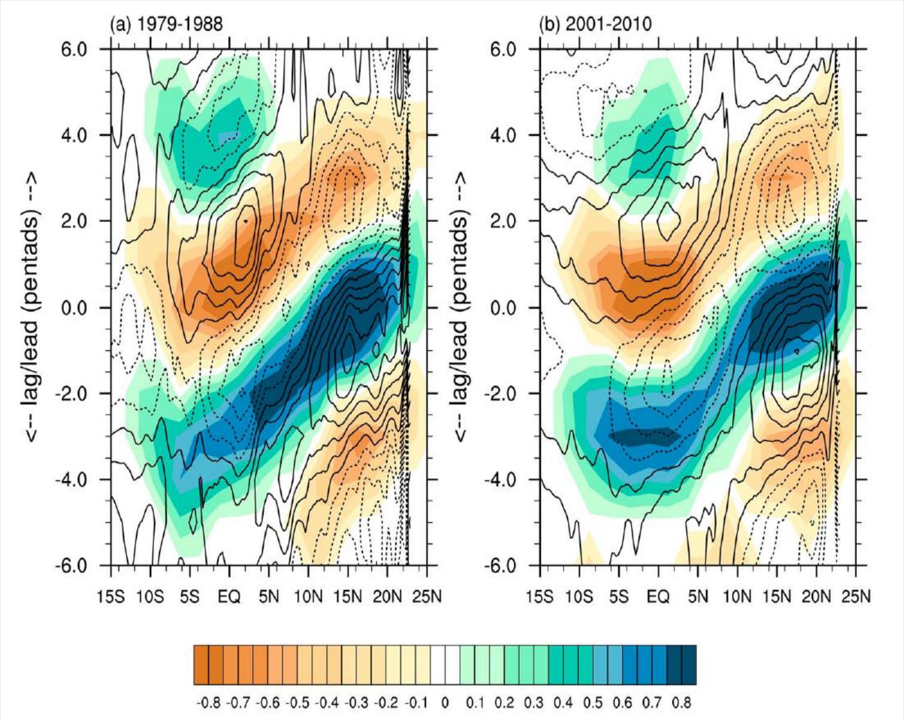
Atmosphere takes more time to respond to a SST anomaly in the recent decade, and therefore, ISO gets more time to build up its amplitude. The increased moisture–holding capacity of the atmosphere in the recent decade due to warming and associated increase in the residence time of the atmospheric moisture may be one possible reason to increase the maximum SST lead in the recent decade.

Sabeerali et al. ,*Climate Dynamics* 2014

Climate Change and the Monsoon – Tropical Ocean warming

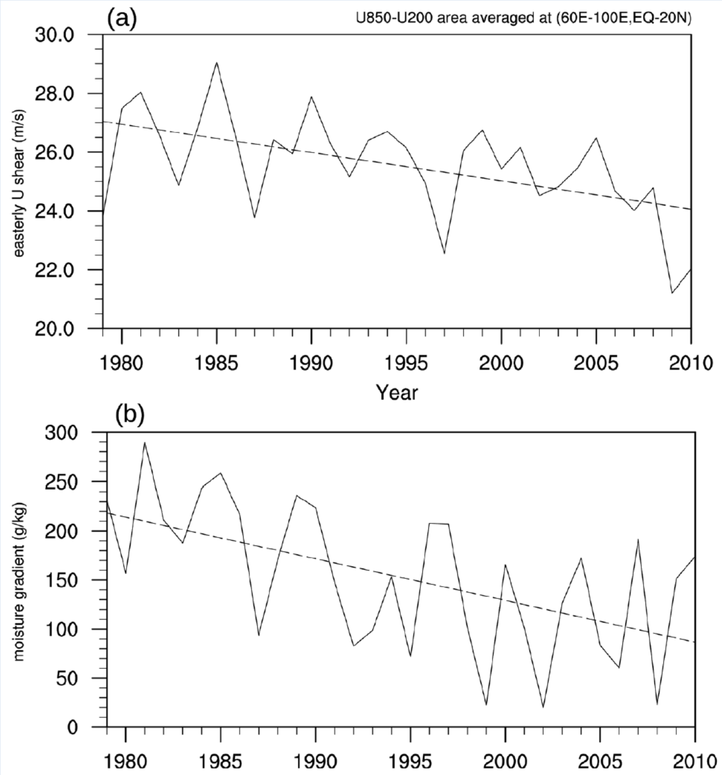
Slowdown in the northward propagation of ISO

Northward propagation of rainfall anomaies,
1979-1988 and 2001-2010



Northward propagation of ISO is proportional to the easterly vertical wind shear and moisture gradient (Jiang et al. 2004)

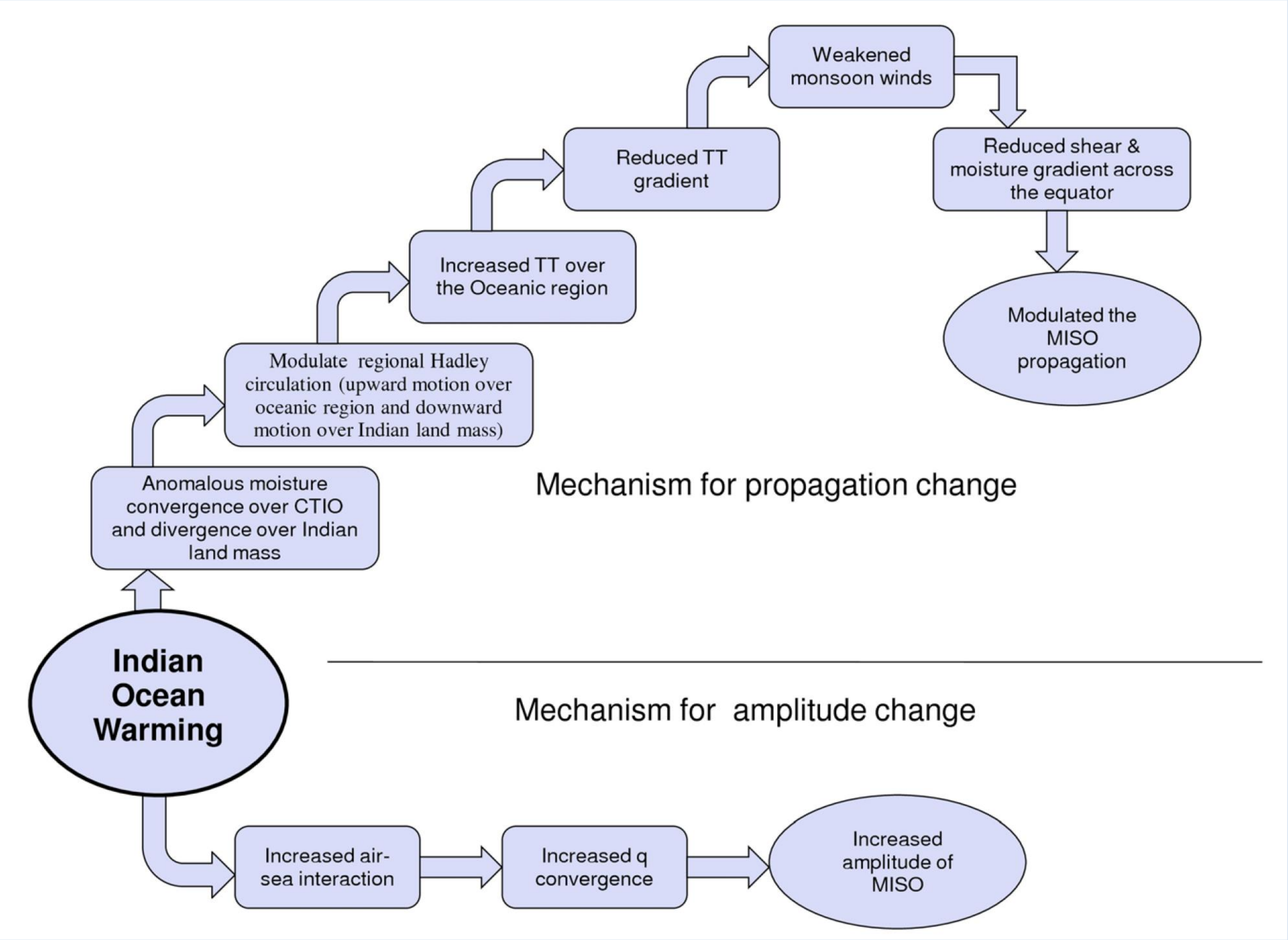
Decreasing wind shear and moisture gradient over the monsoon domain might be slowing down the ISO.



Sabeerali et al., *Climate Dynamics* 2014; Jiang et al., *J Climate* 2004

Climate Change and the Monsoon – Tropical Ocean warming

Changes in Monsoon ISO

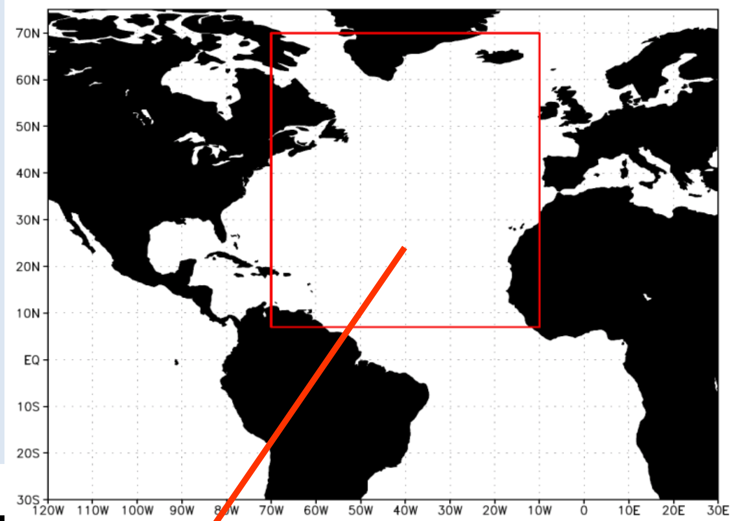


Sabeerali et al., *Climate Dynamics* 2014

Multidecadal variability of the Monsoon

— Atlantic Mutlidecadal Oscillation (AMO)

Positive AMO phase –> Strong NAO
–> Changes in Jetstream and storm tracks
–> Positive TT anomalies over Asia
–> Increased meridional TT gradient –> Strong monsoon



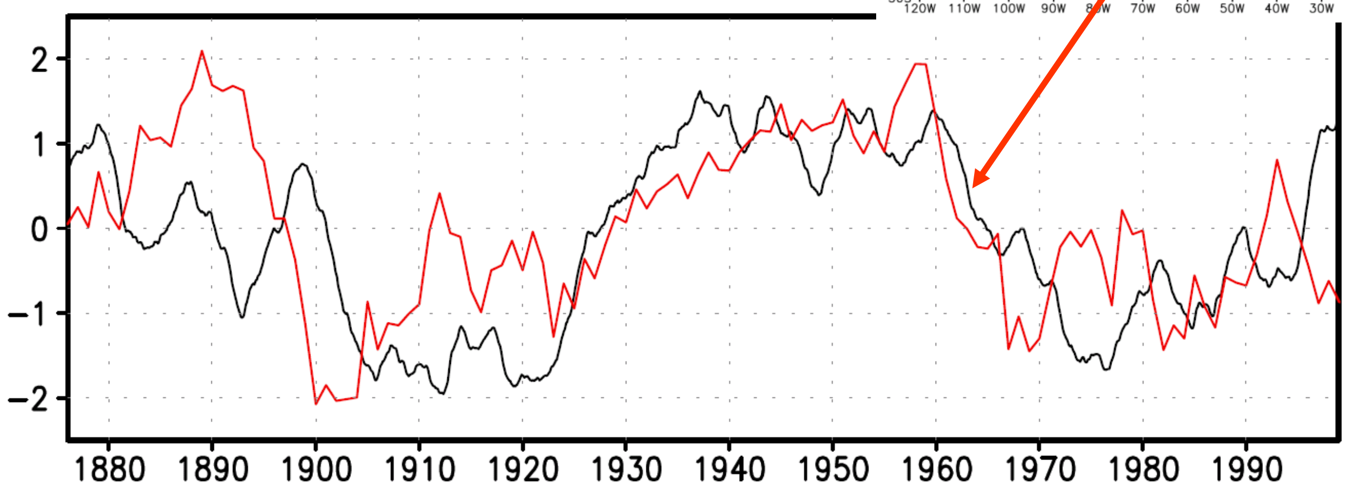
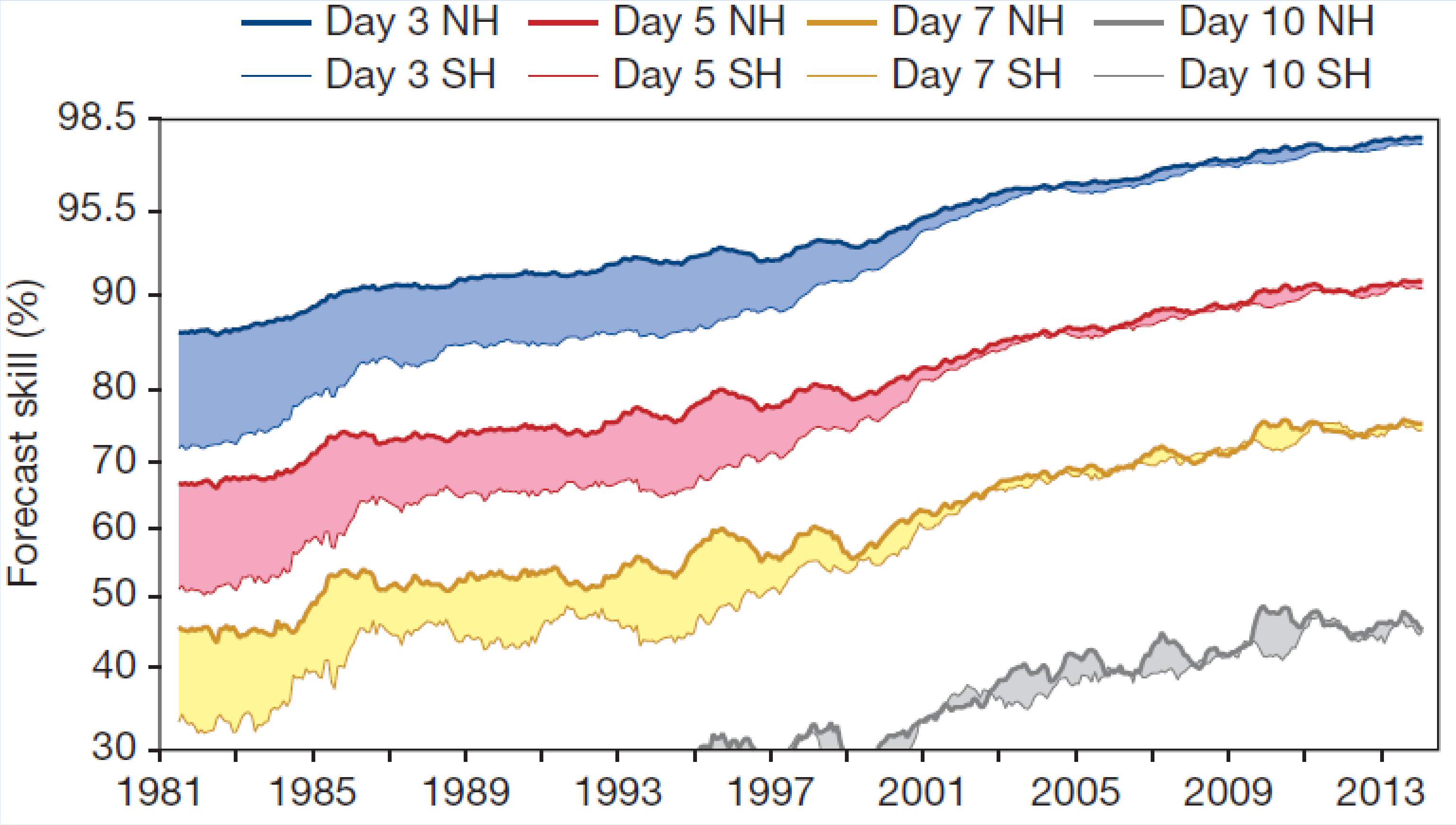


Figure 7: Multidecadal oscillation of AIR (red line, obtained from 11-yr running mean of JJAS mean all India rainfall) and Atlantic multidecadal oscillation (AMO, black line). AMO is based on 60-month running mean of monthly anomalies averaged over Atlantic north of Equator.

Modeling the Monsoon – weather prediction

Weather forecast skills in the northern and southern hemispheres



The convergence of the curves for Northern Hemisphere (NH) and Southern Hemisphere (SH) after 1999 indicates the breakthrough in exploiting satellite data.

Bauer et al., *Nature* 2015

Two kinds of atmospheric predictability

Initial conditions (IC) refer to constraints imposed on the solution in **time**.
In other words, the solutions of a time-dependent differential equation must have a specific value at a certain point in time.
(current state of atmospheric quantities based on satellite and in-situ observations)

Boundary conditions (BC) refer to constraints imposed on the solution in **space**.
In other words, the solutions of a time-dependent differential equation must have a specific value at a certain point in space.
(greenhouse gases – CO_2, aerosols, albedo, SSTs, Sea Ice, Land Surface – vegetation etc.)

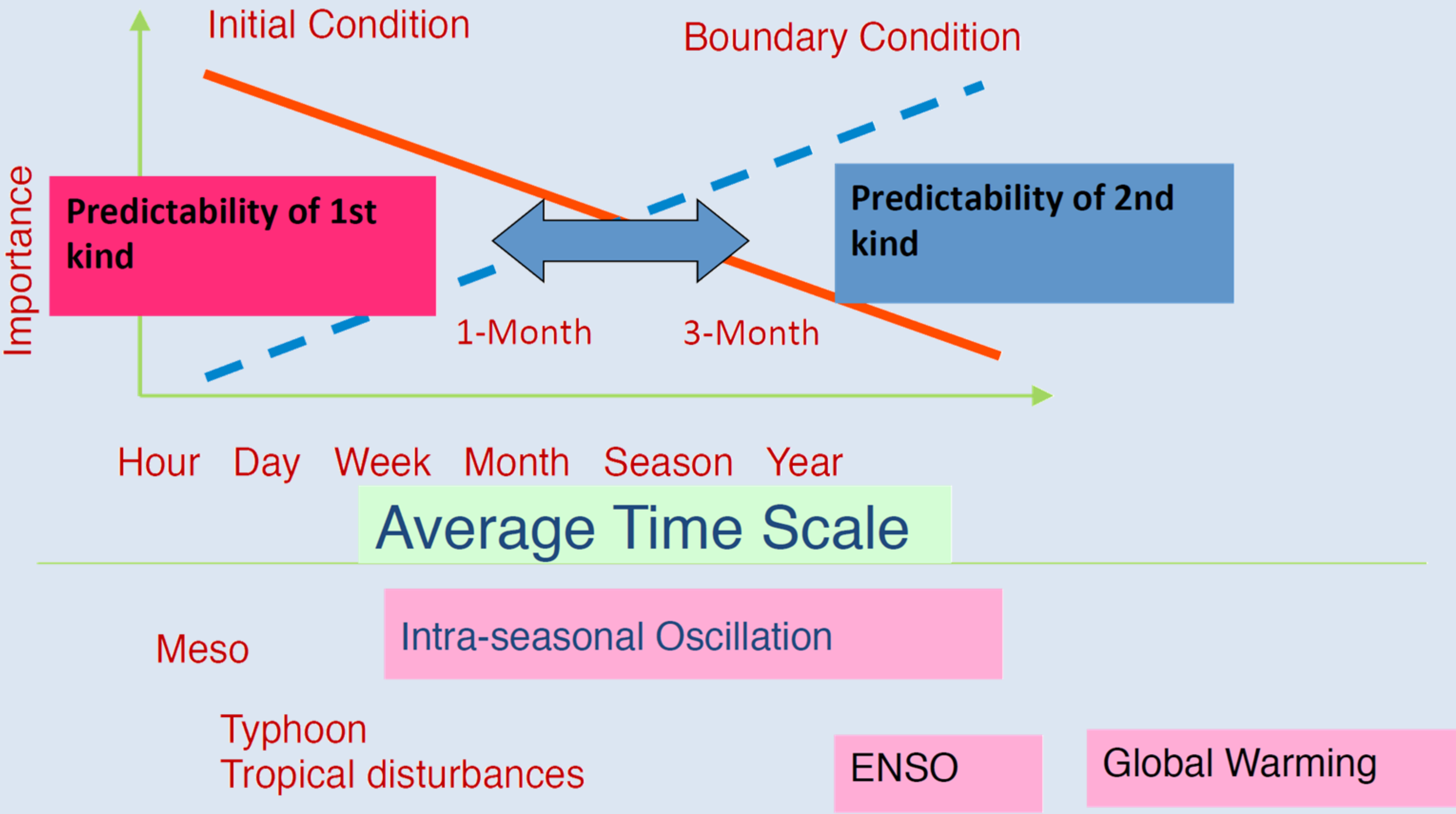
Predictability of the first kind focuses on the initial value problem:
how uncertainties in the initial state of the climate system amplify and spoil the forecast at a given lead time. This is the dominant source of error in weather forecasting. Errors in the atmospheric analysis grow such that the current predictability horizon is often of the order of a week or so.

Predictability of the second kind focuses on the boundary value problem:
how predictable changes in the boundary conditions that affect climate can provide predictive power. A common class of second-kind predictability studies use atmosphere models with prescribed sea surface temperatures (SSTs) in order to asses the upper limit of predictability associated with a perfect knowledge of the future ocean state.

Lorenz, “Climate Predictability” 1975; Collins et al., *J.Climate* 2002

Modeling the Monsoon

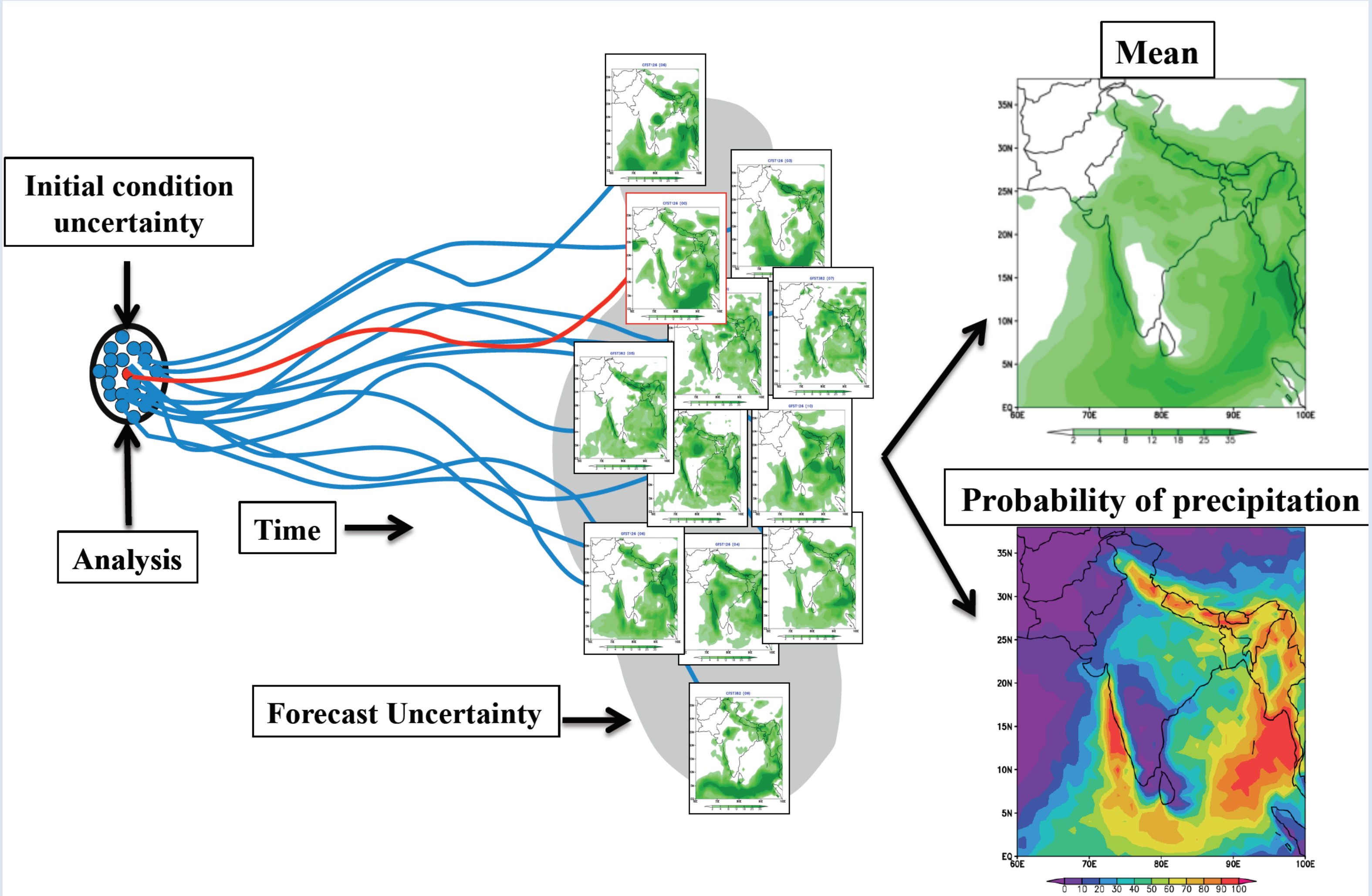
Two kinds of atmospheric predictability



Lorenz, “Climate Predictability” 1975; Collins et al., *J.Climate* 2002

Modeling the Monsoon – weather prediction

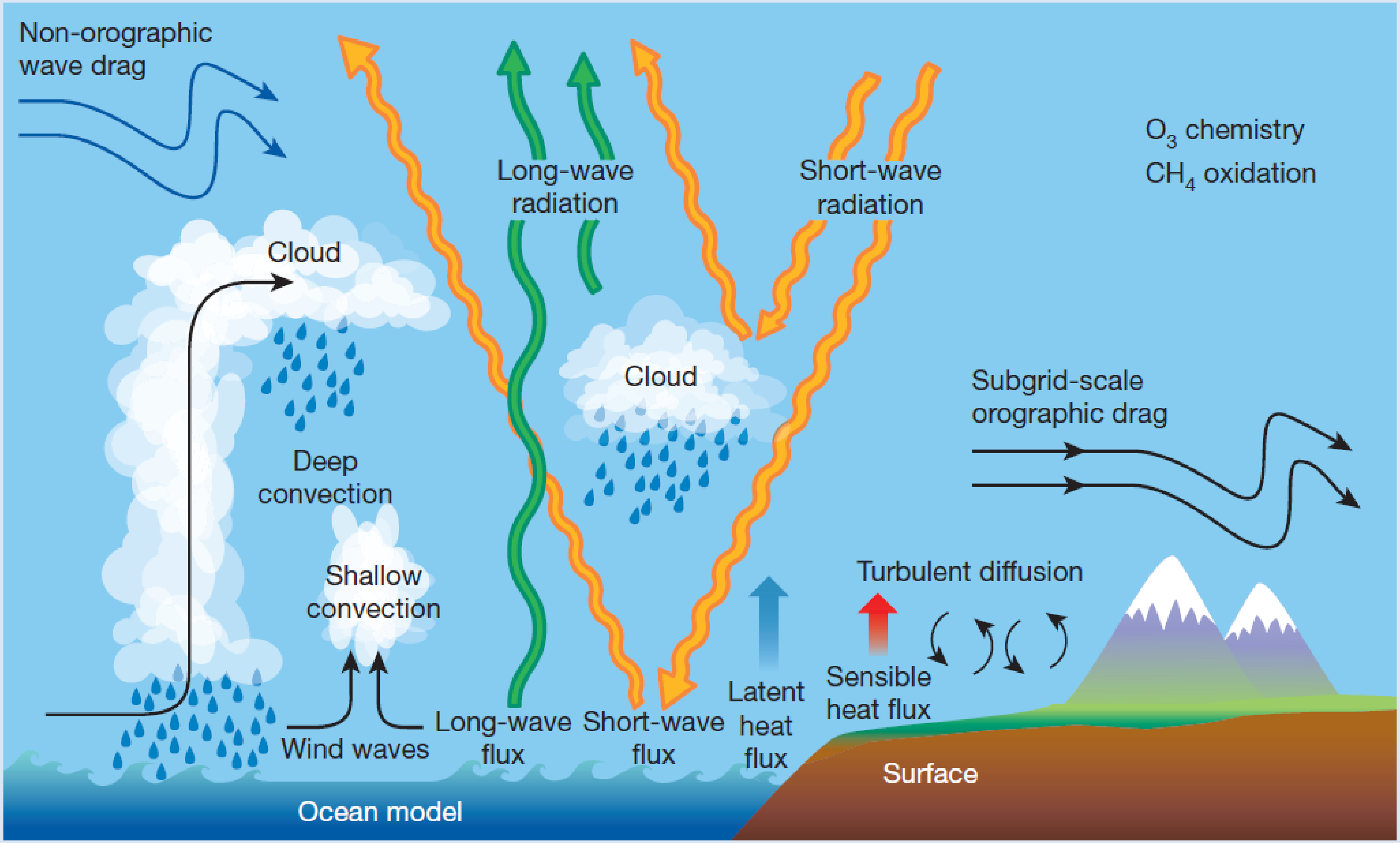
Initial value problem – forecast uncertainty



Probabilities indicate the percent of ensemble members that predict the mean precipitation

Modeling the Monsoon – weather prediction

Physical processes of importance to weather prediction

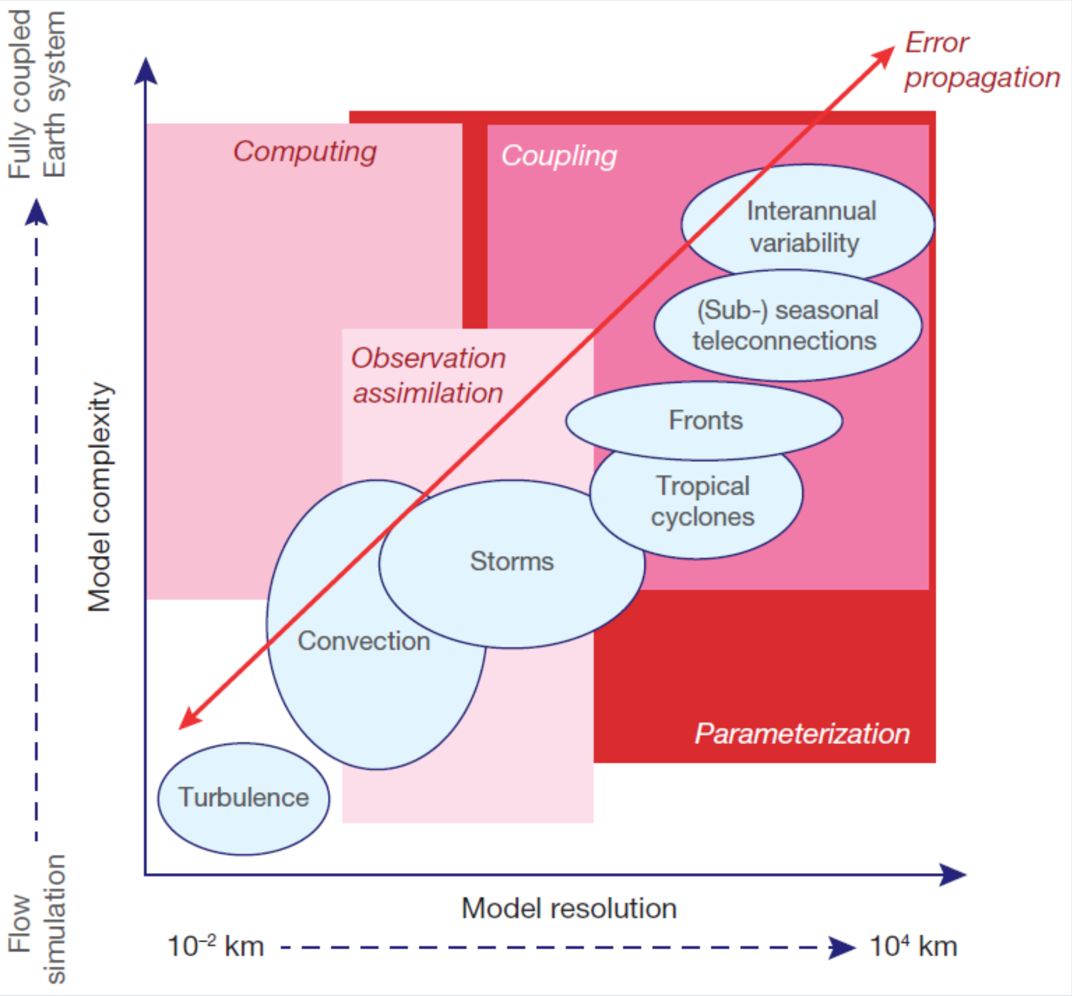


These processes are not explicitly resolved in current NWP models but they are represented via parameterizations describing their contributions to the resolved scales in terms of mass, momentum and heat transfers.

Bauer et al., *Nature* 2015

Modeling the Monsoon – weather prediction

Key challenge areas

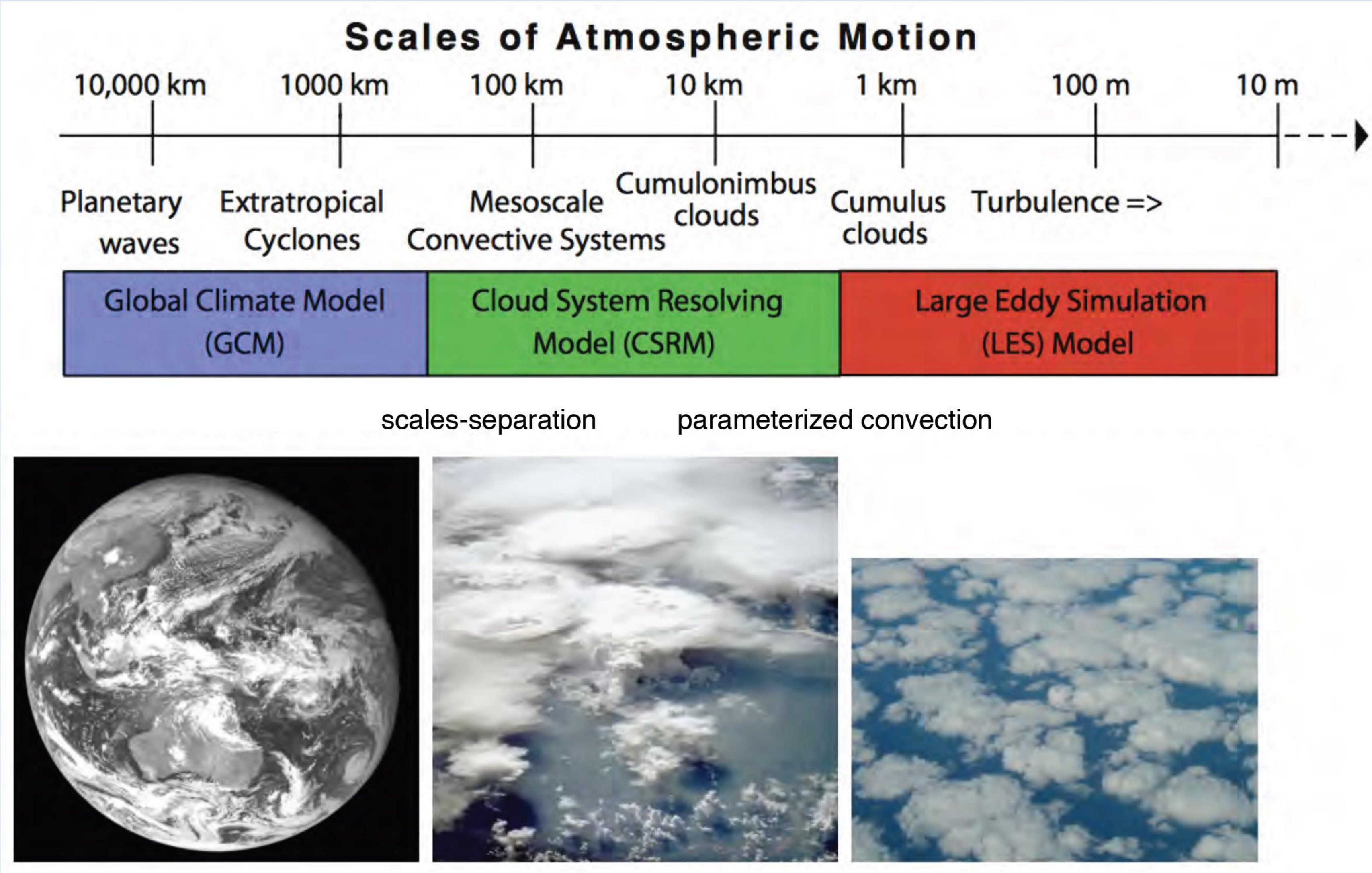


Advances in forecast skill will come from scientific and technological innovation in computing, the representation of physical processes in parameterizations, coupling of Earth–system components, the use of observations with advanced data assimilation algorithms, and the consistent description of uncertainties through ensemble methods and how they interact across scales.

Bauer et al., *Nature* 2015

Modeling the Monsoon – weather prediction

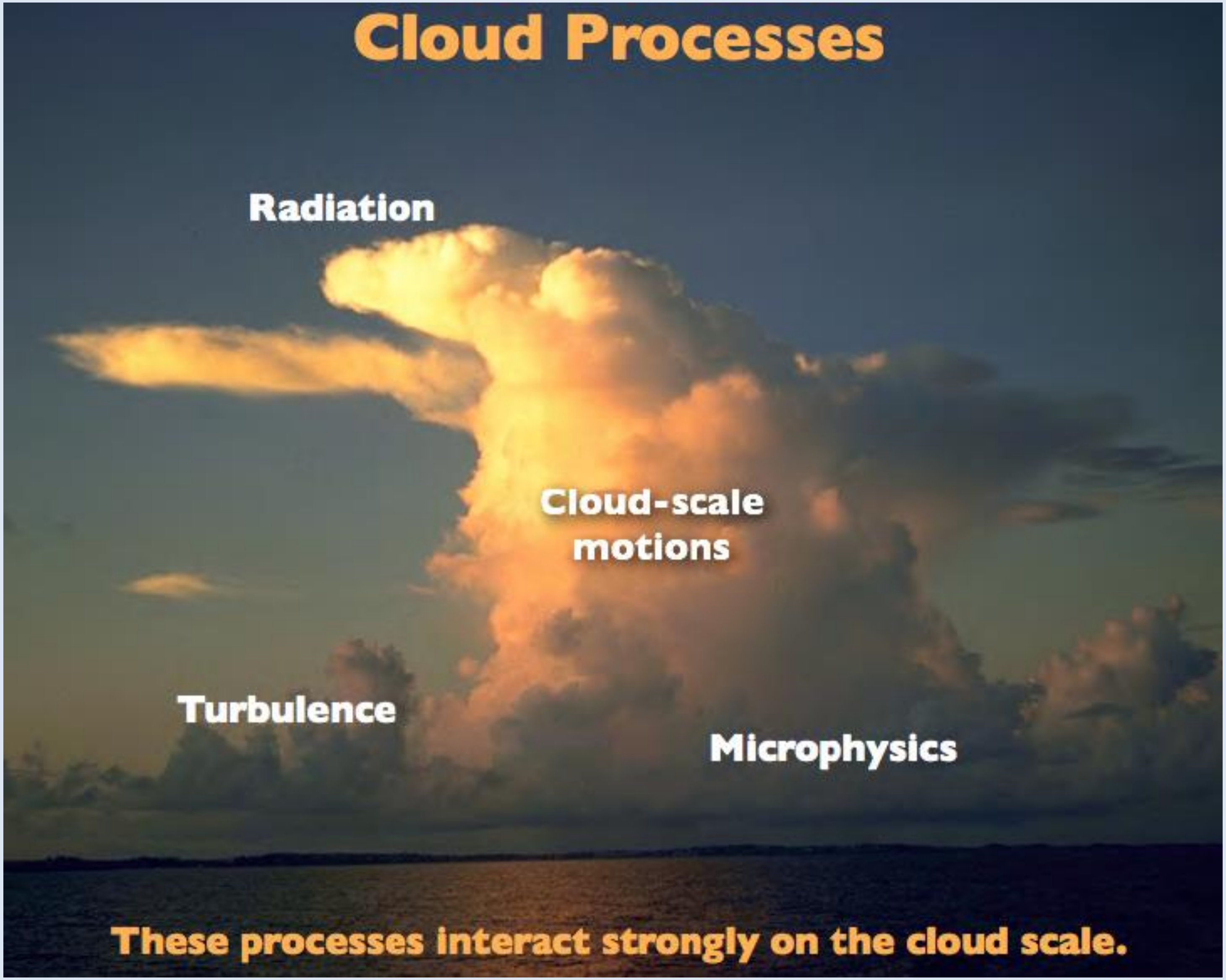
Super-parameterized Convection



Figures: Marat Khairoutdinov

Modeling the Monsoon – weather prediction

Super-parameterized Convection

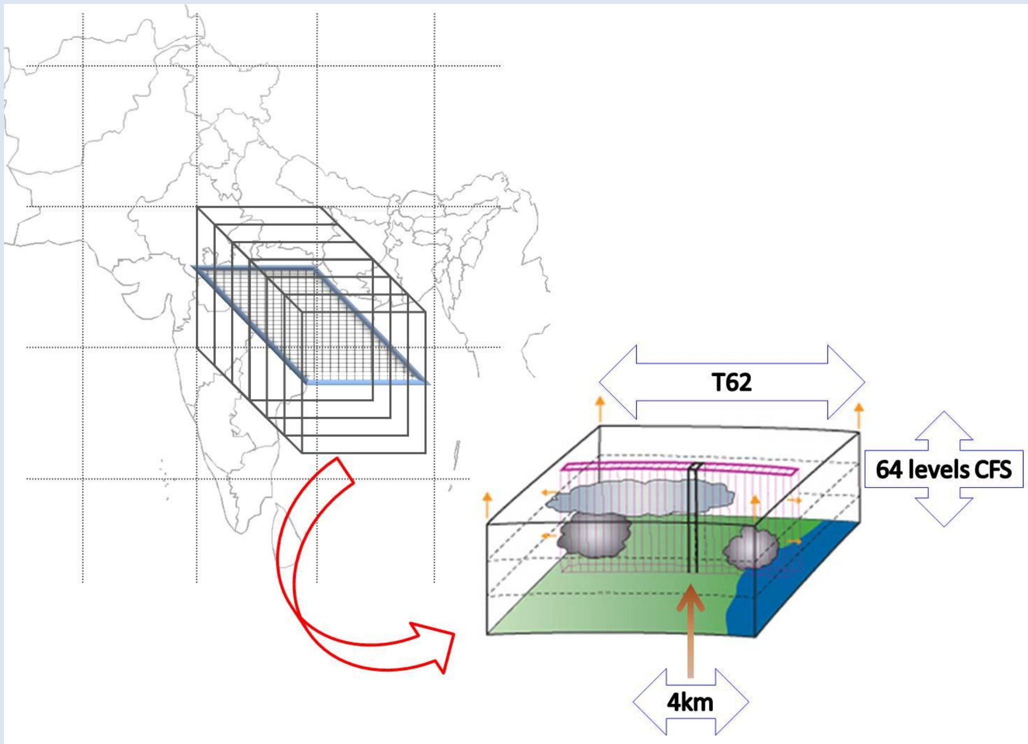


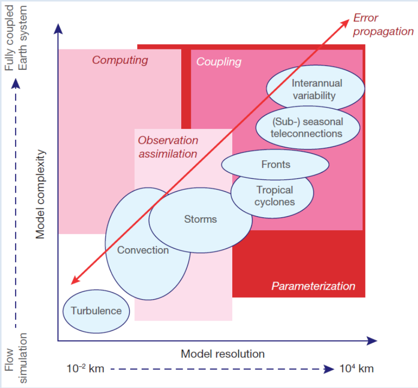
Figures: Marat Khairoutdinov

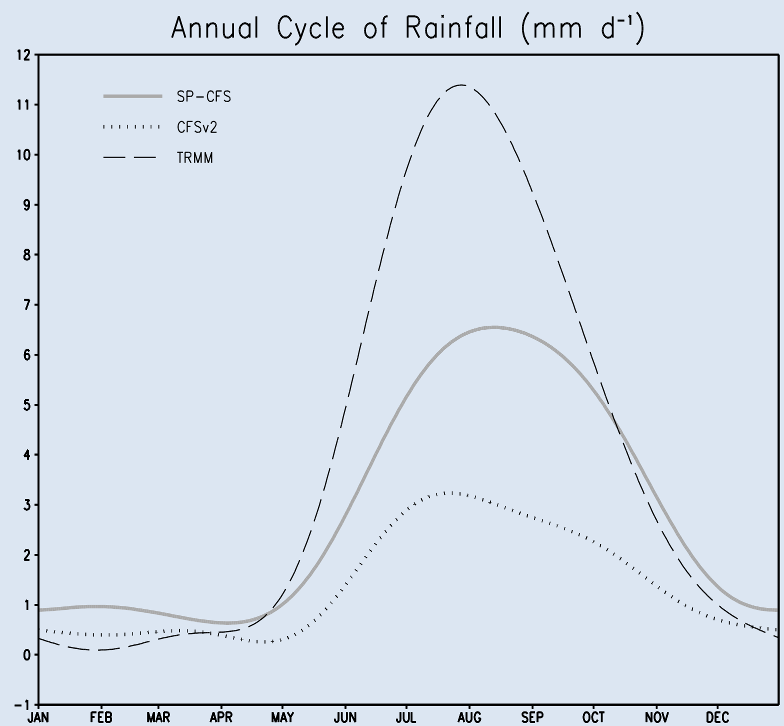
Modeling the Monsoon – weather prediction

Super-parameterized Climate Forecast System (SP-CFS)

Convective tendencies are explicitly simulated with a **C**loud **R**esolving **M**odel running in each GCM grid column which replaces the traditional cumulus parameterization of the GCM.

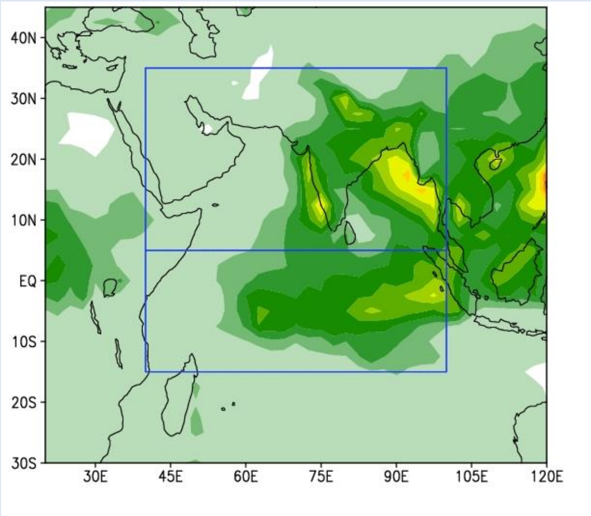






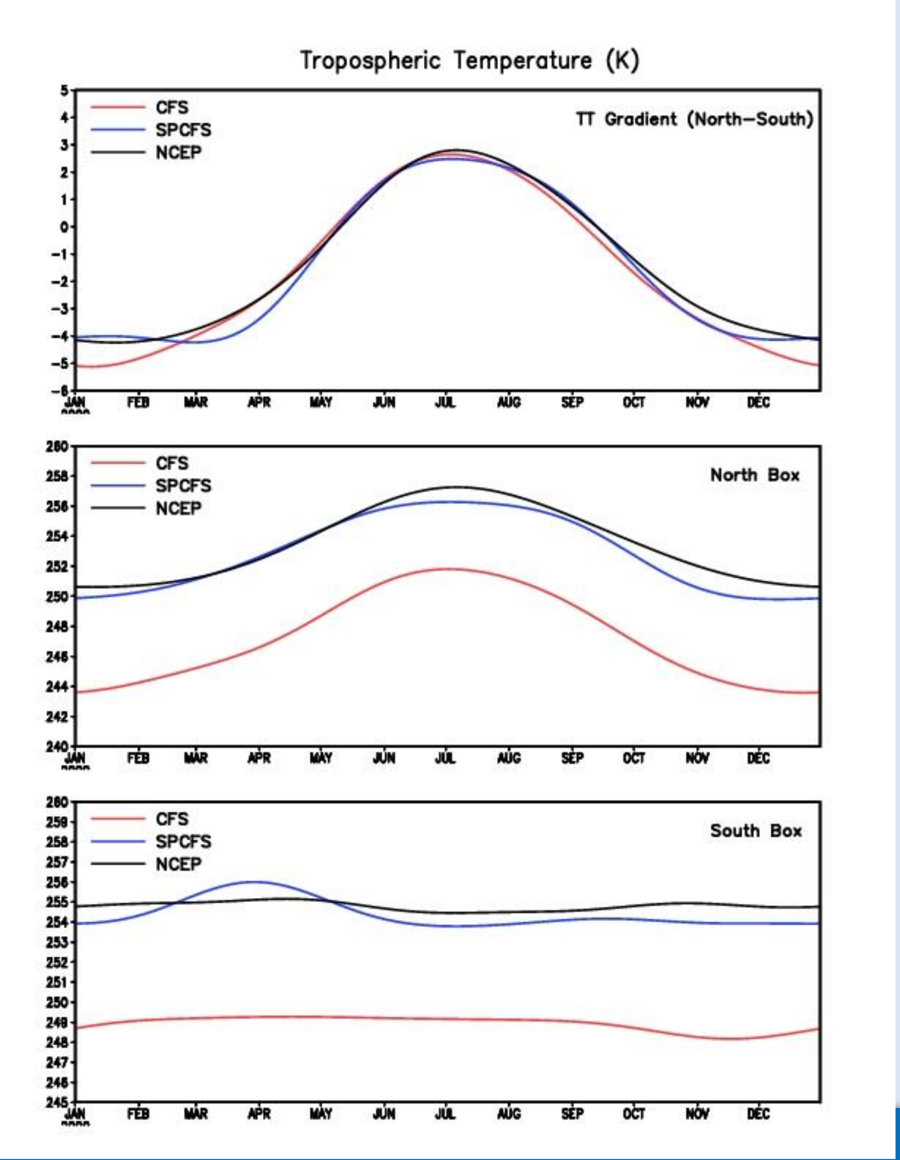
Modeling the Monsoon – weather prediction

Super-parameterized Climate Forecast System (SP-CFS)



Improvement in tropospheric temperature bias is seen in TT gradient. Even though the Gradient looks reasonable in both CFS and SPCFS, but the bias is seen when we see the North and South boxes individually. The TT–gradient in CFS perhaps is consistent with reasonable circulation pattern but deficient moisture, leading to dry monsoon.

Right result due to wrong reason in CFSv2?



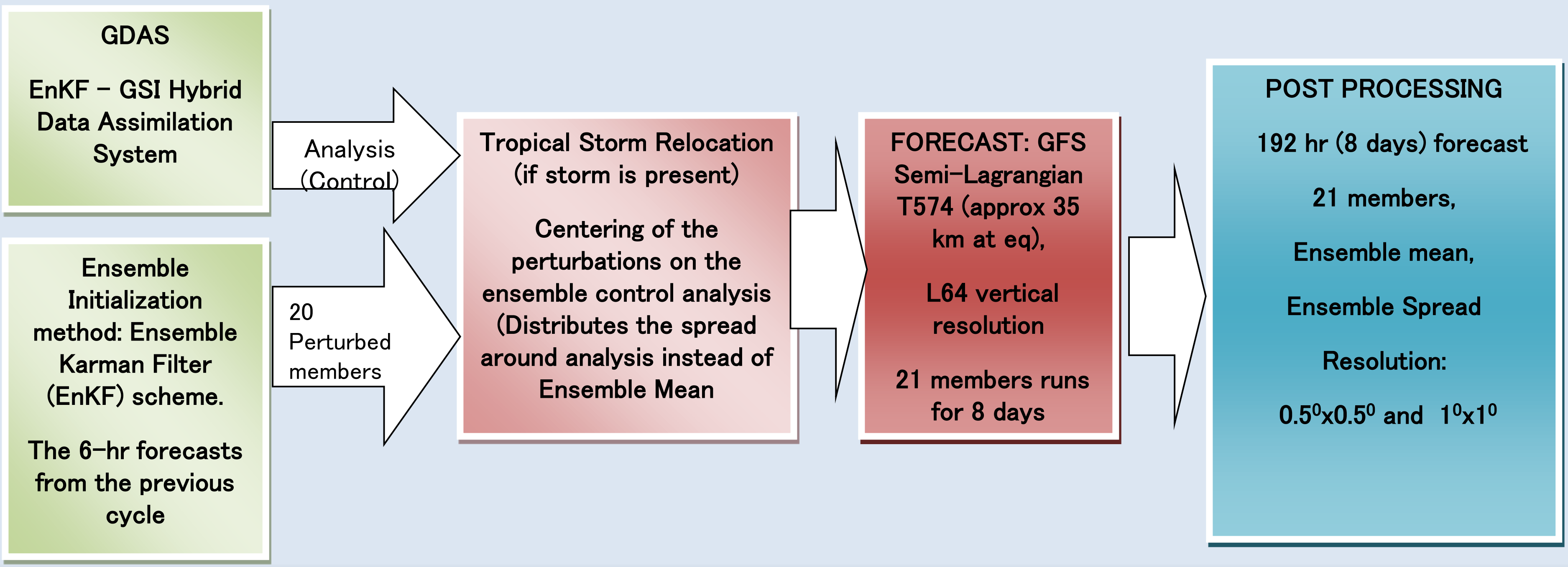
Mukhopadhyay et al.

Modeling the Monsoon – weather prediction

Short Range Ensemble Prediction System at IITM

GEFS T574 and GFS T1534 use Revised simplified Arakawa Schubert convective parameterization scheme. (Han and Pan 2011, Ganai et al. 2015)
– improvement of diurnal cycle of convection. The major difference between the new and old schemes lies in the heating and cooling behavior in lower-atmospheric layers above the planetary boundary layer

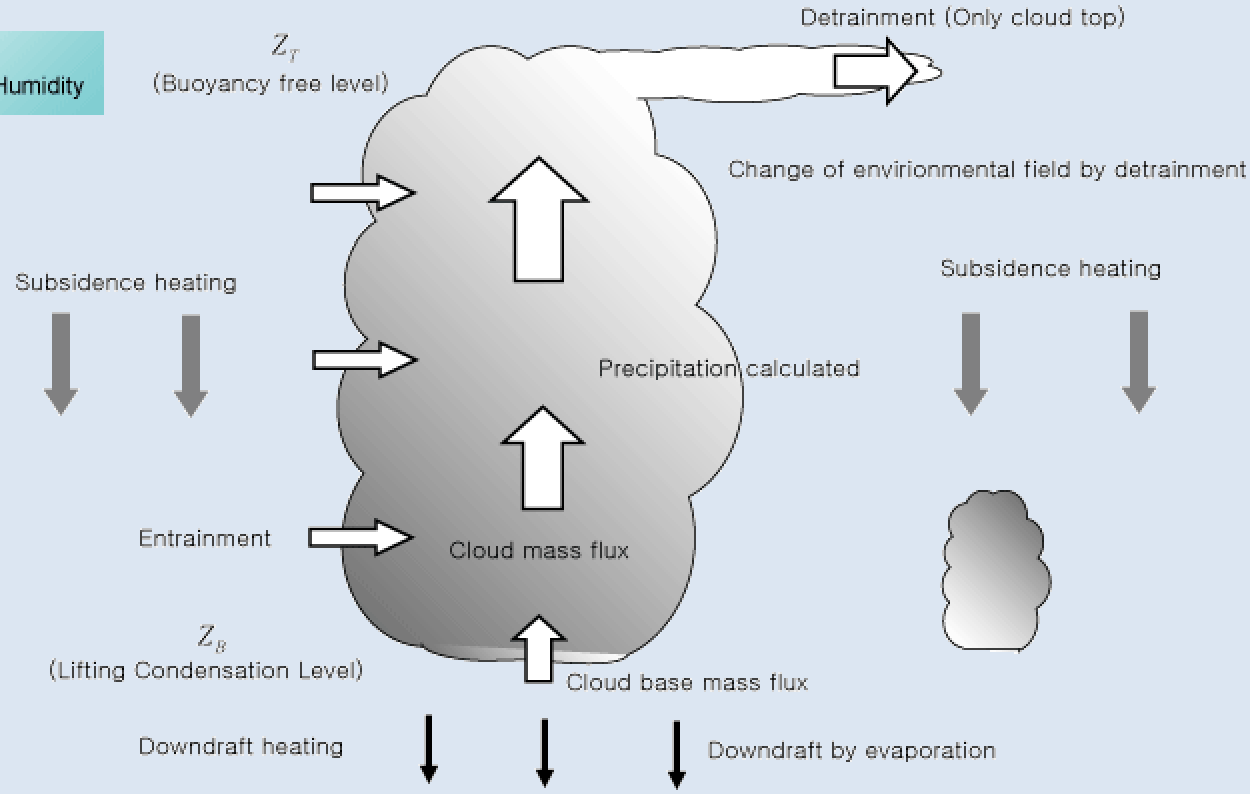
SCHEMATIC OF GEFS (SL) T574 L64 RUNNING AT IITM

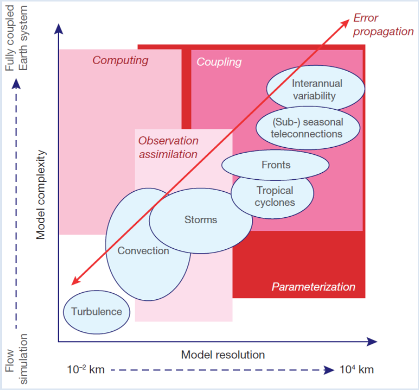


Convection Schemes ...

Convection schemes calculates the tendencies of temperature and humidity by the result of interaction between grid scale circulation and sub-grid scale cloud ensemble. Cloud liquid water and cumulus cloud fraction is also determined for radiative processes.

Input
Temperature, Humidity

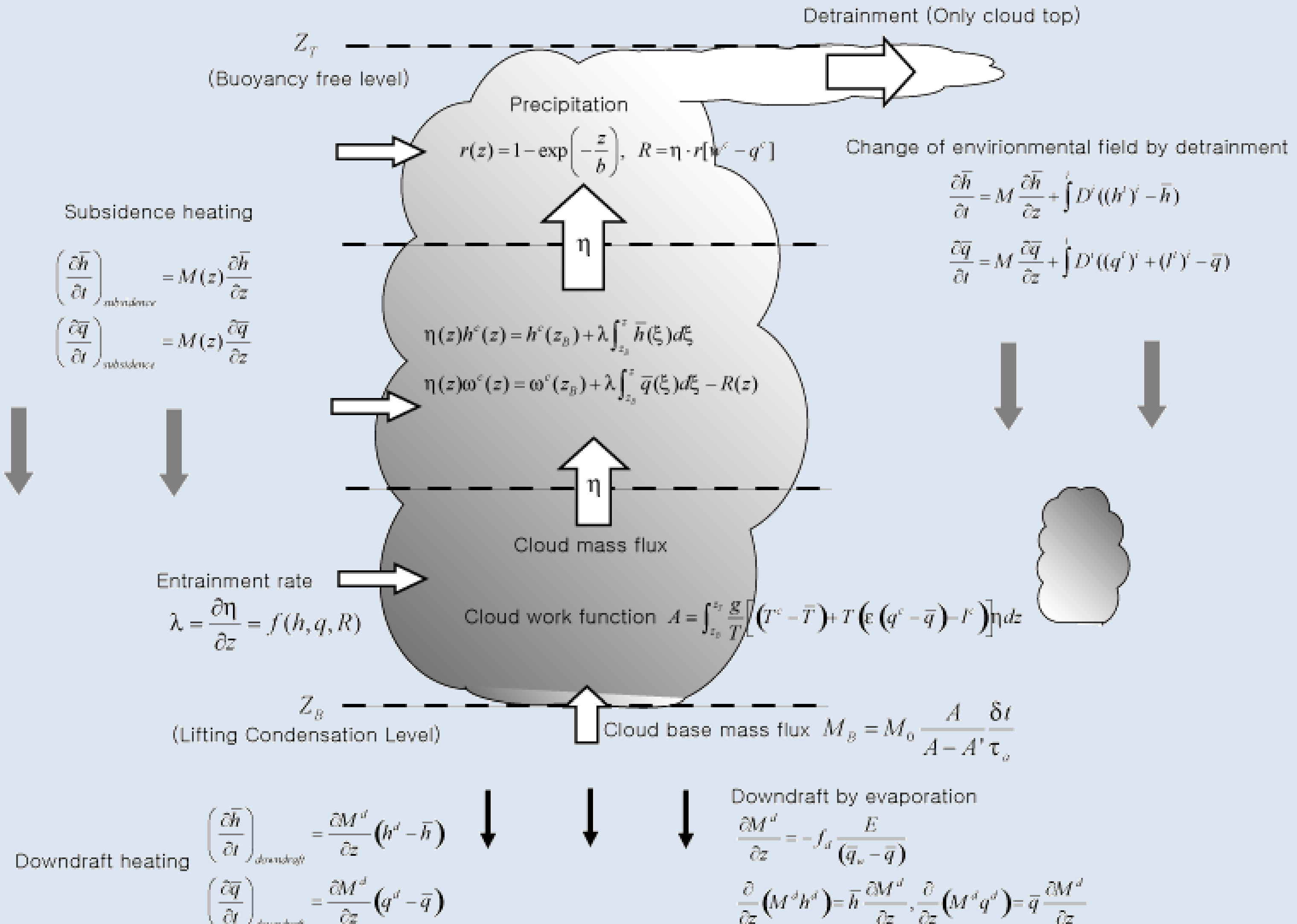




Output
Temperature, Humidity Change (stabilization)
Precipitation
Cumulus water and fraction (to Radiation process)

Convection Schemes …

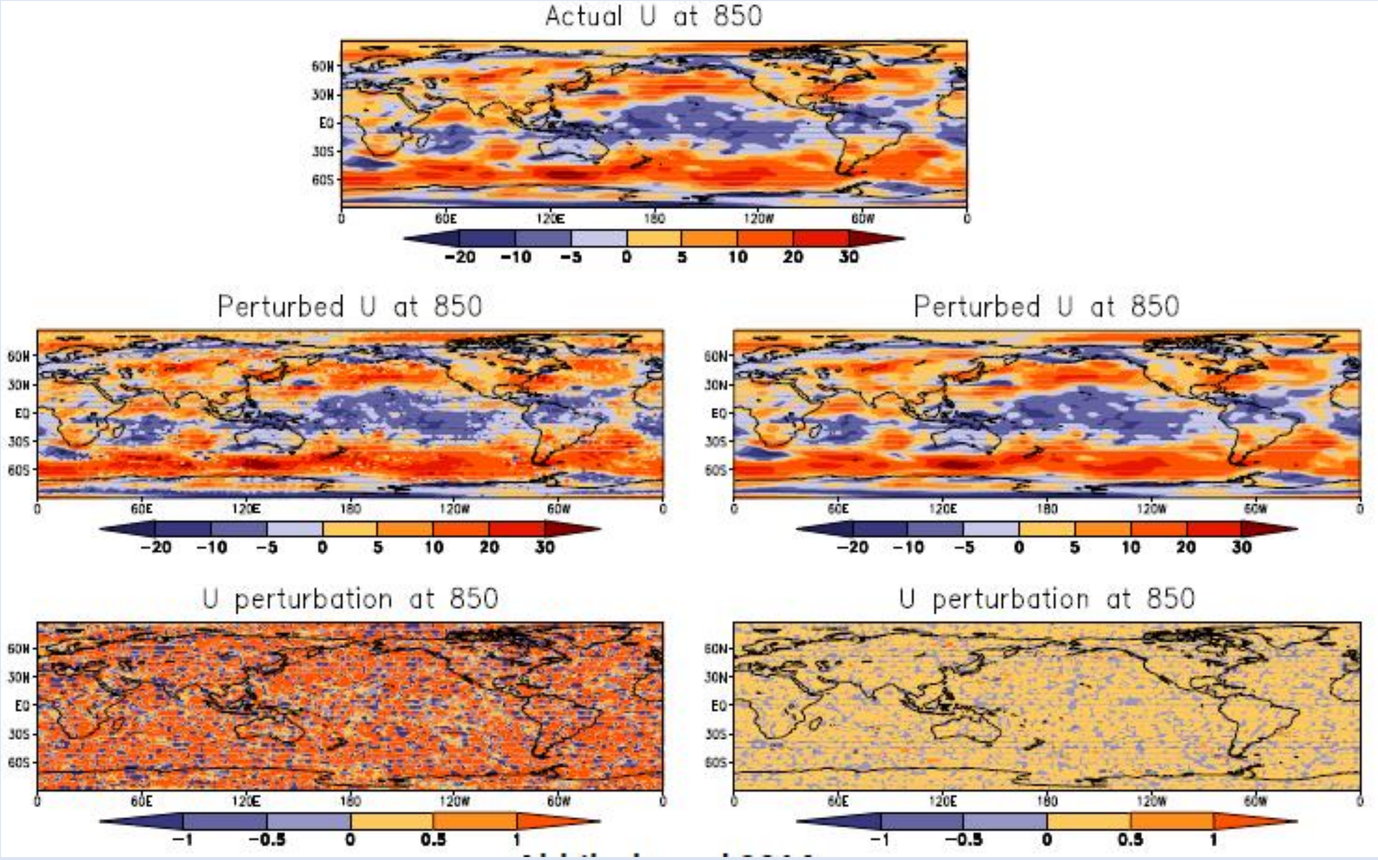
http://climate.snu.ac.kr/gcmdocu/Phy_Cum.htm – Check this website for code!



Modeling the Monsoon – weather prediction

Extended Range Ensemble Prediction System at IITM

Ensemble perturbations: At ECMWF, initial perturbations are generated using singular–vector technique (by determining error growth) and an unperturbed control run (Buizza and Palmer, 1995). At NCEP, the ensemble of initial perturbations are generated in a similar way as at ECMWF, but breeding vectors (Toth and Kalnay, 1993) are used instead of singular vectors. At Meteorological Service of Canada (MSC) different combinations of parameterization schemes is used to generate ensemble of initial conditions for their medium range prediction (Houtekamer et al., 1996, 2005)



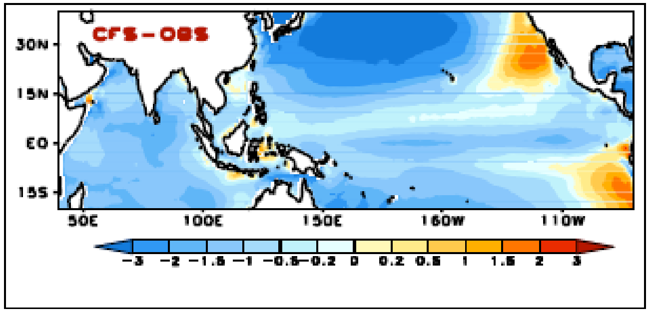
Abhilash et al. 2014

Modeling the Monsoon – weather prediction

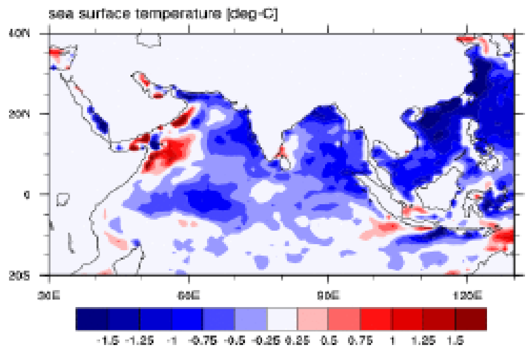
Extended Range Ensemble Prediction System at IITM

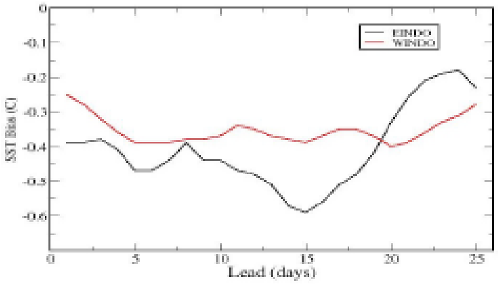
Bias correction technique

SST Bias from Long Simulation



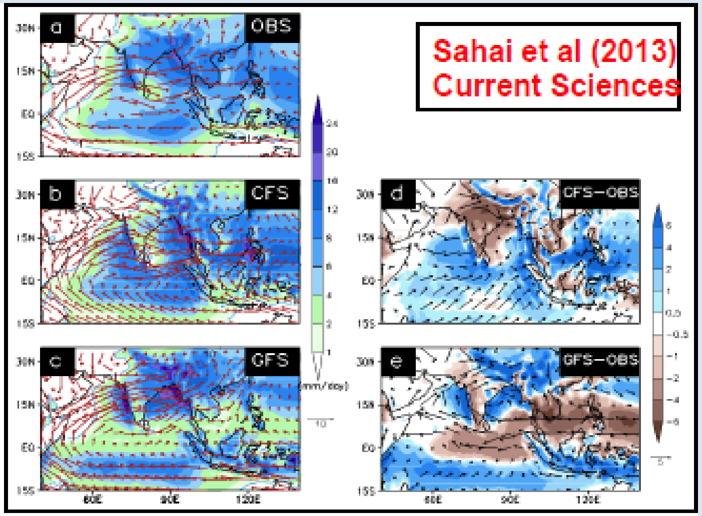
SST Bias
20 day Lead



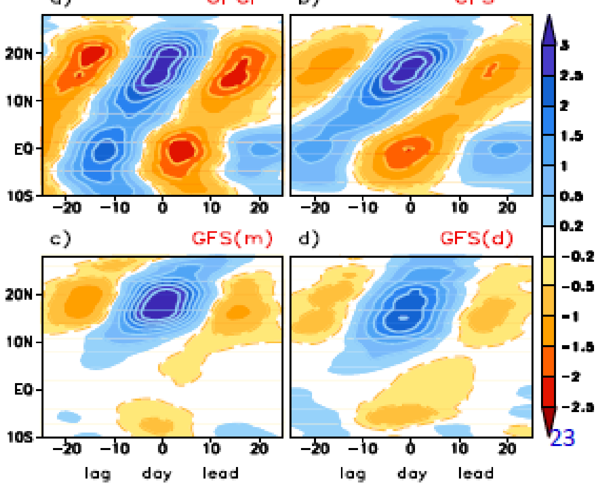


Lead
Dependant
Bias

Abhilash et al., 2013



Northward propagation of ISO



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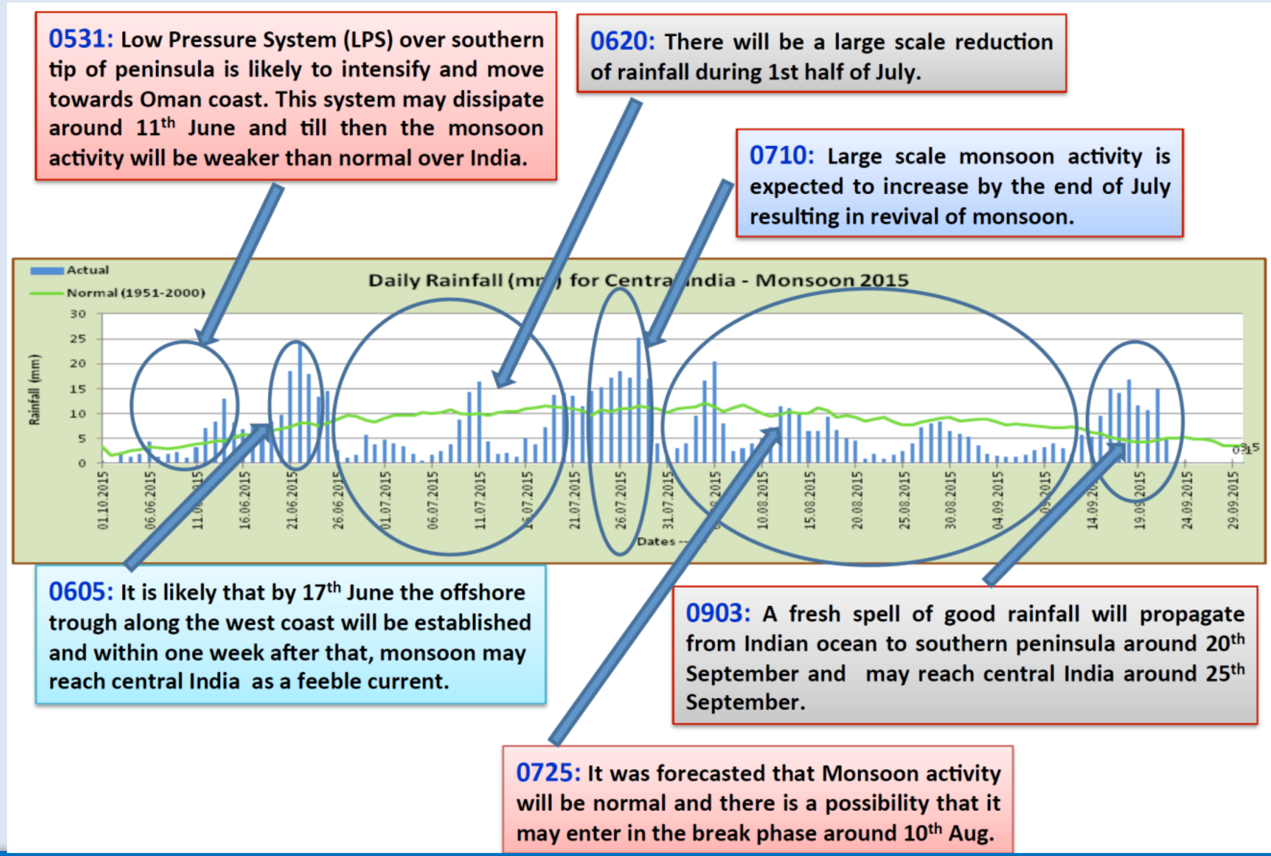
Abhilash et al. 2014

Modeling the Monsoon – weather prediction

Extended Range Ensemble Prediction System at IITM

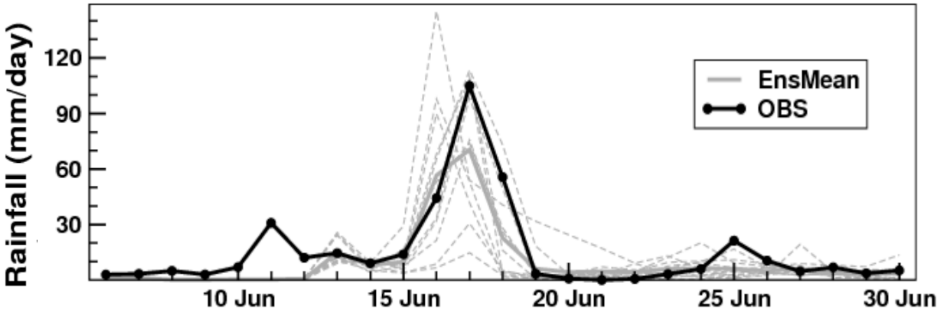
The ensembles are generated not only by perturbing the initial condition, but also by using different resolutions, parameters, and coupling configurations of the same model (CFS and its atmosphere component, the Global Forecast System). Each of these configurations was created to address the role of different physical mechanisms known to influence error growth on the 10–20-day time scale. MME has been formulated using 21ensembles of GFSbc, 11 Ensembles of CFS126 and 11 ensembles of CFS382.

Prediction of 2015 monsoon:



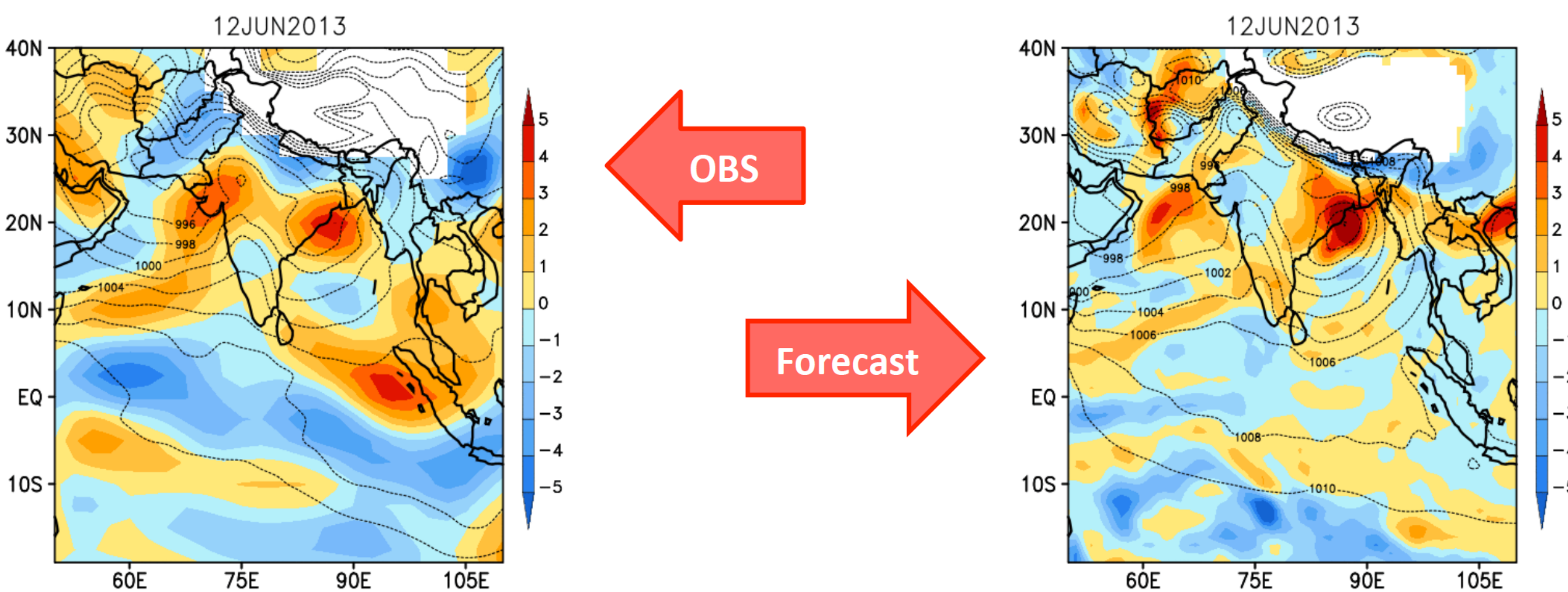
Modeling the Monsoon – weather prediction

Prediction of heavy rainfall events



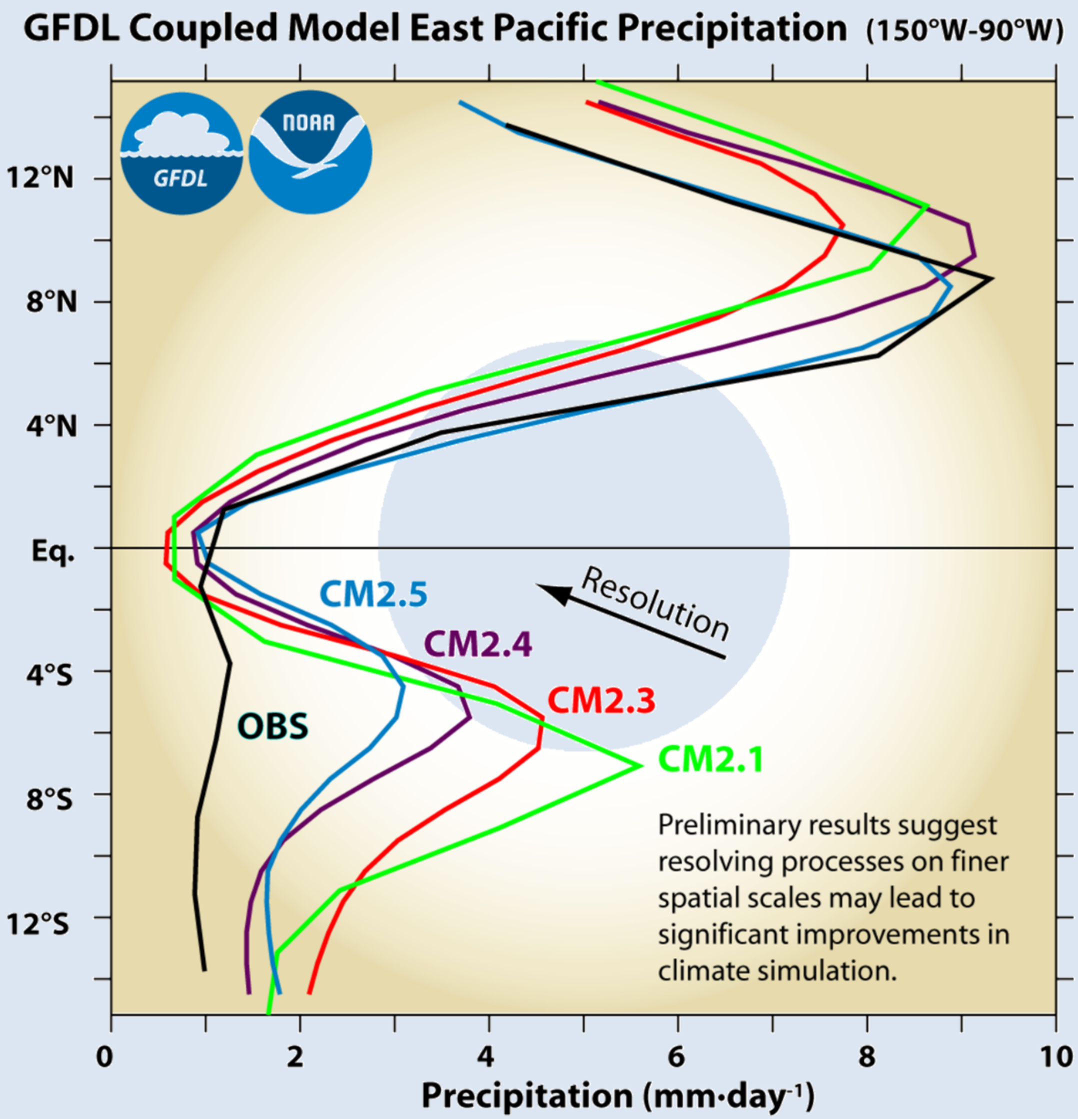
Uttarakhand event in June 2013

Evolution of Potential Vorticity (PV; x10^{-7} s^{-1}) anomalies at 700 hPa and mean sea level pressure



Modeling the Monsoon – seasonal prediction

Improvement with enhanced resolution and improved coupling



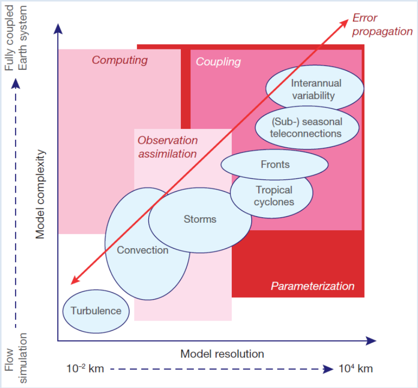
Observed rainfall

GFDL CM2.1
2° Atmosphere
1° Ocean

GFDL CM2.3
1° Atmosphere
1° Ocean

GFDL CM2.4
1° Atmosphere
1/4° Ocean

GFDL CM2.5
1/2° Atmosphere
1/4° Ocean



Modeling the Monsoon – seasonal prediction

Improvement with enhanced resolution and improved coupling

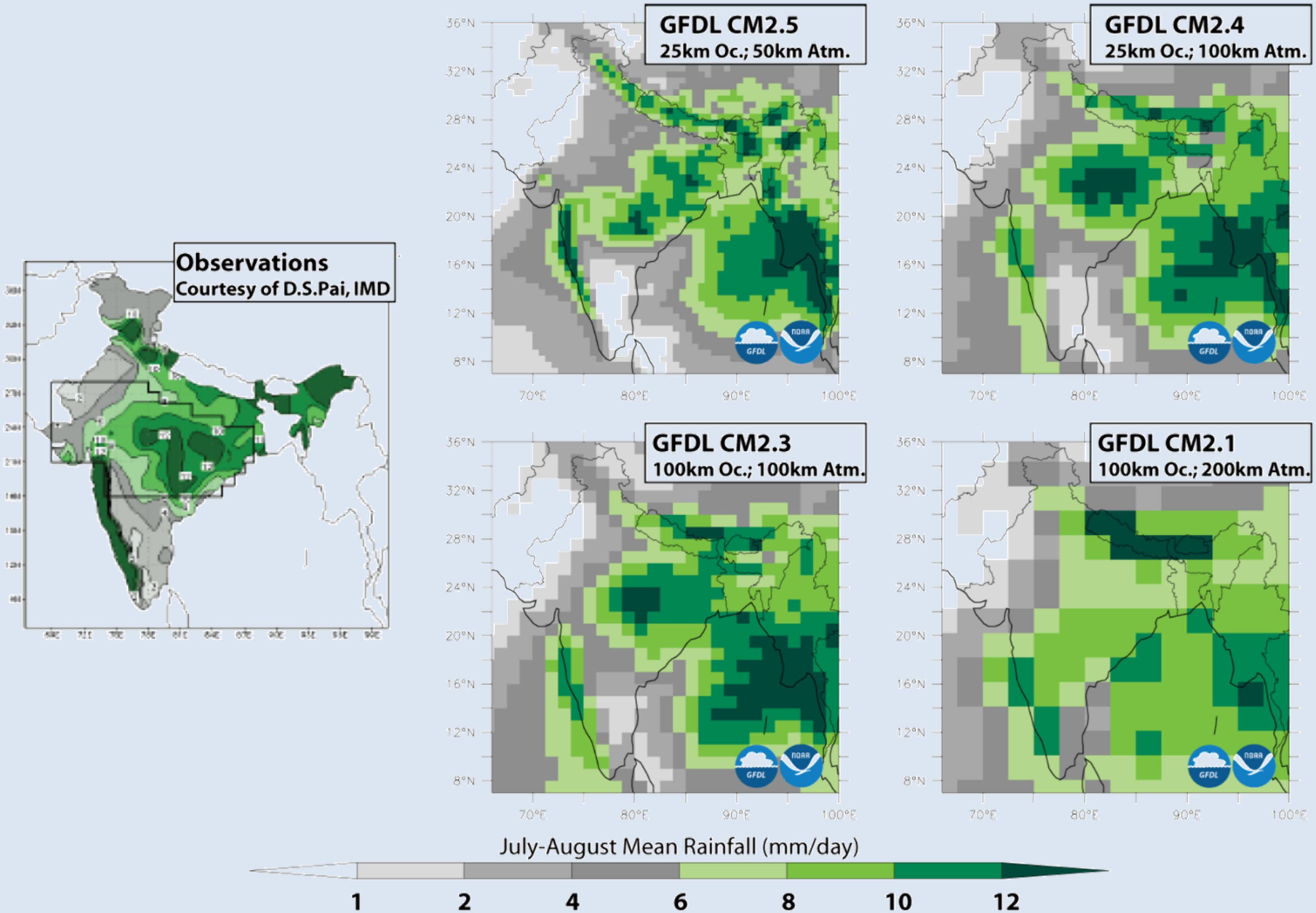
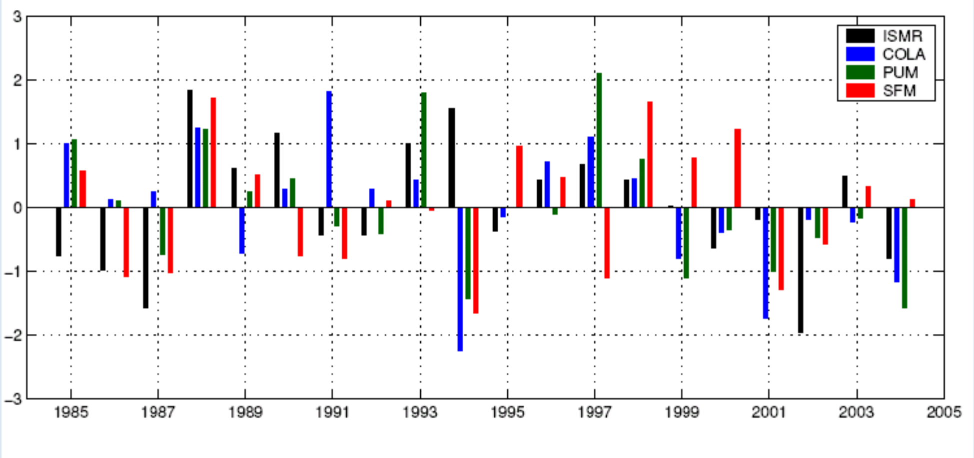


Figure: Gabriel Vecchi

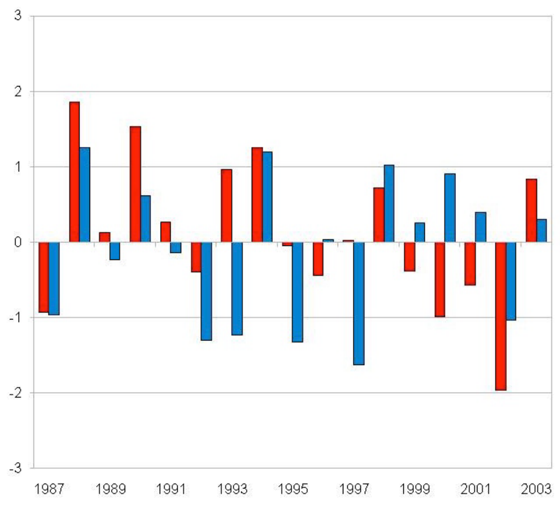
Modeling the Monsoon – seasonal prediction

Dynamical model prediction skills

Dynamical AGCM prediction skill,
CC = 0.39



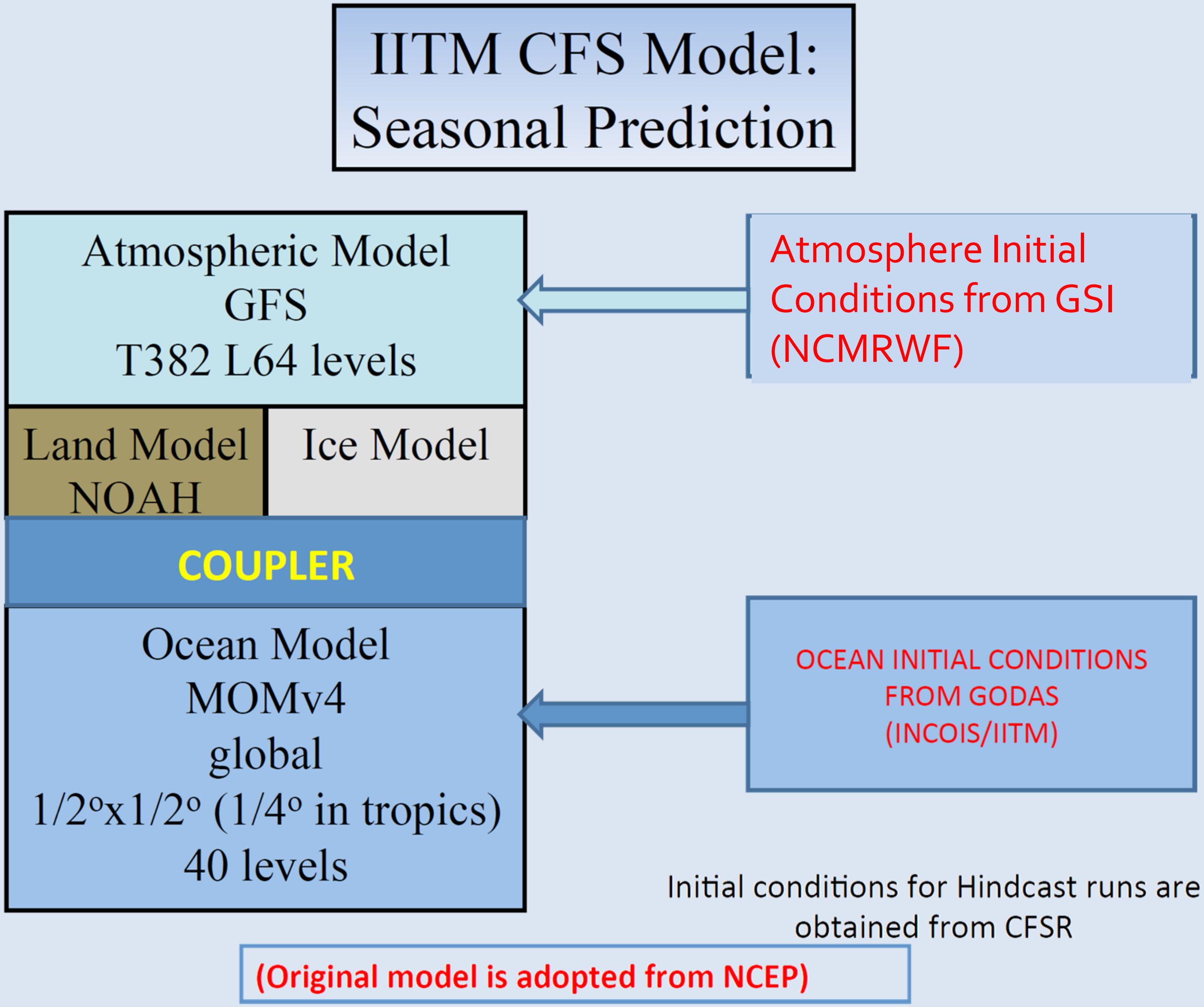
Dynamical CGCM prediction skill,
NCEP CFSv2: CC=0.45



Gadgil and Srinivasan, *Current Science*, 2012; Pattanaik and Arun Kumar, Climate Dynamics, 2010

Modeling the Monsoon – seasonal prediction

Monsoon Mission – CFSv2



CFSv2 model biases and improvement
National Monsoon Mission

Major Biases in CFSv2

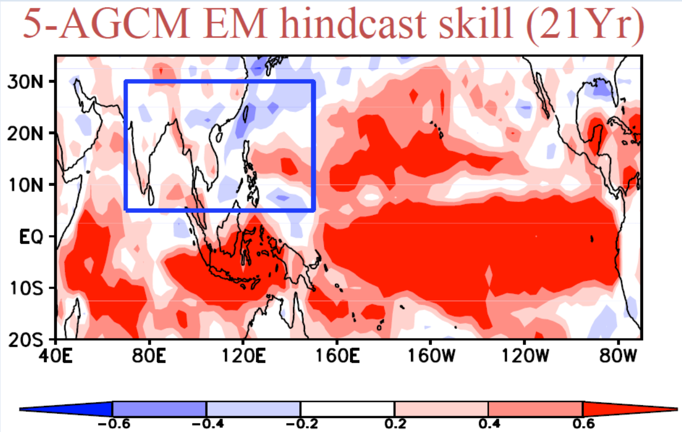
Dry bias over India
Cold bias in SST
Mixed layer bias
Cold land and trop. Temperature
Excess Eurasian snow
Excessive convective rainfall over tropics
(Roxy et al. 2012, Saha et al. 2013)

Attempts to reduce these biases:

Convective parameterization (New SAS, Han and Pan, 2011; Ganai et al. 2014)
Cloud Microphysics (Hazra et al. 2015; Abhik et al. 2016)
Super parameterization (Goswami et al. 2015)
Improved snow physics in Land Surface Model (Saha et al. 2016)
High resolution model (Ramu et al. 2015)
Earth System Model (Swapna et al. 2014)

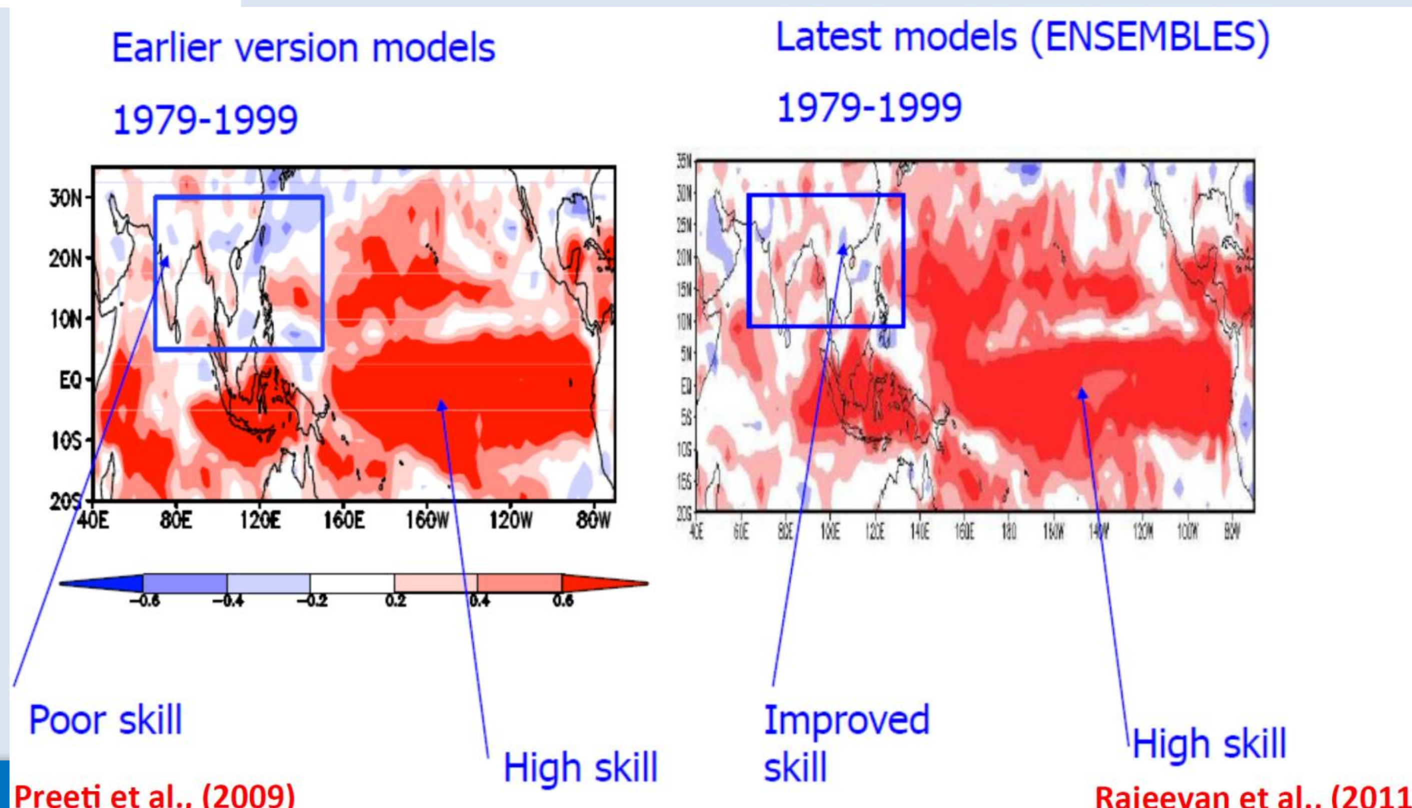
Modeling the Monsoon – seasonal prediction

CFSv2 model biases and improvement



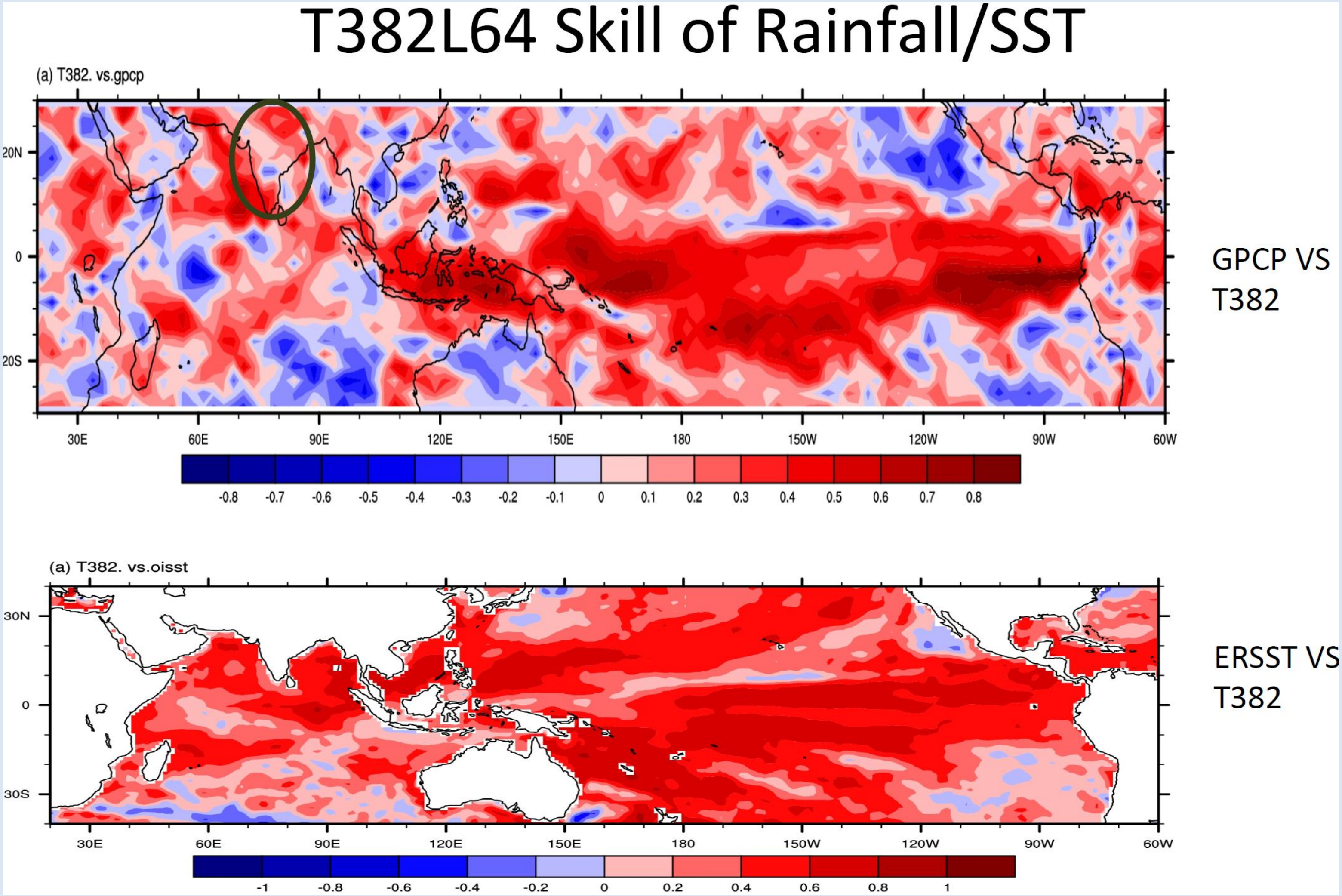
AGCMs were unable to predict ASM rainfall.

Inherent lack of ocean–atmospheric coupling, and treating monsoon as a slave to prescribed SST results in the failure.



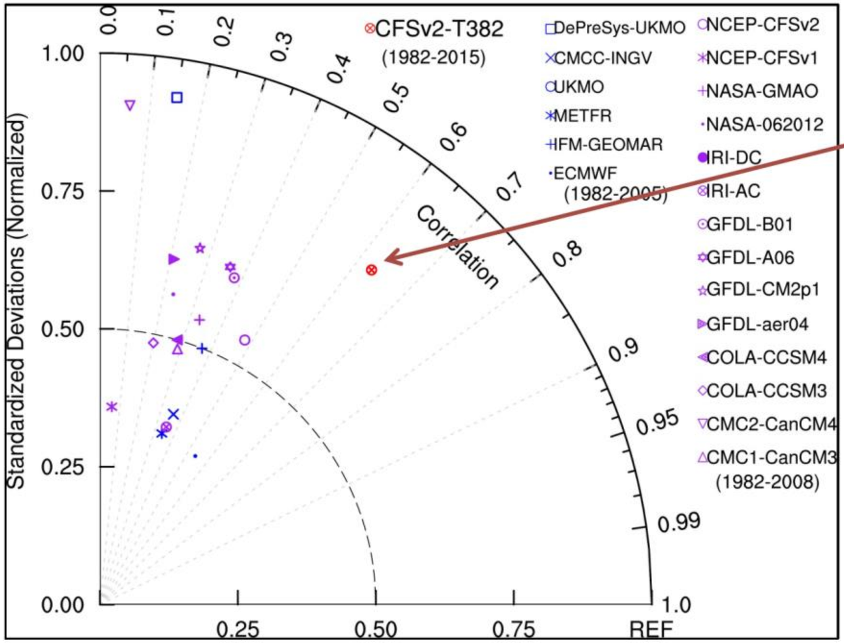
Modeling the Monsoon – seasonal prediction

CFSv2 model biases and improvement

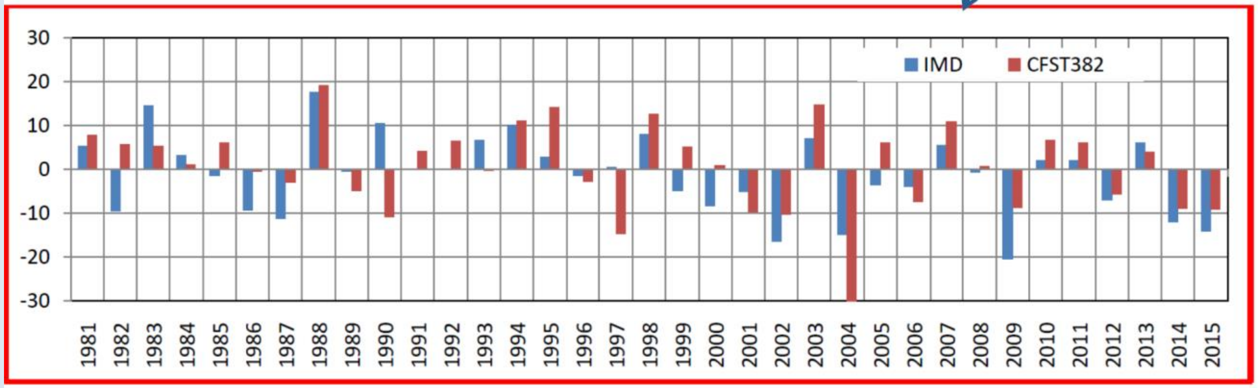


Modeling the Monsoon – seasonal prediction

CFSv2 model biases and improvement



Monsoon Mission Model Performance (Prediction Skill as well as interannual variance) is better than other models for Indian Monsoon.

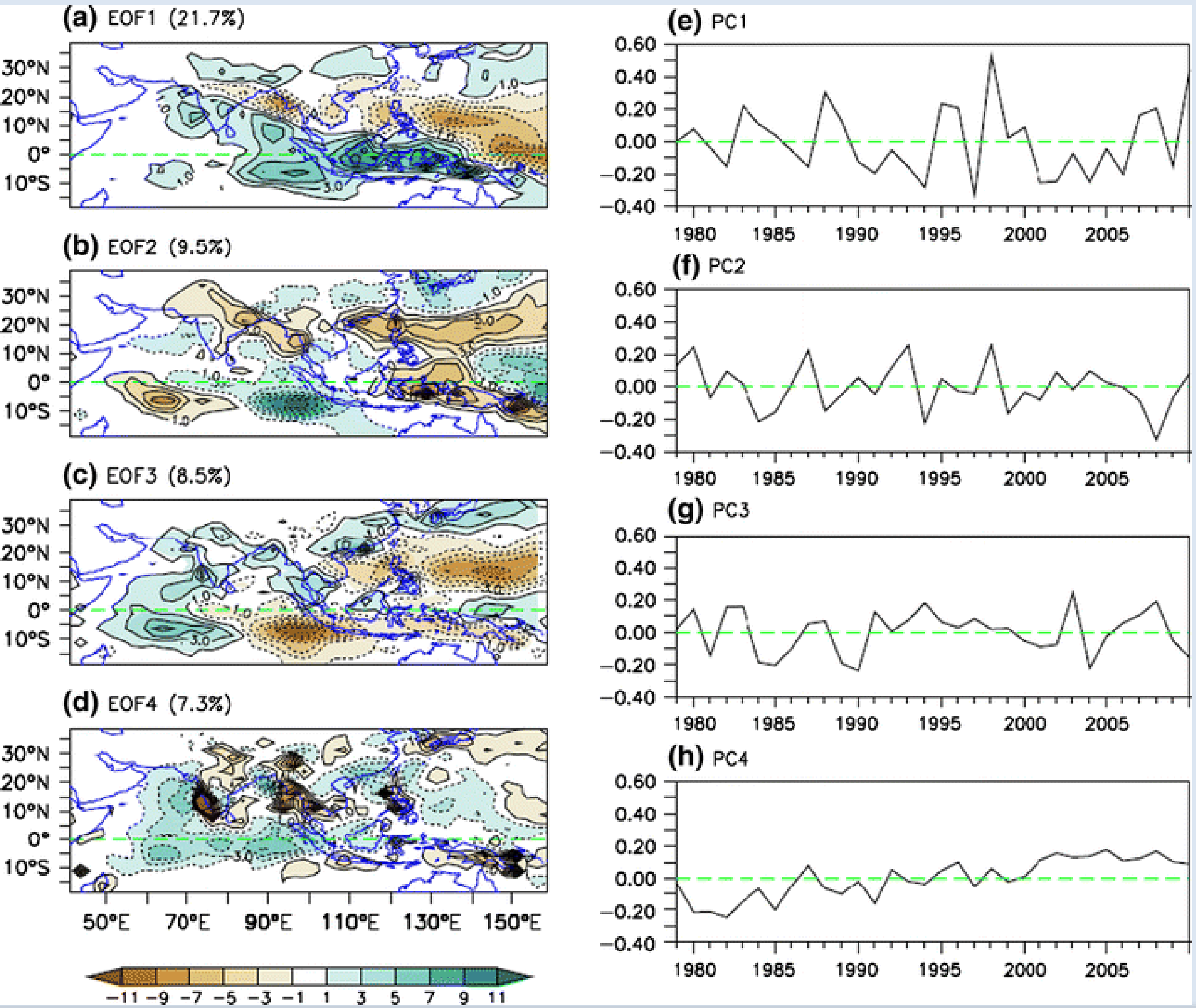


Modeling the Monsoon – seasonal prediction

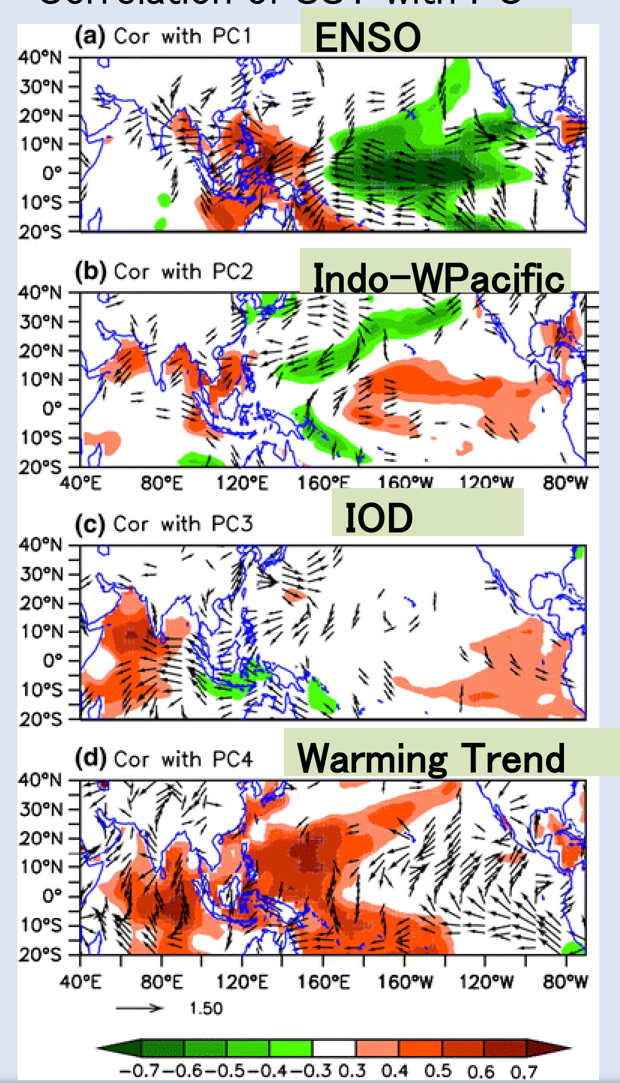
predictable mode analysis

ocean-atmospheric processes – 47% of total variance

EOFs and corresponding PCs of precipitation



Correlation of SST with PC

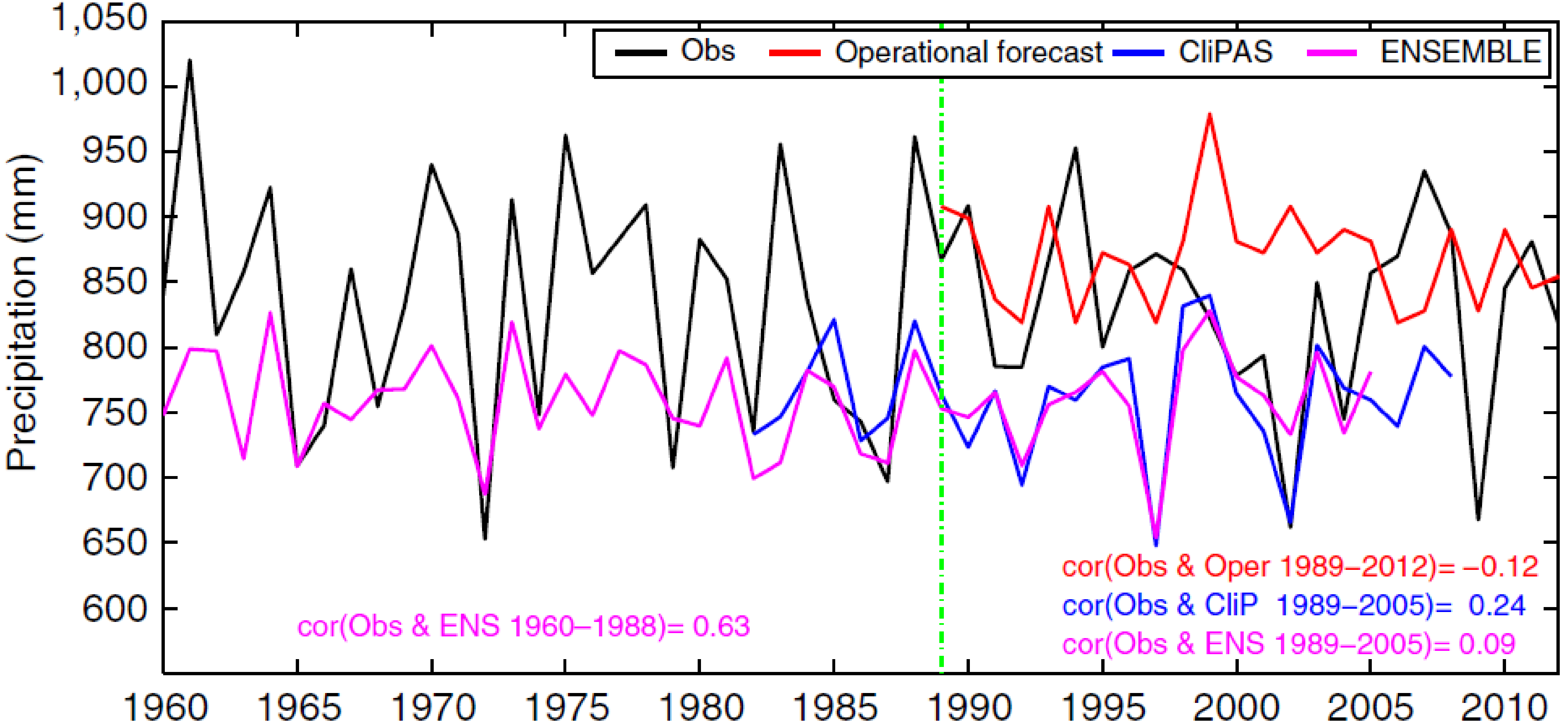


Wang, Lee, et al., *Climate Dynamics*, 2015

Modeling the Monsoon – seasonal prediction

— models unable to account for changing ocean-atmospheric processes and teleconnections due to recent global warming

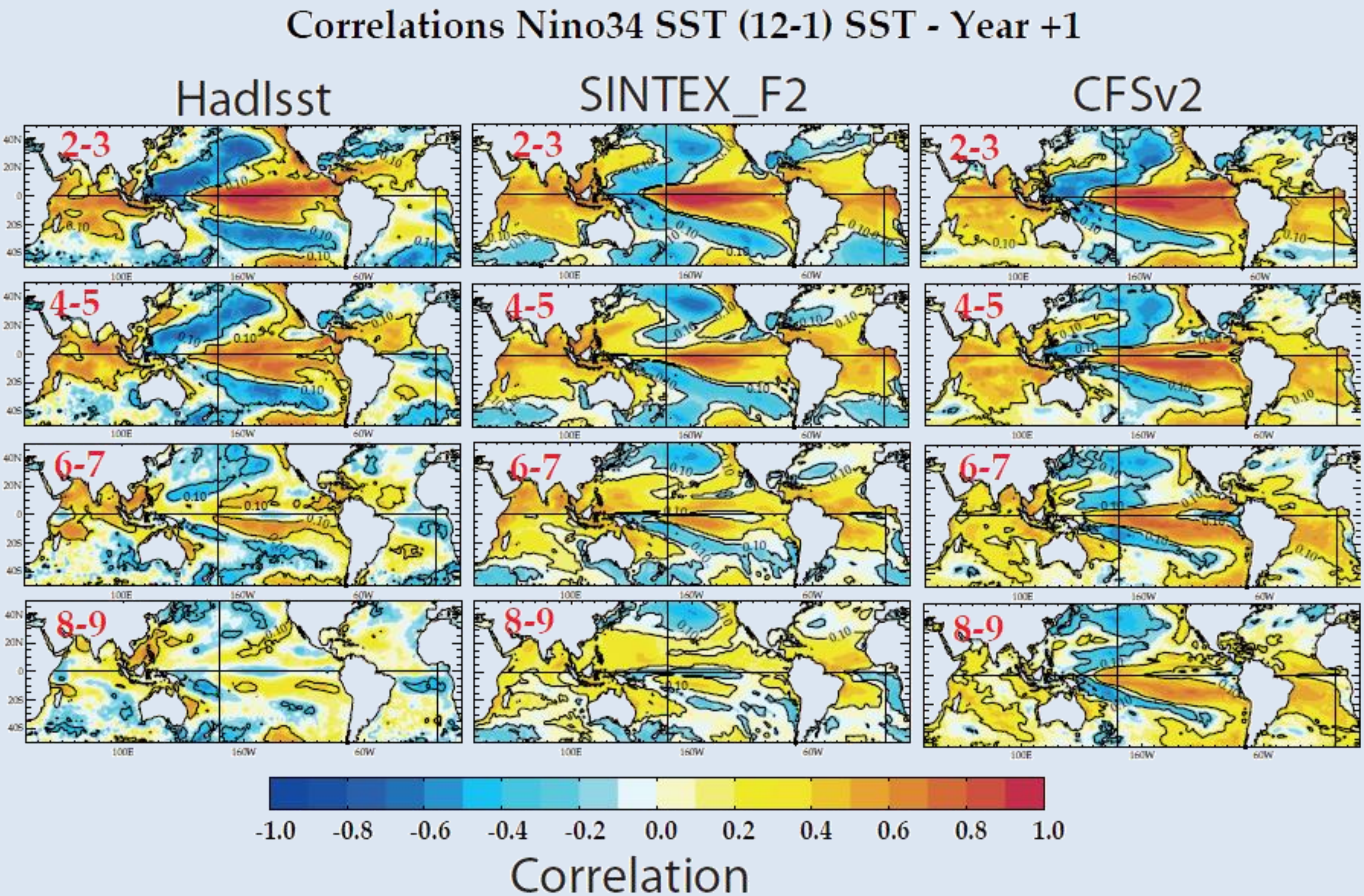
Despite enormous progress in predicting ISMR since 1886, the operational forecasts during recent decades (1989–2012) have little skill. This recent failure is largely due to the models' inability to capture new predictability sources emerging during recent global warming, such as ENSO Modoki.



Wang et al., *Nature Communications* 2015

Modeling the Monsoon – seasonal prediction

— models unable to reproduce ENSO cycle and magnitude



Figures: Pascal Terray

Modeling the Monsoon – climate prediction

Seasonal forecast model to a climate model

THE IITM EARTH SYSTEM MODEL

Transformation of a Seasonal Prediction Model to a Long-Term Climate Model

BY P. SWAPNA, M. K. ROXY, K. APARNA, K. KULKARNI, A. G. PRAJEESH, K. ASHOK, R. KRISHNAN, S. MOORTHI, A. KUMAR, AND B. N. GOSWAMI

Improved Energy Balance in IITM ESMv2: Reduction of positive net radiation bias

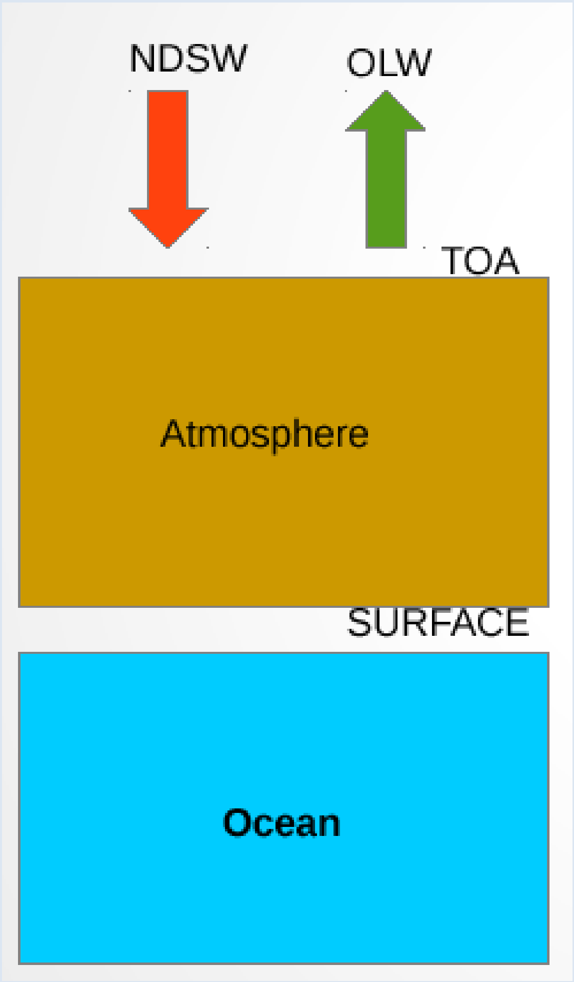
Bias of OLR is reduced largely by including TKE dissipative heating (Bretherton et al. 2012)
Replace of Zhou –Carr Cloud Microphysics by Brad–Ferrier Scheme
Reduction of bias in the Sea–Ice distribution

Swapna, Roxy et al., *BAMS* 2014

Modeling the Monsoon – climate prediction

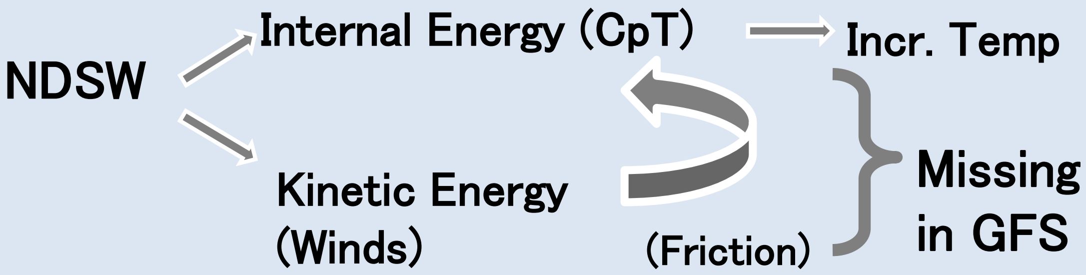
Seasonal forecast model to a climate model

TOA Energy Balance



NDSW – Net downward Short wave flux at TOA

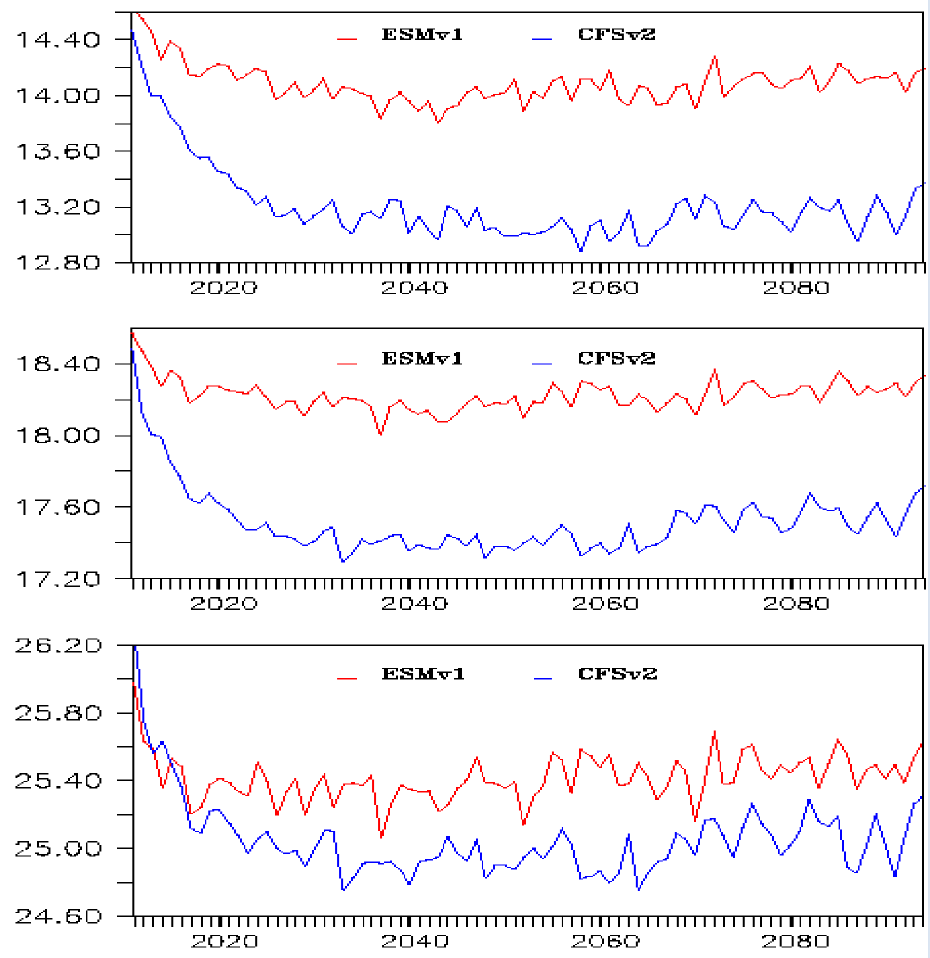
OLW – Outgoing Longwave flux (depends on layer temperature according to Stefan Boltzman law)



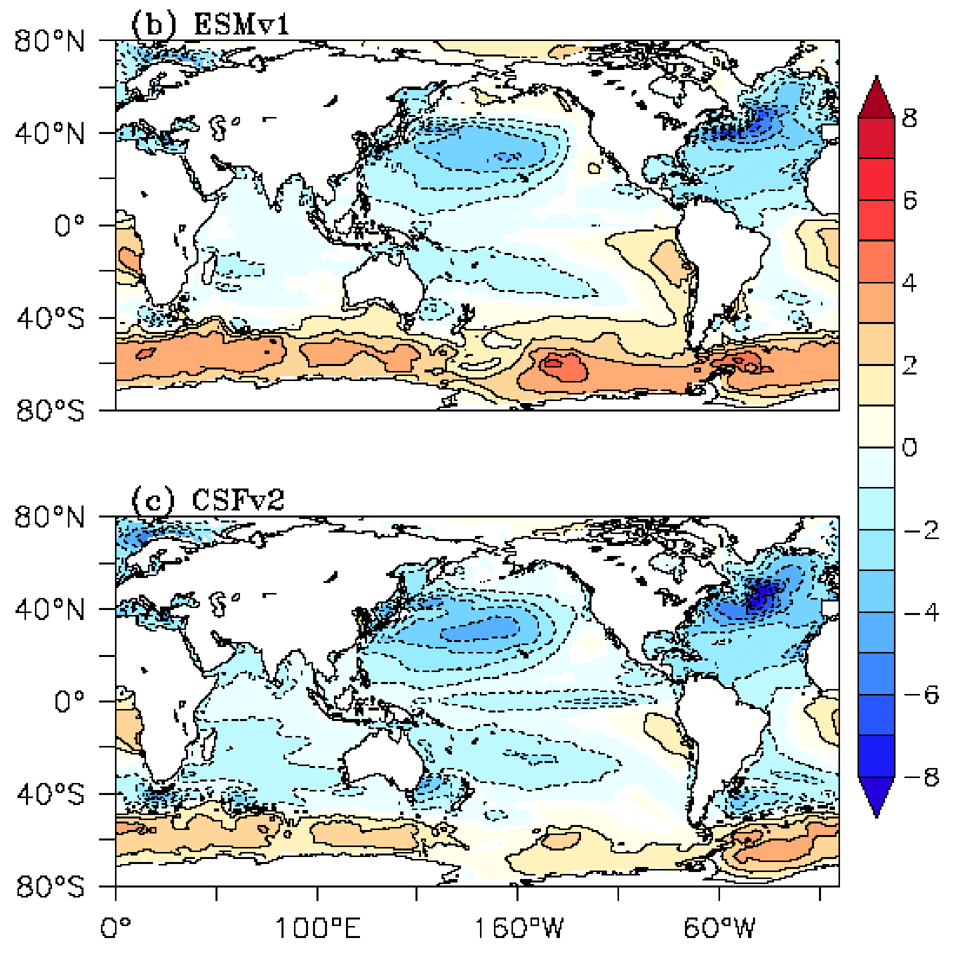
Modeling the Monsoon – climate prediction

Seasonal forecast model to a climate model

Global mean surface temperature



Annual mean SST bias



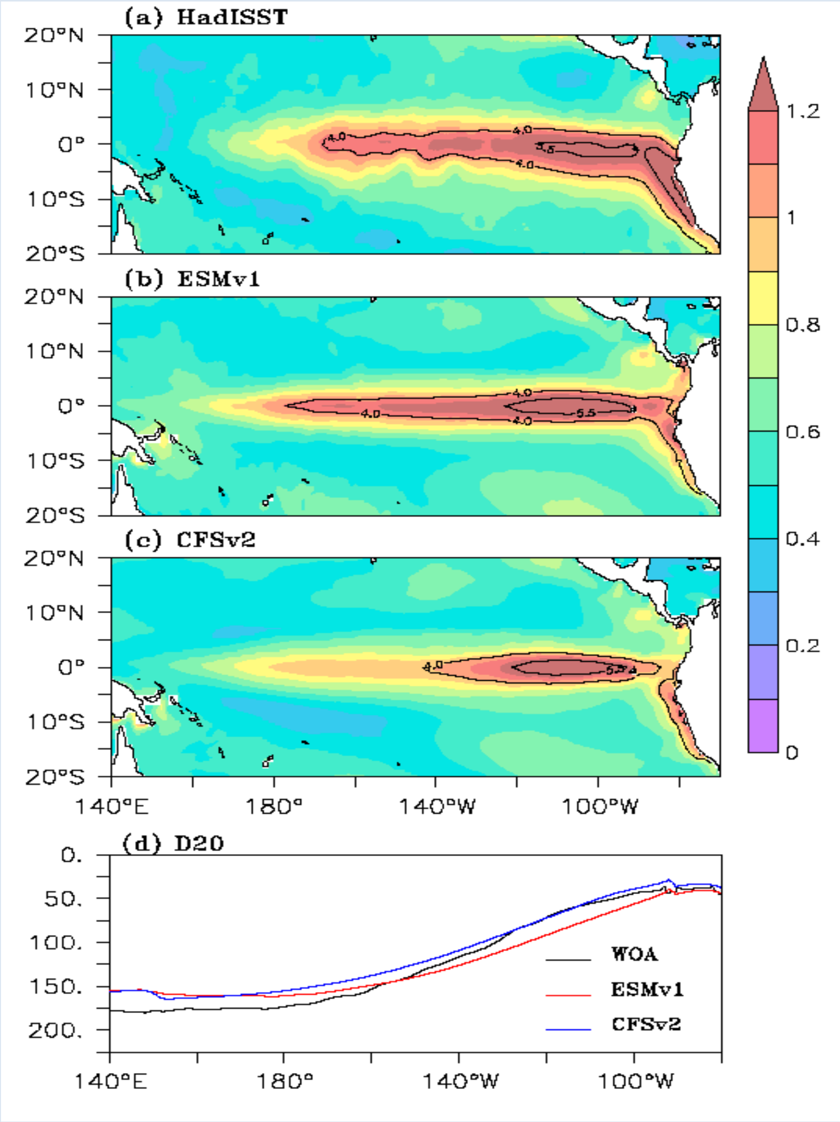
The drift in surface temperature is minimum in IITM ESMv1 compared to CFSv2

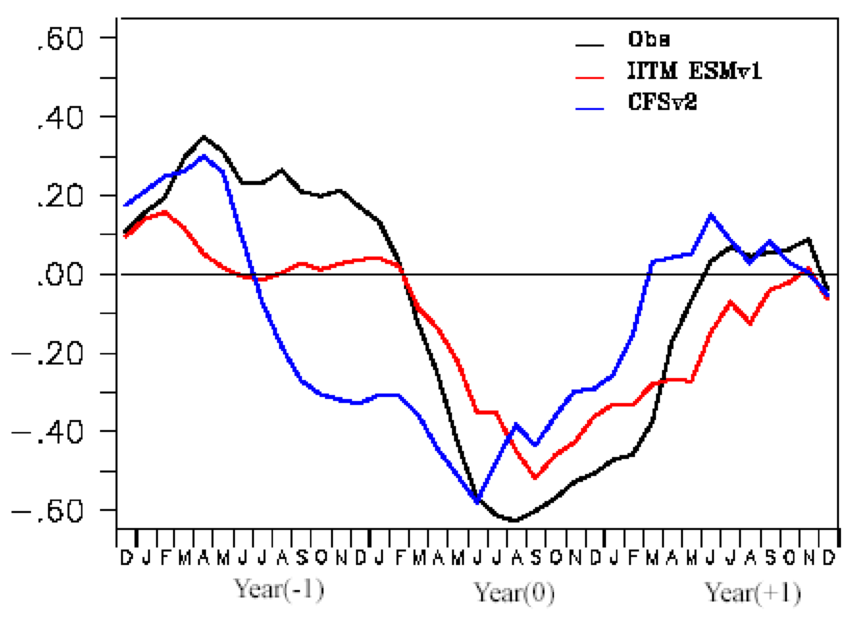
Significant reduction in cold SST bias in tropical IO and subtropical Pacific

Swapna, Roxy et al., *BAMS* 2014

Modeling the Monsoon – climate prediction

Seasonal forecast model to a climate model

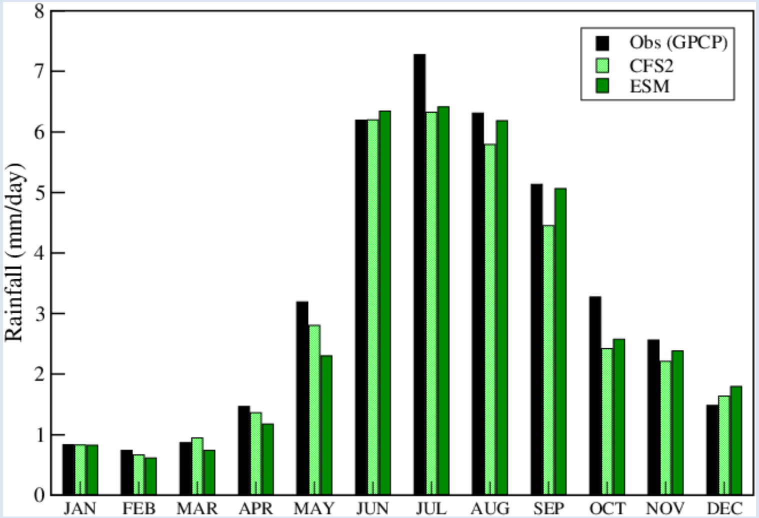


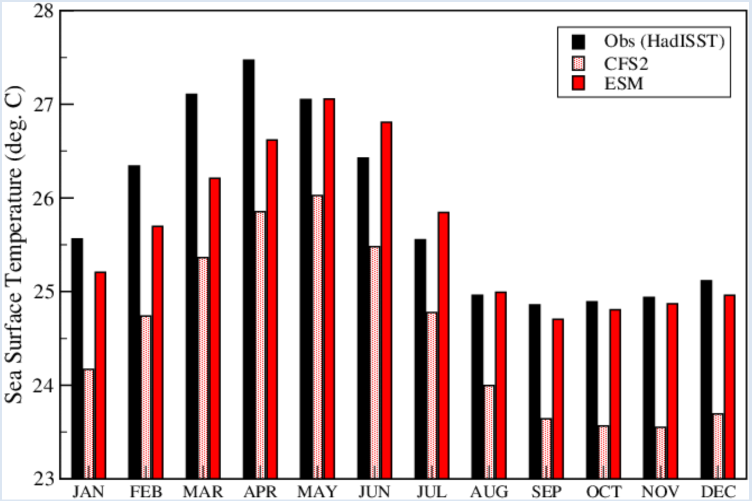


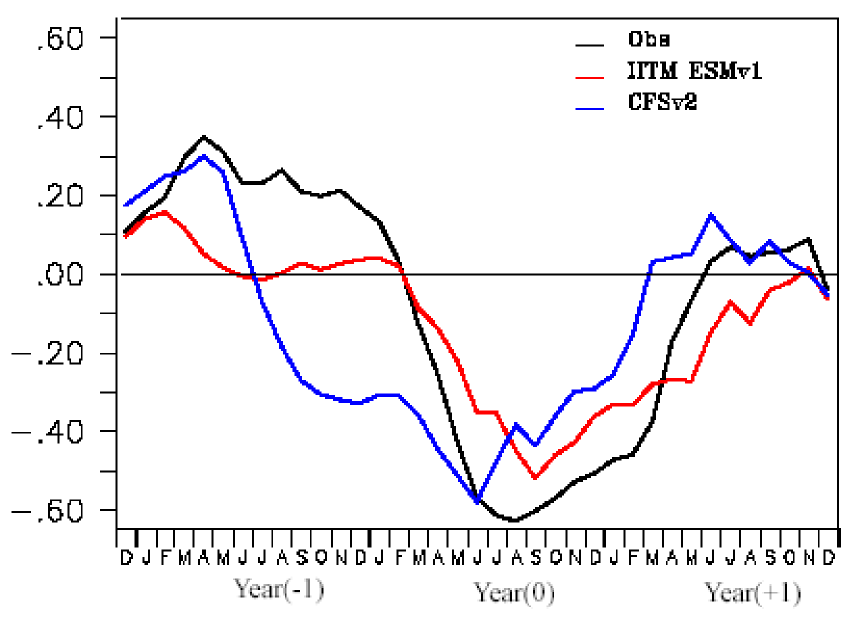
ENSO is better.

Modeling the Monsoon – climate prediction

Seasonal forecast model to a climate model







ENSO – Monsoon relation is better.

Swapna, Roxy et al., *BAMS* 2014