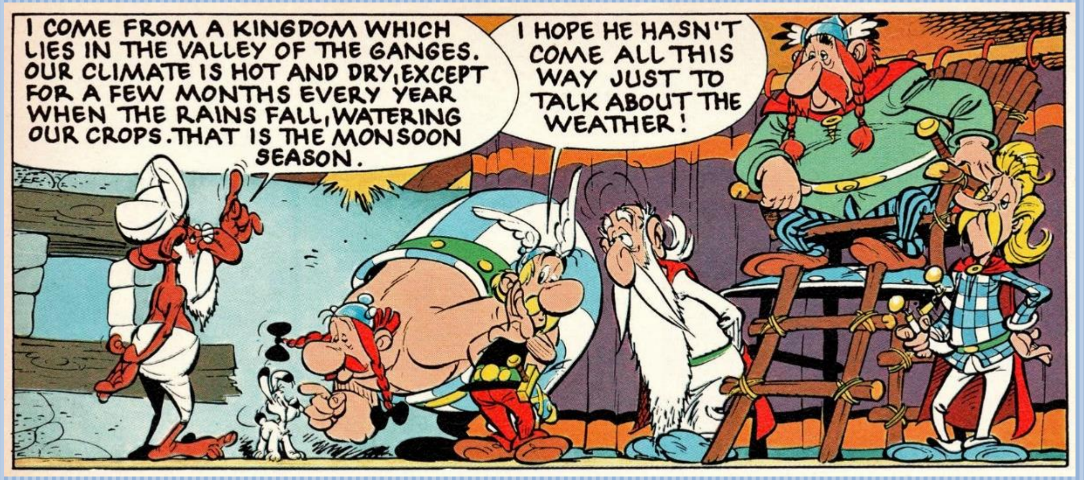
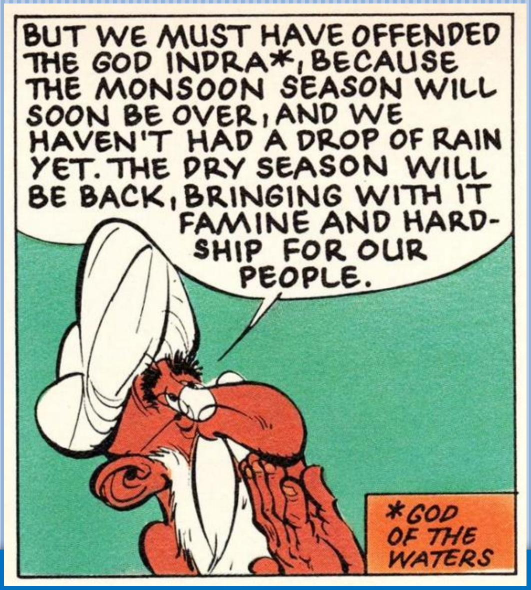
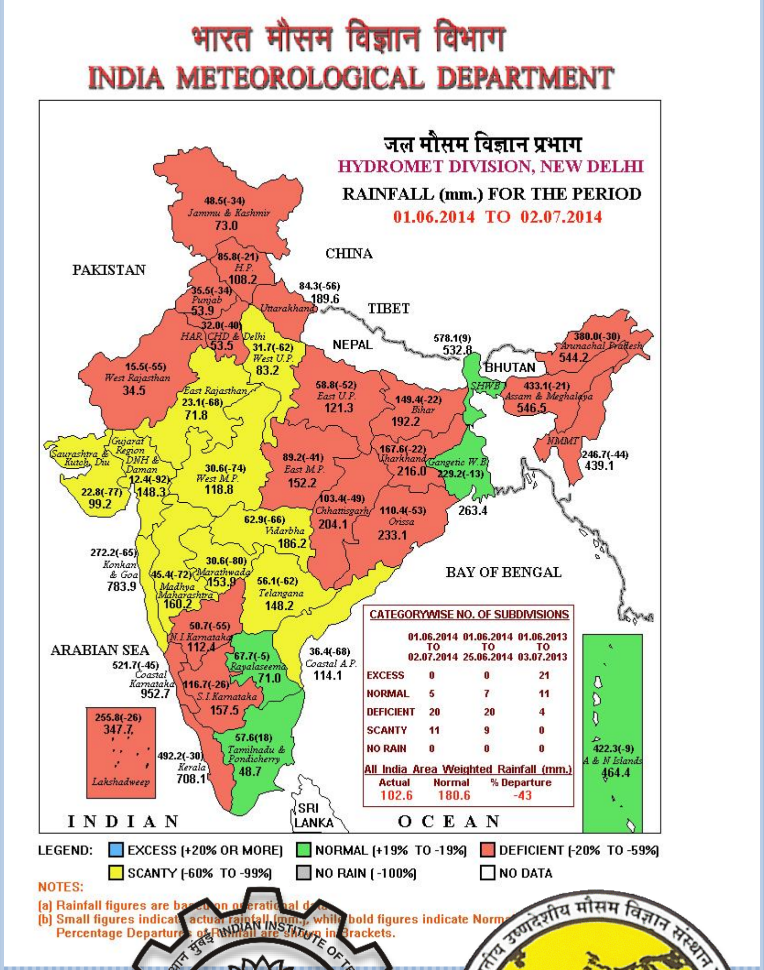
Monsoon, where art thou?







The great Indian Drought of 2014?

M. K. Roxy
Indian Institute of Tropical Meteorology, Pune

The Indian Monsoon

1. Past: History of Monsoon

2. Present: The Monsoon we know/live
   - Driving mechanisms and factors
   - Variability: Interannual, Intraseasonal, etc.

3. Monsoon Modeling

4. Role of Ocean on the Monsoon

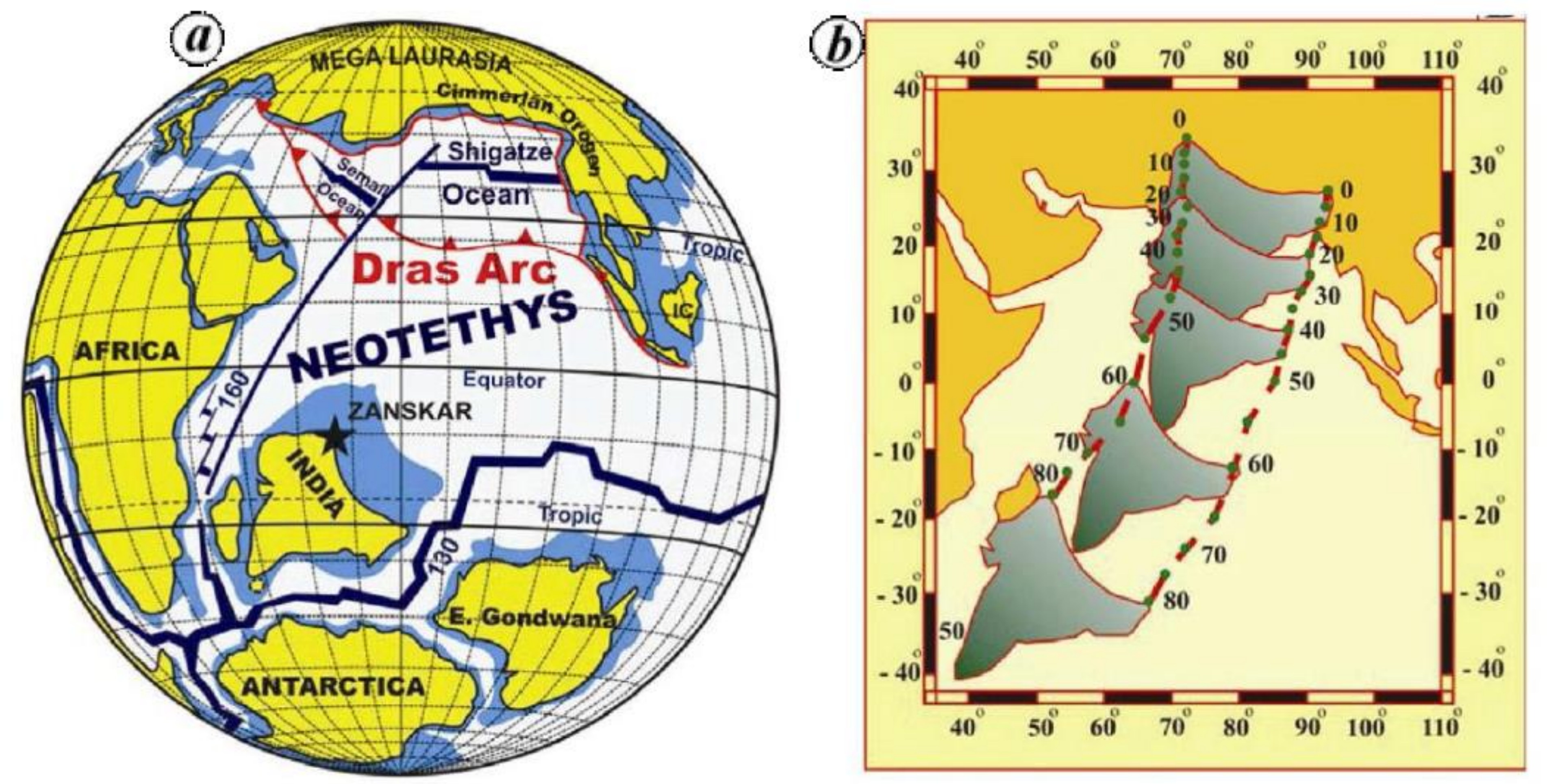
5. Future: Changing Climate and the Monsoon

6. Monsoon 2014

M. K. Roxy
Indian Institute of Tropical Meteorology, Pune

History of Monsoon, 80 Mya

Plate tectonics – factors leading to modern monsoon

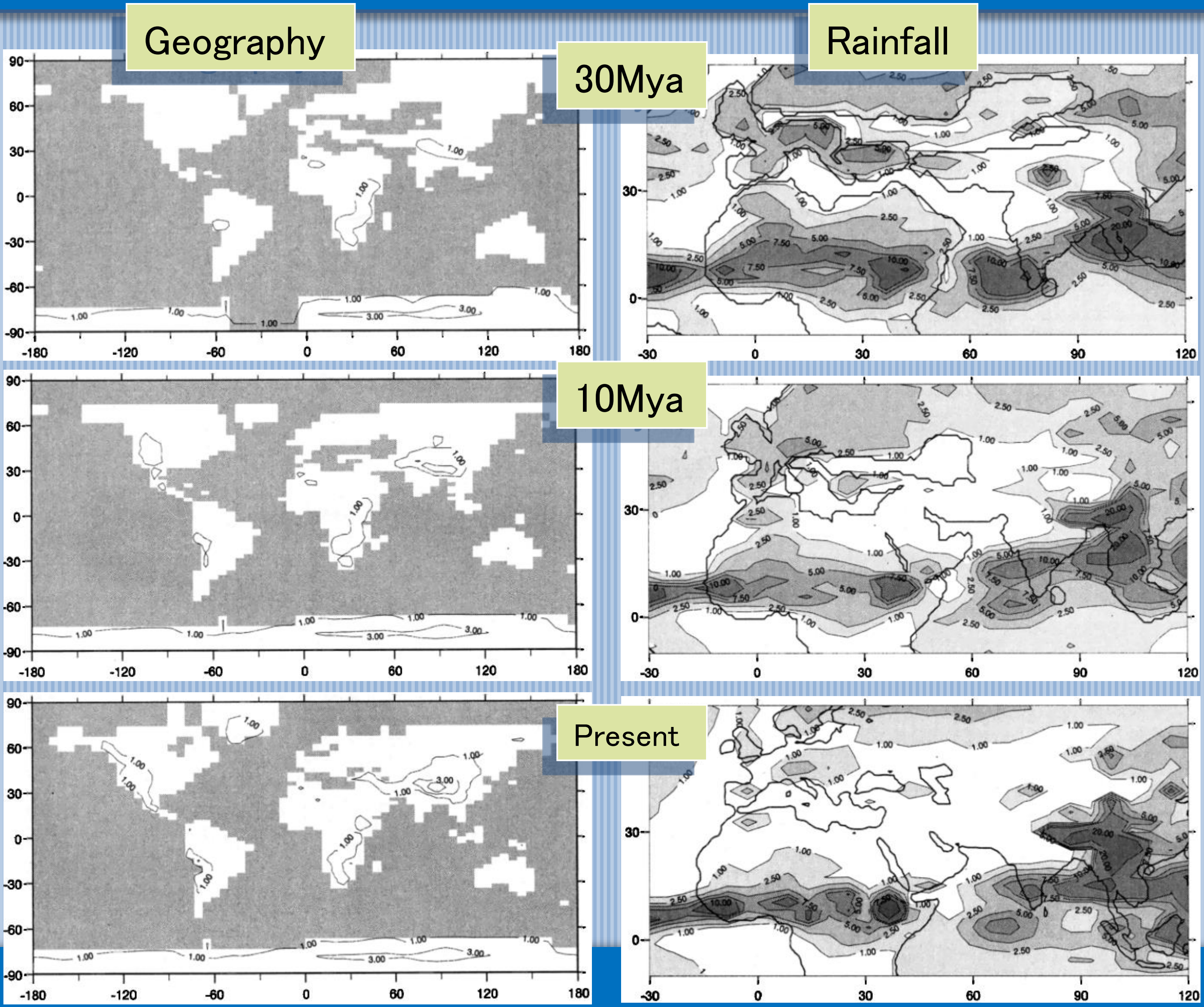


Indian plate motion: rate of ~ 15cm/yr – collided with Asia c.20–30 Mya.

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

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.

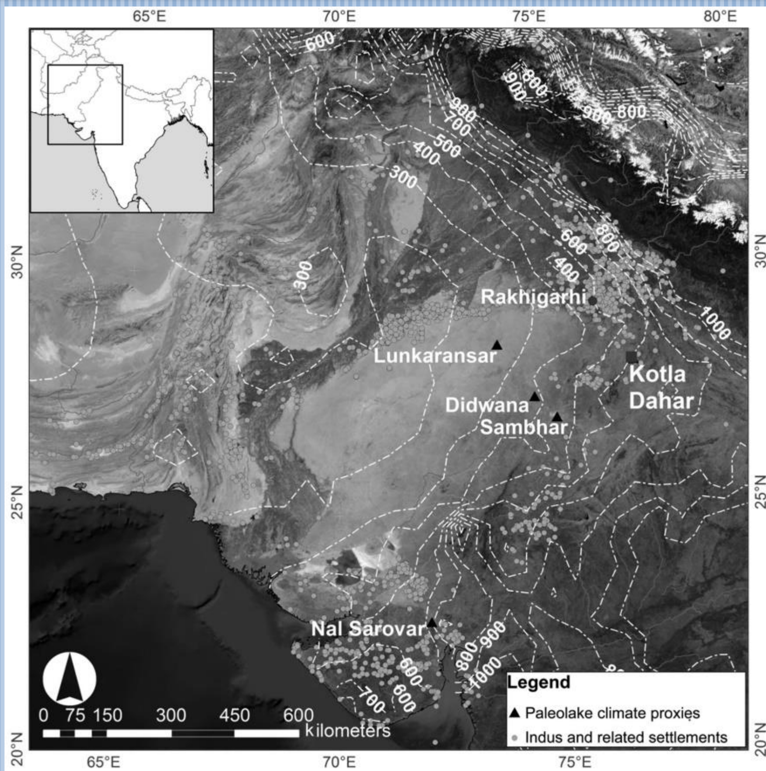
Role of Orography:

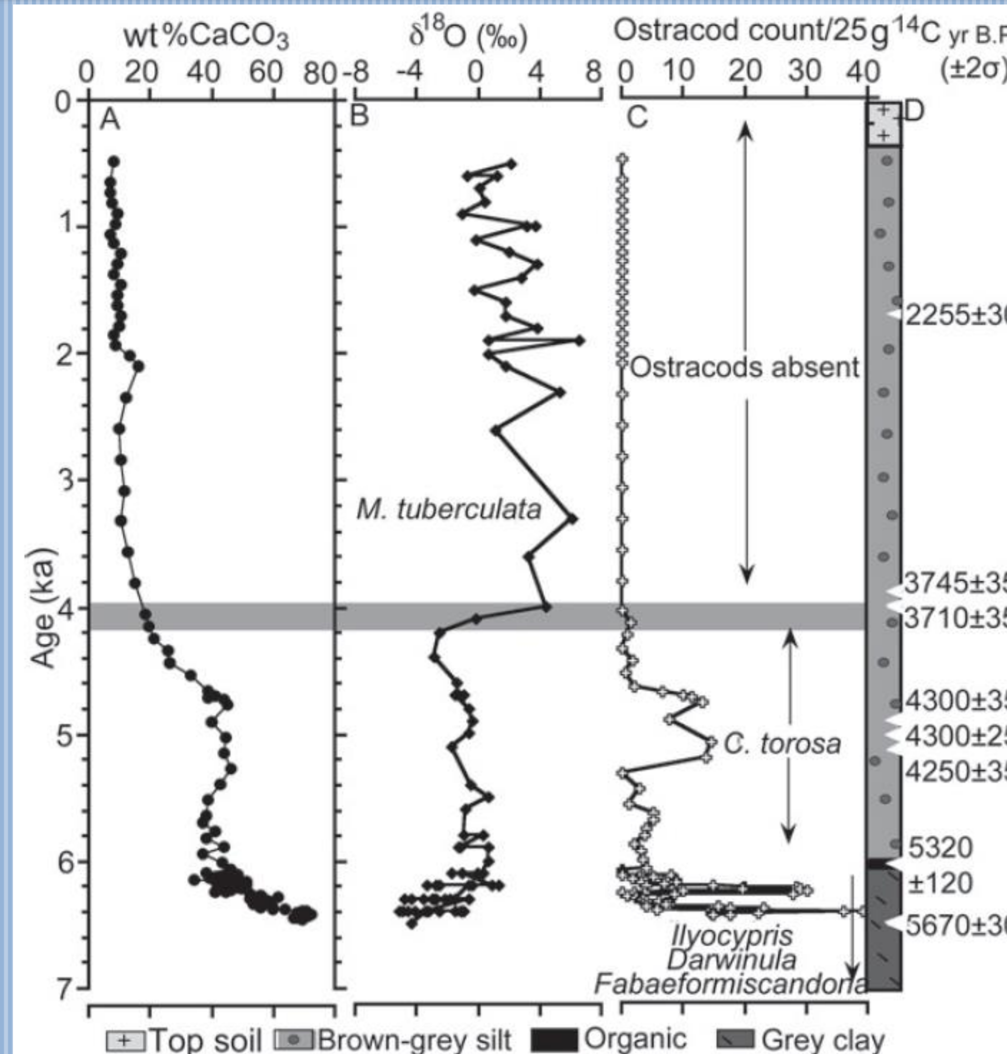
1. Upward deflection of large scale horizontal flow by orography
2. Uplifted moist air will expand, cool and condense – forming clouds

Fluteau et al. *JGR*, 1999

History of Monsoon, 4.1Kya

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.

Dixit et al., *Geology*, 2014

History of Monsoon, 1500 AD

Trade Winds – History Changers!

Cabral's voyage to Brazil and Calicut, 1500

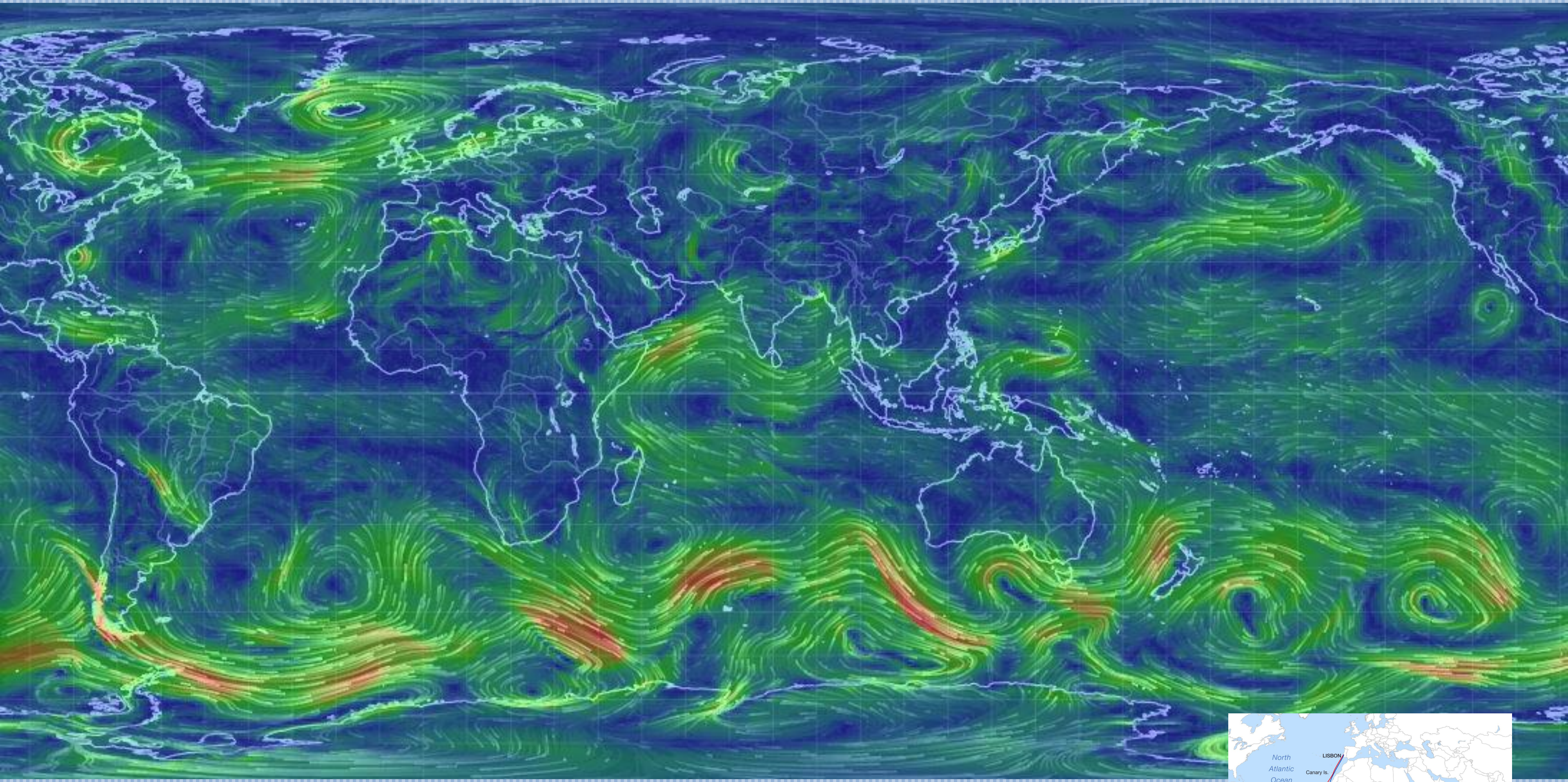
Using the trade wind secret, Indian and Arabian traders were able to dominate the lucrative market by concealing the true source of their cargoes for centuries.

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

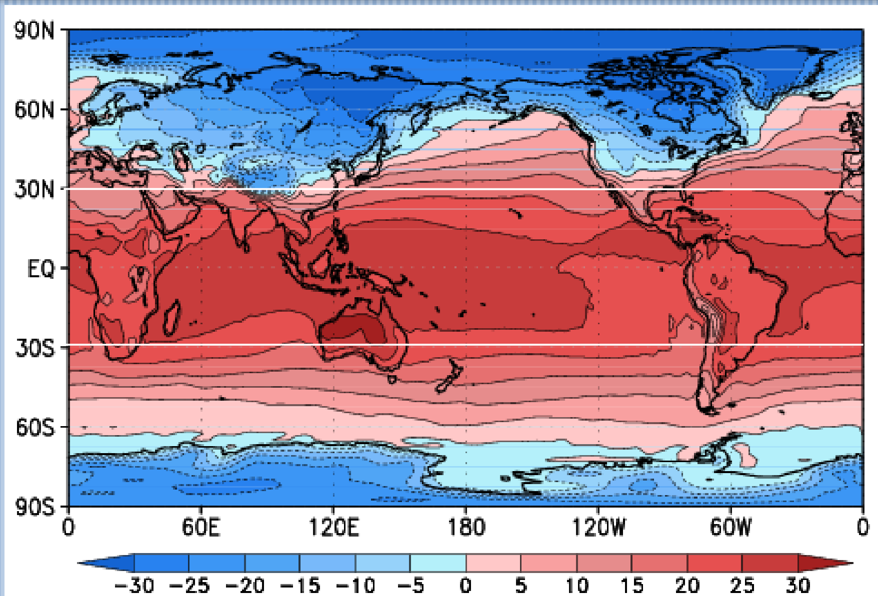
Trade Winds



850 hPa wind flow during this week – July 2014

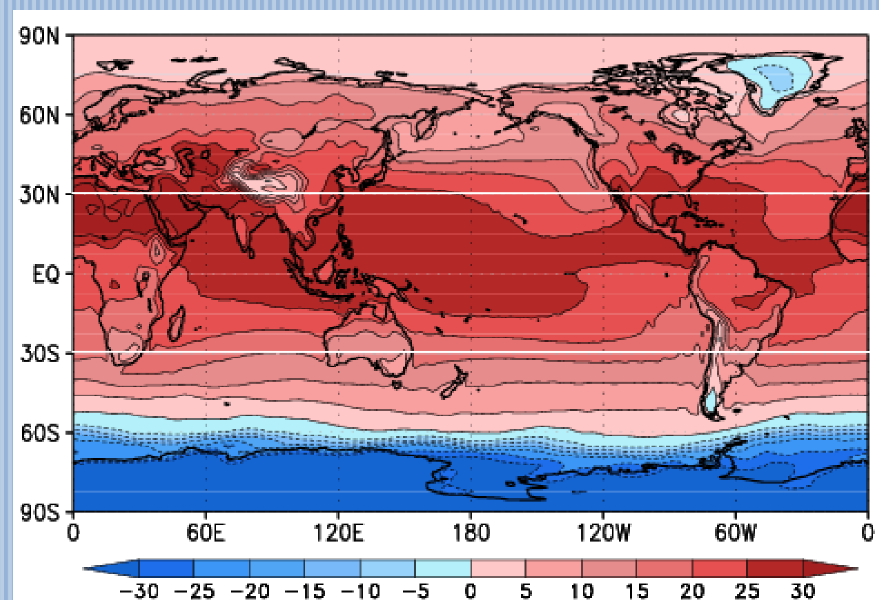
Monsoon, manifested by Surface Temperatures

Seasonal migration of solar insolation



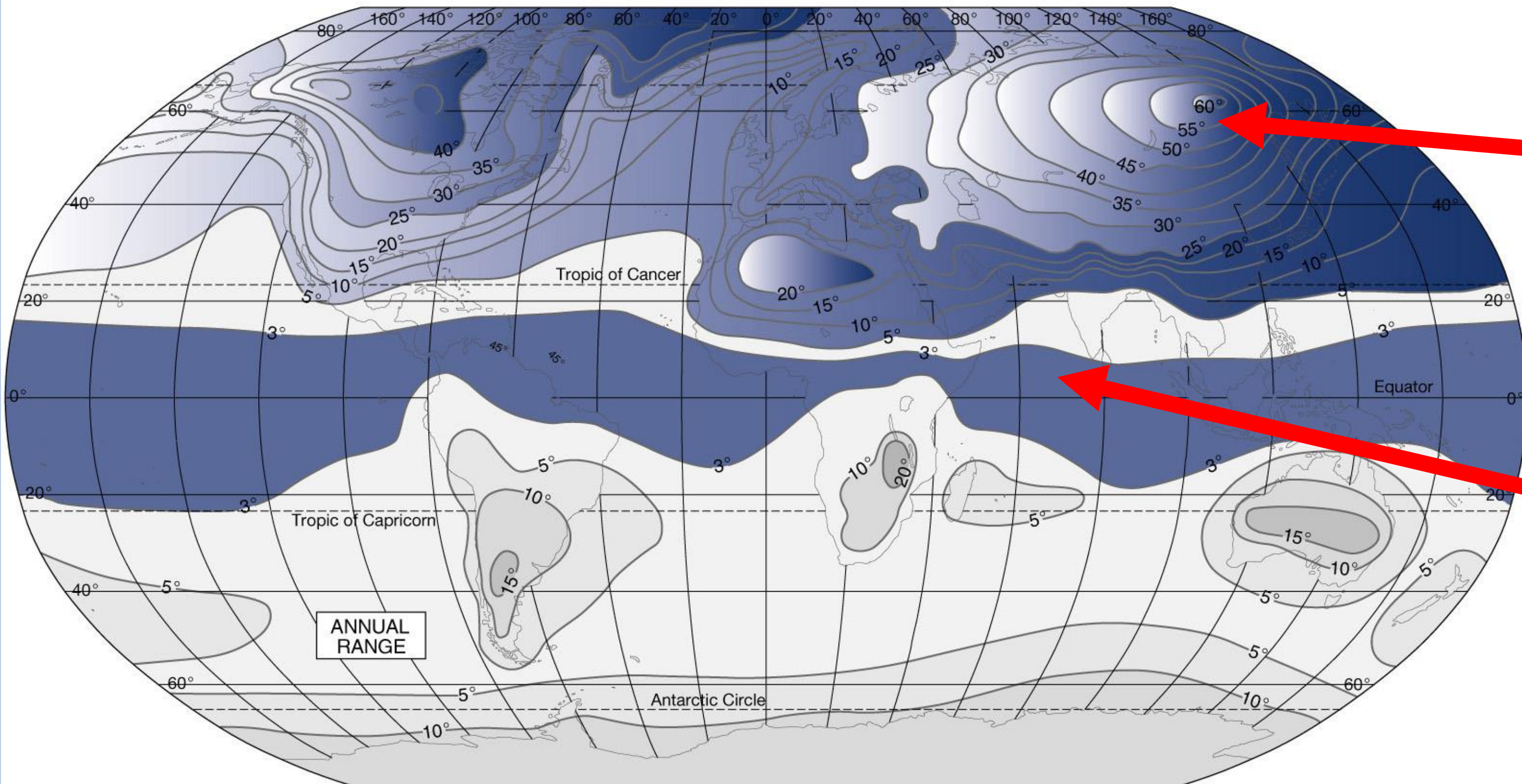
January

July



Monsoon, manifested by Thermal Contrast

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



0 1500 3000 Miles

0 1500 3000 Kilometers

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°

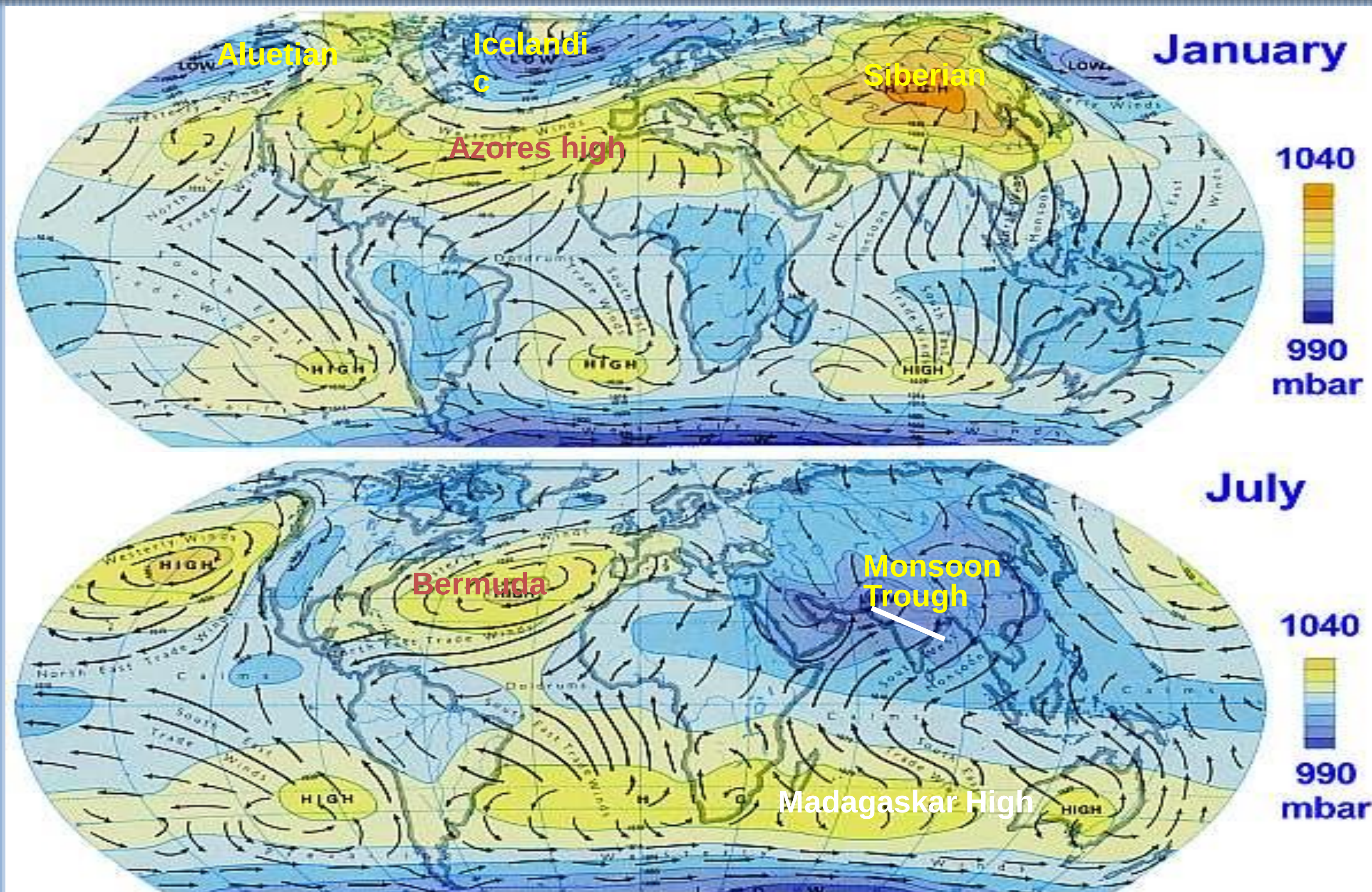
(c)

Tibetan plateau: range of 60° C

Ocean: range of 3 to 5° C

Monsoon, manifested by Pressure Gradient

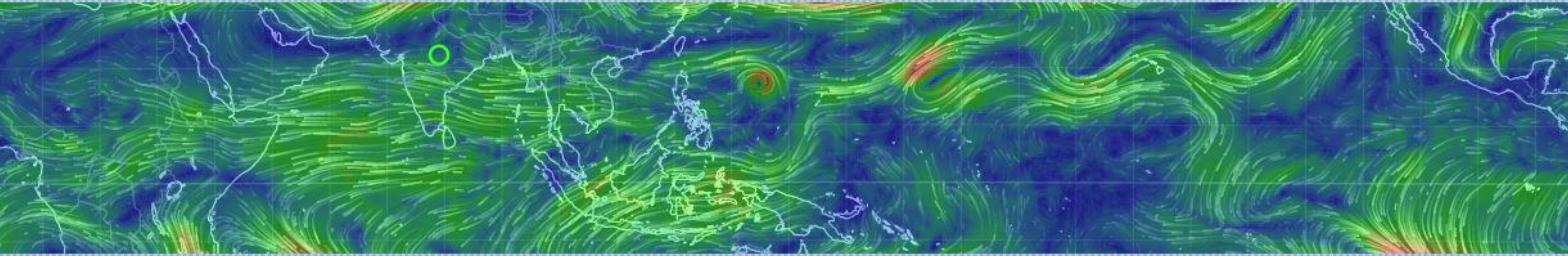
Monsoon Trough and 120° shift in wind direction



1. Madagascar-Mascarene High/Anticyclone and Monsoon Trough
2. Low-level cross-equatorial Jet: splits in 2 branches at around 10°N, 60°E

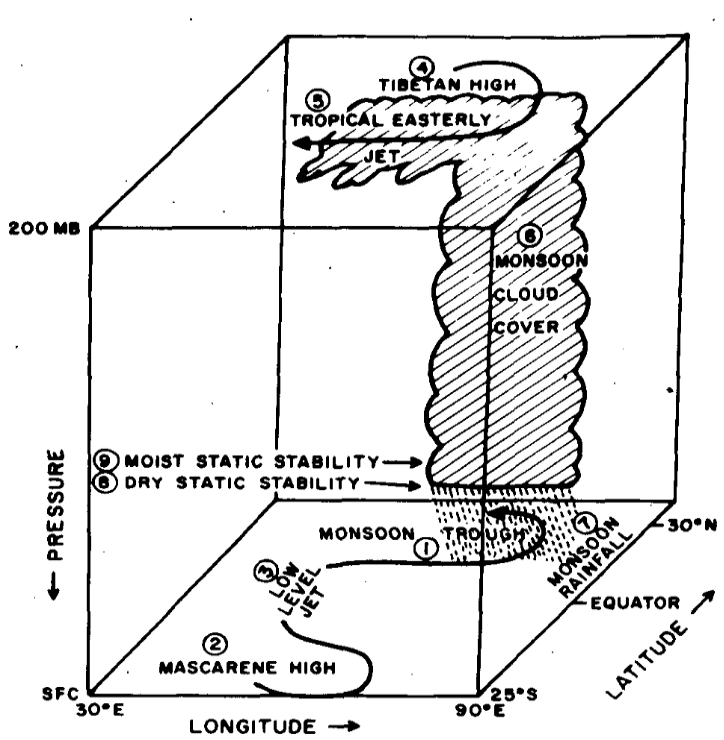
Monsoon, Tropical Easterly Jet

Low-level convergence matched by upper level divergence



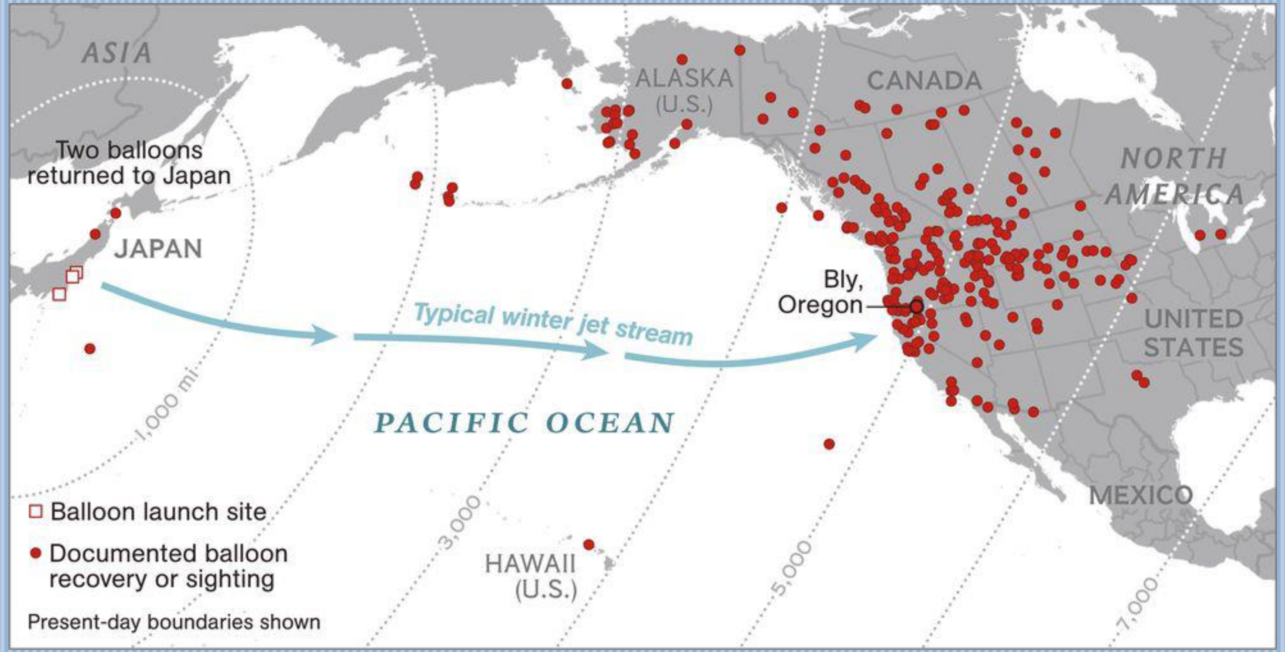
Tibetan high results in an upper-level anticyclone; located over n.India above the monsoon trough.

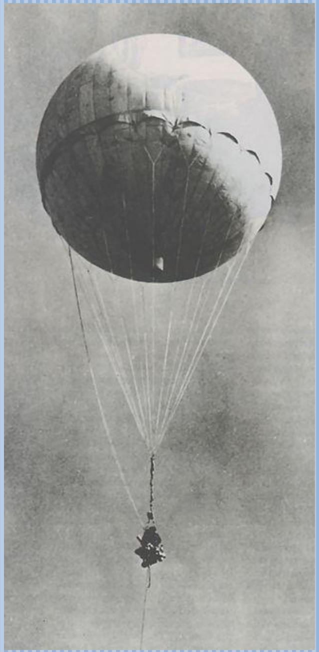
Moves in a south-southeast direction following the zone of maximum surface heating and low pressure



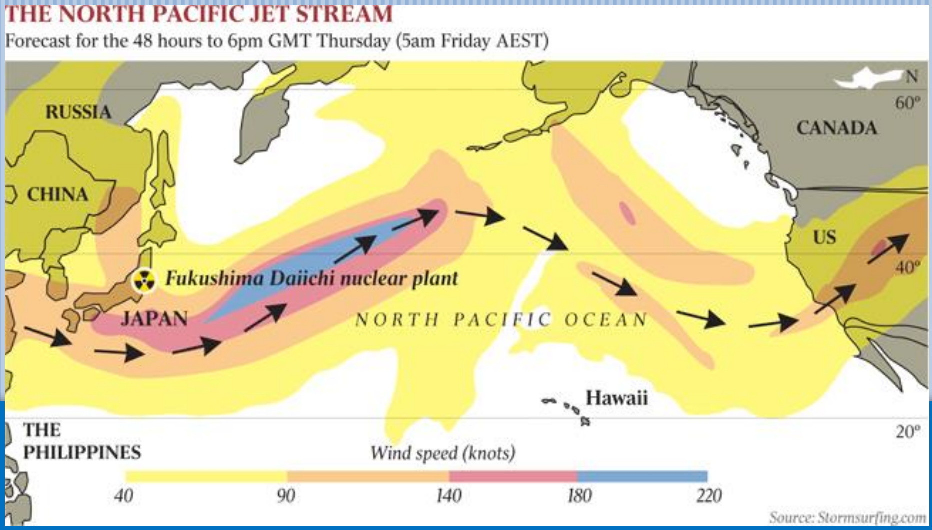
Tropical Jet streams …and World War II

Westerly in Winter



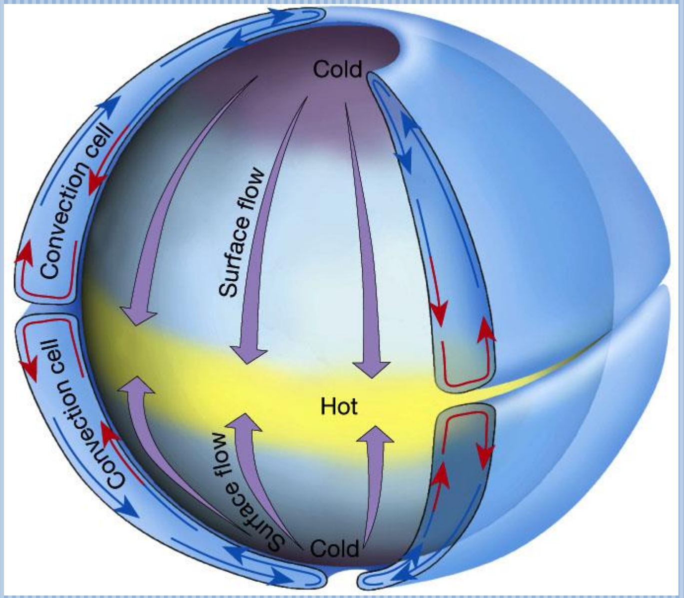


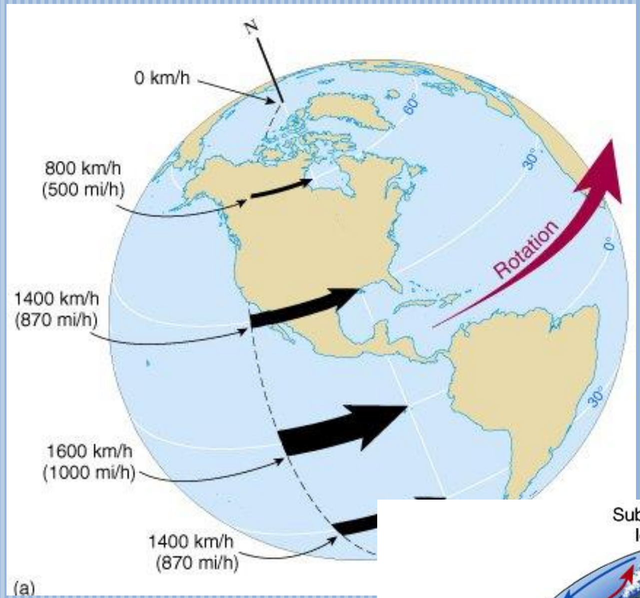
Japanese used the jet stream across Pacific to launch and drop balloon bombs in the US. About 9000 balloons were deployed, and 1000 reached destination after travelling 6000 miles, in 2–3 days!



Monsoon and Coriolis Effect

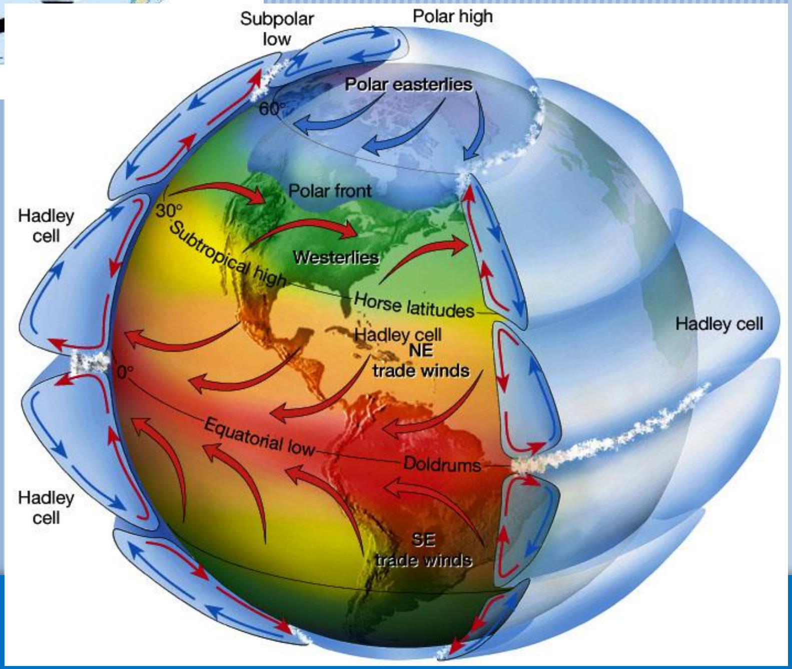
Earth rotates! and at different speeds at diff latitudes!





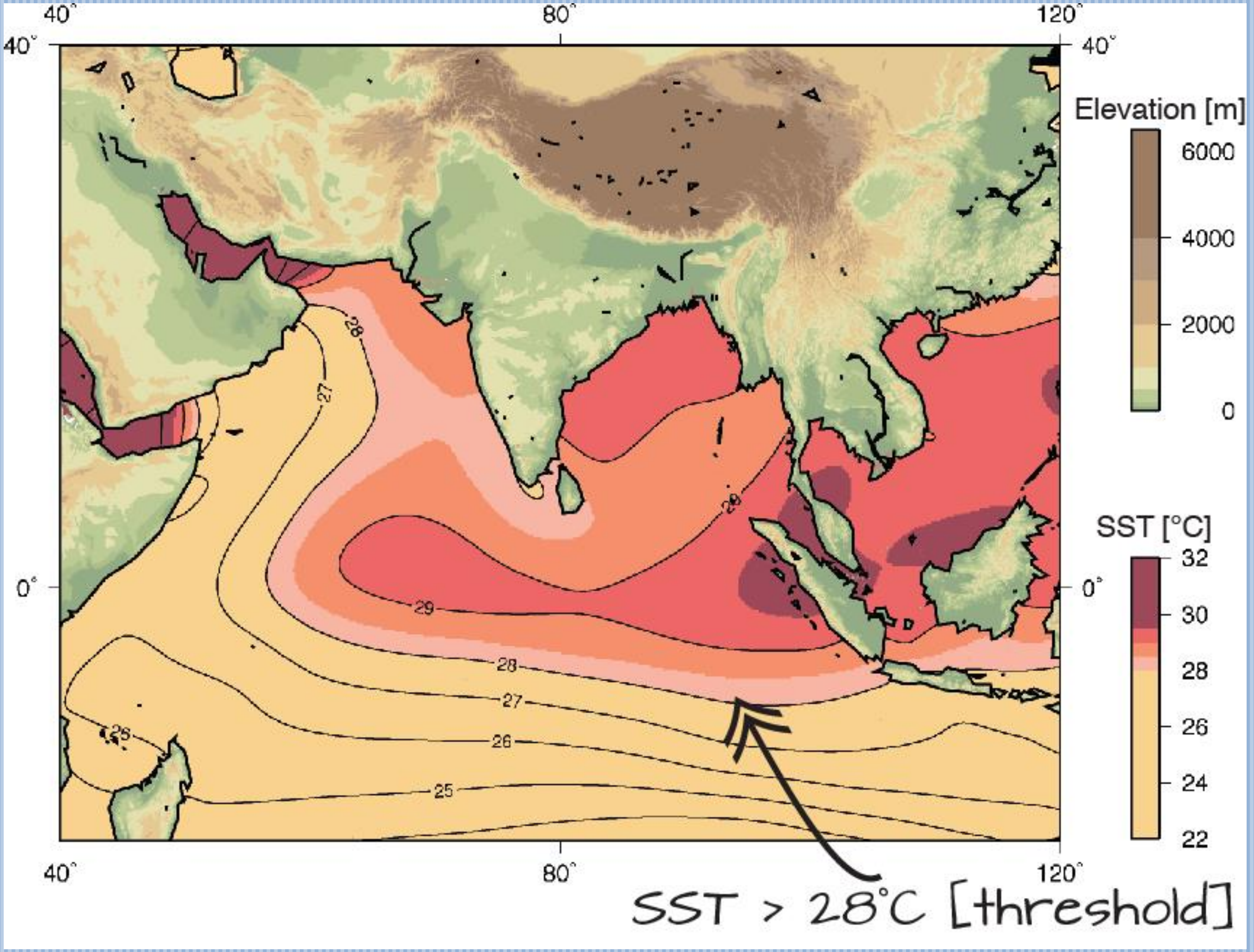
add land masses ->

unequal heating and cooling of the Earth



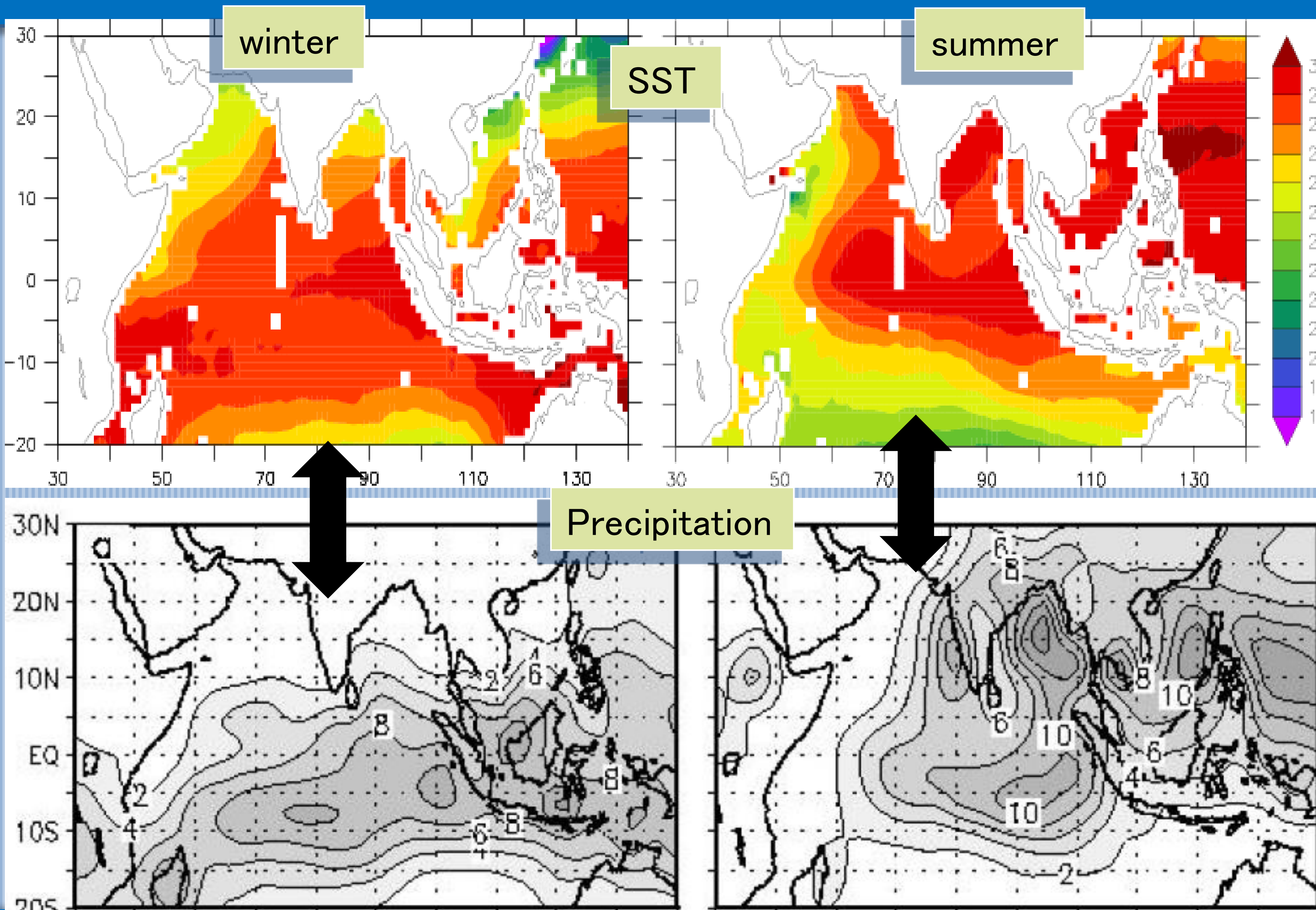
Monsoon, manifested by conducive SST

SST > 28C conducive for enhanced convective activity



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

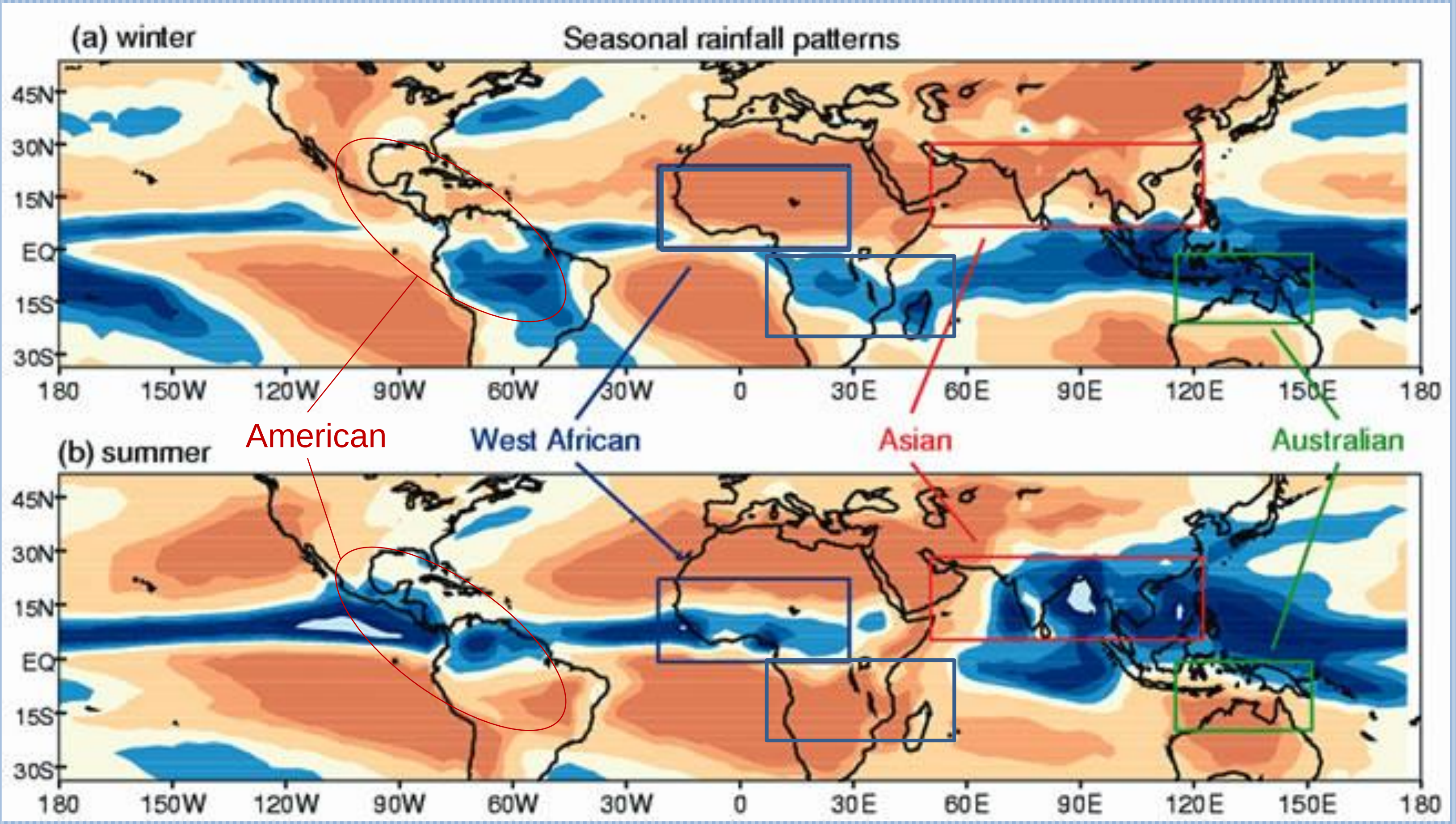
SST conducive for Convection



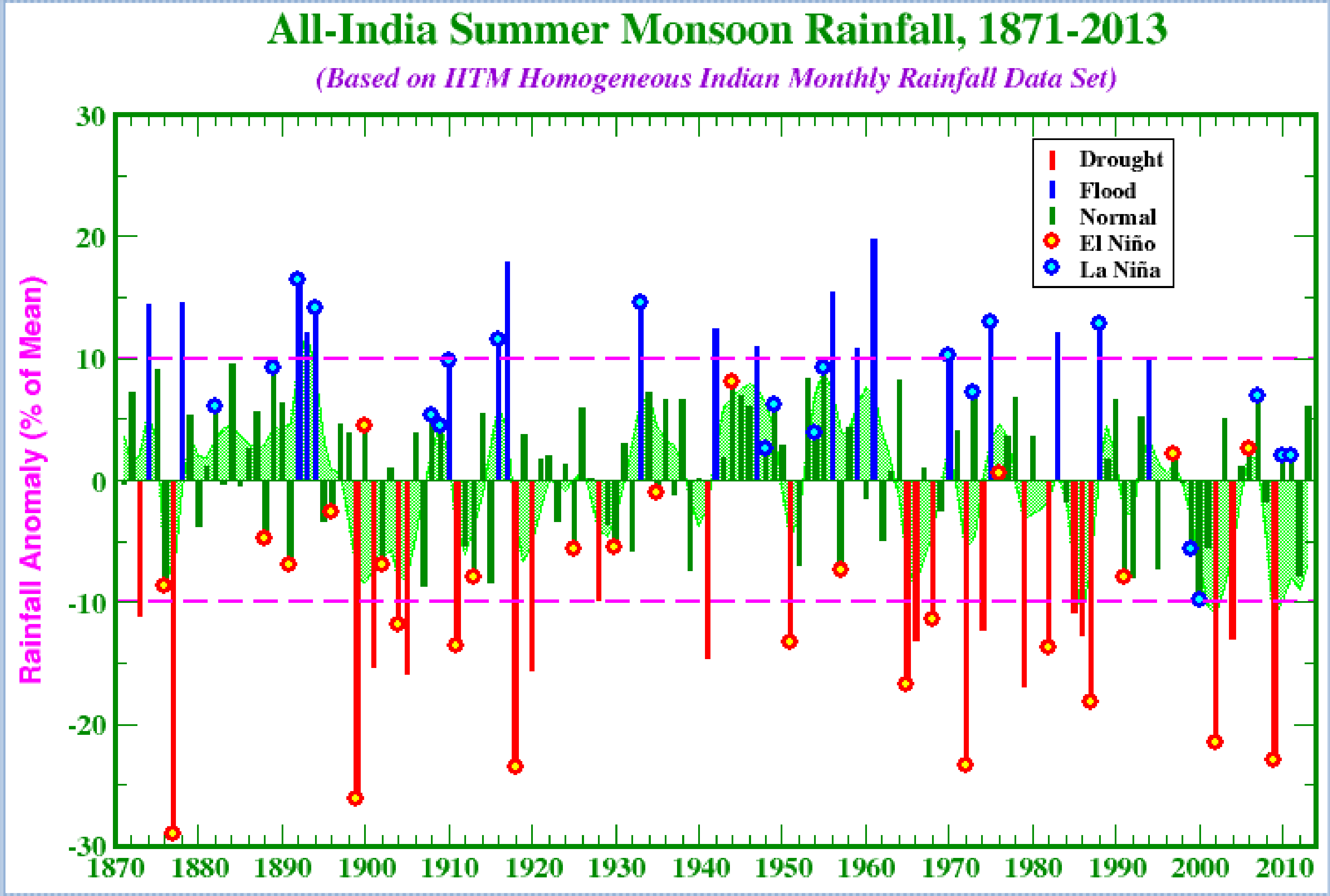
Regions of climatological warm SST (SST > 28° C) tend to be collocated with high mean precipitation.

Other Monsoon Systems and TCZ

Seasonal Migration



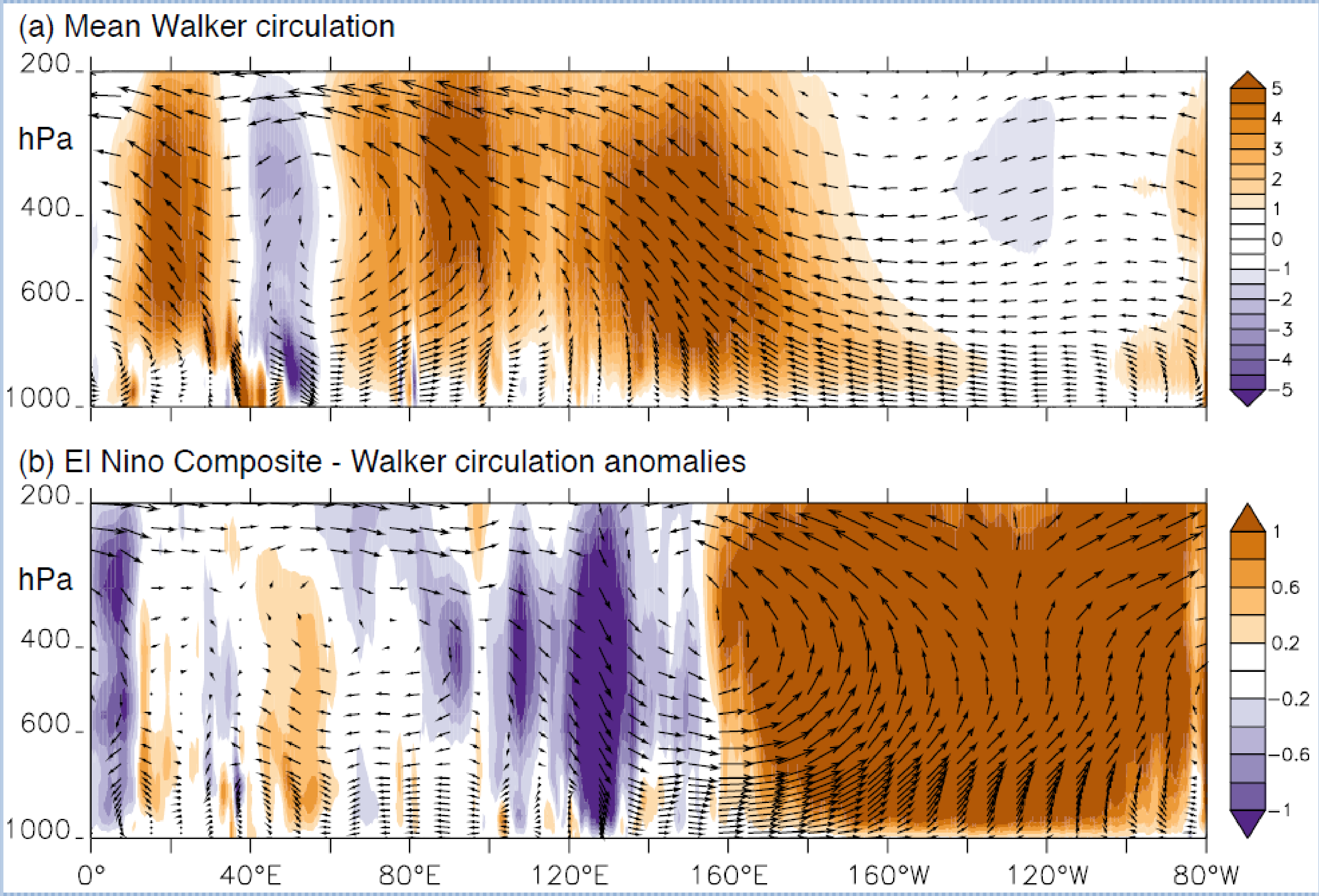
Interannual Variability of the Indian Monsoon
ENSO is a major driver



Generally, weak monsoon coincides with El Nino and strong monsoon with La Nina.
Indian Ocean Dipole and El Nino flavors can change the scenario. Ashok et al. 2004, 2007

Interannual Variability of the Indian Monsoon

ENSO is a major driver

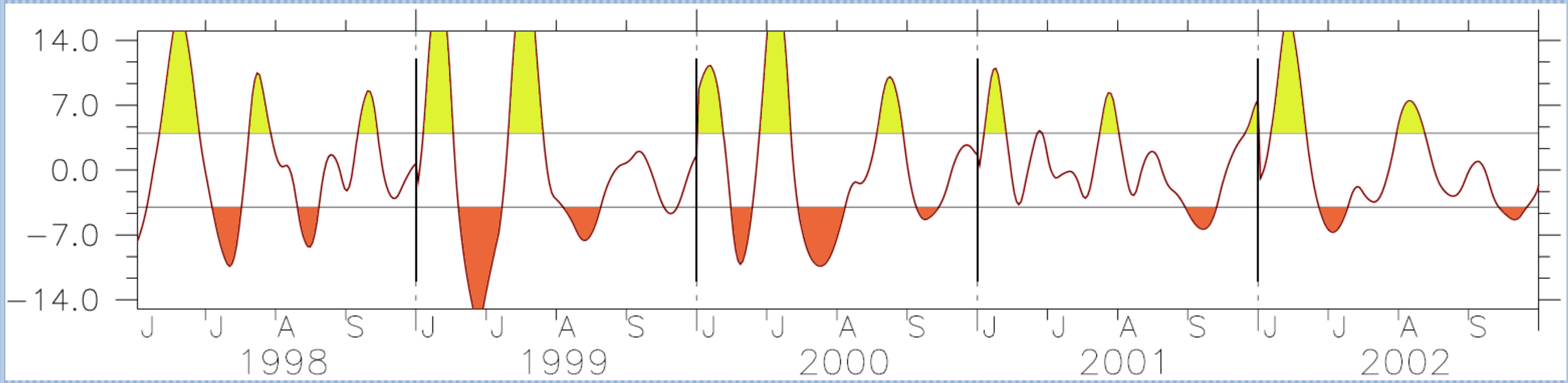


Walker circulation features during summer.

El Nino conditions weaken the monsoon southwesterlies.

Intraseasonal Variability of the Indian Monsoon

Active and Break Phases

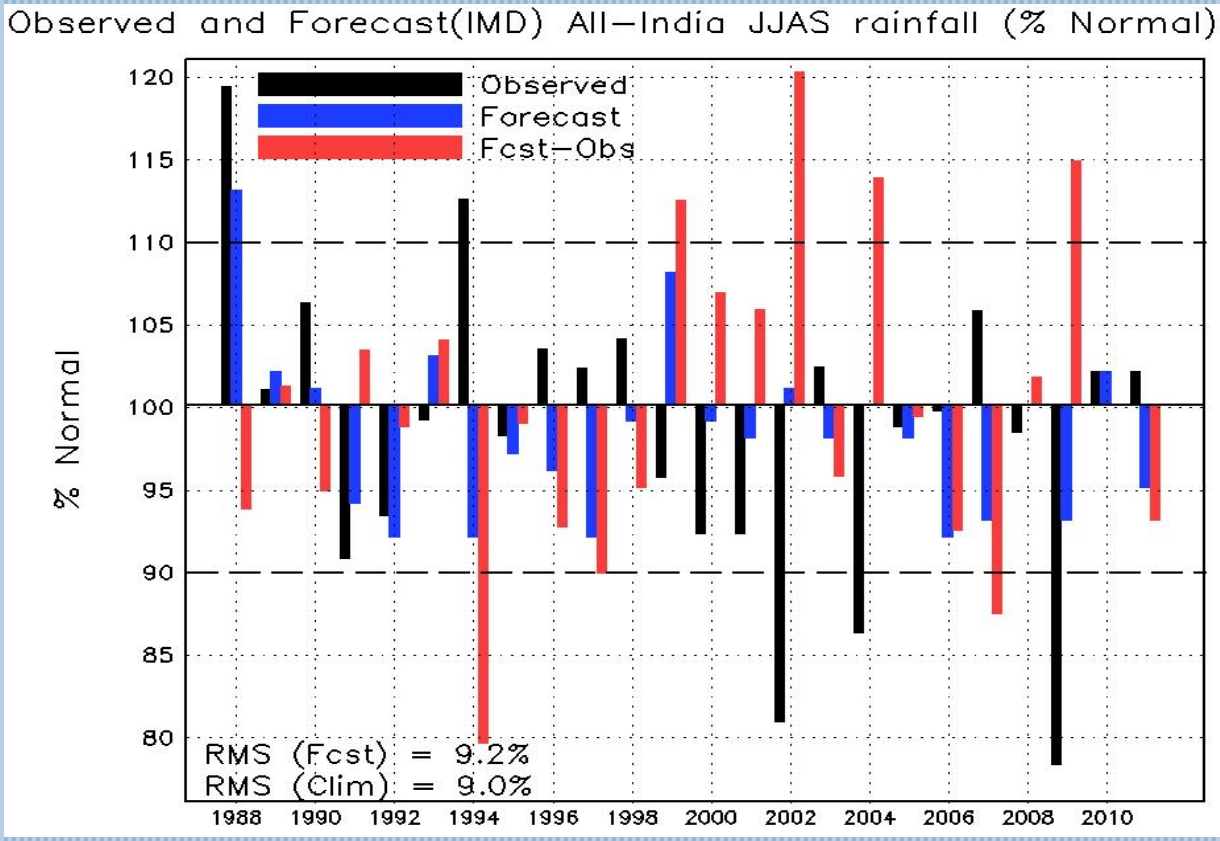


Higher frequency of occurrence of active conditions would result in stronger than normal seasonal mean, and vice-versa.

Goswami and AjayaMohan, 2001

Modeling the Monsoon

Statistical Seasonal Forecasts had poor skill (1988–2010)



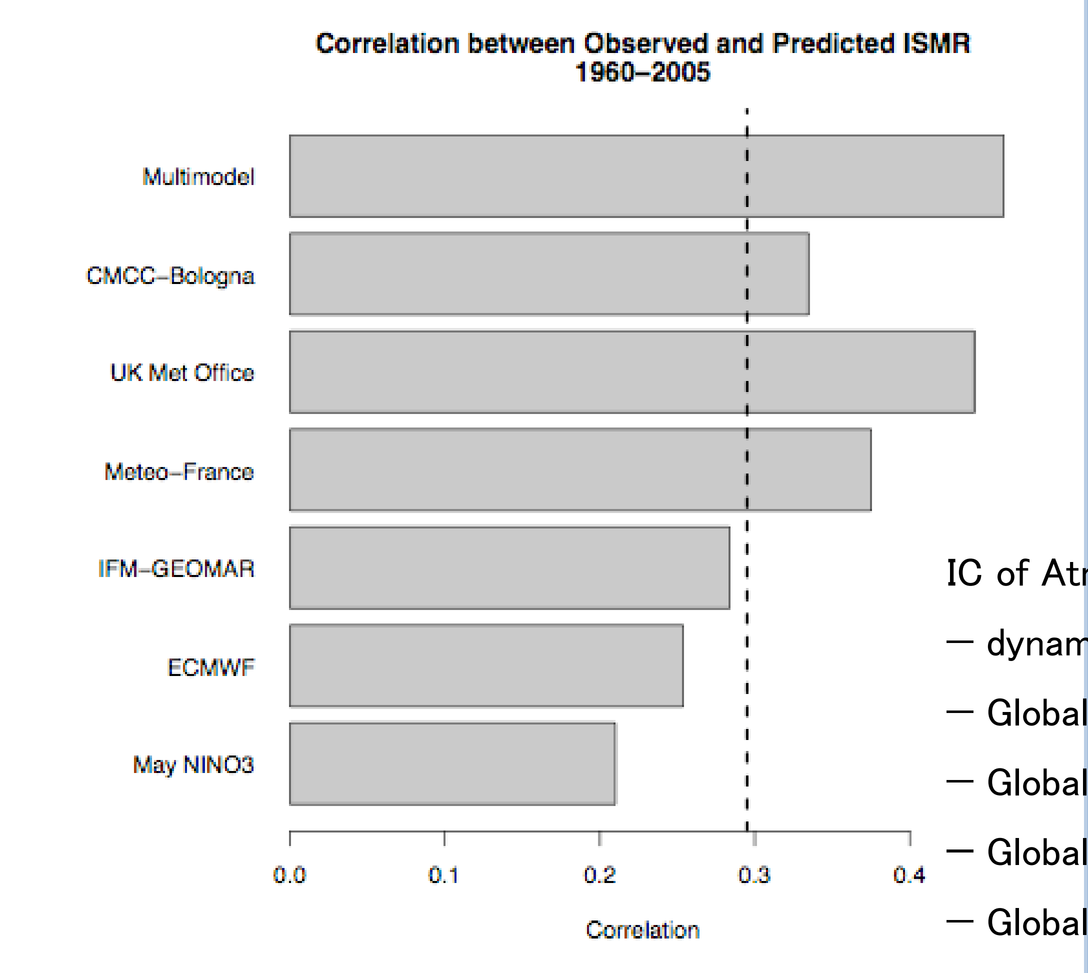
	Predictor (Period)	Used for
1	North Atlantic Sea Surface Temperature (December + January)	April and June
2	Equatorial SE Indian Ocean Sea Surface Temperature (February + March)	April and June
3	East Asia Mean Sea Level Pressure (February + March)	April and June
4	NW Europe Land Surface Air Temperatures (January)	April
5	Equatorial Pacific Warm Water Volume (February+March)	April
6	Central Pacific (Nino 3.4) Sea Surface Temperature Tendency (MAM–DJF)	June
7	North Atlantic Mean Sea Level Pressure (May)	June
8	North Central Pacific Wind at 1.5 Km above sea level (May)	June

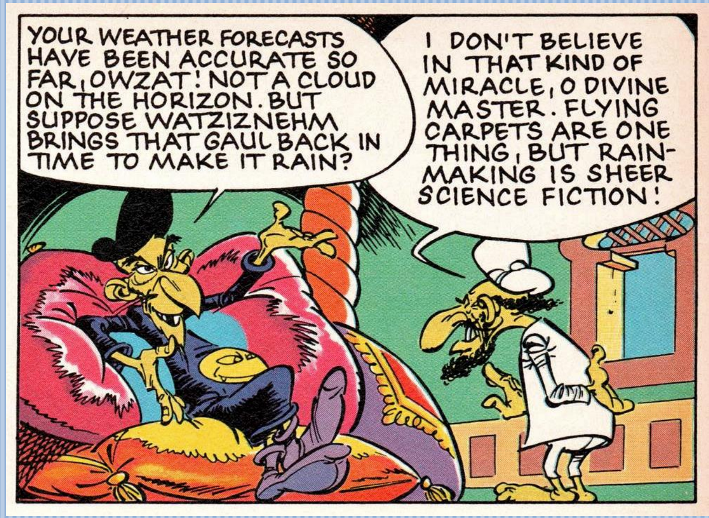
Limitations of Indian Seasonal Forecasts:

- Too many predictors are used in statistical model (over–fitting)
- Method of choosing predictors gives artificial predictability (fishing)

Modeling the Monsoon

Dynamical Seasonal Forecasting, improving gradually





IC of Atmos + IC of Ocean, Land, Atmosphere

— dynamically coupled and consistent IC

— Global ocean (especially upper ocean); sea ice

— Global Atmos. including stratosphere (IC)

— Global GHG (especially CO_2, O_3)

— Global land (soil moisture, vegetation, snow depth) IC

IC = Data for Initial Conditions.

Eg: Ocean Temperature of April for JJAS seasonal forecast

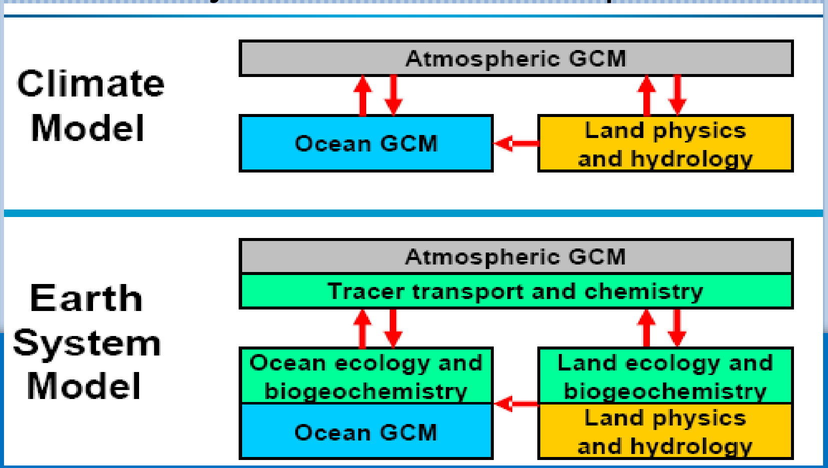
Modeling the Monsoon
National Monsoon Mission

NCEP Climate Forecast System – CFSv2

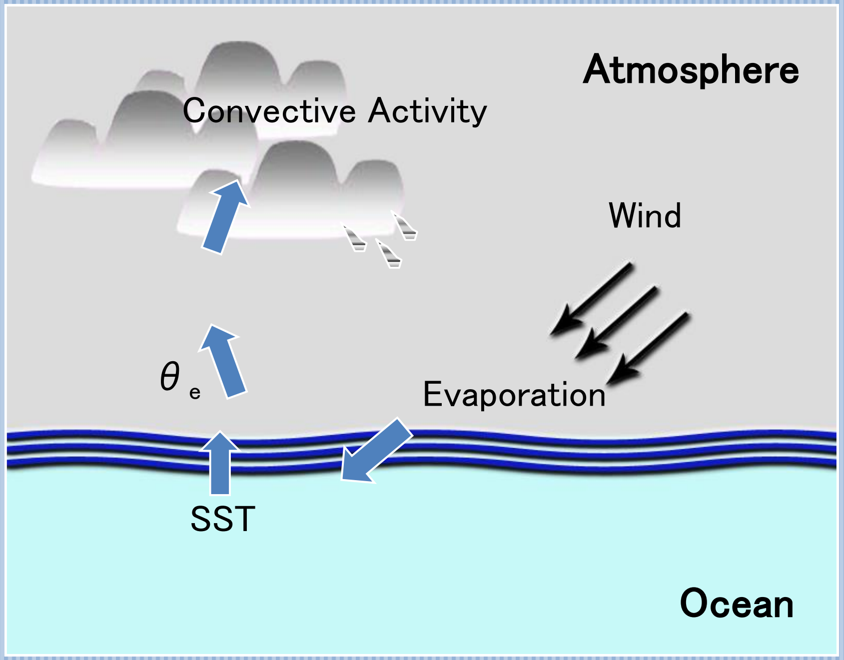
- **Atmosphere**:
  NCEP Global Forecast System (GFS)
  - horizontal: spectral T126, ~80 km
  - vertical: 64 sigma-pressure hybrid levels
- **Ocean**:
  GFDL Modular Ocean Model v4 (MOM4p0)
  - 40 levels in vertical, 0.25-0.5 resolution
- **Sea Ice**:
  GFDL Sea Ice Simulator (SIS)
  an interactive, 2 layer sea-ice model
- **Land**:
  NOAH, an interactive land surface model
  with 4 soil levels

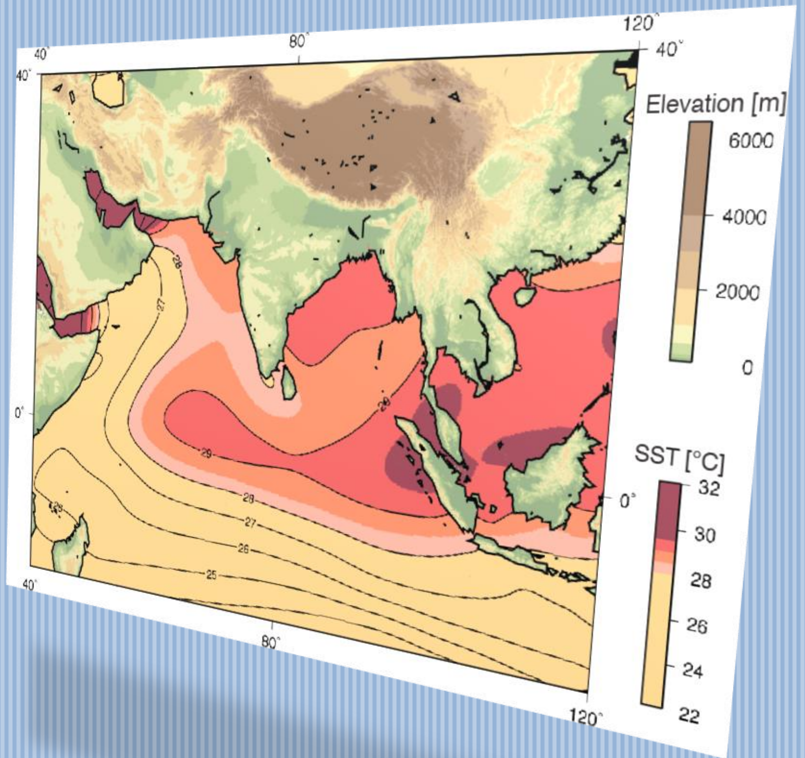
HPC: Fastest in India, In the TOP 100

Earth System Model development



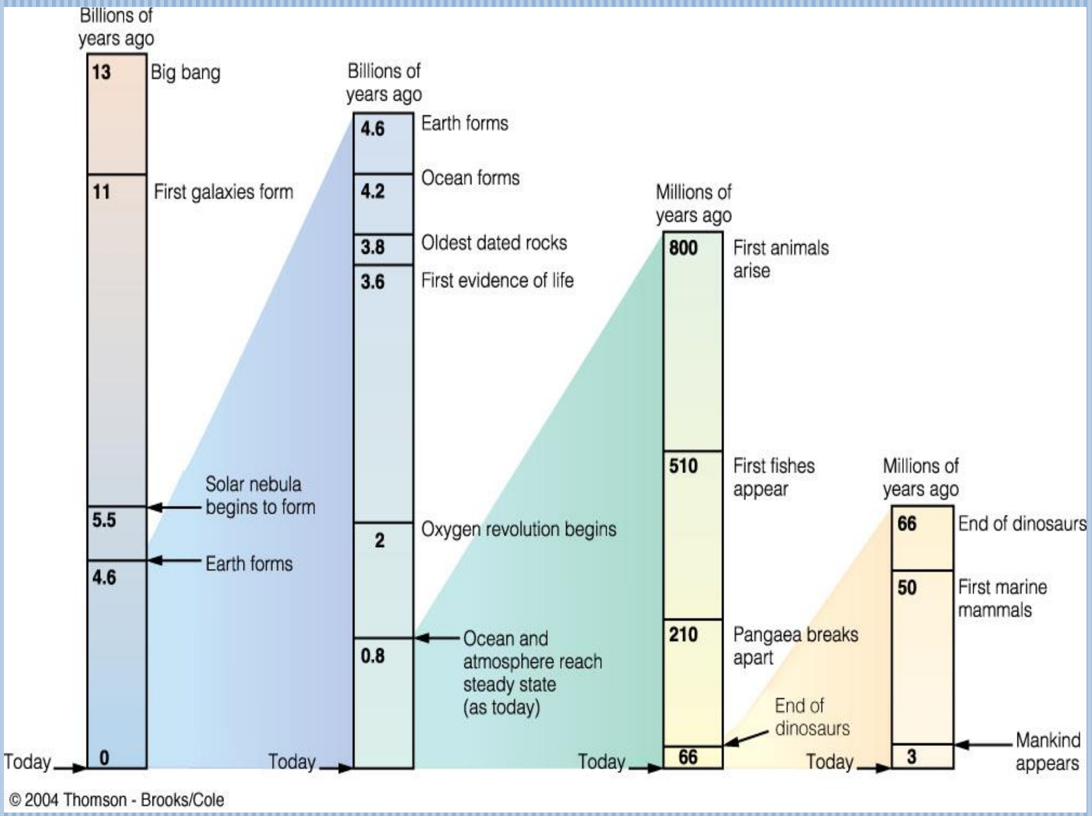
Interactions between the Indian ocean and the atmosphere during the summer monsoon

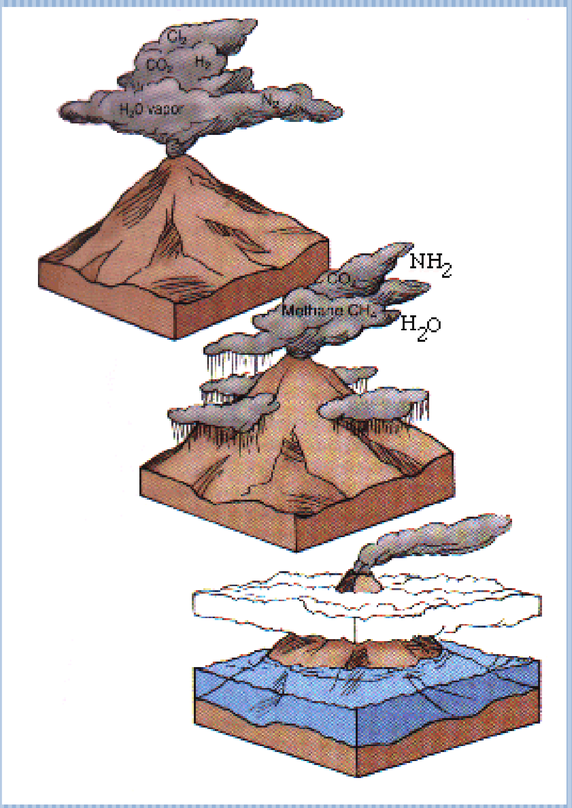




1. Ocean – atmosphere interactions
2. Spatial variability of the interaction
3. Relevance to climate change

Our whole universe was in a hot dense state …





··· and the ocean was in the atmosphere

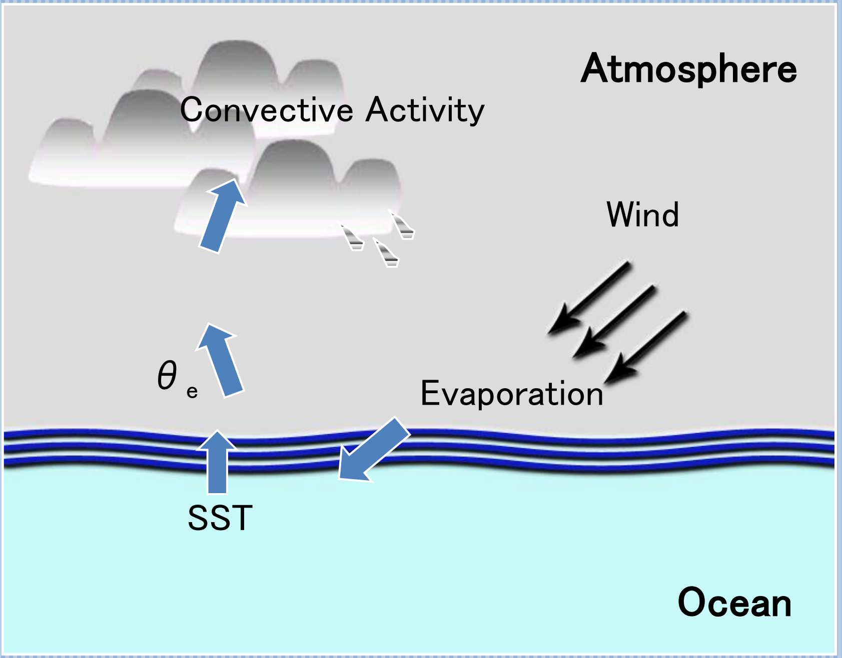
It was thought that …

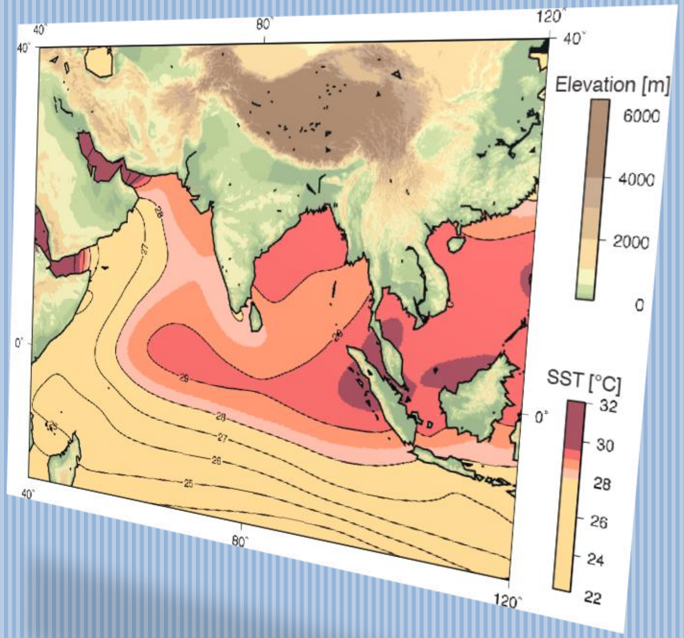
Greek	French	English
ōkeanós ->	**occean ->**	**ocean**

… **Okeanos** (or Oceanus), was the great equatorial-encircling river, the source of all the earth's fresh-water: including rivers, wells and rain-clouds. Okeanos' wife was **Tethys**, was thought to distribute his water to the earth via subterranean streams.

Greek Mythology. Image: Trevi Fountain of Okeanos at Rome.

Ocean and Sea Surface Temperature

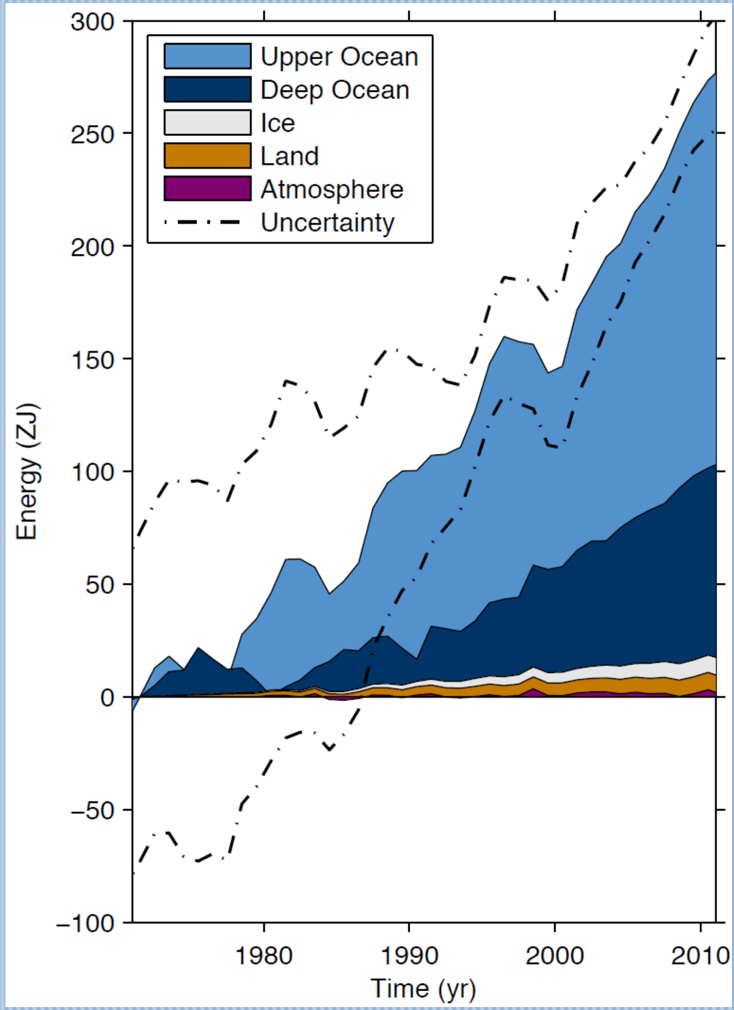




The oceans' thermal inertia is communicated to the atmosphere via turbulent and radiative energy exchange at the sea surface. These energy fluxes in turn depend on a single oceanic quantity, the sea surface temperature (SST), as well as several atmospheric parameters including wind speed, air temperature, humidity, and cloudiness. SSTs thus play a key role in regulating climate and its variability.

Deser et al., *Annu. Rev. Mar. Sci.,* 2010

Ocean and SST in a changing climate



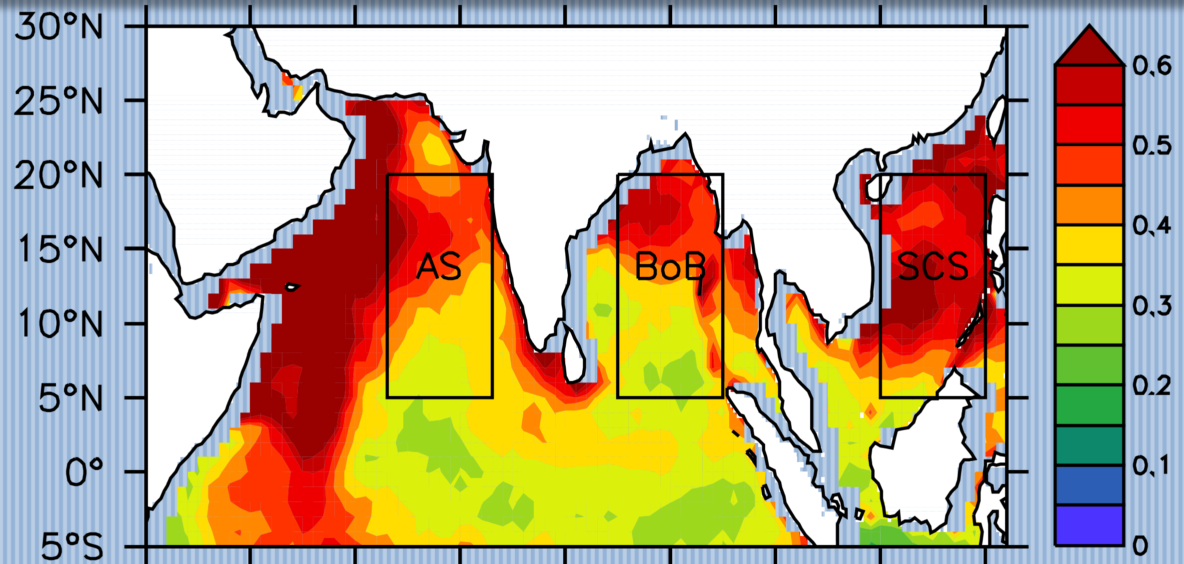
Where has all the heat gone?

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (high confidence)

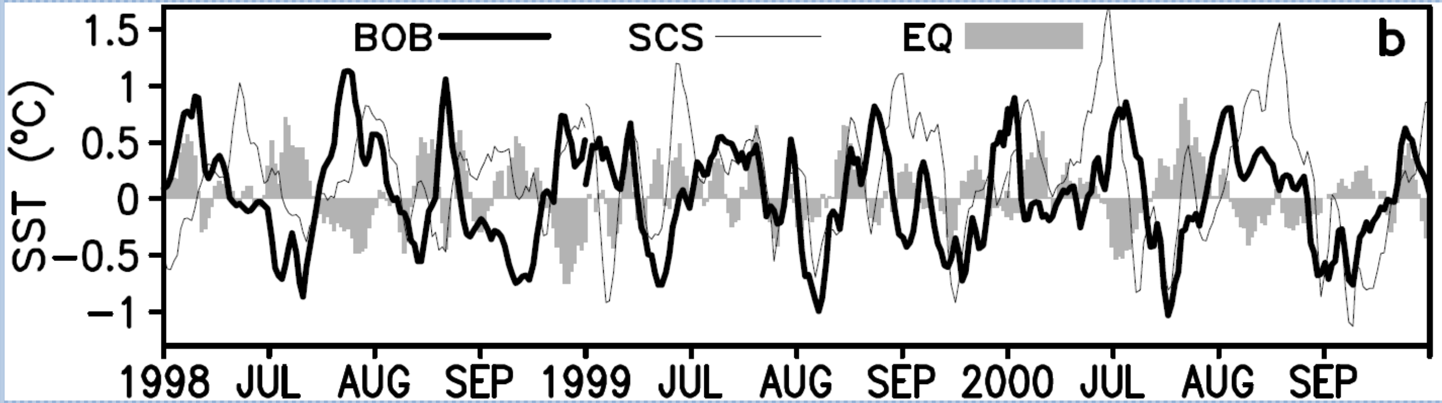
IPCC, *AR5*, 2013

SST variability over the monsoon basins

SST variability during summer



SST and heat flux anomalies associated with monsoon ISV are observed over a large domain, Arabian Sea -> s. China Sea -> w. North Pacific



Sengupta et al., *GRL,* 2001; Xie et al., *J.GR,* 2007

Webster et al., *JGR,* 1998

Ocean-atmosphere interactions over the monsoon basins

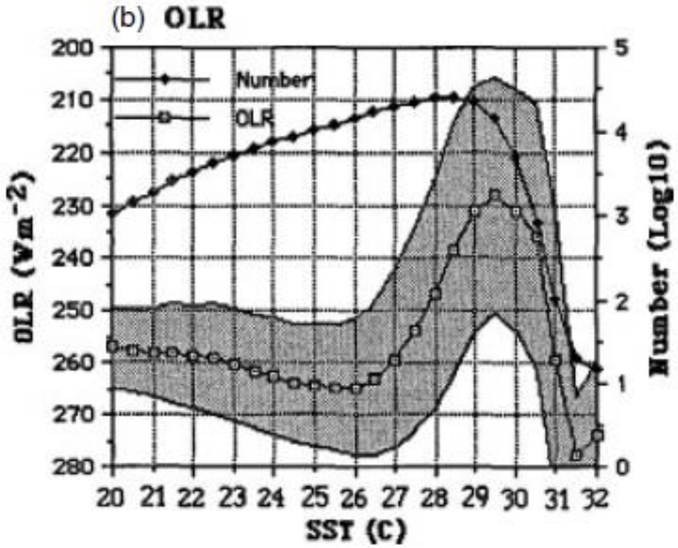
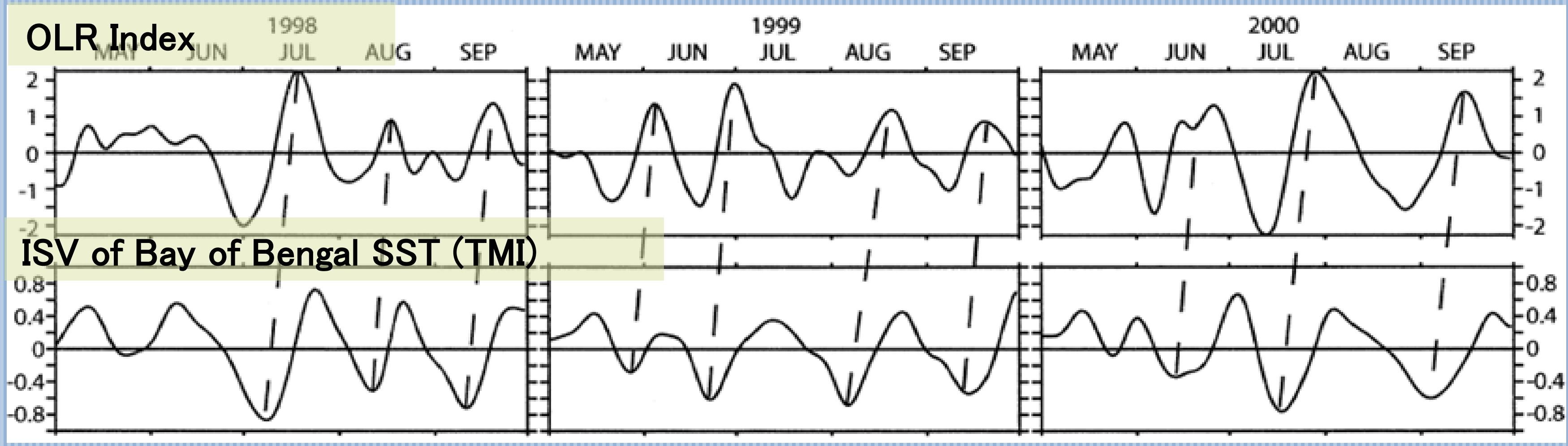


Figure 1. SST–convection relation in the global tropics (reproduced from Waliser *et al*., 1993) for monthly values in 2° × 2° latitude–longitude squares of global tropics 25 °S to 25 °N for the period 1975–1985: (a) SST and HRC and (b) SST and OLR. The right ver-

SSTs beyond **26 ℃** conducive for increased convection

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

Ocean-atmosphere interactions over the monsoon basins



Over "Bay of Bengal":

Intraseasonal SST influence the atmospheric variability, eg: Precipitation

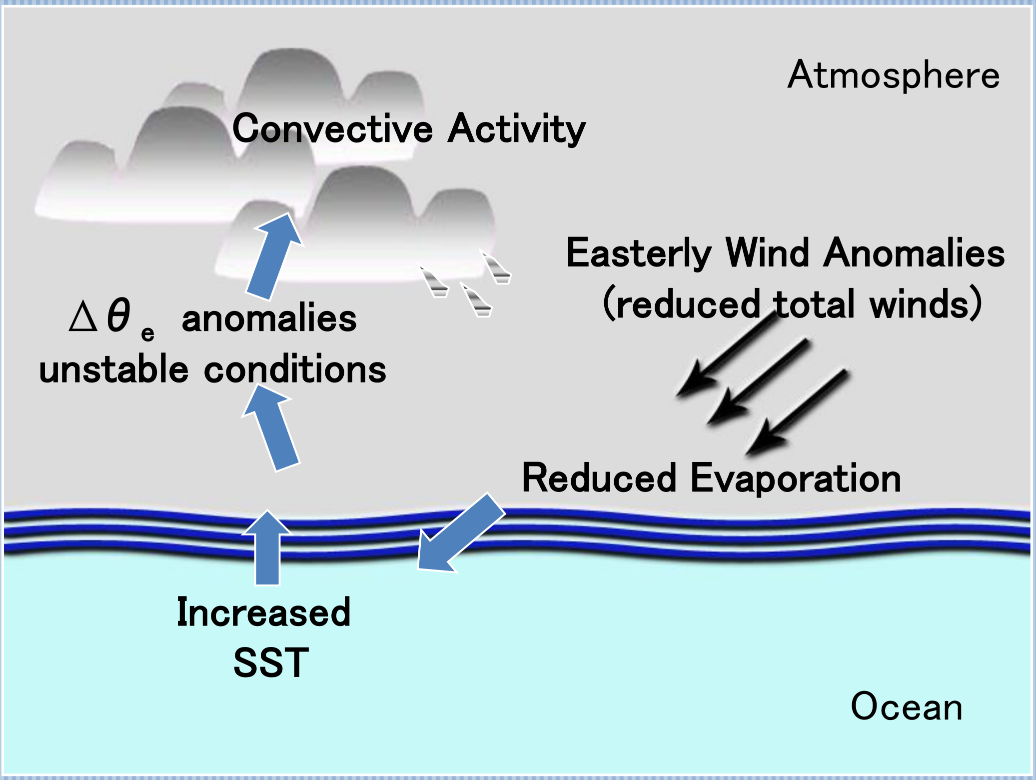
Negative SST lead monsoon break by 10 days (r = 0.67).

Step by step process on the SST– precipitation relationship?

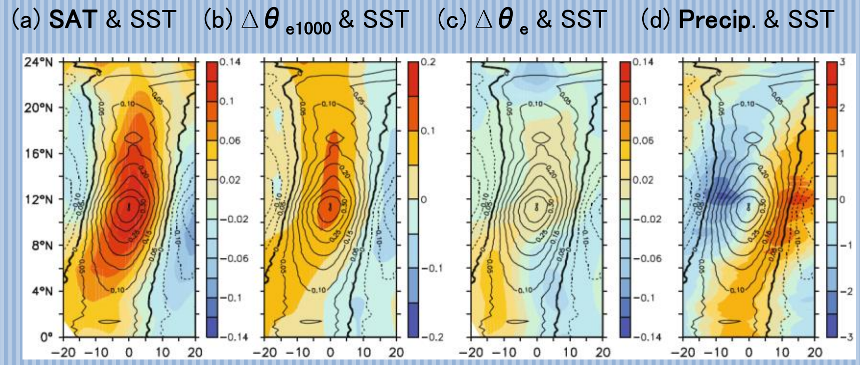
Vecchi and Harrison, *J. Climate*, 2002

Fu et al., 2008

Ocean-atmosphere interaction over Indian/w.Pacific
– positive SSTa enhance convection

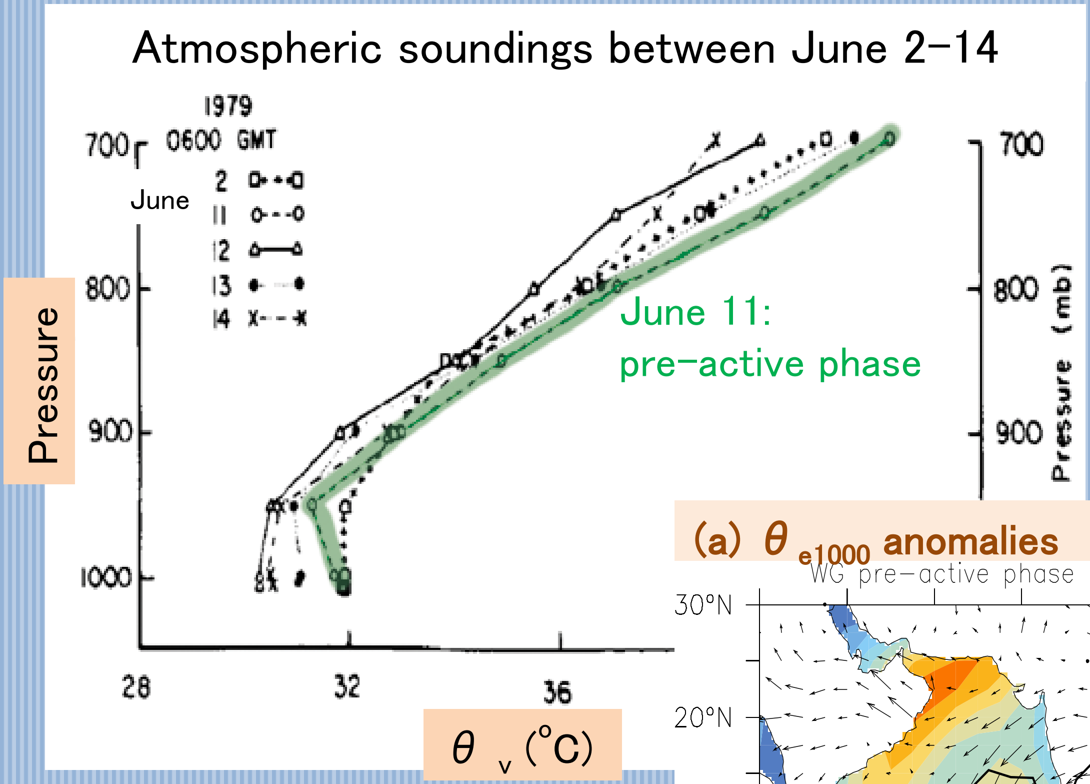


positive SST anomalies
=> destabilize lower atmos. column
=> convective activity

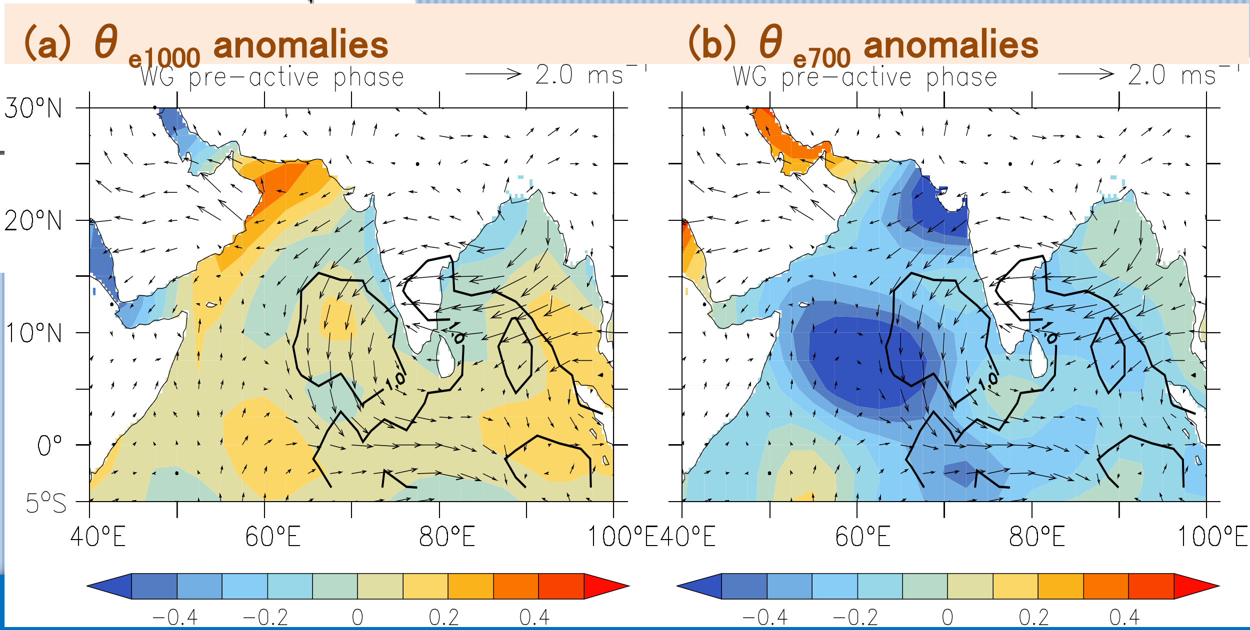


Roxy and Tanimoto, *J.Met.Soc.Japan,* 2007; Roxy and Tanimoto, *Climate Dynamics,* 2011
Wu et al., *GRL,* 2008

Ocean-atmosphere interactions over the monsoon basins

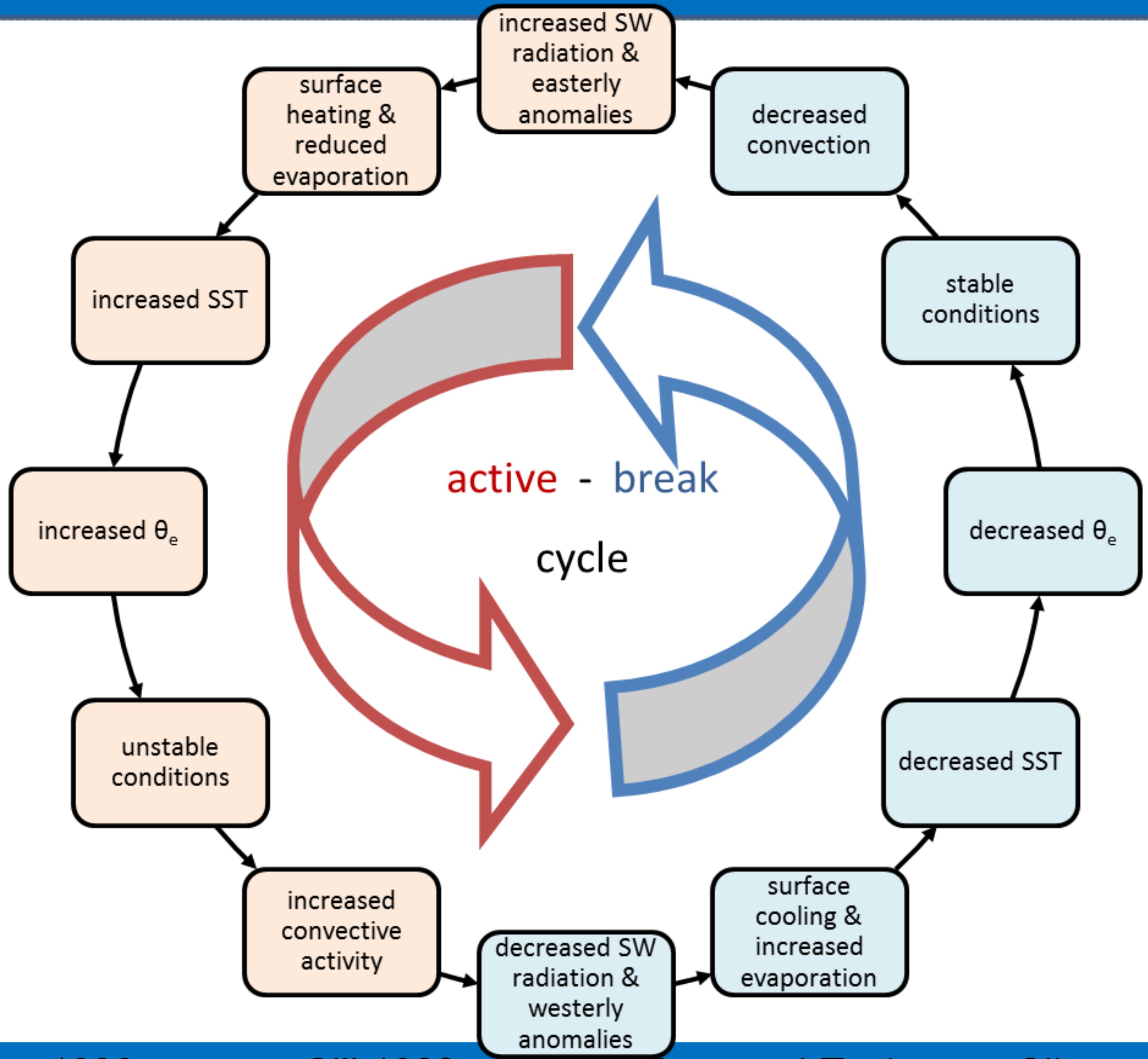


Mean profile of virtual potential temperature θ_v, for 0600 GMT on 2 June (pre-monsoon) and 11-14 June (onset) from **MONEX 79 ship data over Arabian Sea**.



Holt and Raman, 1987

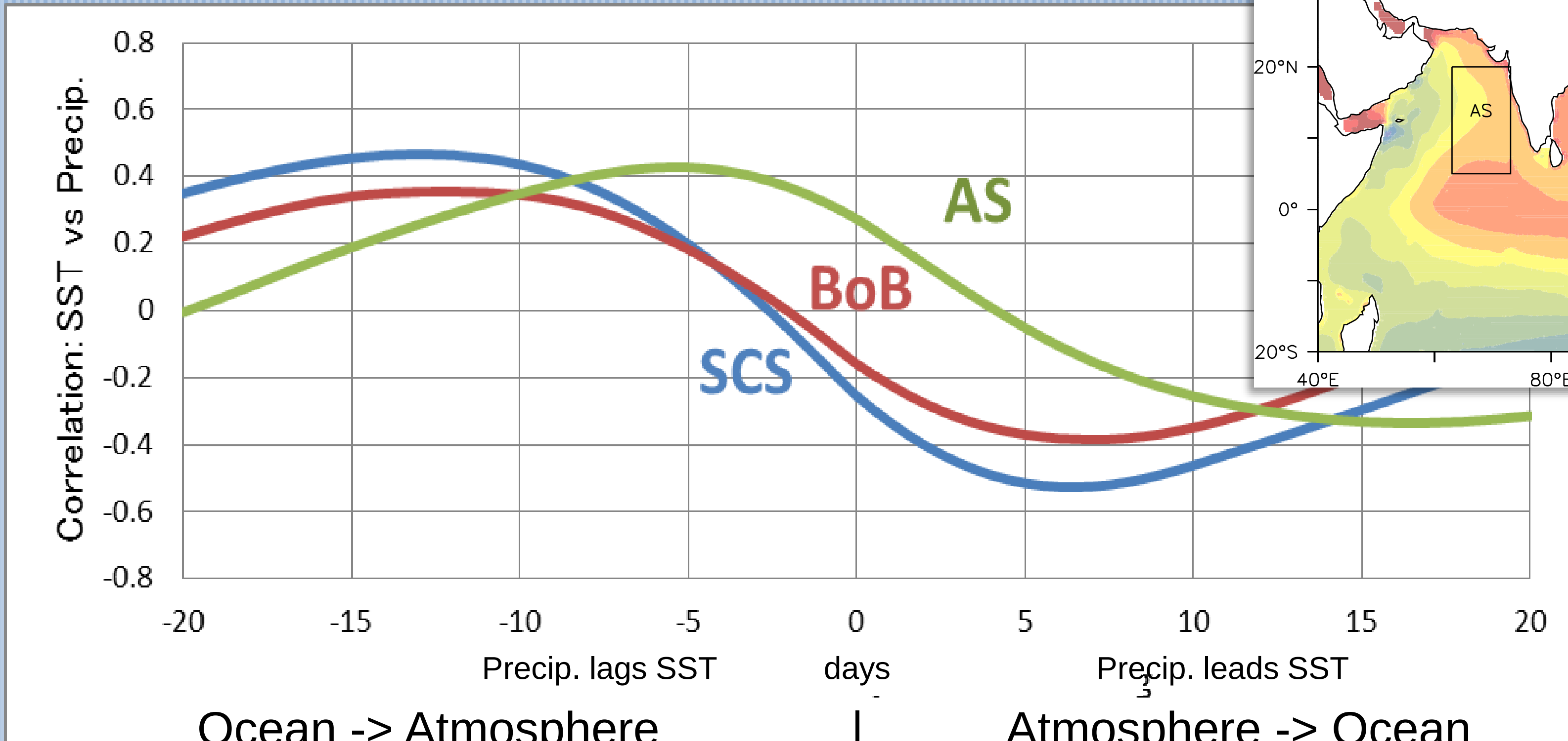
Ocean-atmosphere interactions over the monsoon basins

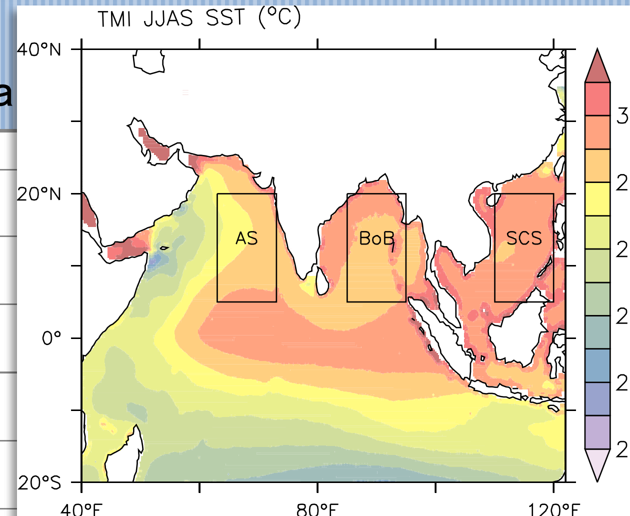


Matsuno, 1996; Gill 1980; Roxy and Tanimoto, *Climate Dynamics*, 2010

Spatial variability of SST–precipitation relationship

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



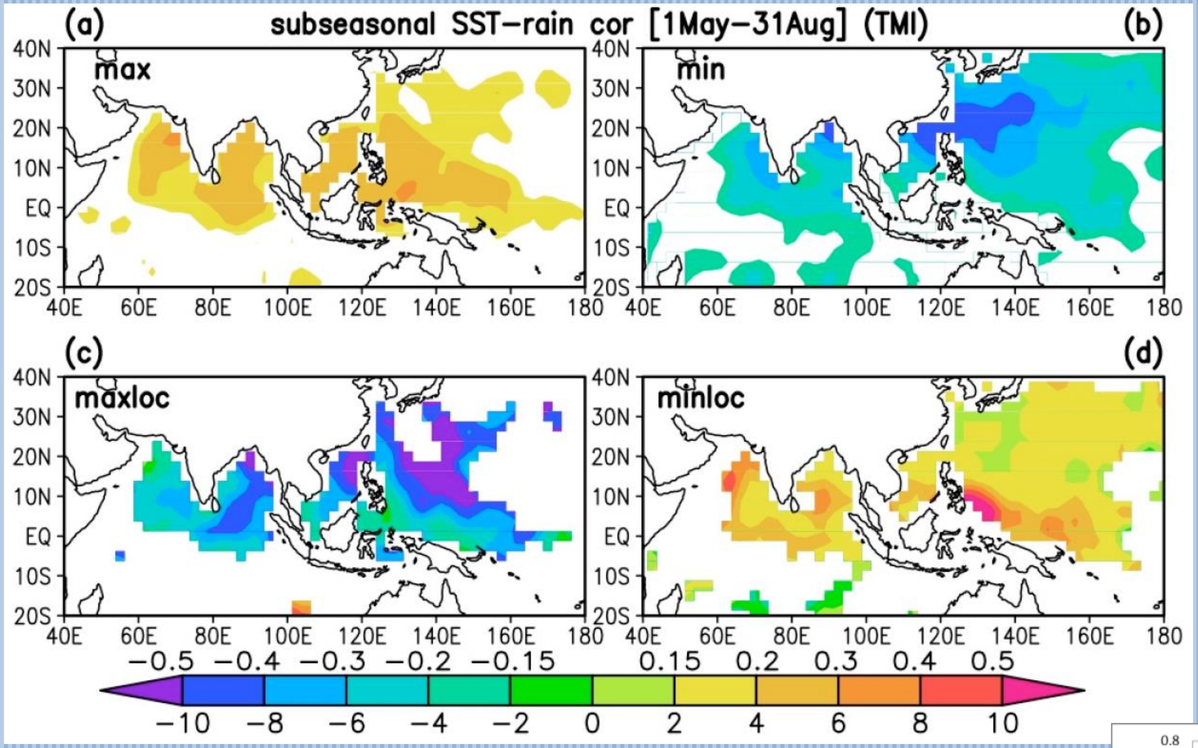


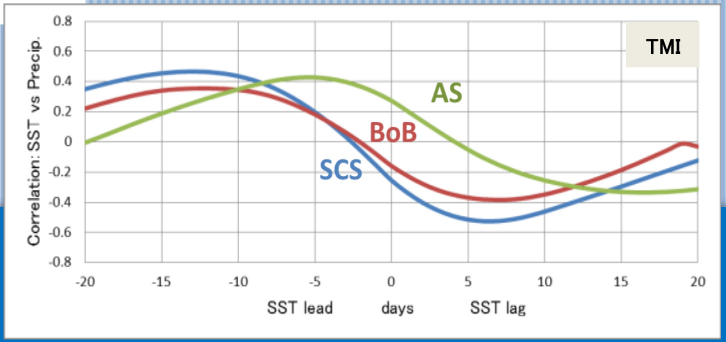
Spatial variability: response time difference of 1 week!

Roxy et al., *Climate Dynamics*, 2012

Spatial variability of SST–precipitation relationship

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

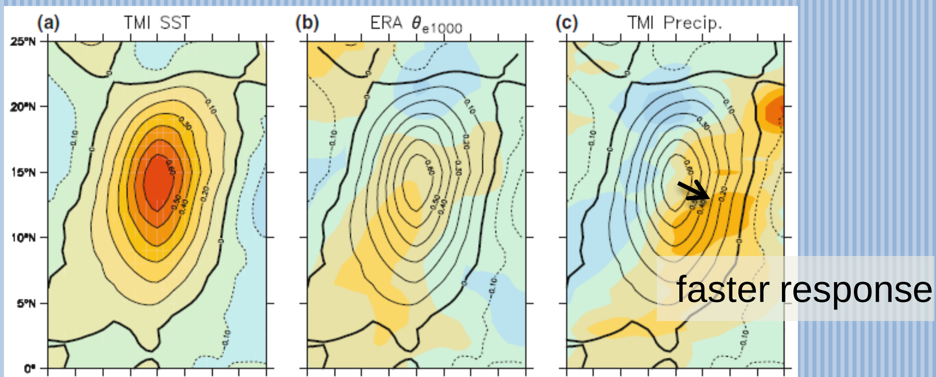




Wu et al., *GRL,* 2008

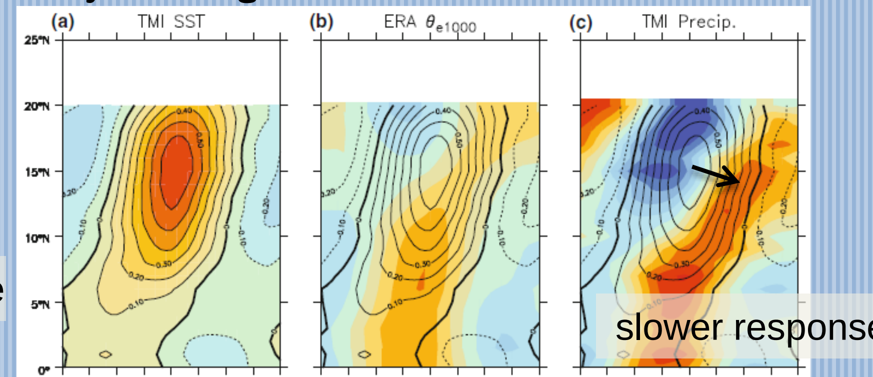
Why is the response time different over the basins? – ocean-atmosphere interaction?

Arabian Sea

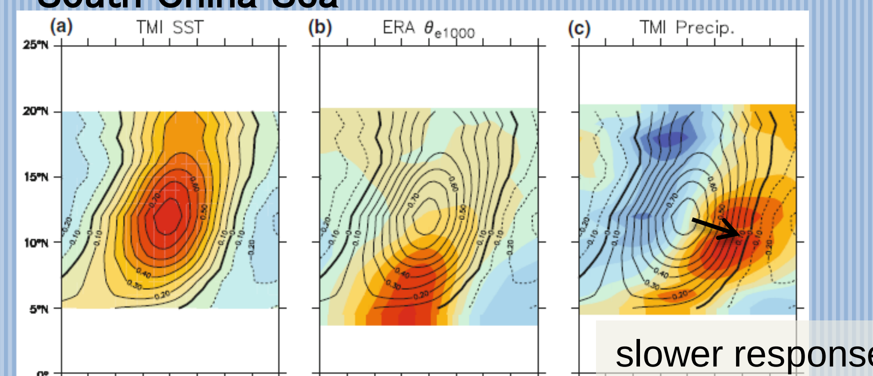


(a) **SST** & SST (b) θ_e & SST (c) **Precip**. & SST

Bay of Bengal

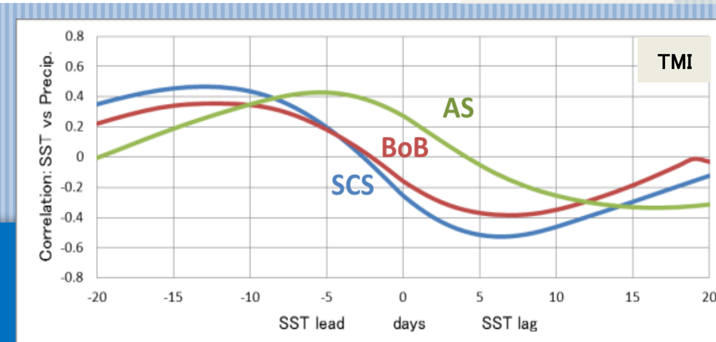


South China Sea



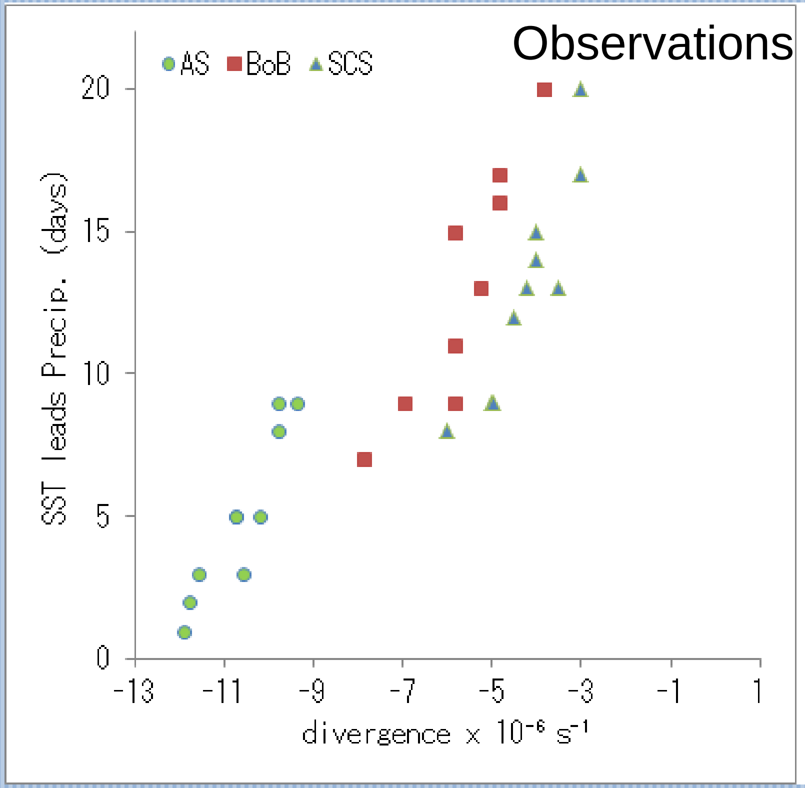
SSTa -> θe : instantaneous over all the basins,
θe -> precipitation response is different.

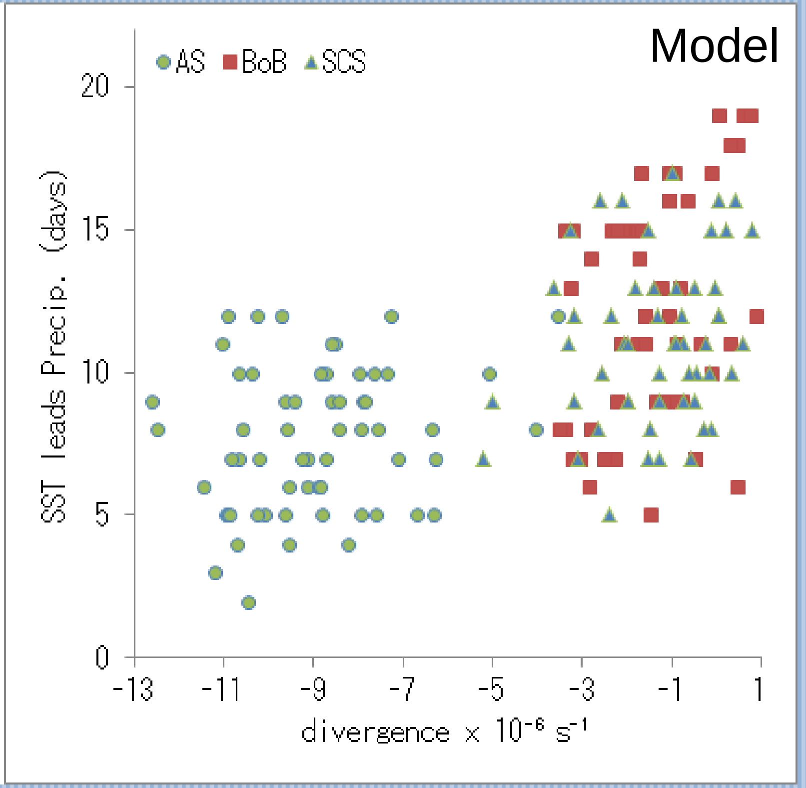
Convective max located south of SST max.



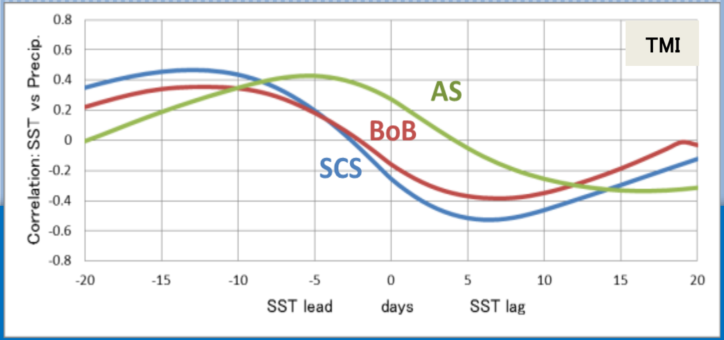
Roxy et al., *Climate Dynamics*, 2012

Why is the response time different over the basins? – role of surface convergence





Relatively **stronger surface convergence** over the Arabian Sea **accelerates the uplift of the moist air**, resulting in a relatively faster response in the local precipitation anomalies

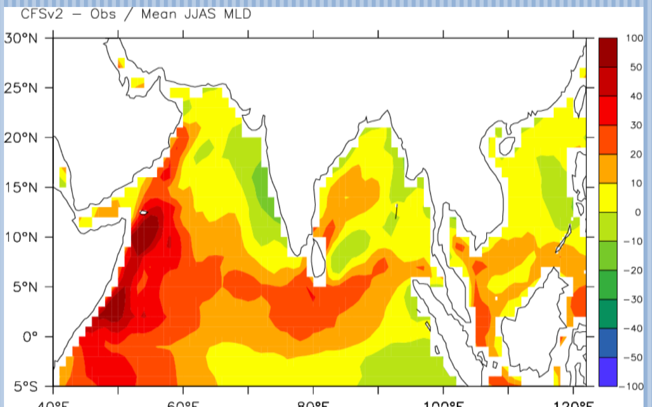


Roxy et al., *Climate Dynamics*, 2012

Why is the response overestimated in CFSv2 model?

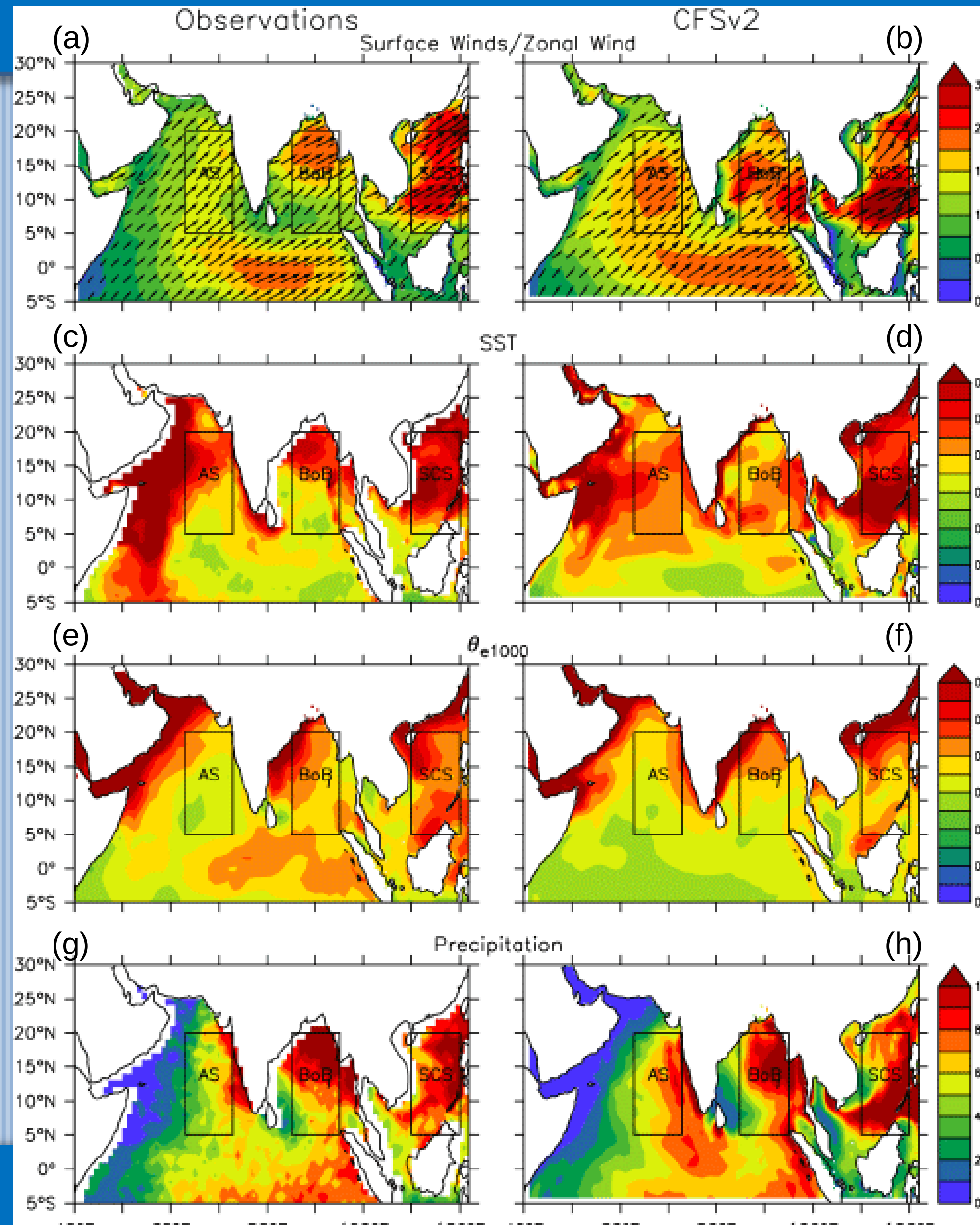
Is it the MLD bias?

JJAS MLD Diff. [CFSv2 - Boyer]

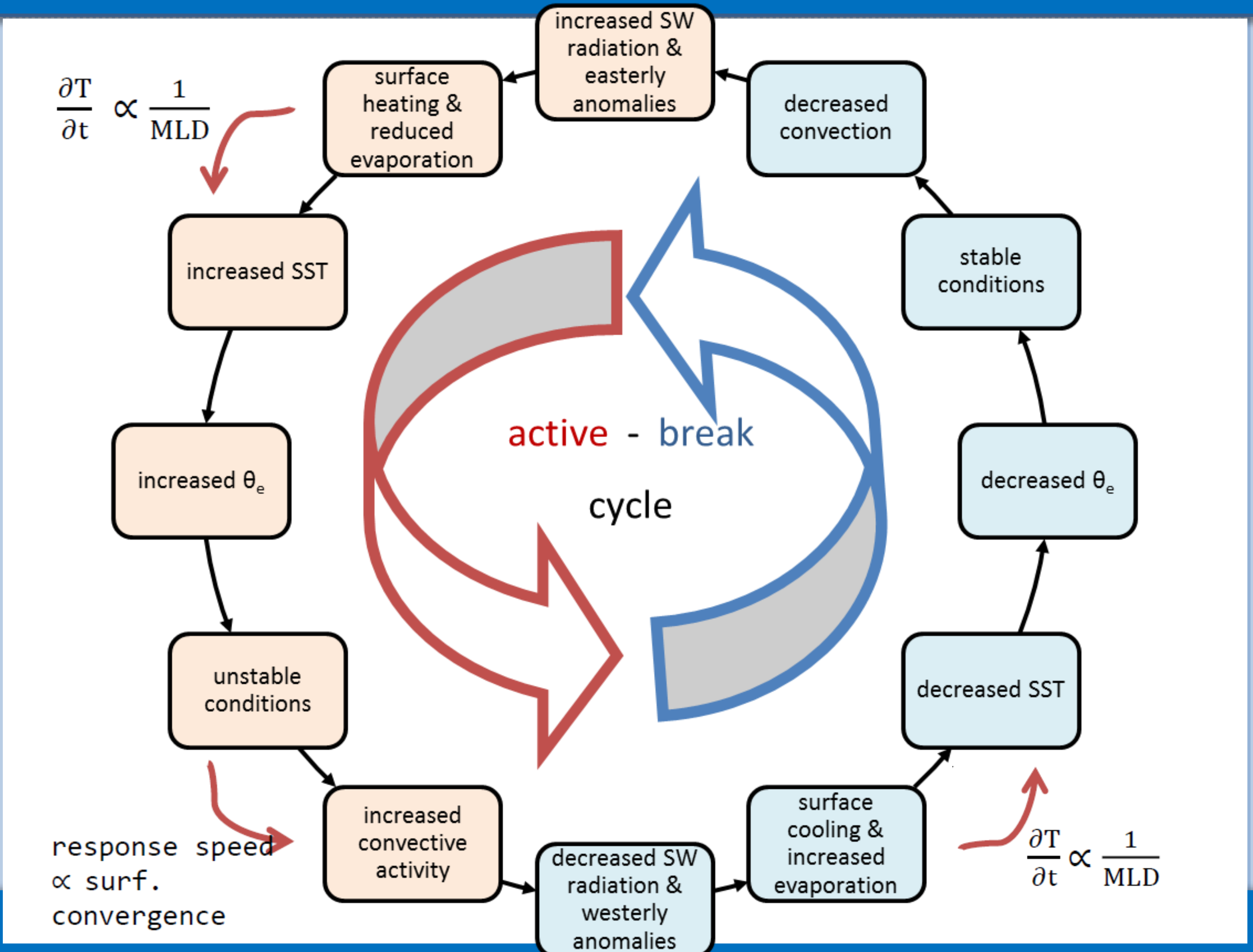


$$\frac{\partial T_s}{\partial t} = \frac{F_{tot}}{\rho c_p * \mathbf{MLD}}$$

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

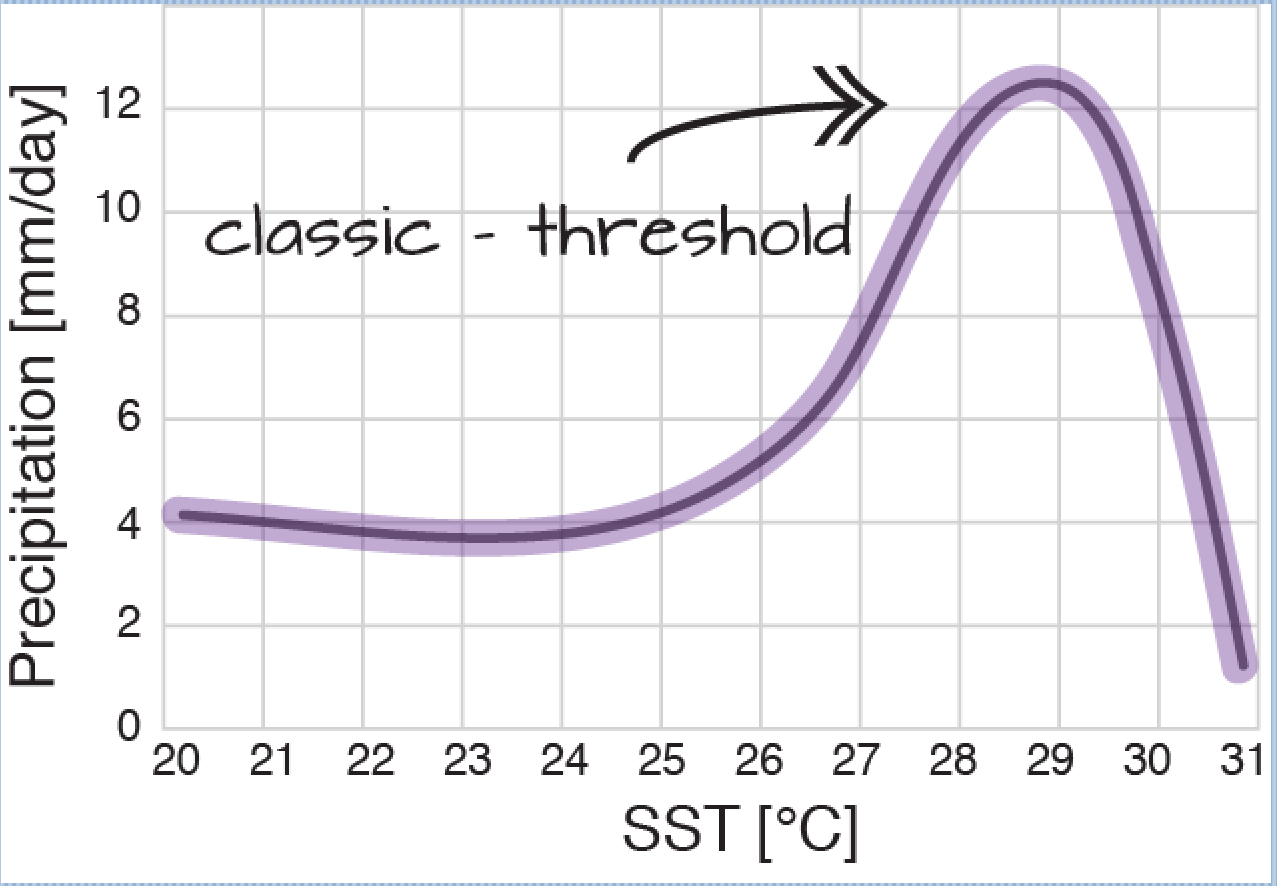


Ocean-atmosphere interactions over the monsoon basins



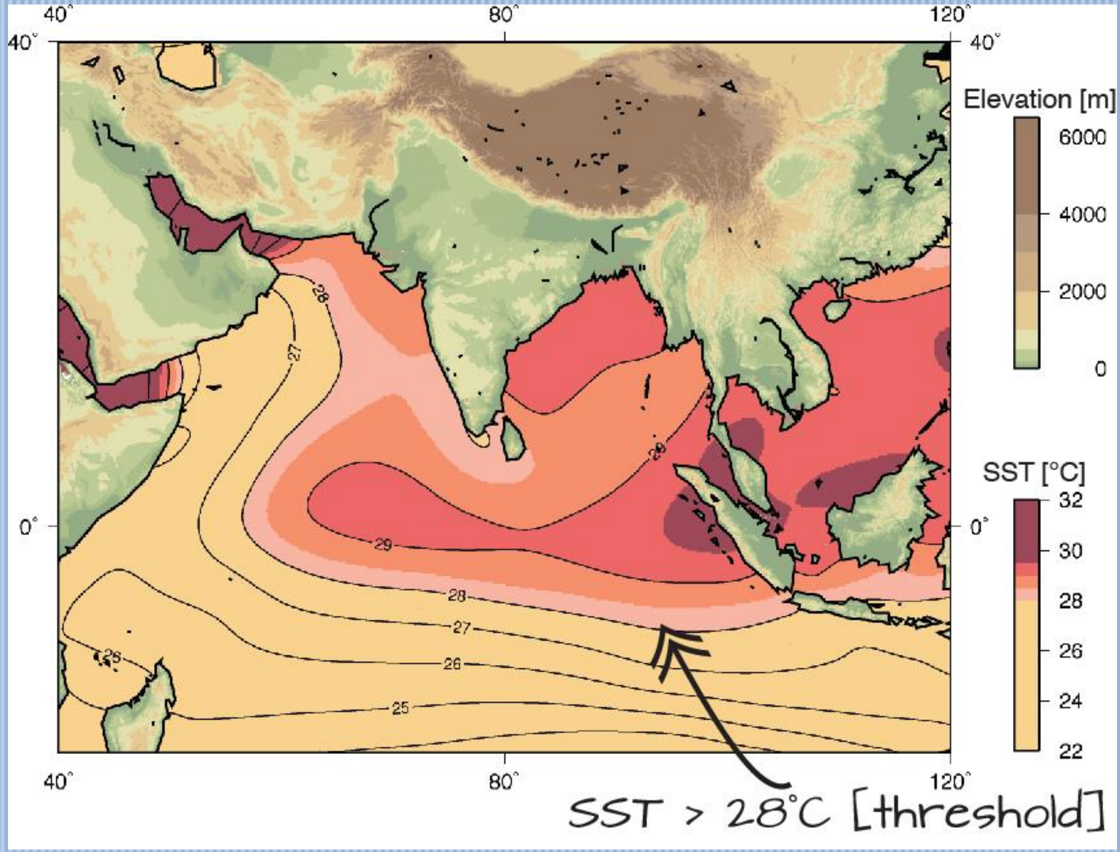
Roxy et al., *Climate Dynamics*, 2012

SST–precipitation relationship over Tropics

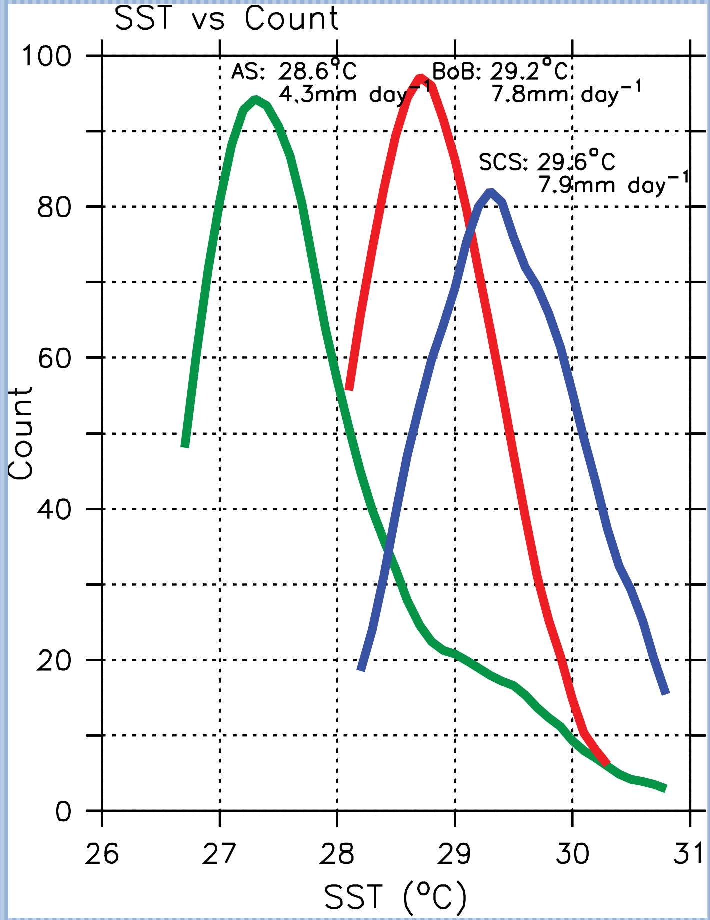


Gadgil et al., *Nature,* 1984
Waliser et al., *J. Climate,* 1993

Does high SSTs have an active role on Monsoon?
– mean SSTs above 28.5 over basins



SSTs averaged over the open basins



SST–precipitation relationship over Tropics
– the upper threshold and CAPE

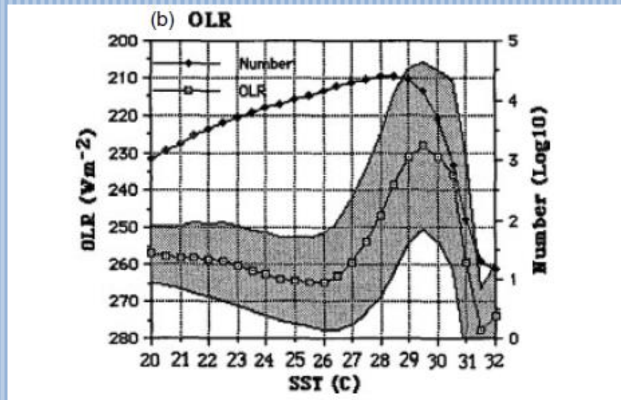


Figure 1. SST–convection relation in the global tropics (reproduced from Waliser *et al.*, 1993) for monthly values in 2° × 2° latitude–longitude squares of global tropics 25°S to 25°N for the period 1975–1985: (a) SST and HRC and (b) SST and OLR. The right ver-

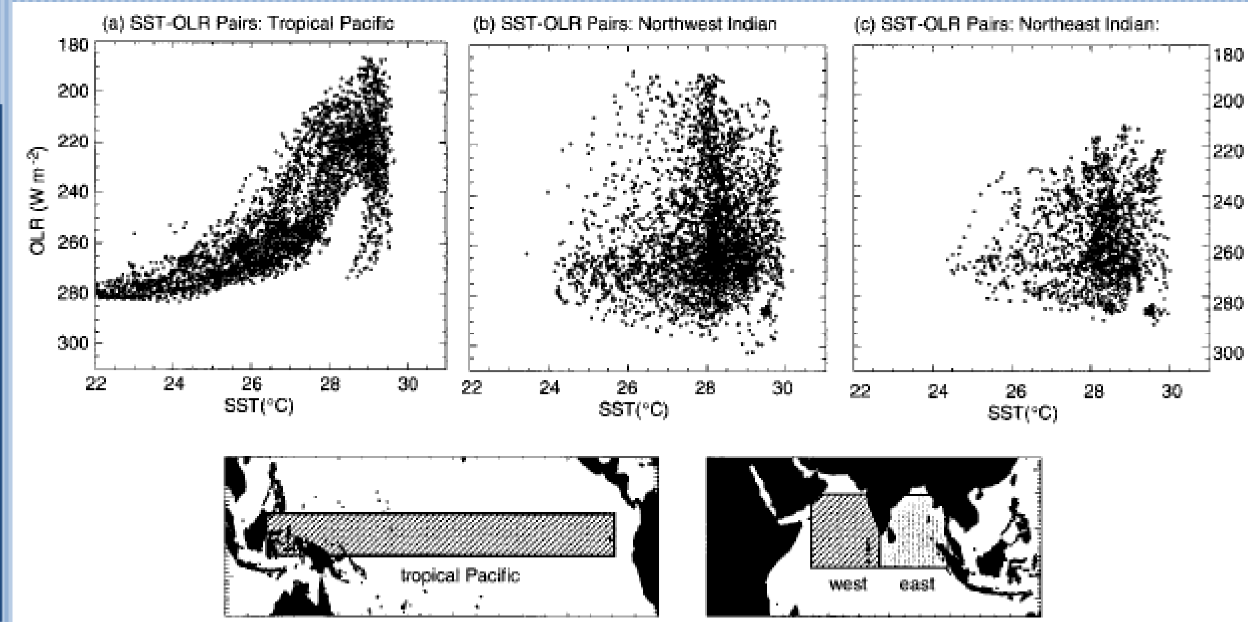


FIG. 3. OLR–SST (W m^{-2} and °C with ordinate scale reversed) pairs for (a) the tropical Pacific Ocean in the region 5°S–5°N, 120°E–90°W, (b) the northern Indian Ocean for the region equator–20°N, 55°–80°E, and (c) the northern Indian Ocean, equator–20°N, 80°–100°E. The geographical areas are depicted 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., *Nature,* 1984; Waliser et al., *J. Climate,* 1993
Loschnigg and Webster, *J. Climate,* 2000; Bhat et al., *J. Met. Soc. Japan,* 1996

SST–precipitation relationship over Indian Ocean – where SSTs above upper threshold!

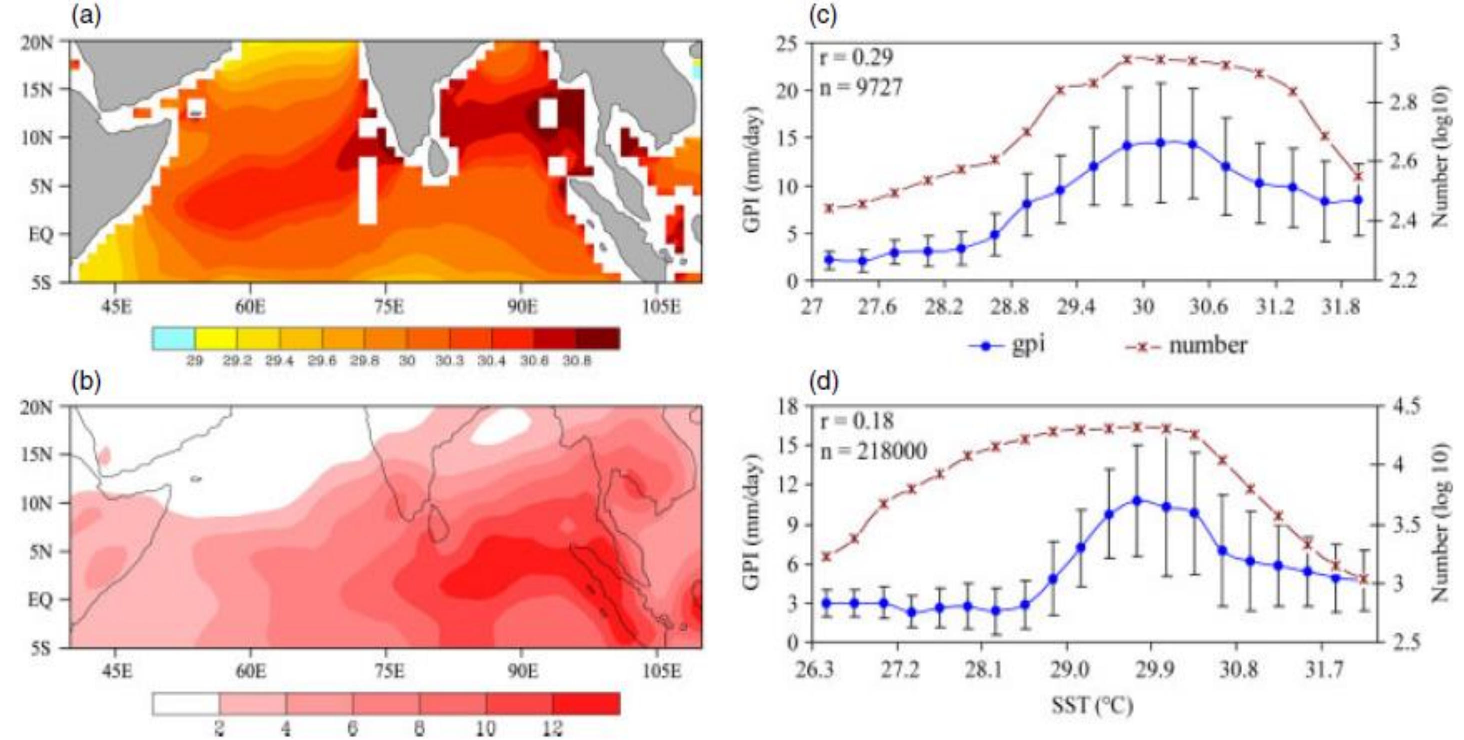
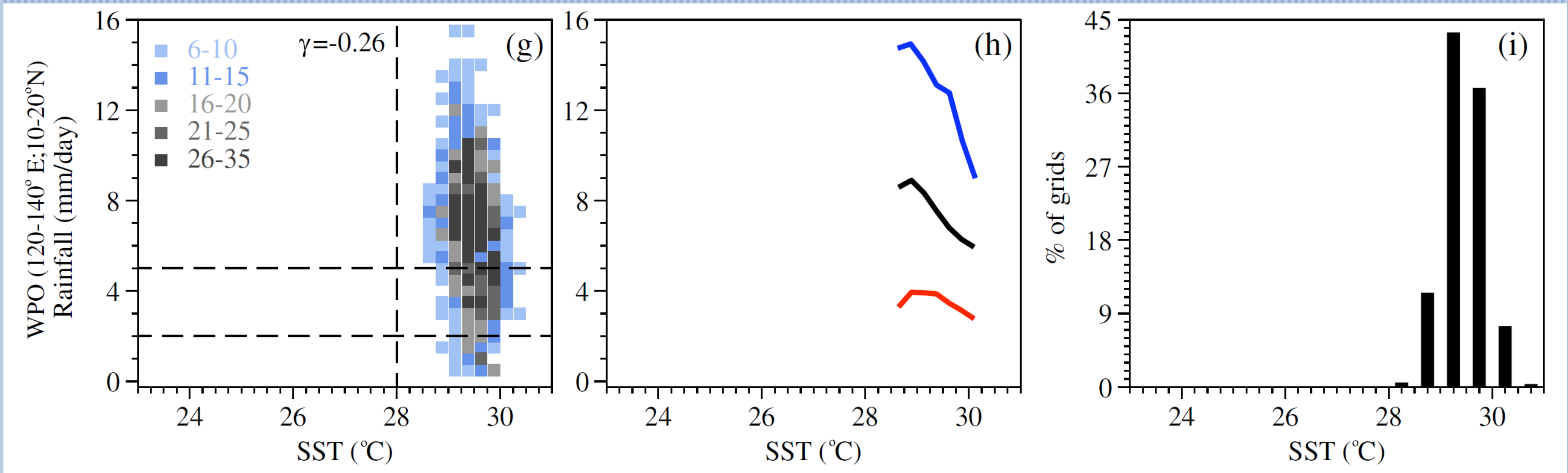


Figure 2. Over north Indian ocean (a) mean TMI SST in °C of 16 April to 15 May of 8 years 1998 to 2005. (b) Mean GPI rain fall of the same area and period. The SST–convection relation for data averaged over 1° lat × 1° long squares. (c) In monthly data and (d) in daily data. Length of the vertical bars represents the standard deviation on either side of the mean. The right vertical axes specify the number of parameter pairs used [in (c) and (d), the linear correlation coefficient and number of observational pairs are marked at top left]. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Sabin et al., *Int. J. Climatology*, 2012
Rajendran et al., *J. Earth System Science*, 2012

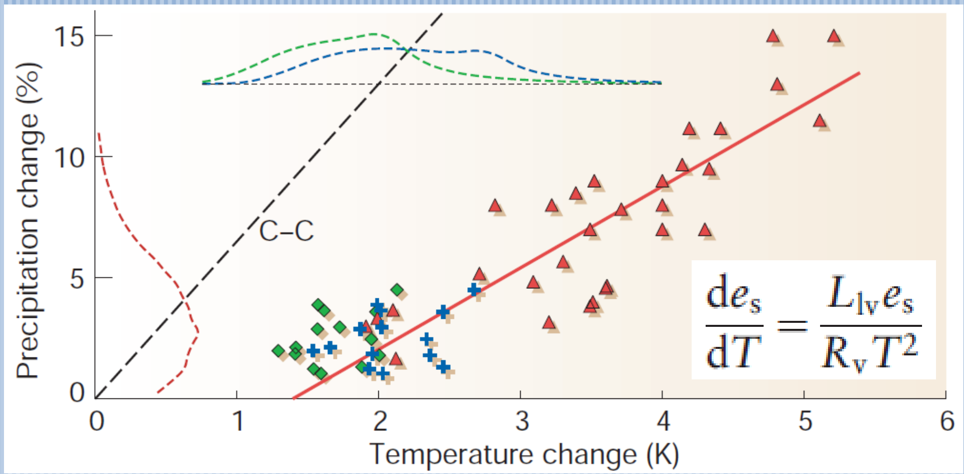
SST-precipitation relationship over west Pacific – negative relationship at SSTs > 29°C?



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

Clausius–Clapeyron
– moisture increase with increasing temp.

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.

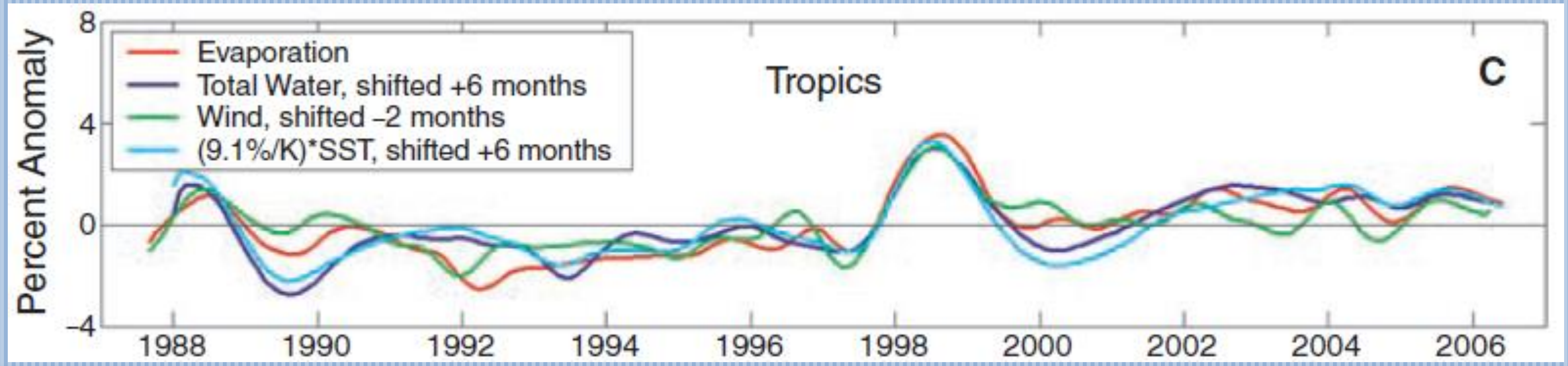


C–C also controls how "wet gets wetter, and dry gets drier".

Observations suggest that precipitation and total atmospheric water have increased at about the same rate over past 2 decades.

–> with SST, moisture has increased

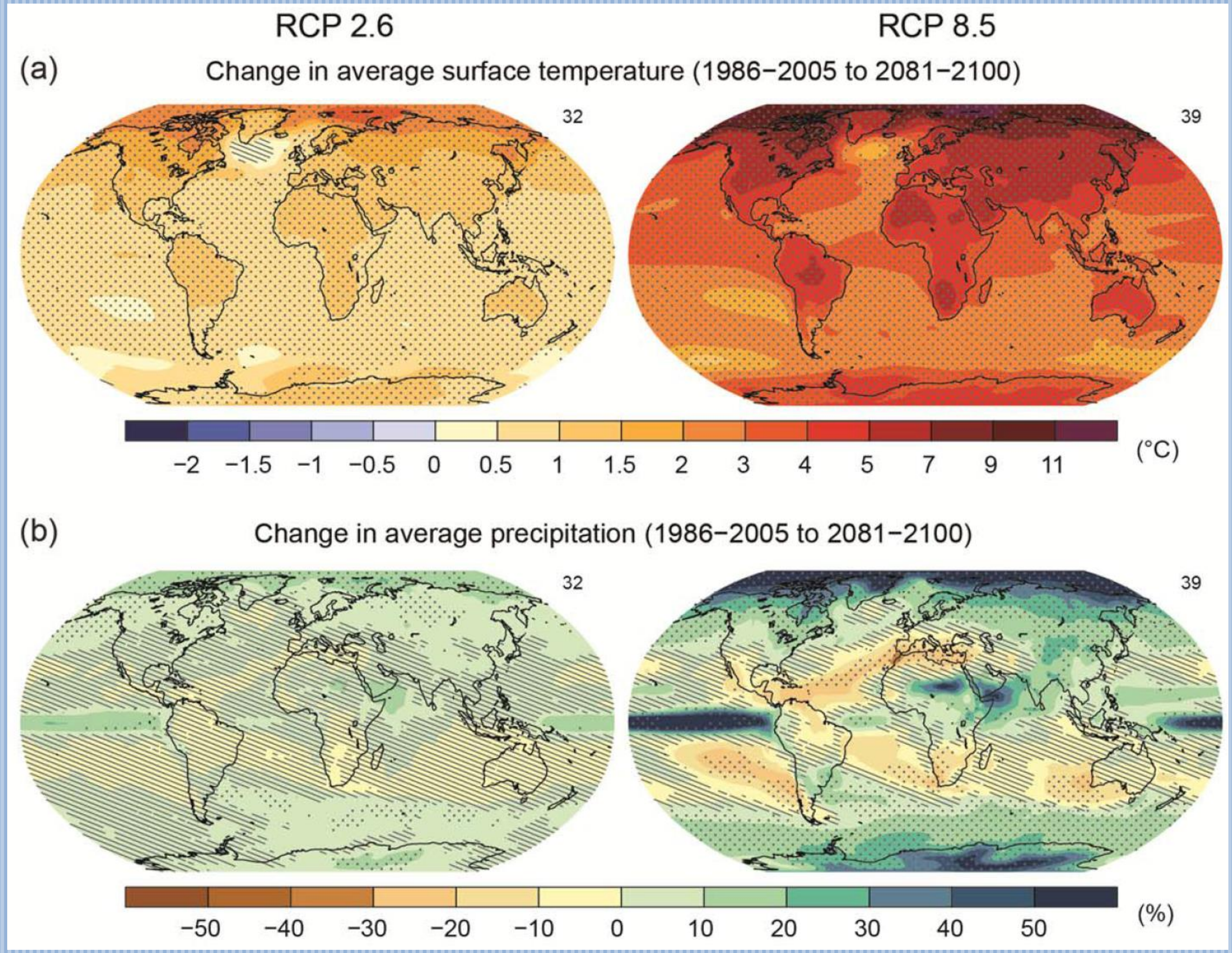
–> with moisture, rainfall has increased



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

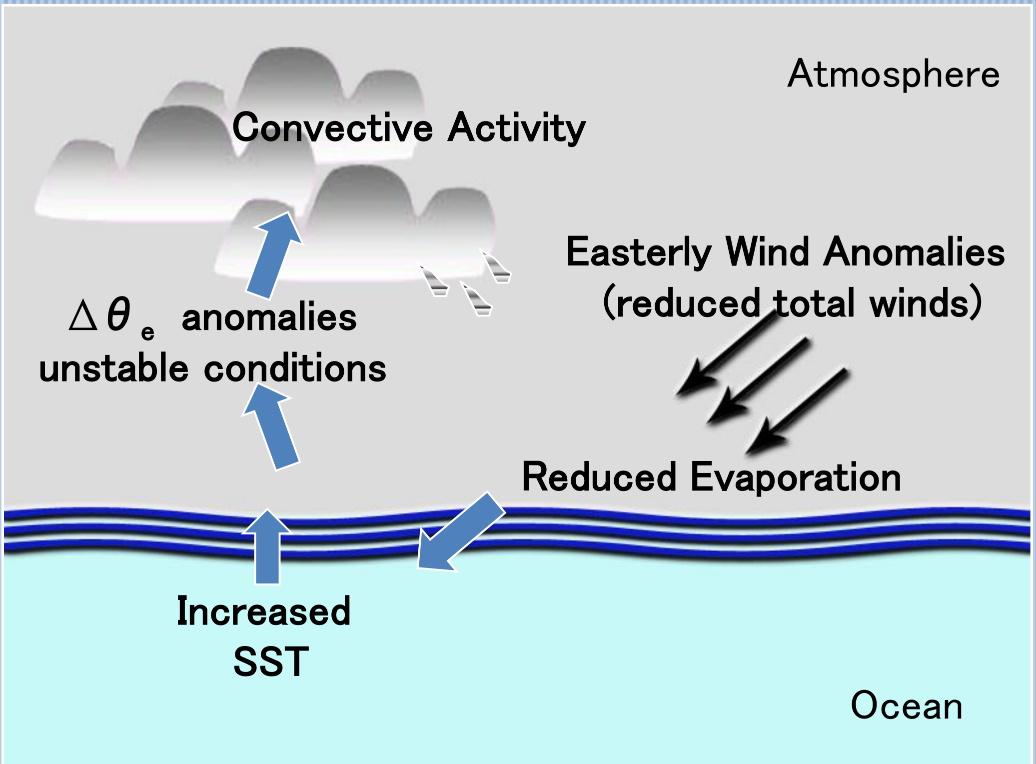
Rich gets richer

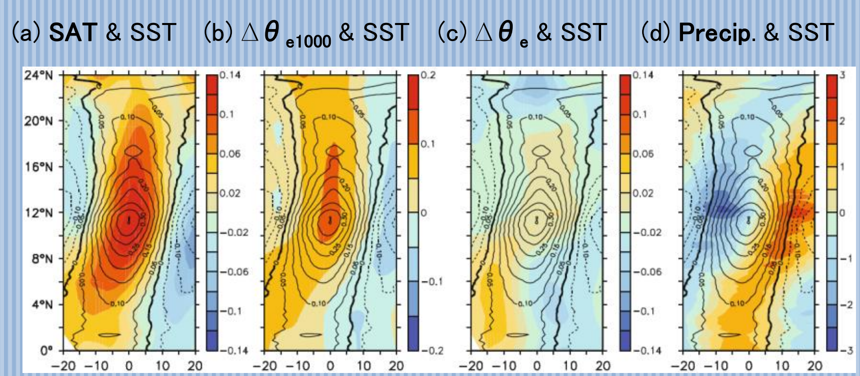
– poor gets poorer



IPCC, *AR5*, 2013

Ocean-atmosphere interaction over Indian/w.Pacific – positive SSTa enhance convection



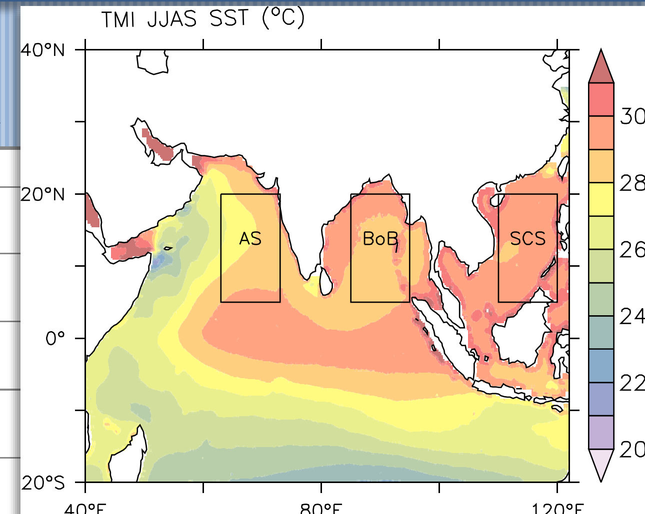


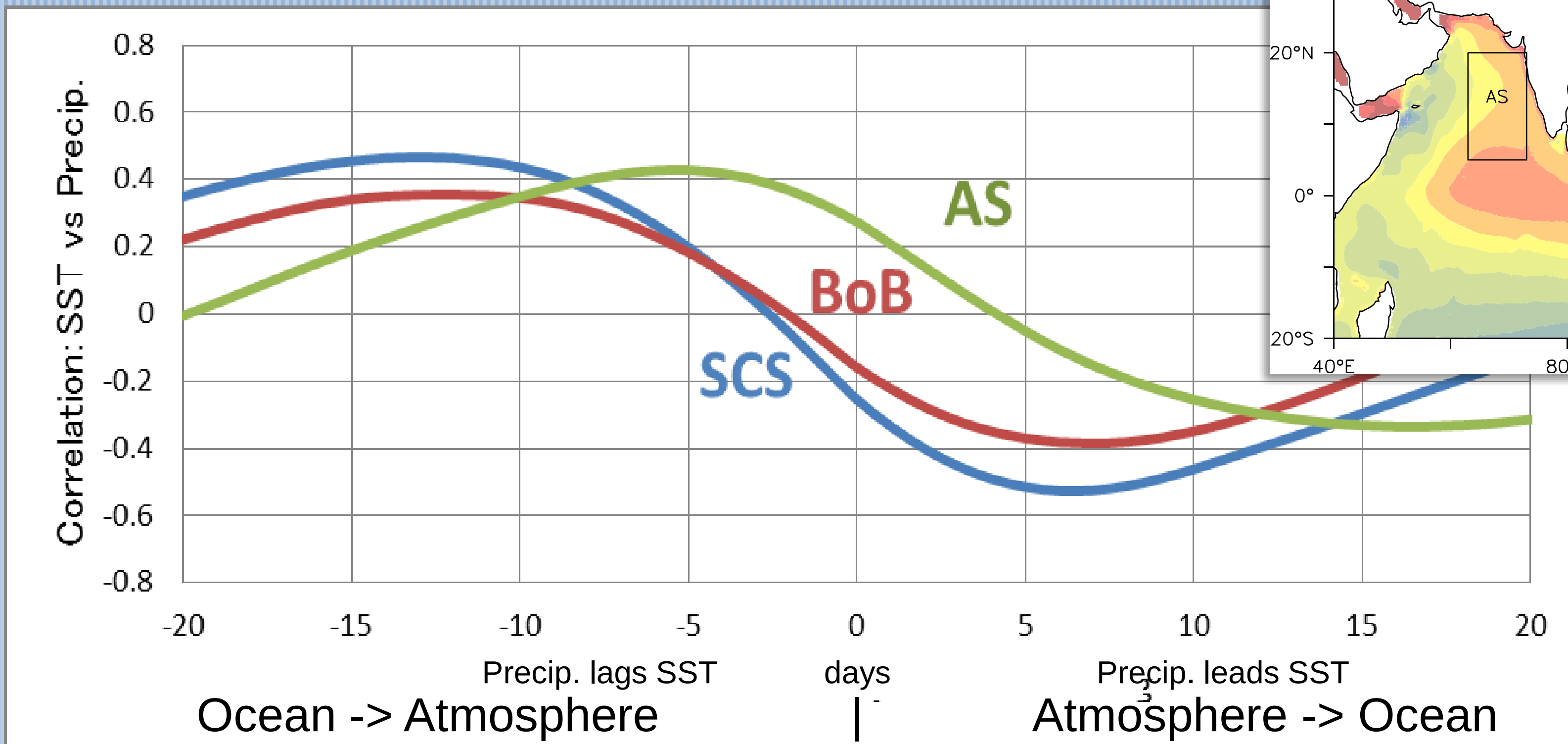
positive SST anomalies
=> destabilize lower atmos. column
=> convective activity

Roxy and Tanimoto, *J.Met.Soc.Japan,* 2007; Roxy and Tanimoto, *Climate Dynamics,* 2011
Wu et al., *GRL,* 2008

Temporal & Spatial variability to be considered
– response time difference of 1 week!

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



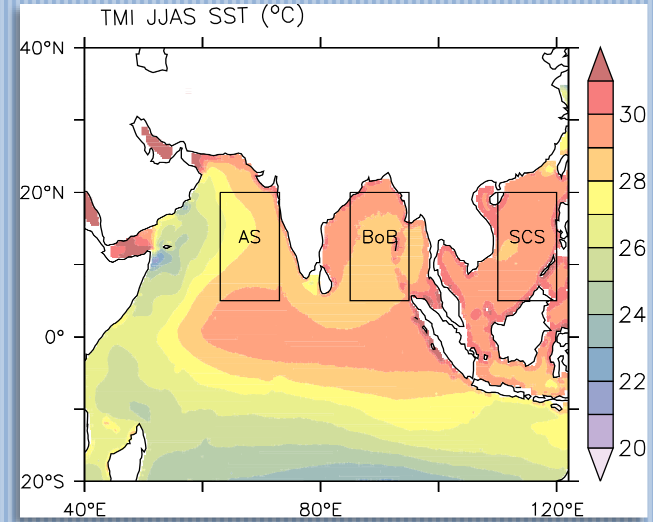


The magnitude of the correlation refers to the intensity of the driving force, and the corresponding lag (lead) time denotes how quickly the atmosphere responds to the SST anomalies and vice versa.

Roxy et al., *Climate Dynamics*, 2012

What is the change in perspective we are looking at? – lag, domain w.r.to air sea interaction, isv

1. There is a lag between SST and Precip., from 5 days to 2 weeks.
2. This lag has a spatial variability



3. Calendar months not useful due to:
   (a) the above lag (in days) and spatial variability
   (b) SST change might be in one month and corresponding precipitation change might be in next month.
   Eg: Lag over BoB can be up to 2 weeks!

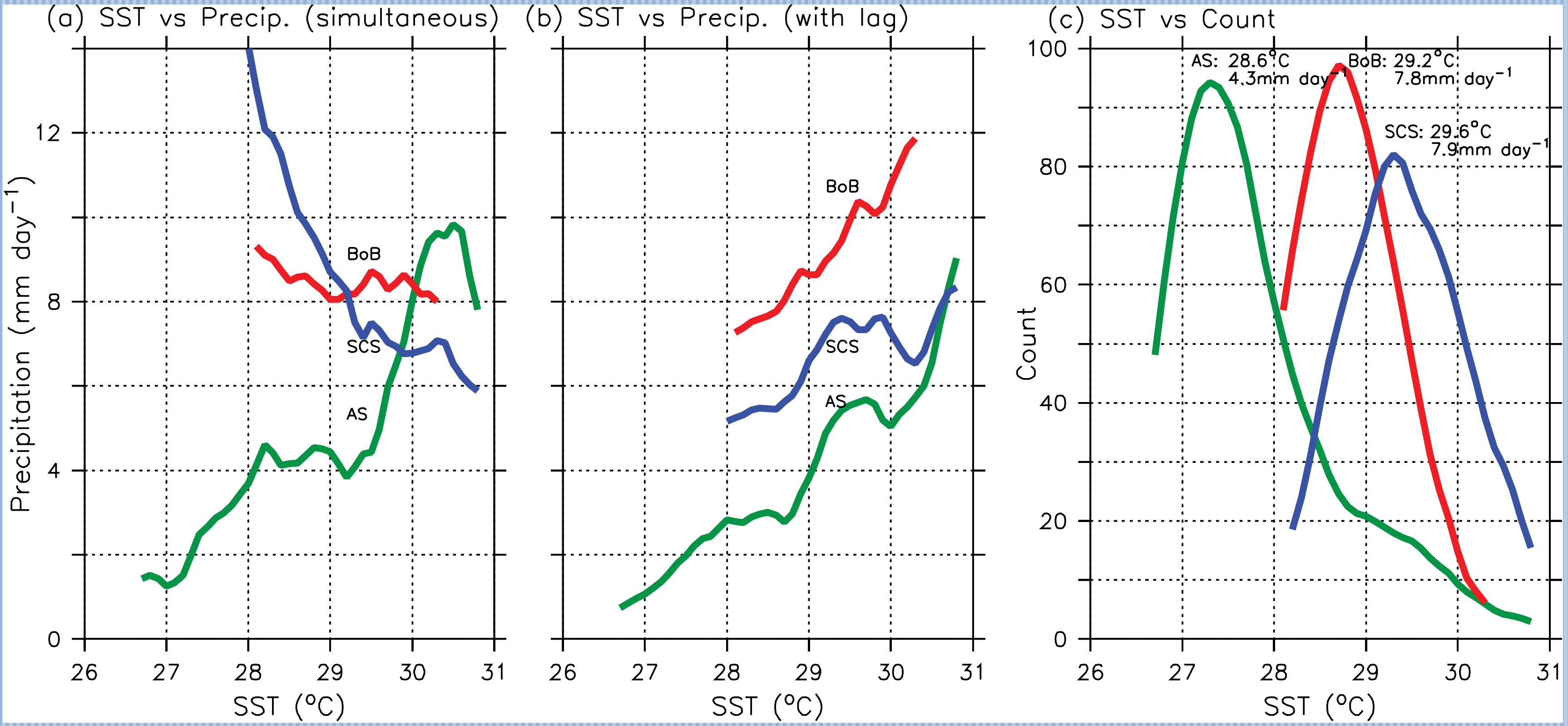
4. Averaging over large domains not useful:
   Intraseasonal variability over Arabian Sea and Bay of Bengal are at different phases at a time.

5. Simultaneous analysis gives the effect of SST on precipitation and the effect of precipitation on SST, making it difficult to separate them.

Hence an analysis considering the time lag, over different domains is necessary

Wu et al., *GRL,* 2008
Roxy et al., *Climate Dynamics,* 2012; Roxy, *Climate Dynamics,* 2013

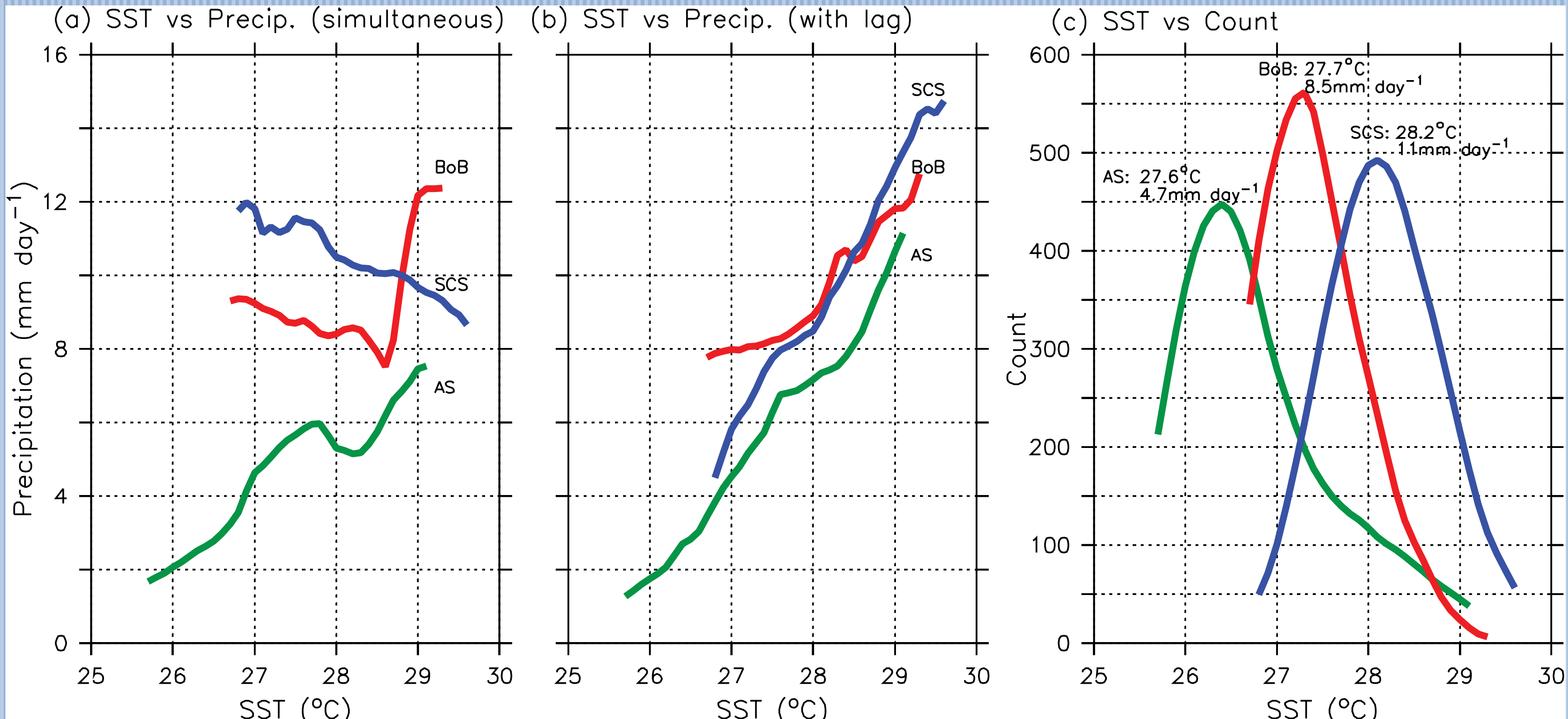
SST – Precipitation relationship with/without lags – in observations



Quantified: 1℃ rise in SST -> 2 mm/day in rainfall

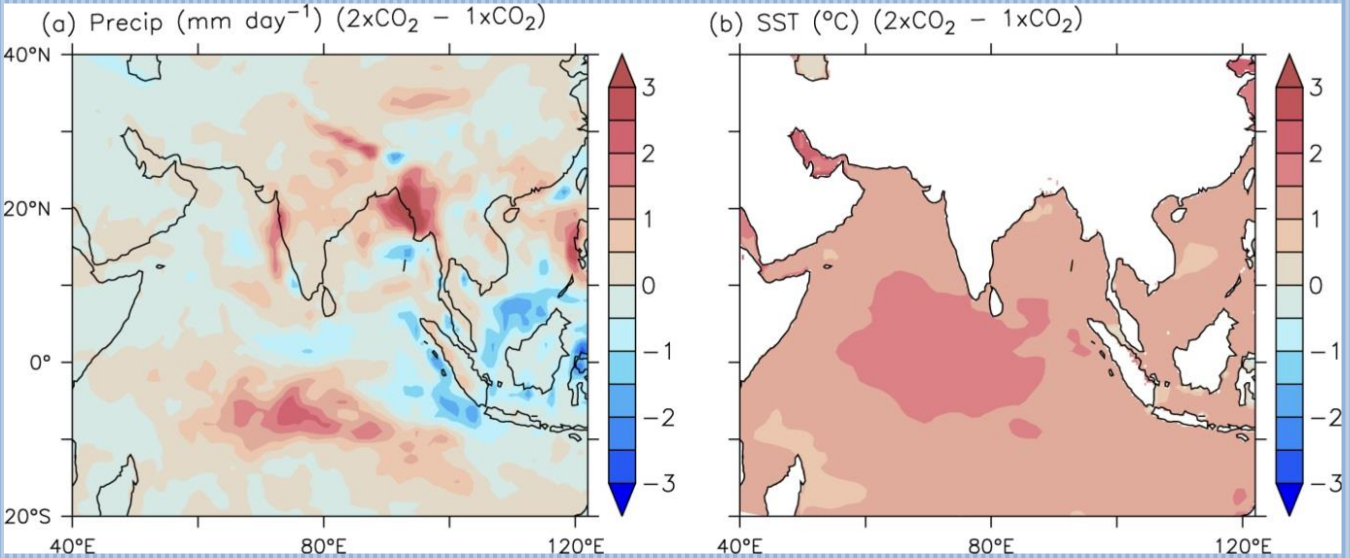
Roxy et al., *Climate Dynamics*, 2013

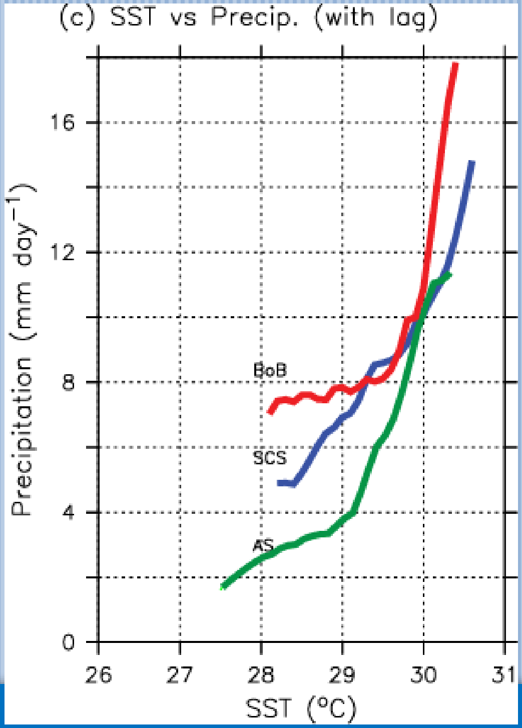
SST – Precipitation relationship with/without lags – in model simulations



Quantified: 1℃ rise in SST -> 2 mm/day in rainfall

Monsoon precipitation in a changing climate – in CFSv2 climate projections

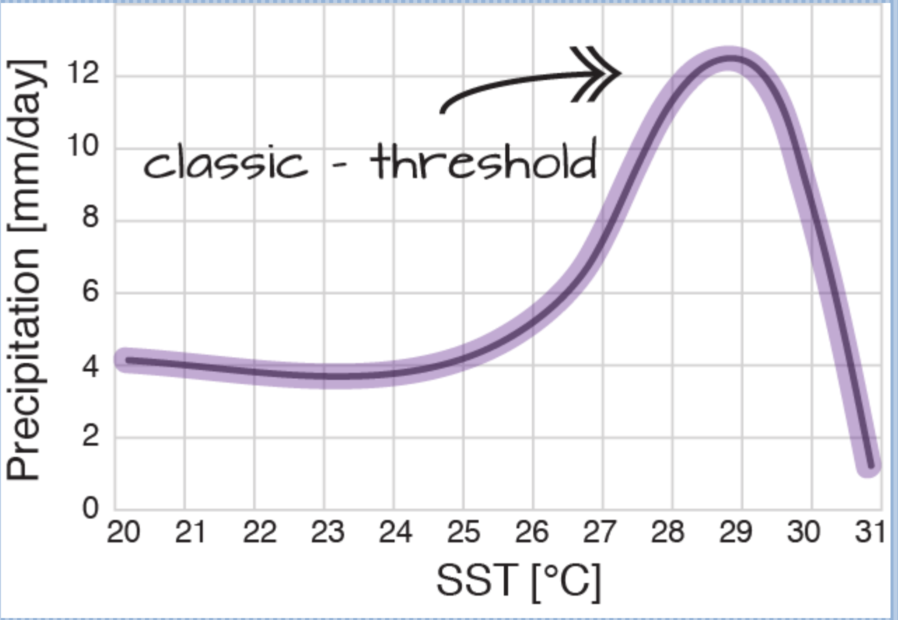


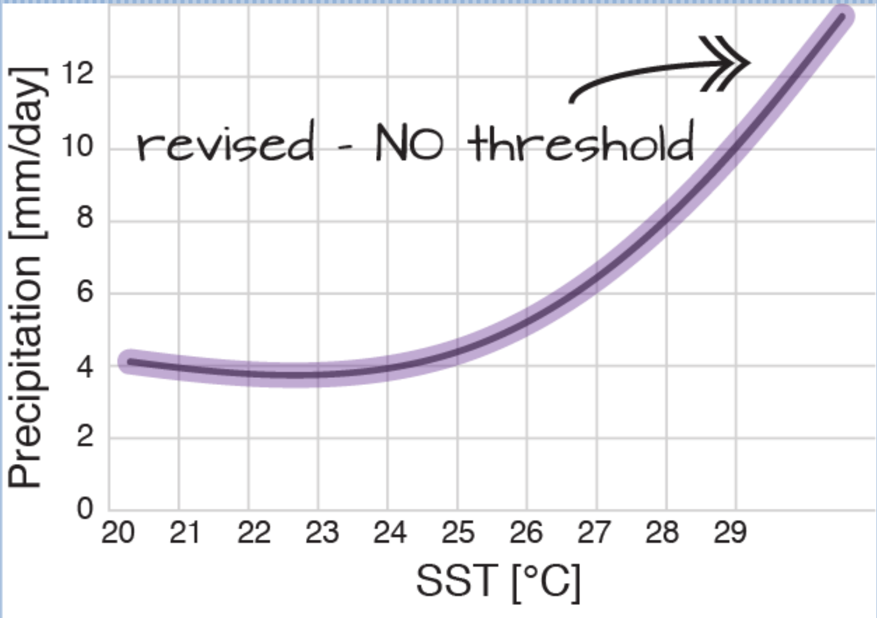


Increase in Monsoon Precipitation with increasing SST

Regions of maximum precipitation tends to be located at the ascending branches of the tropical circulation (Lau et al. 1997)

Revised SST – Precipitation relationship





Remember…

…the ocean was in the atmosphere

Roxy, *Climate Dynamics*, 2013

A new paradigm for SST-precipitation relationship – and its relevance to climate

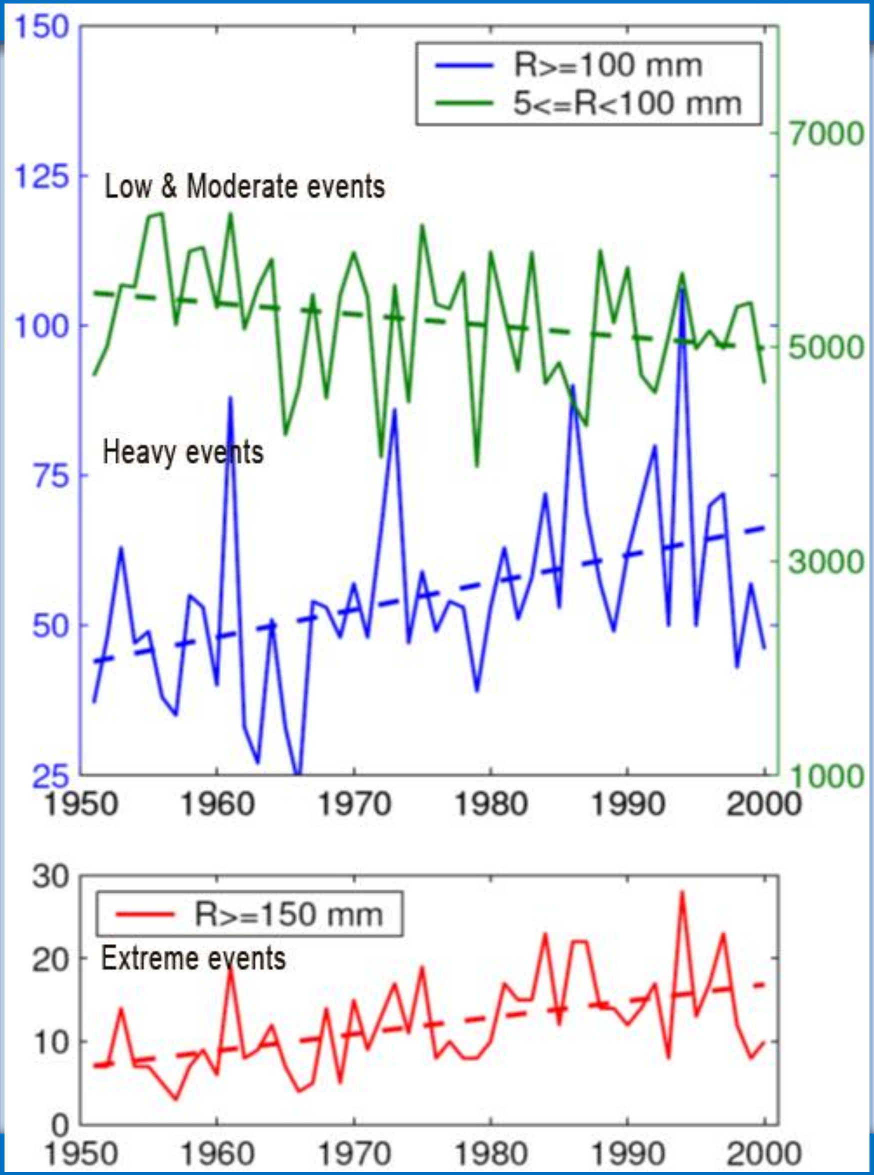
1. SST – precipitation relation has a spatial variability over the monsoon basins, with a **lag** of:
   ~ 5 days over the Arabian Sea
   ~ 12 days over the Bay of Bengal and South China Sea

2. Considering this lag, a **quantifiable** relationship can be deduced between SST (above 26°C) and precipitation:
   1°C rise in SST -> 2 mm/day in rainfall

3. Relationship holds for a changing climate.

Changing Climate and Monsoon

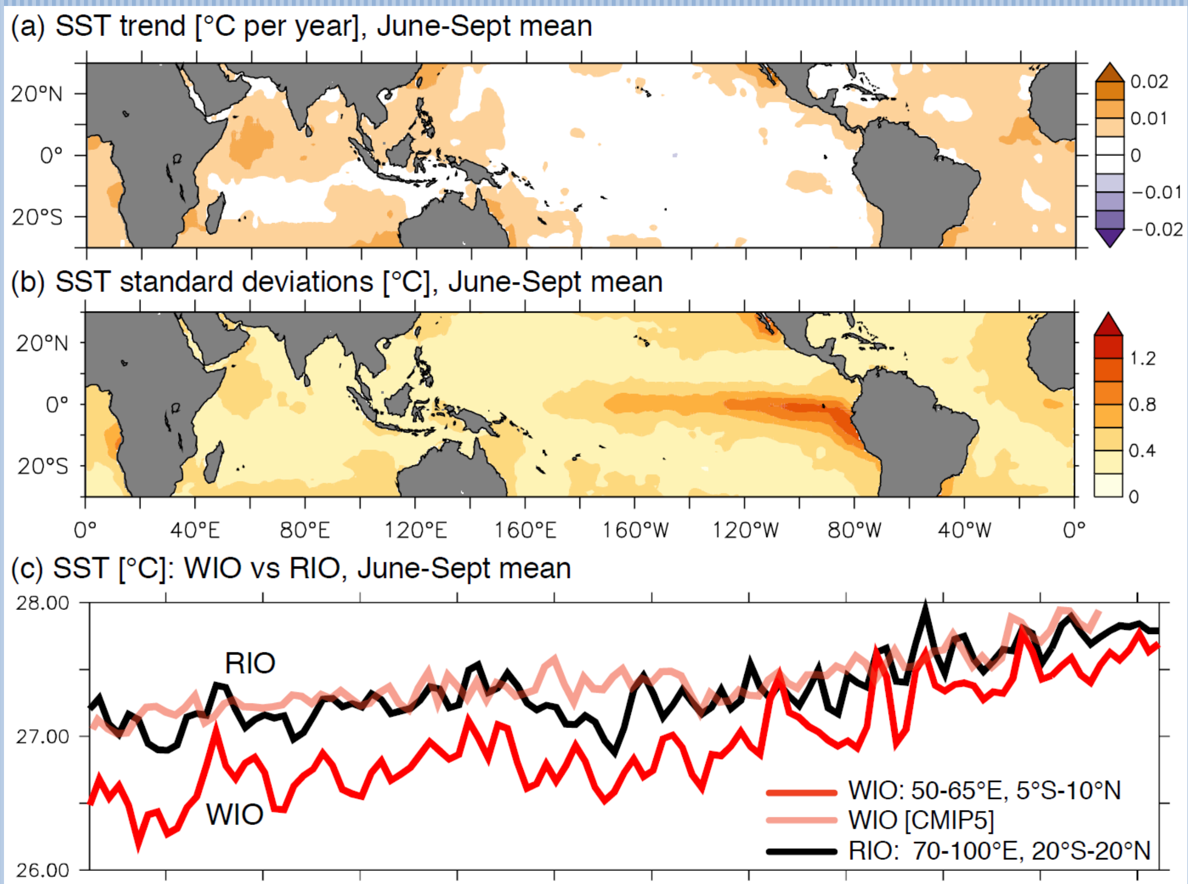
Extreme Events

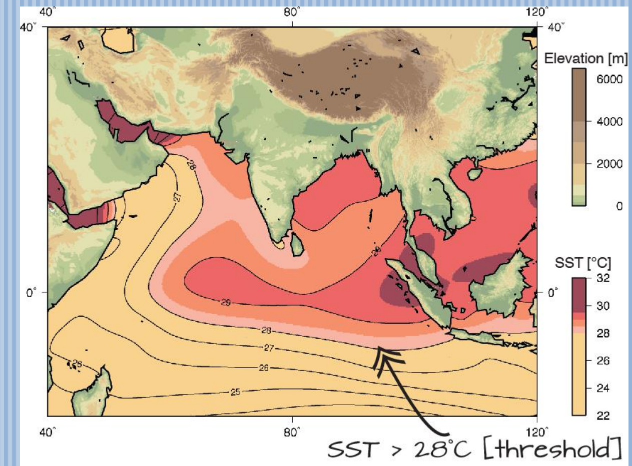


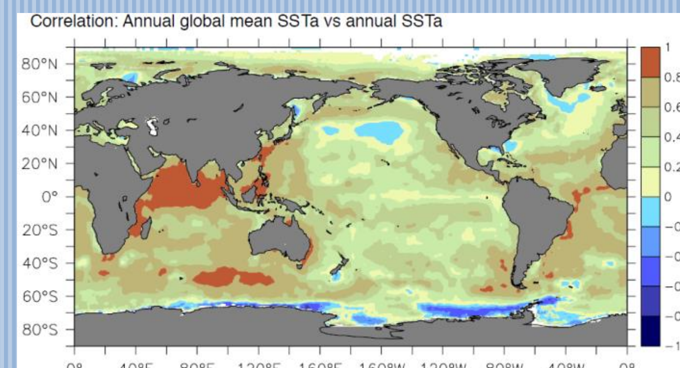
Goswami et al. *Science*, 2006

Indian Ocean in a Changing Climate

Indian Ocean warming: 1.2C in the western Indian Ocean

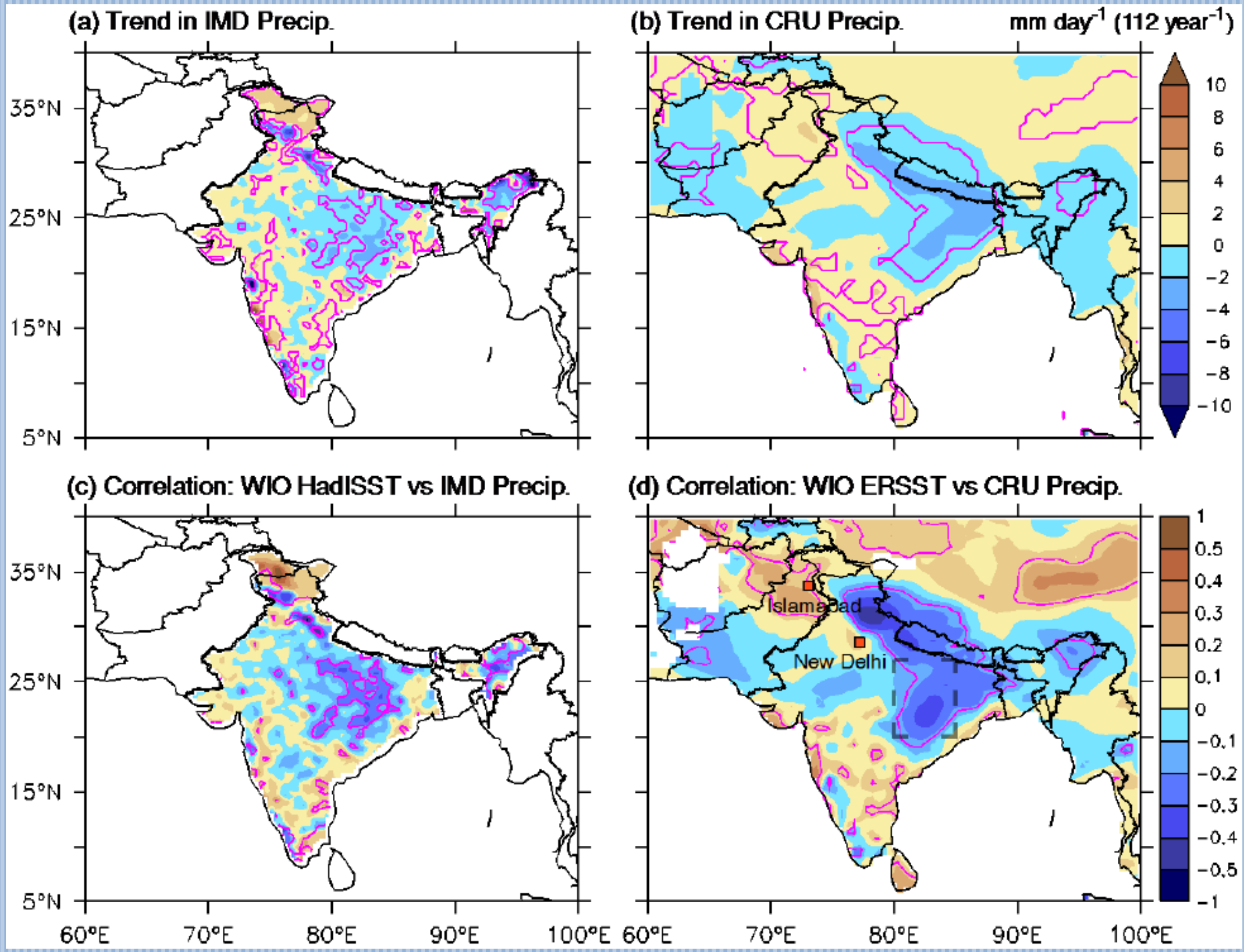






Roxy et al. *J.Climate*, 2014, *Under Review*

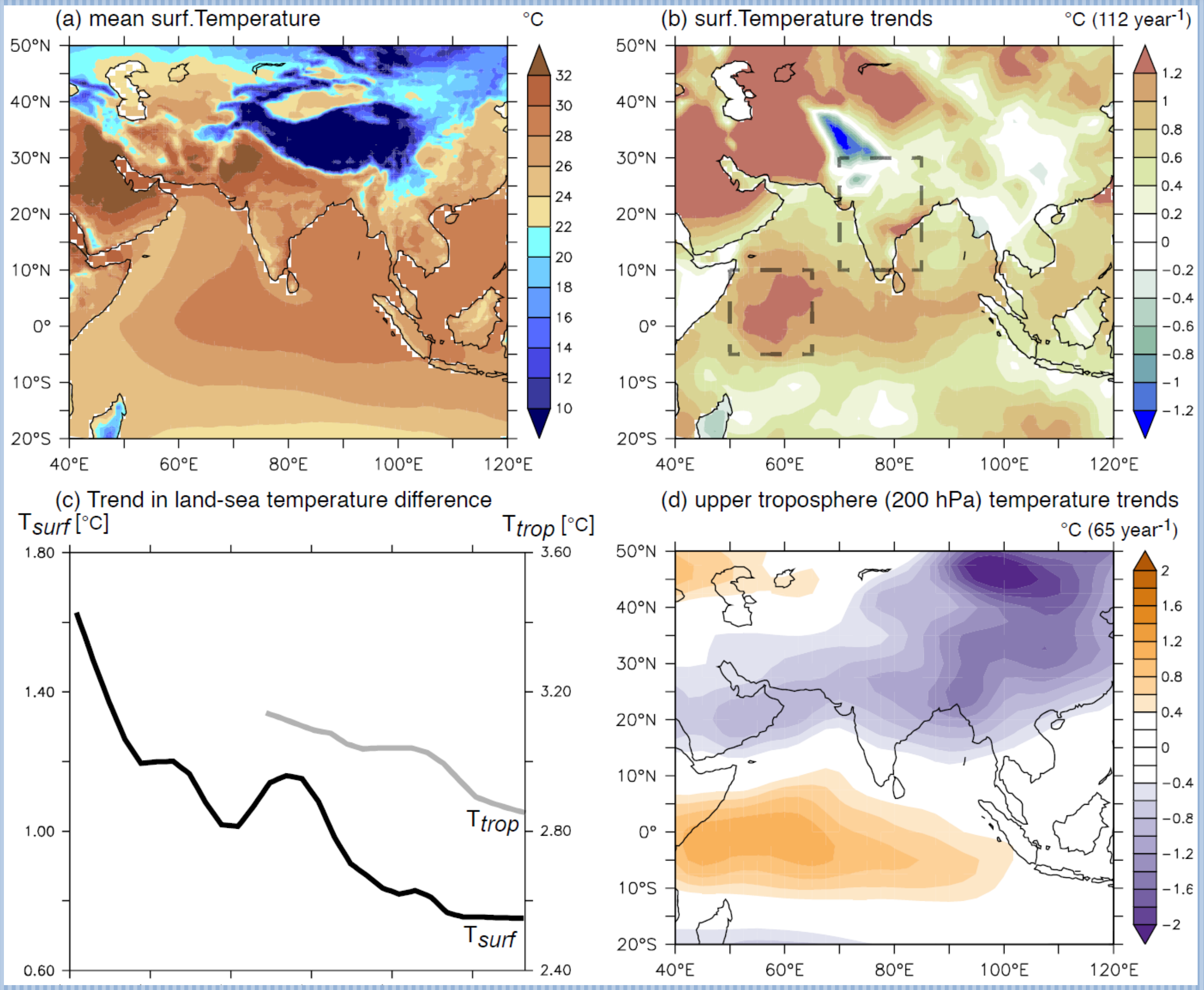
Monsoon in a Changing Climate
Weakening Trend in Rainfall over central South Asia

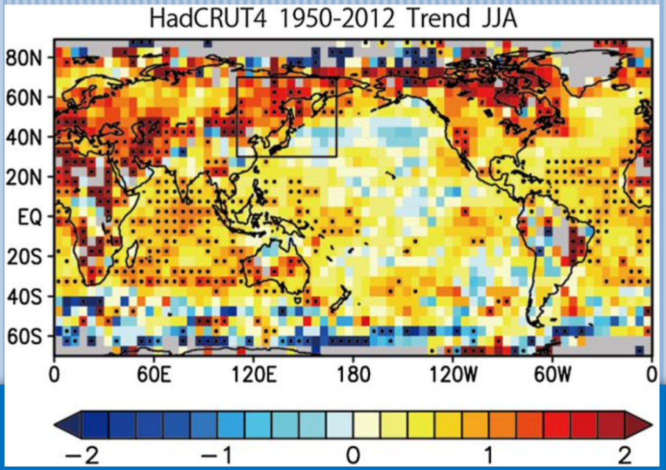


Roxy et al. *Nature Geoscience*, 2014, *Under Review*

Monsoon in a Changing Climate

Warm Ocean, Weak Monsoon?

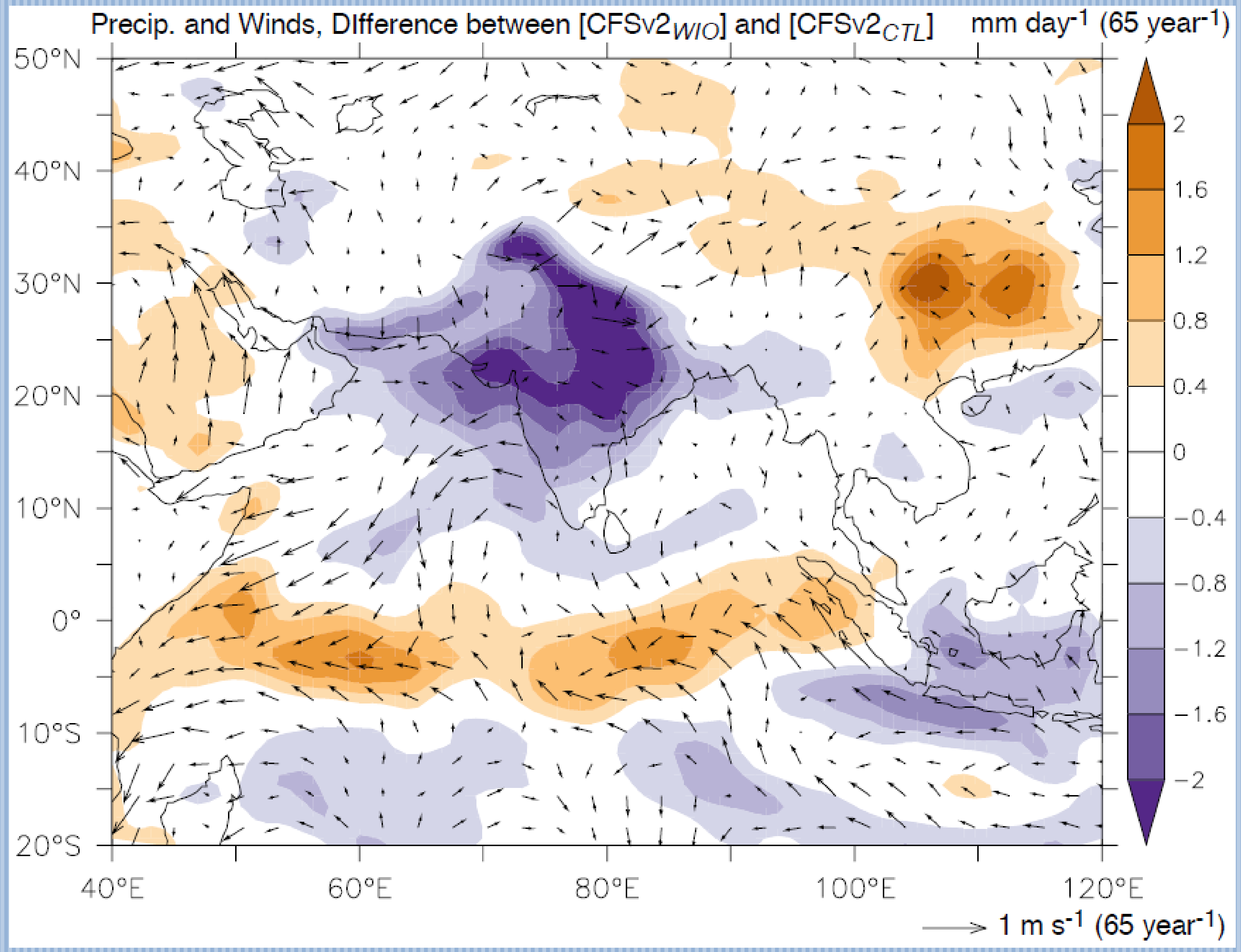




Roxy et al. *Nature Geoscience*, 2014, *Under Review*

Monsoon in a Changing Climate

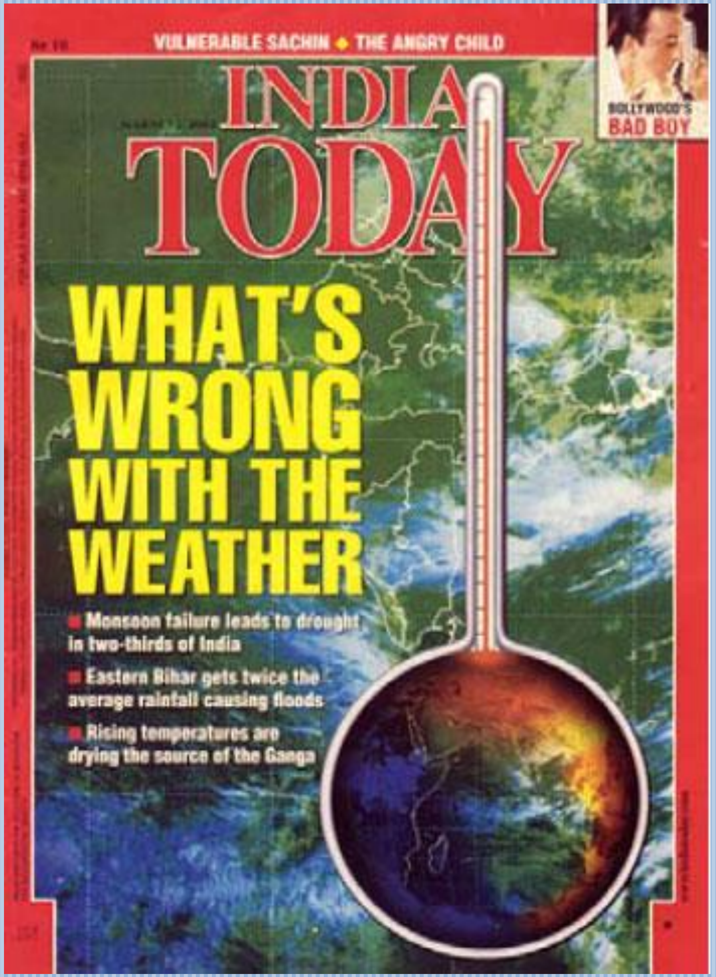
Model response to warm western Indian Ocean

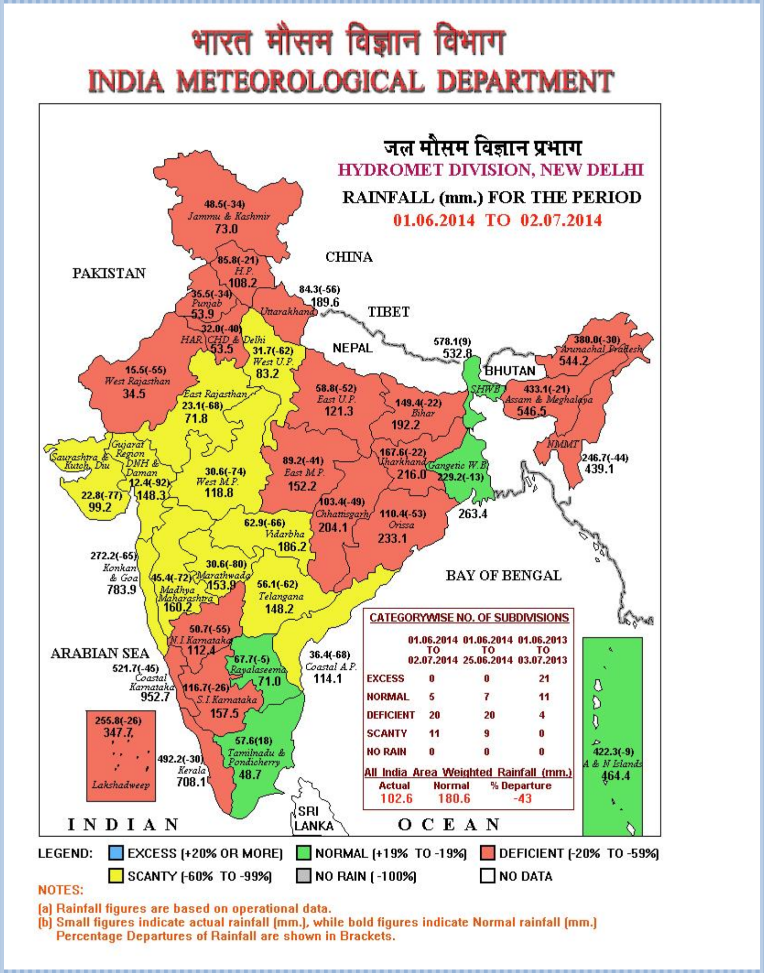


Roxy et al. *Nature Geoscience*, 2014, *Under Review*

Monsoon 2014

– what went wrong?





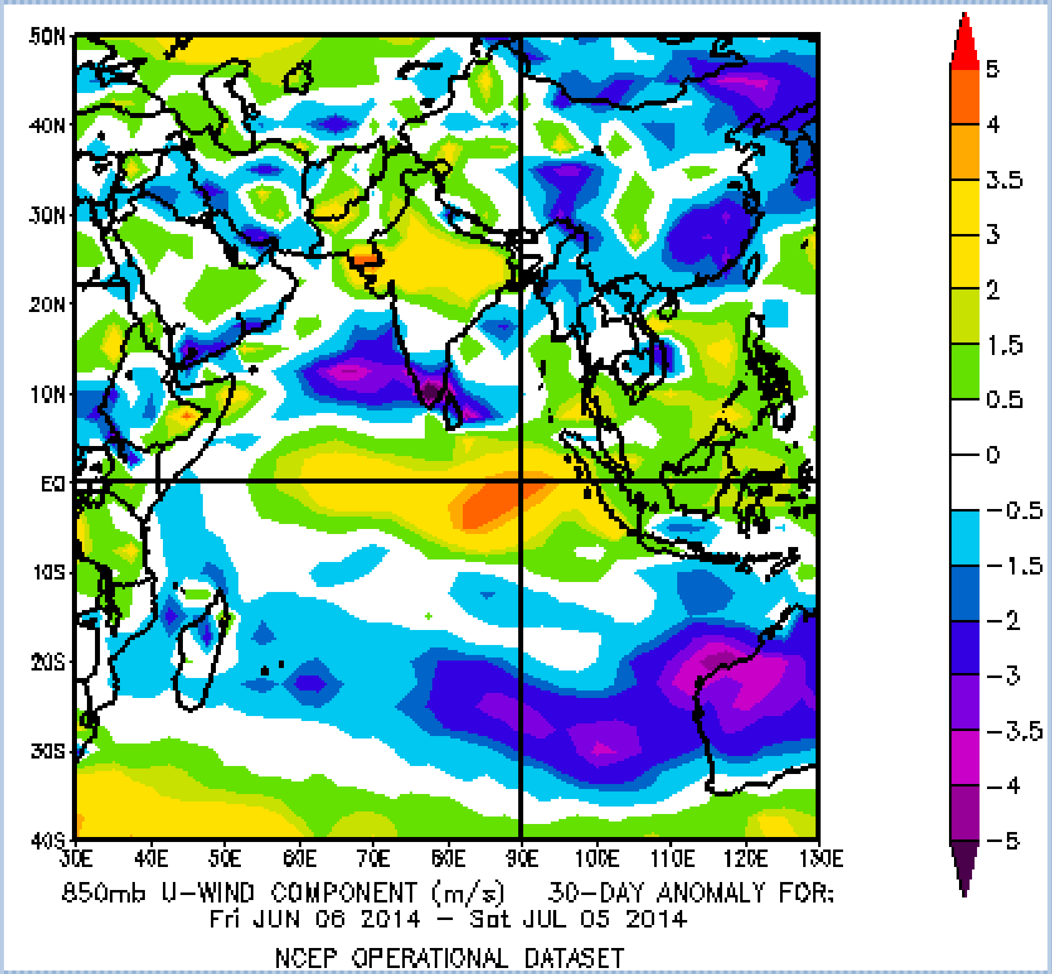
	01.06.2014 TO 02.07.2014	01.06.2014 TO 25.06.2014	01.06.2013 TO 03.07.2013
EXCESS	0	0	21
NORMAL	5	7	11
DEFICIENT	20	20	4
SCANTY	11	9	0
NO RAIN	0	0	0

All India Area Weighted Rainfall (mm.)

Actual	Normal	% Departure
102.6	180.6	-43

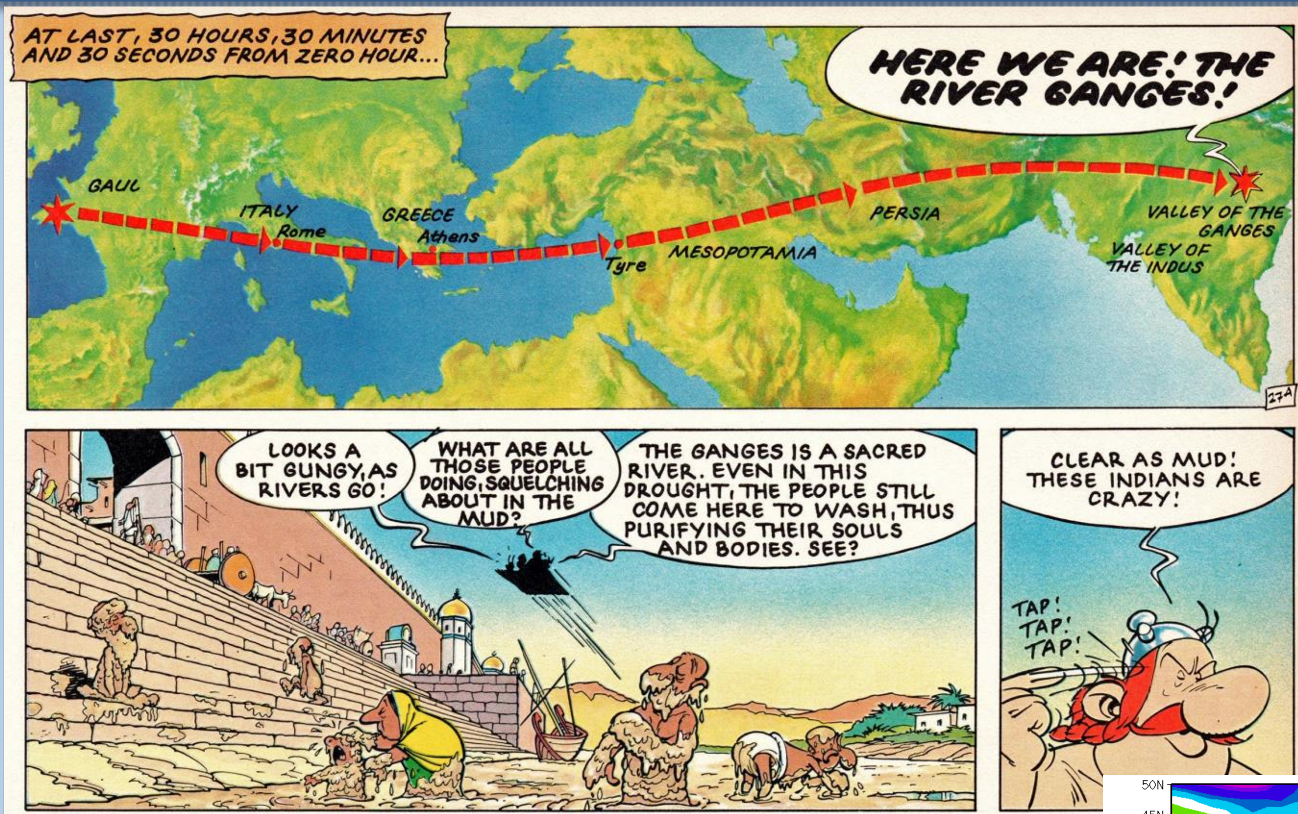
June-July: deficient rains

Monsoon 2014
– what went wrong?



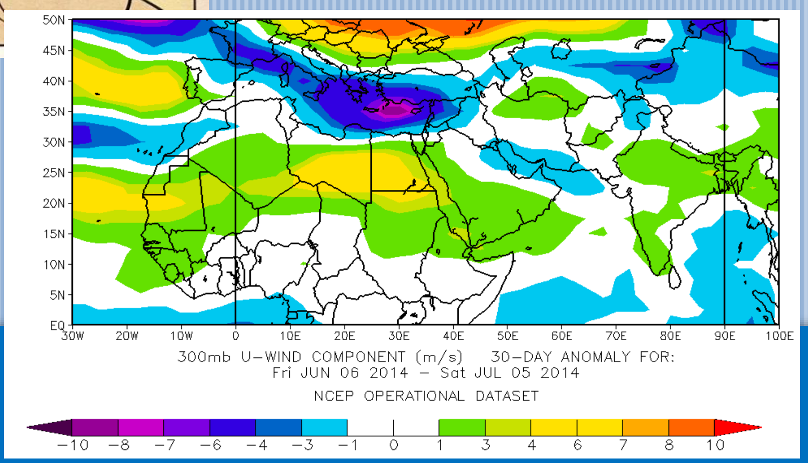
June–July: deficient rains, weak monsoon winds

Monsoon 2014
– weak jet stream?



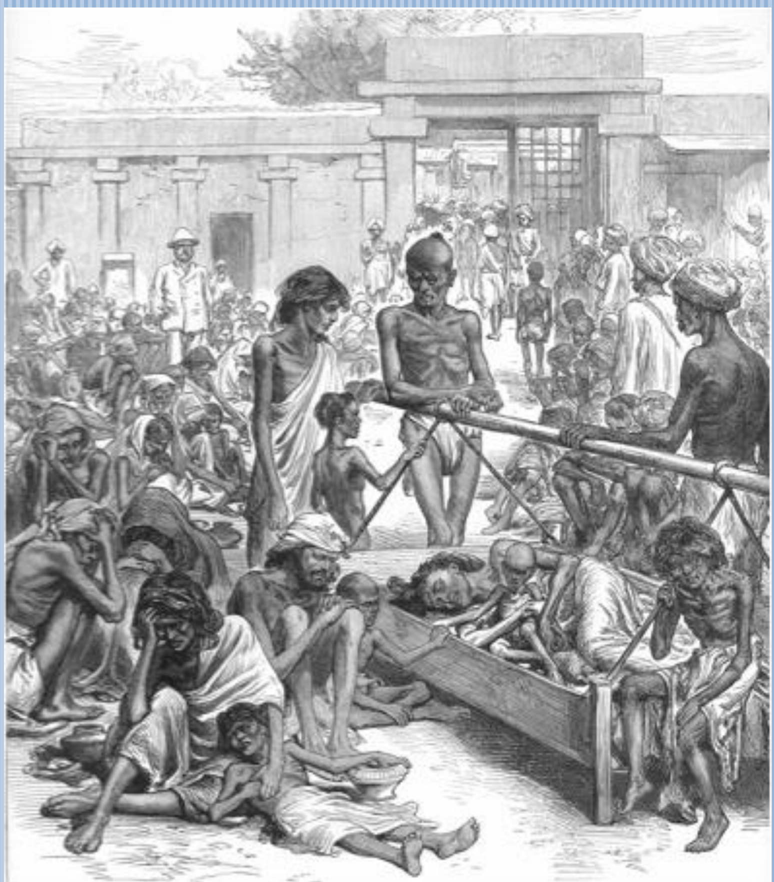
June–July:

- deficient rains
- weak monsoon winds
- weak jet stream

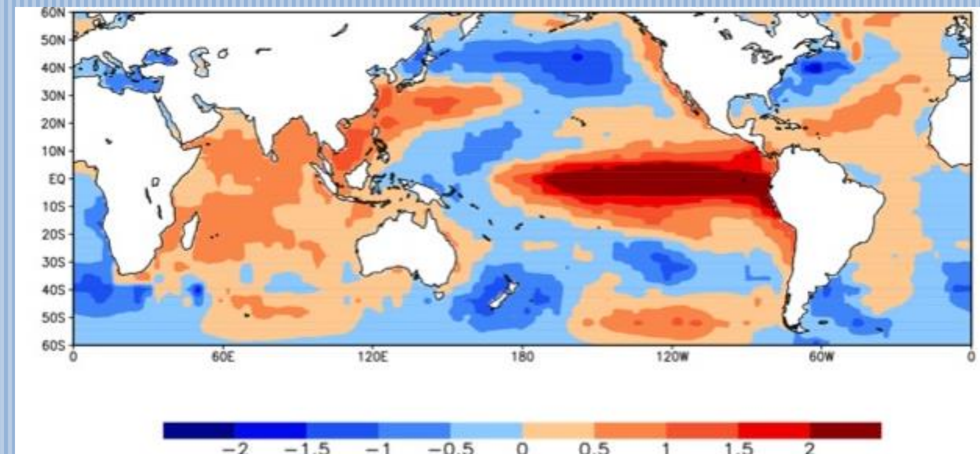


Monsoon 2014
– El Nino? Developing El Nino?

Great Famine of 1877–79



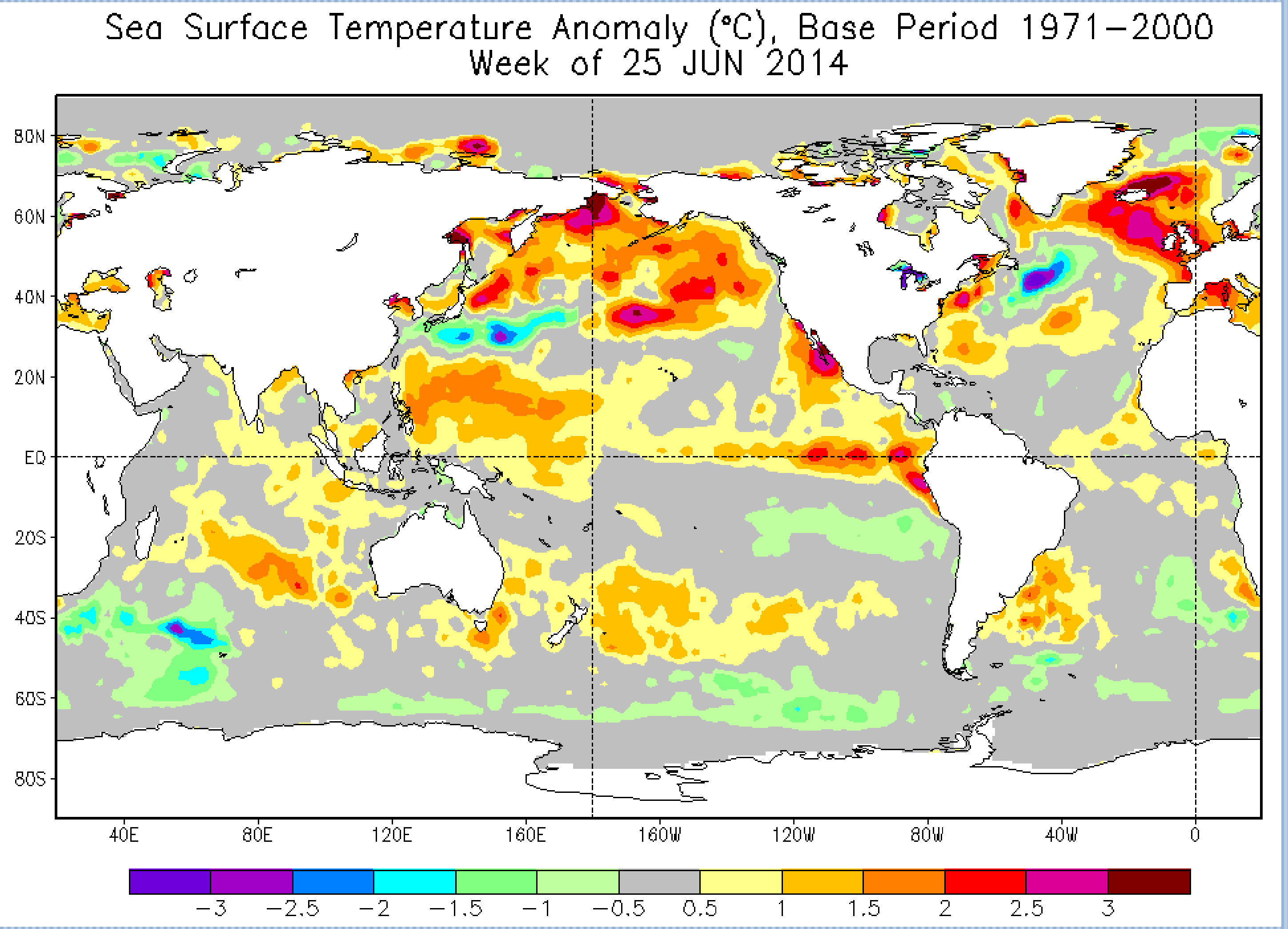
SST anomalies of DJF 1877



All India Monsoon Rainfall: −29%; Drought Area: 670,000 km²; Estimated Deaths: 5.5 – 8.2 million (?)
Governance: British Rule, exported food from India to England despite famines.

Monsoon 2014

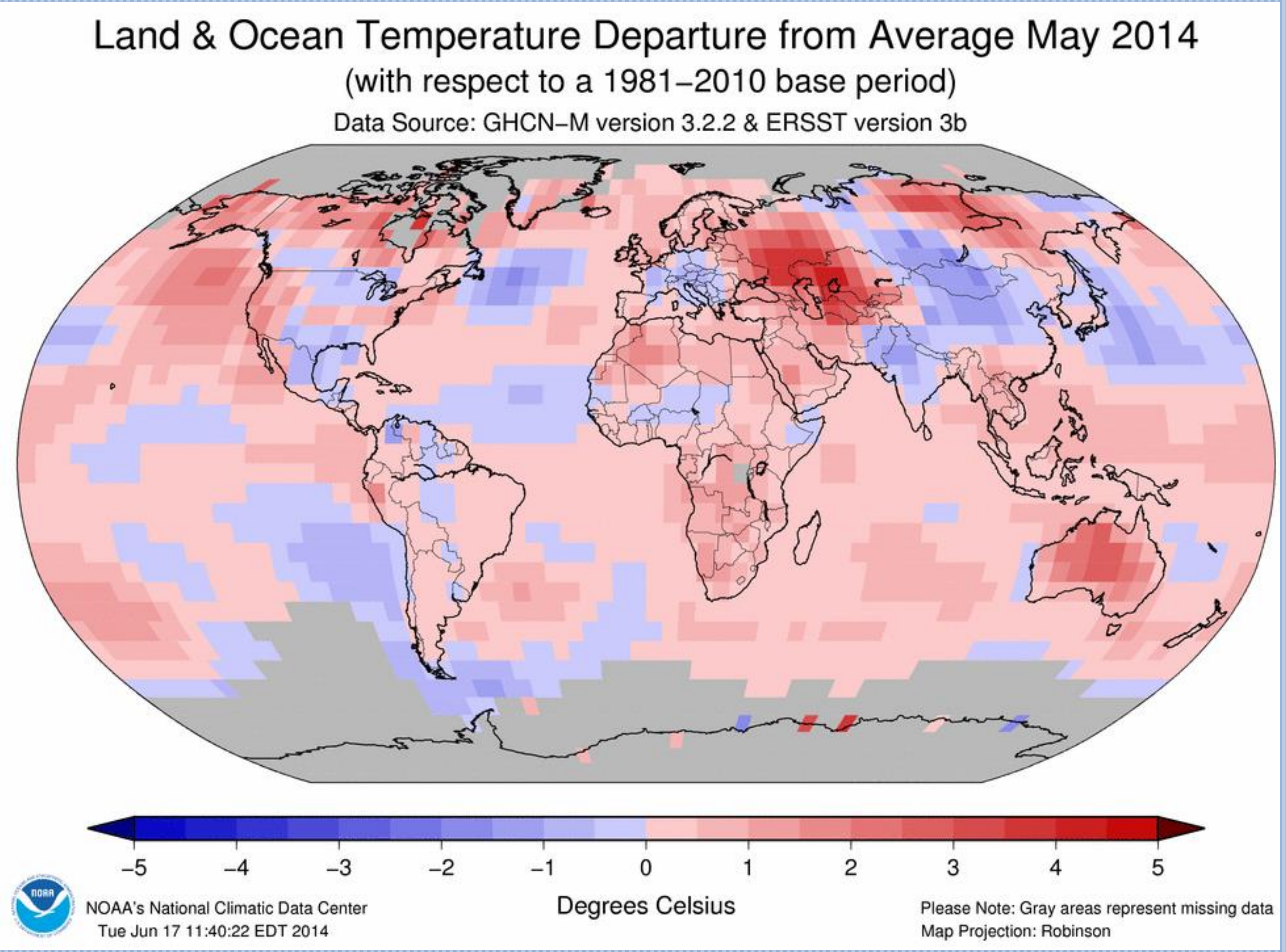
– Pacific conditions similar to 2009



Ascending air in Pacific has to subside somewhere…
Ashok et al., *GRL*, 2012

Monsoon 2014

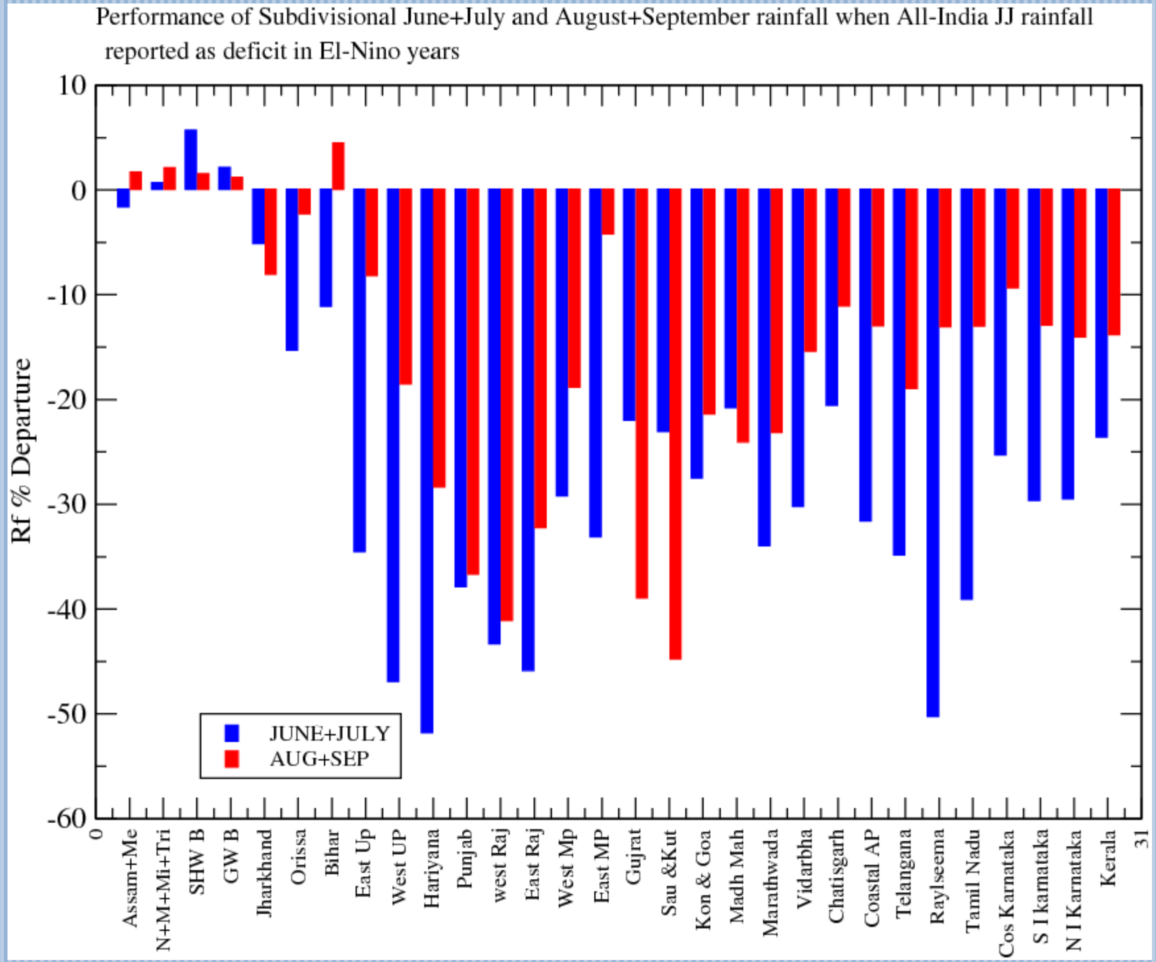
anomalous land-sea contrast?



Does the changes in thermal contrast have a role?
Mid-latitude incursion? Atlantic conditions – jet stream??

Monsoon 2014

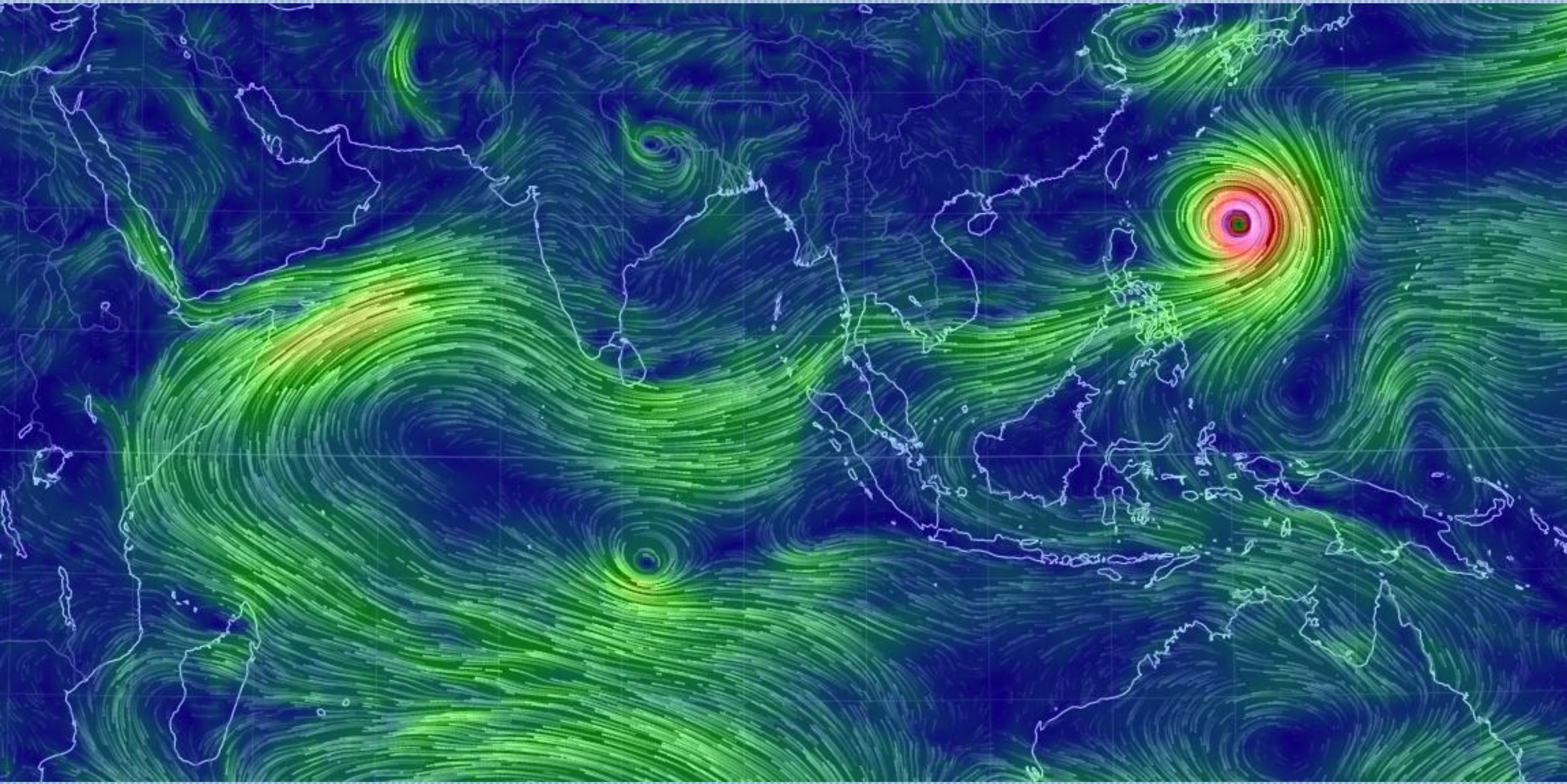
– will monsoon revive? some statistics…



The wind and SST anomaly pattern developed in June tend to persist through out the season. To develop such type of anomaly some global scale feature (like El Nino this year) must be responsible

Kothawale and Kulkarni, 2014, Under Review

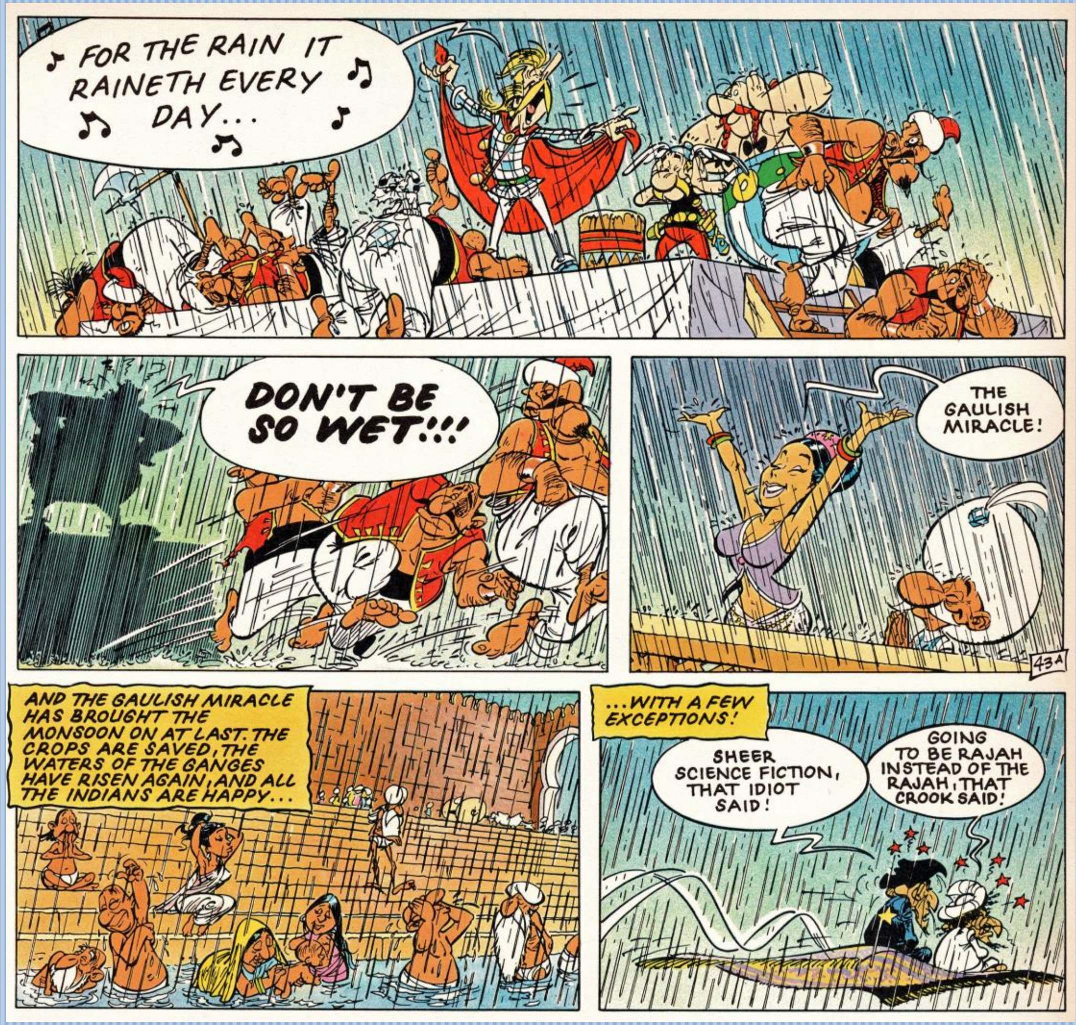
Monsoon 2014, this week
– super cyclone Neoguri pulling away the monsoon?



ERPAS IITM-Forecast: Enhanced cyclonic activity over West Pacific will hamper the intensification of monsoon over central India for next few days. Monsoon will intensify once the system over West Pacific move northwards. The central and peninsular India will receive good amount of rainfall after 10 July. Large scale MISO forecast suggests that monsoon activity will be strong over central India from 10-20 July and gradually shifting towards foothills.

Monsoon 2014

will cacofonix sing? will monsoon revive?



Thank You