Understanding the Indian monsoon behavior in a changing climate using the IITM Earth System Model - Implications for monsoon predictability

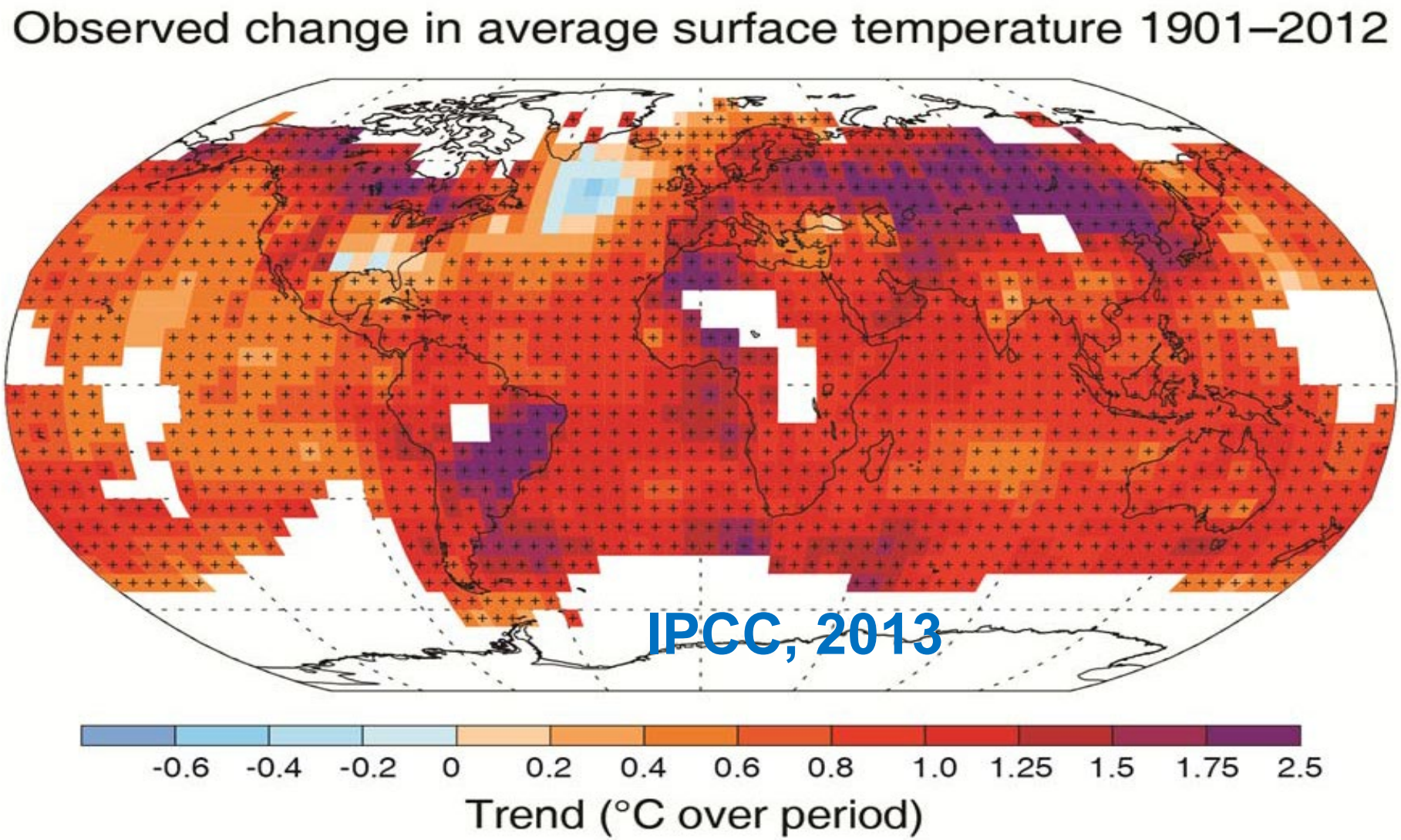
R. Krishnan
Centre for Climate Change Research (CCCR)
Indian Institute of Tropical Meteorology, Pune, India

Collaborators: P. Swapna, Ayantika Dey Choudhury, Prajeesh, Sandeep Narayansetti, Manmeet Singh, Ramesh Vellore, T.P. Sabin

National Centers for Environmental Prediction-Environmental Monitoring Center (NCEP-EMC)
Maryland, USA

15 May 2019

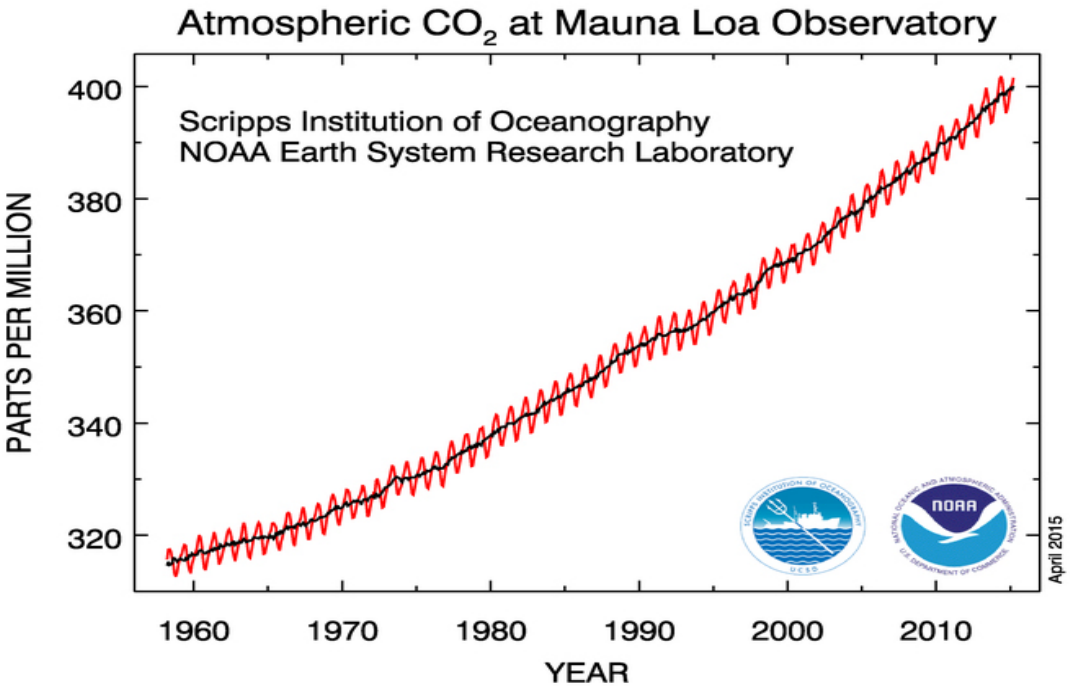
Recent climate change report



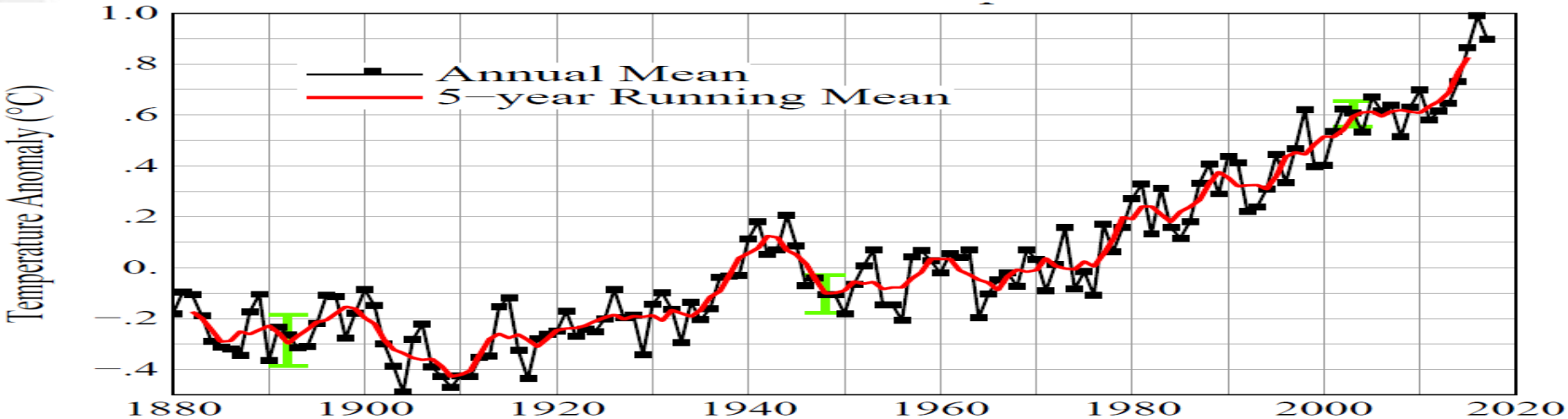
Planet has warmed by 0.85 K over 1880-2012

CO_2 problem

Charles Keeling

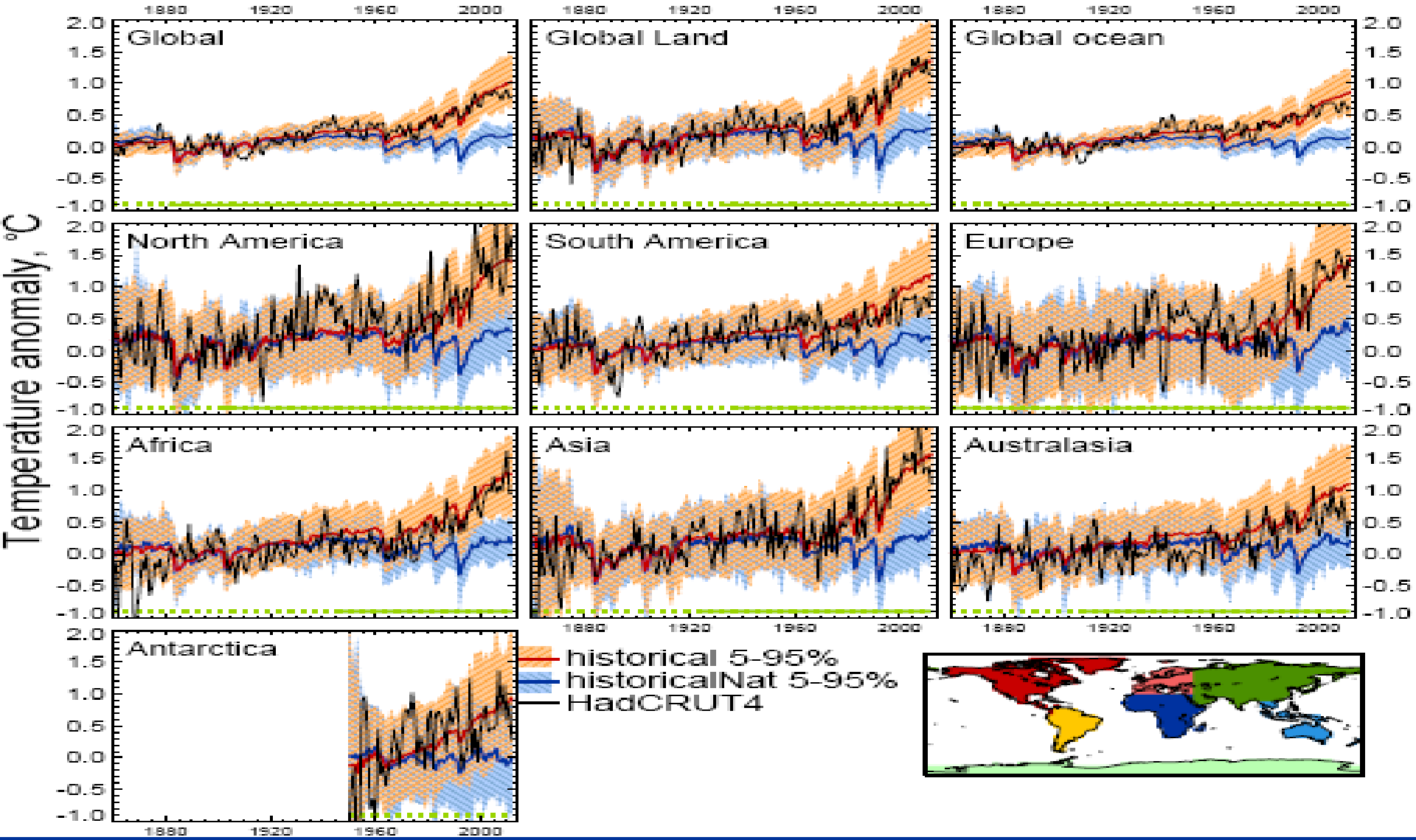


Time-series of global mean surface temperature index relative to base period 1951-1980

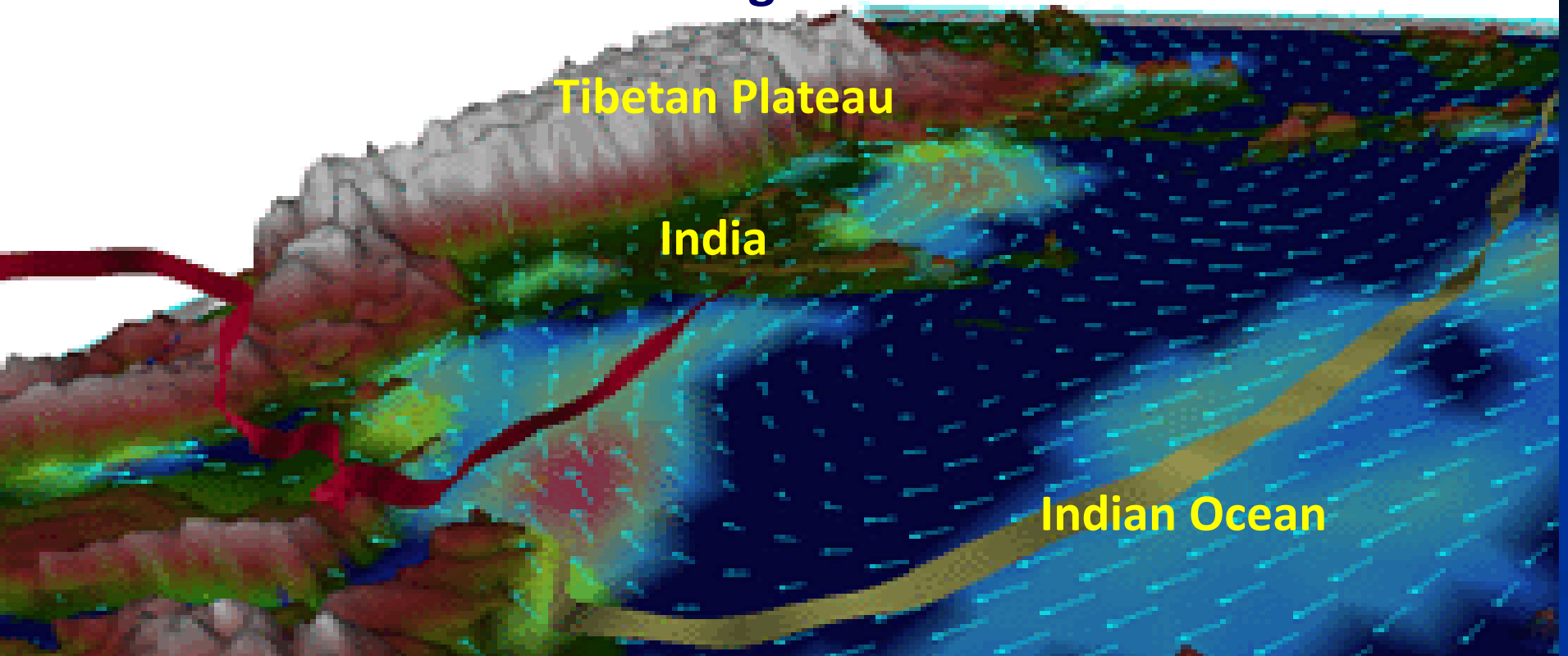


Source: https://data.giss.nasa.gov/gistemp/graphs/

IPCC: Warming of the Climate System is unequivocal



Influence of Climate Change on the Indian Monsoon ?

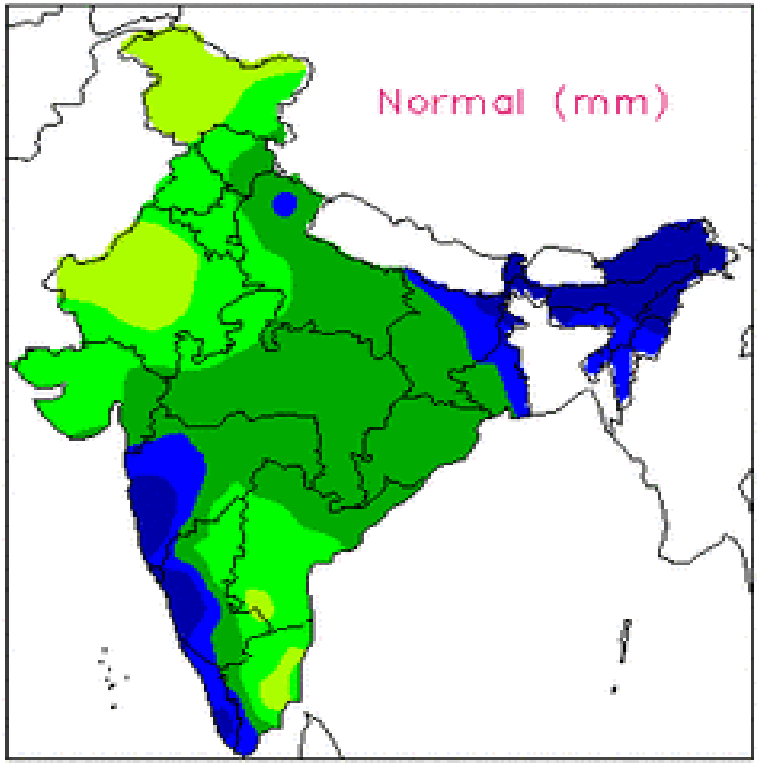


Monsoon circulation and rainfall: A convectively coupled phenomenon

Requires a thermal contrast between land & ocean to set up the monsoon circulation

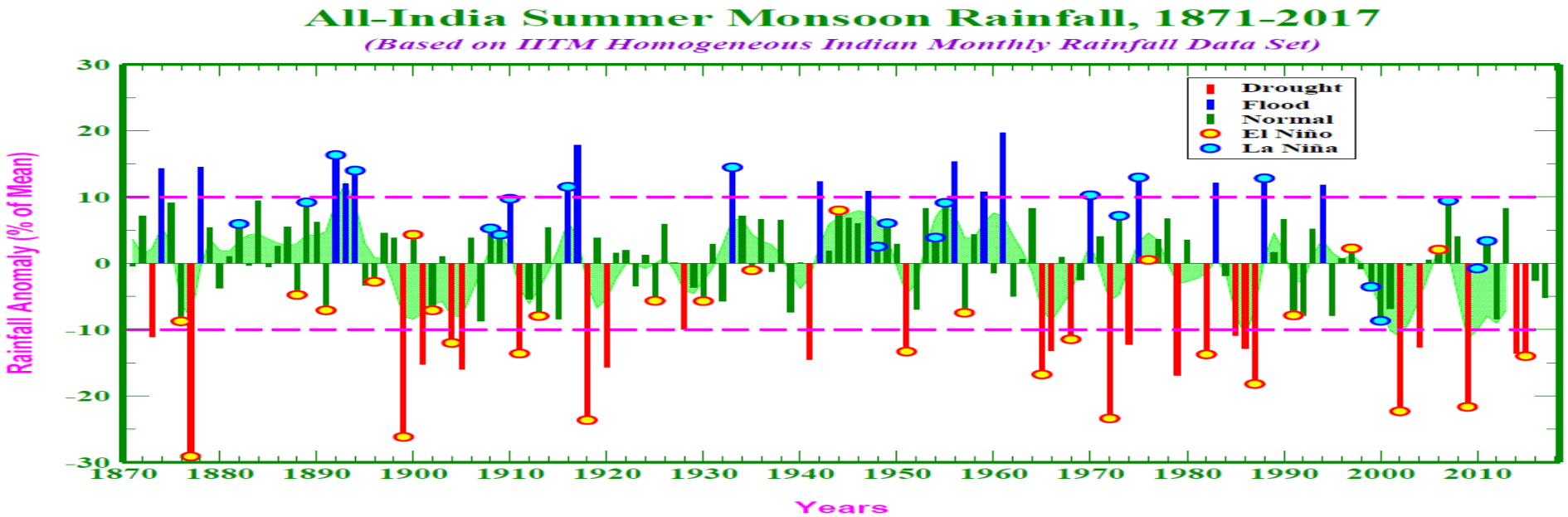
Once established, a positive feedback between circulation and latent heat release maintains the monsoon

The year to year variations in the seasonal (June – September) summer monsoon rains over India are influenced internal dynamics and external drivers

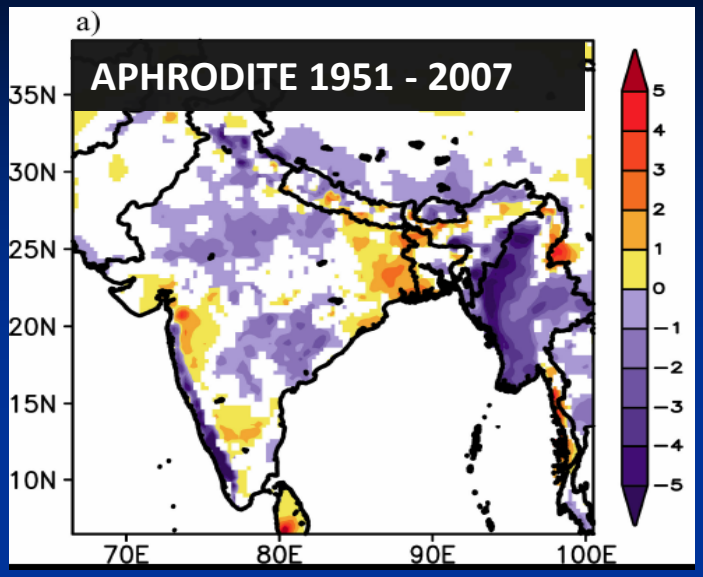


Long-term climatology of total rainfall over India during (1 Jun - 30 Sep) summer monsoon season (http://www.tropmet.res.in)

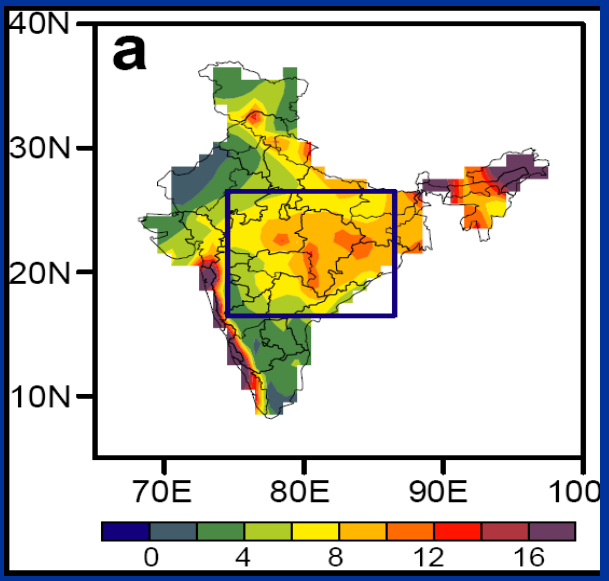
Interannual variability of the Indian Summer Monsoon Rainfall



Spatial map of linear trend of JJAS rainfall (1951 – 2007)

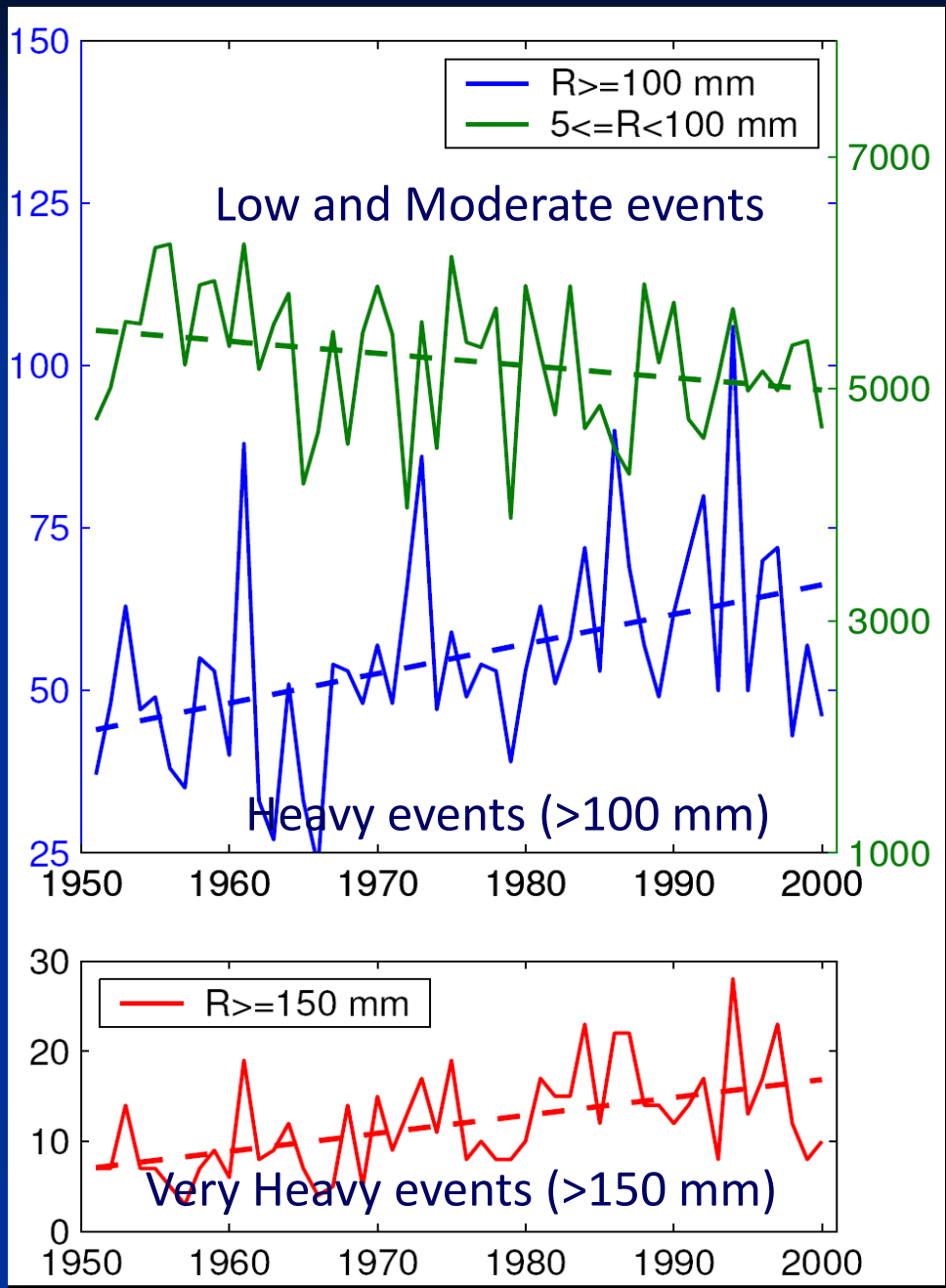


Increasing Trend of Extreme Rain Events over India in a Warming Environment

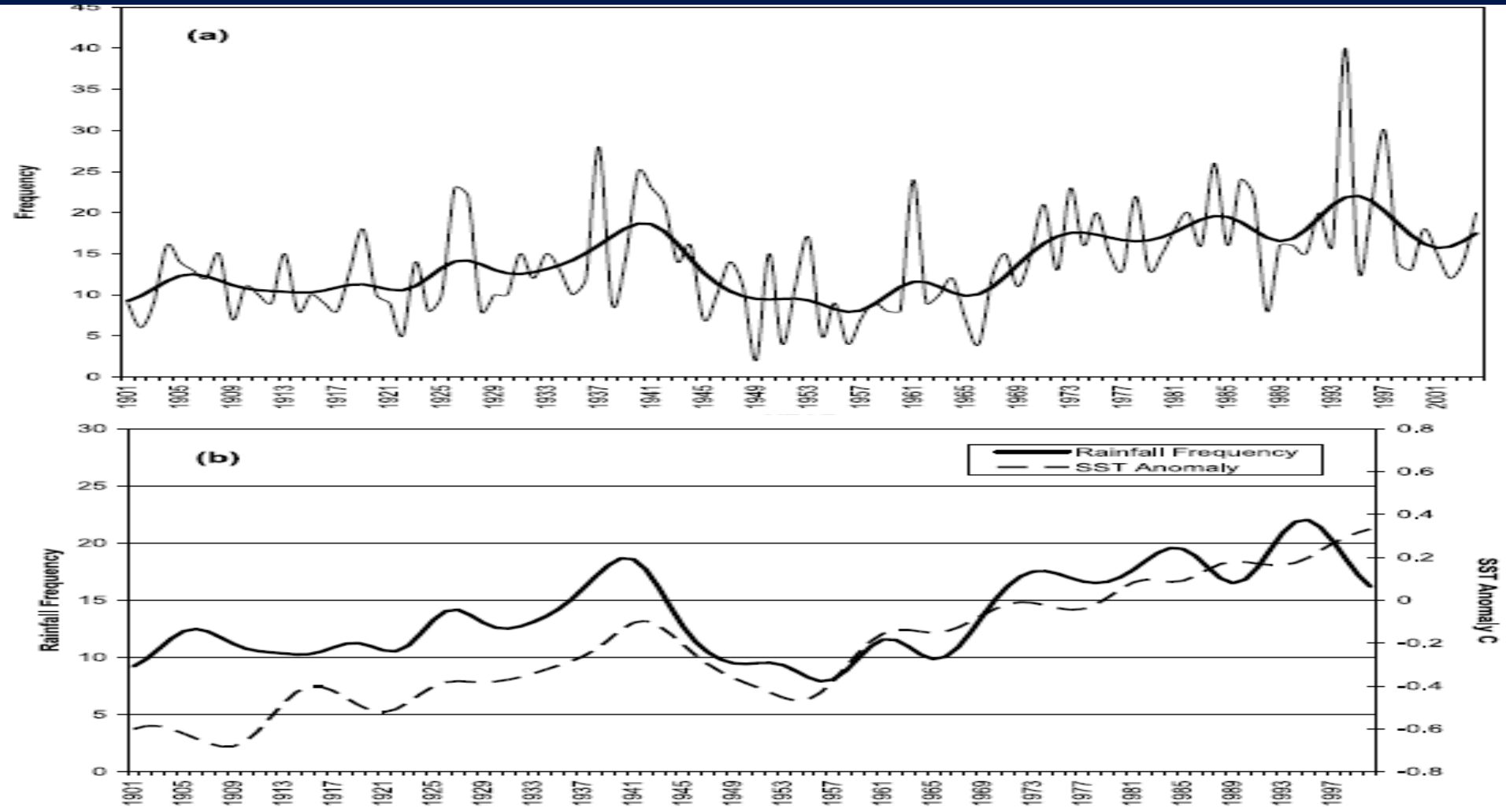


Goswami et al. 2006, Science

Time series of count over Central India



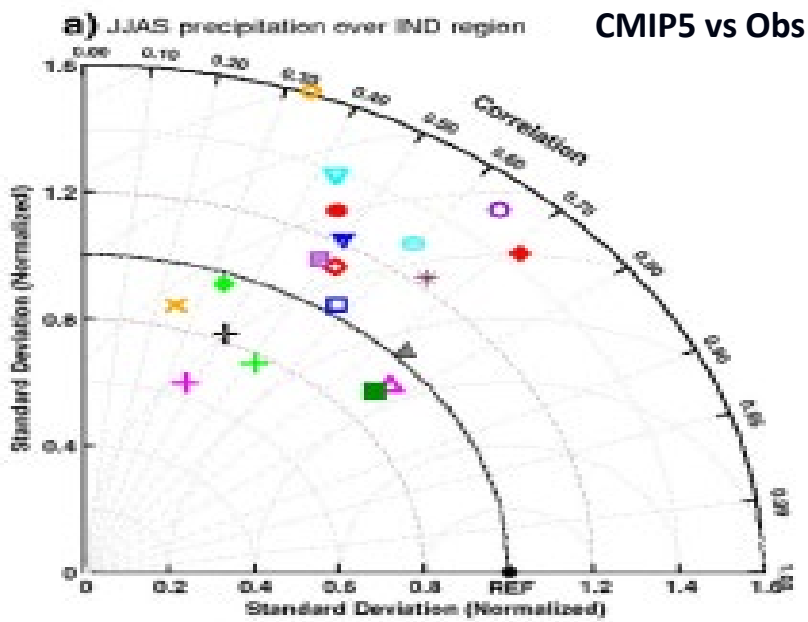
Interannual, Interdecadal and long-term trends of extreme rainfall events over Central India modulated by equatorial Indian Ocean SST variations –Rajeevan et al. 2008



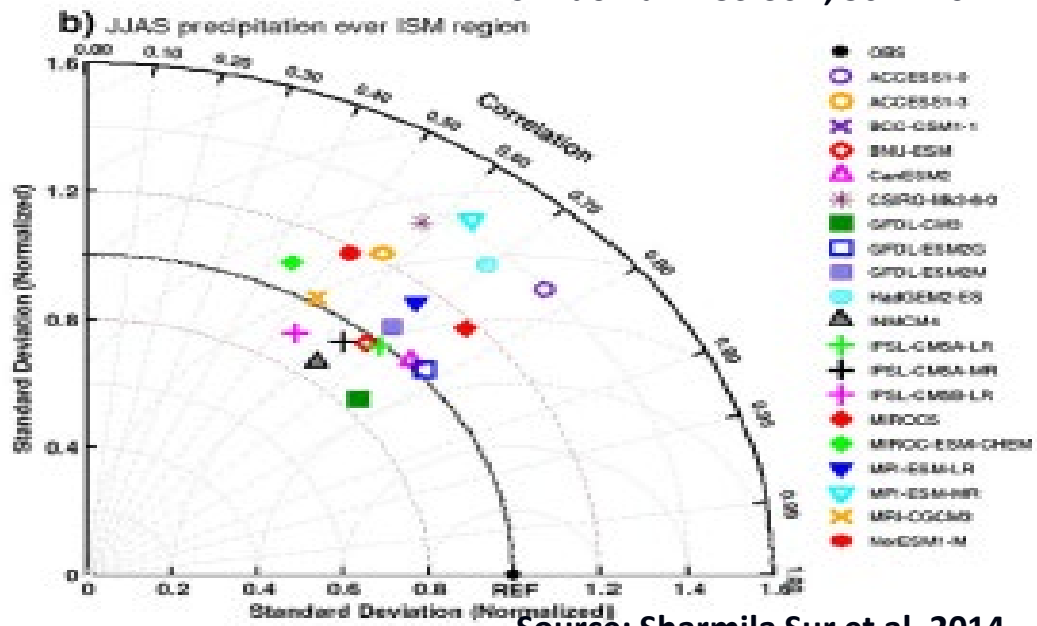
(a) Temporal variation of frequency of very heavy rainfall events (R > 150 mm/day) over Central India (thin line) and its smoothed variation (thick line) during 1901-2004 **(b)** Smoothed variation of frequency of very heavy rainfall events over central India and SST anomalies over Equatorial Indian ocean - Rajeevan et al. 2008 GRL

Wide variations among CMIP5/ CMIP3 models in capturing the South Asian monsoon

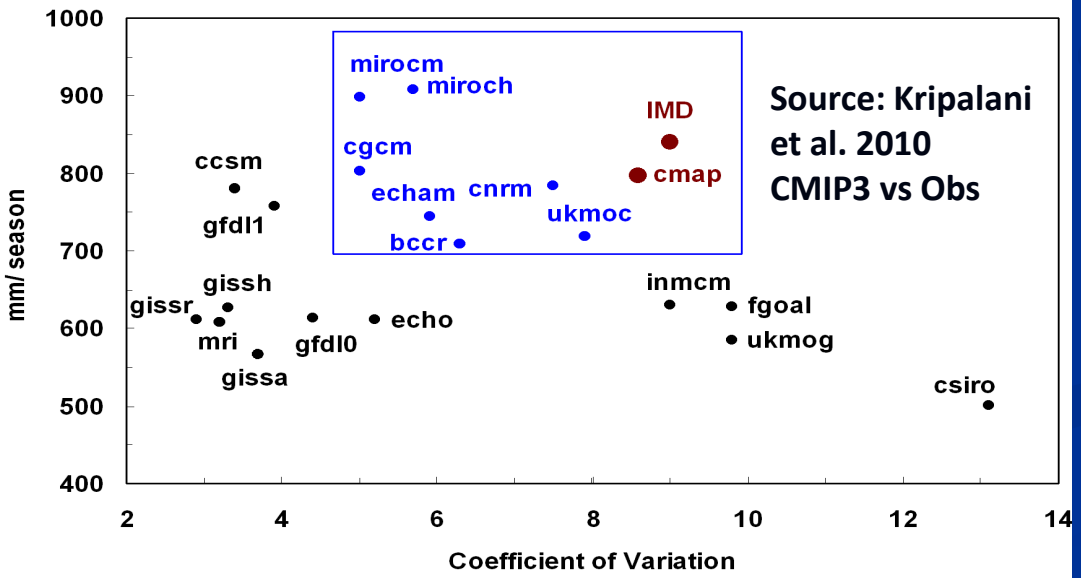
Indian Land:
CMIP5 vs Obs



ISM domain 15S-30N, 50E-120E



Source: Sharmila Sur et al. 2014



Source: Kripalani et al. 2010
CMIP3 vs Obs

Realism of present-day climate simulation is an essential requirement for reliable assessment of future changes in monsoon

Part 1: Development of the IITM Earth System Model (ESM)

Science of climate change

Detection, attribution & projection of global climate and regional monsoons, variability and change

Roadmap for Earth System Model (ESM) development

- Start with an atmosphere-ocean coupled model with realistic mean climate
  - Fidelity in capturing the global and monsoon climate
  - Realistic representation of monsoon interannual variability
  - Features of ocean-atmosphere coupled interactions
  - …
- Include components / modules of the ESM
  - Biogeochemistry
  - Interactive Sea-ice
  - Aerosol and Chemistry Transport
  - …

Basic modeling framework: Coupled Forecast System (CFS-2) T126L64

Formal agreement for collaboration: The Ministry of Earth Sciences, Govt. of India and NOAA, USA in 2011. Implement the NCEP CFS-2 model at IITM, Pune for seasonal prediction of the Indian monsoon.

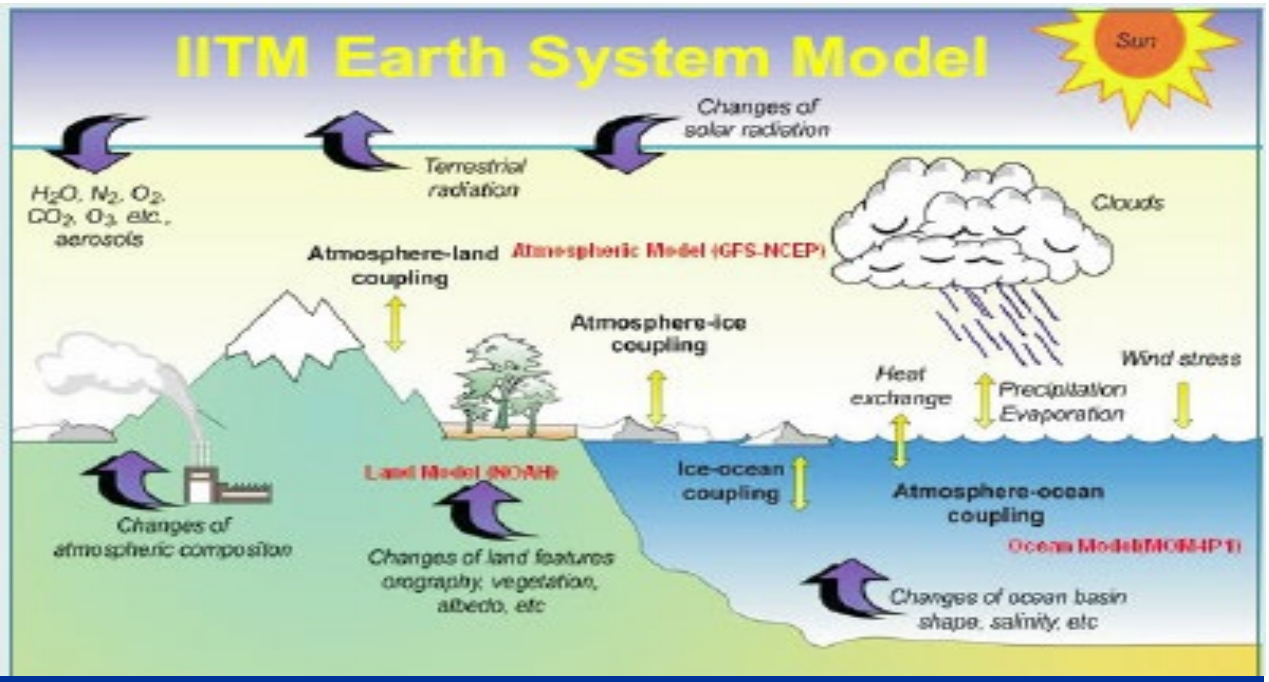
- The **NCEP CFS** Components
- Atmospheric **GFS (Global Forecast System) model**
  - – T126 ~ 110 km; vertical: 64 sigma – pressure hybrid levels
  - – Model top 0.2 mb
  - – Simplified Arakawa-Schubert convection (Pan)
  - – Non-local PBL (Pan & Hong)
  - – SW radiation (Chou, modifications by Y. Hou)
  - – Prognostic cloud water (Moorthi, Hou & Zhao)
  - – LW radiation (GFDL, AER in operational wx model)
  - - Land surface processes (Noah land model)
- Interactive Ocean: **GFDL MOM4** (Modular Ocean Model, ver.4)
  - – 0.5 deg poleward of 10°N and 10°S; and 0.25 deg near equator (10°S – 10°N)
  - – 40 levels
  - – Interactive sea-ice

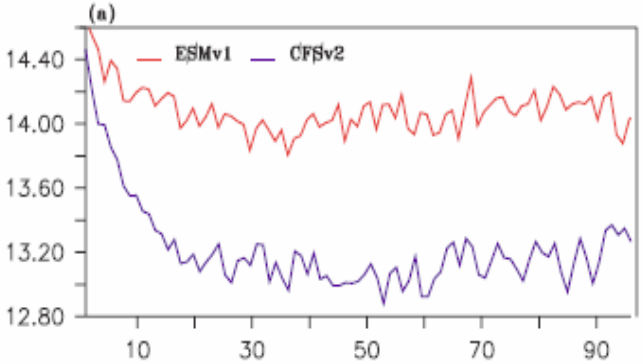
THE IITM EARTH SYSTEM MODEL

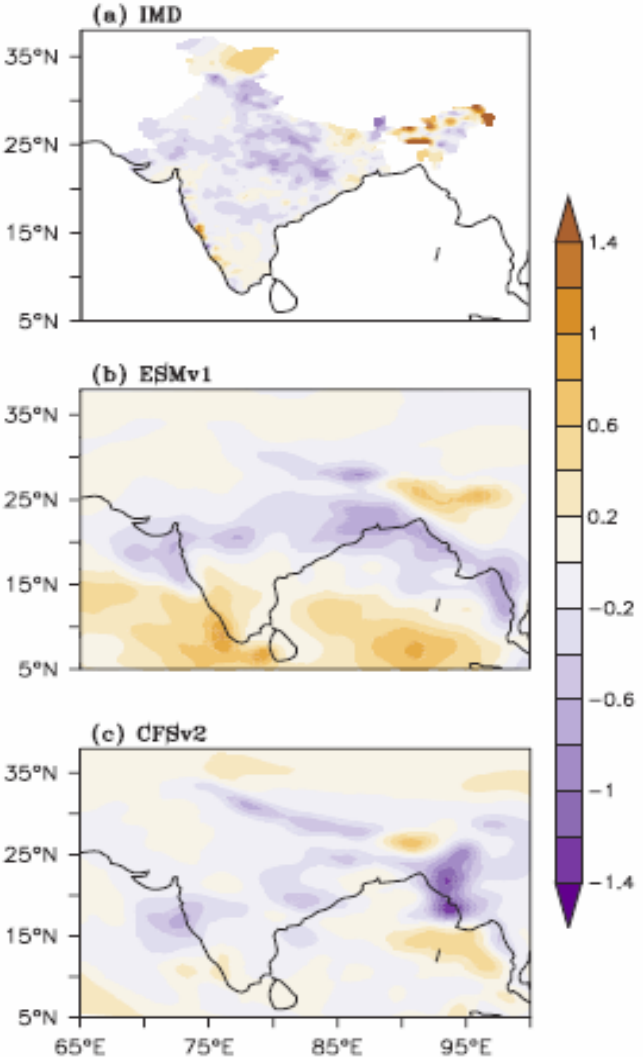
Transformation of a Seasonal Prediction Model to a Long-Term Climate Model

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

This work documents the fidelity of the newly developed Indian Institute of Tropical Meteorology climate model simulations and demonstrates its suitability to address the climate variability and change issues relevant to the South Asian monsoon.



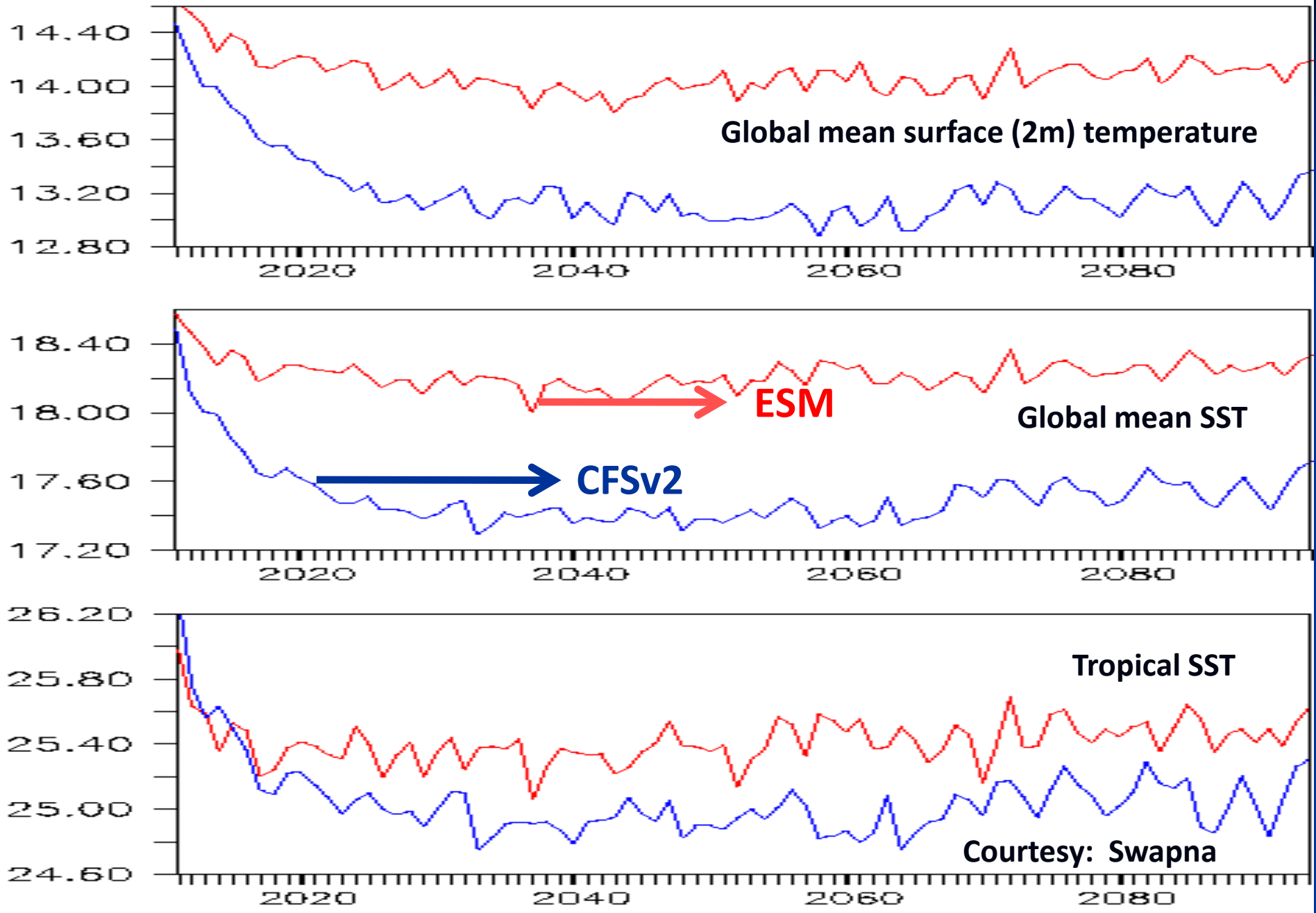




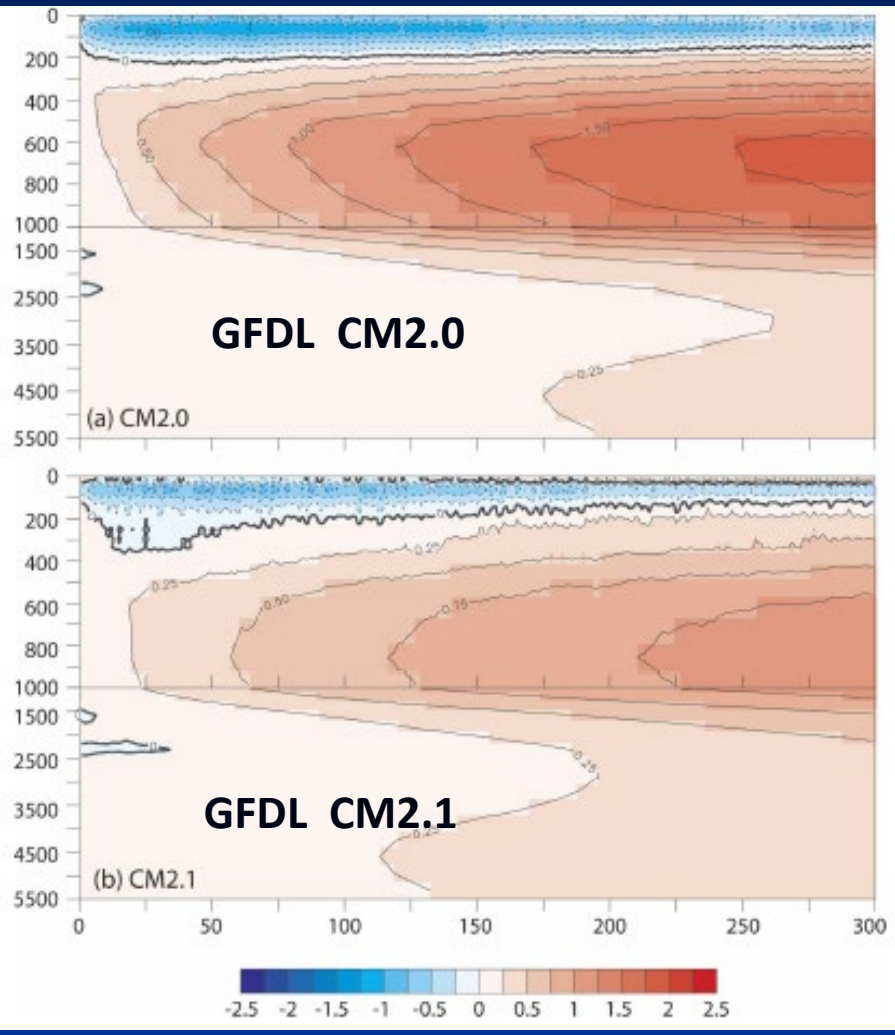
Atmosphere: T126 spectral (~ 190 km), 64 vertical levels – ESMv1

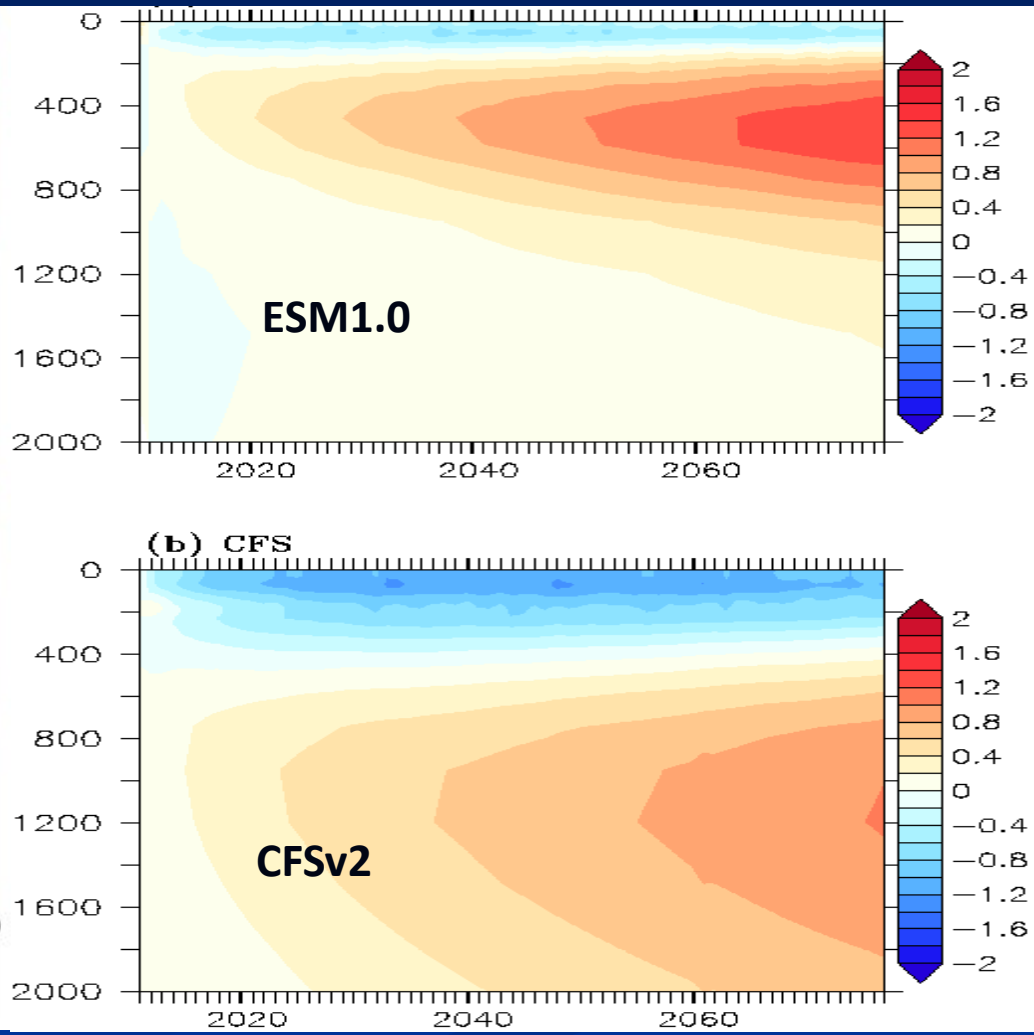
Ocean : 0.5 deg grid, ~ 0.25 deg between 10N-10S, 40 vertical levels

Annual mean temperature



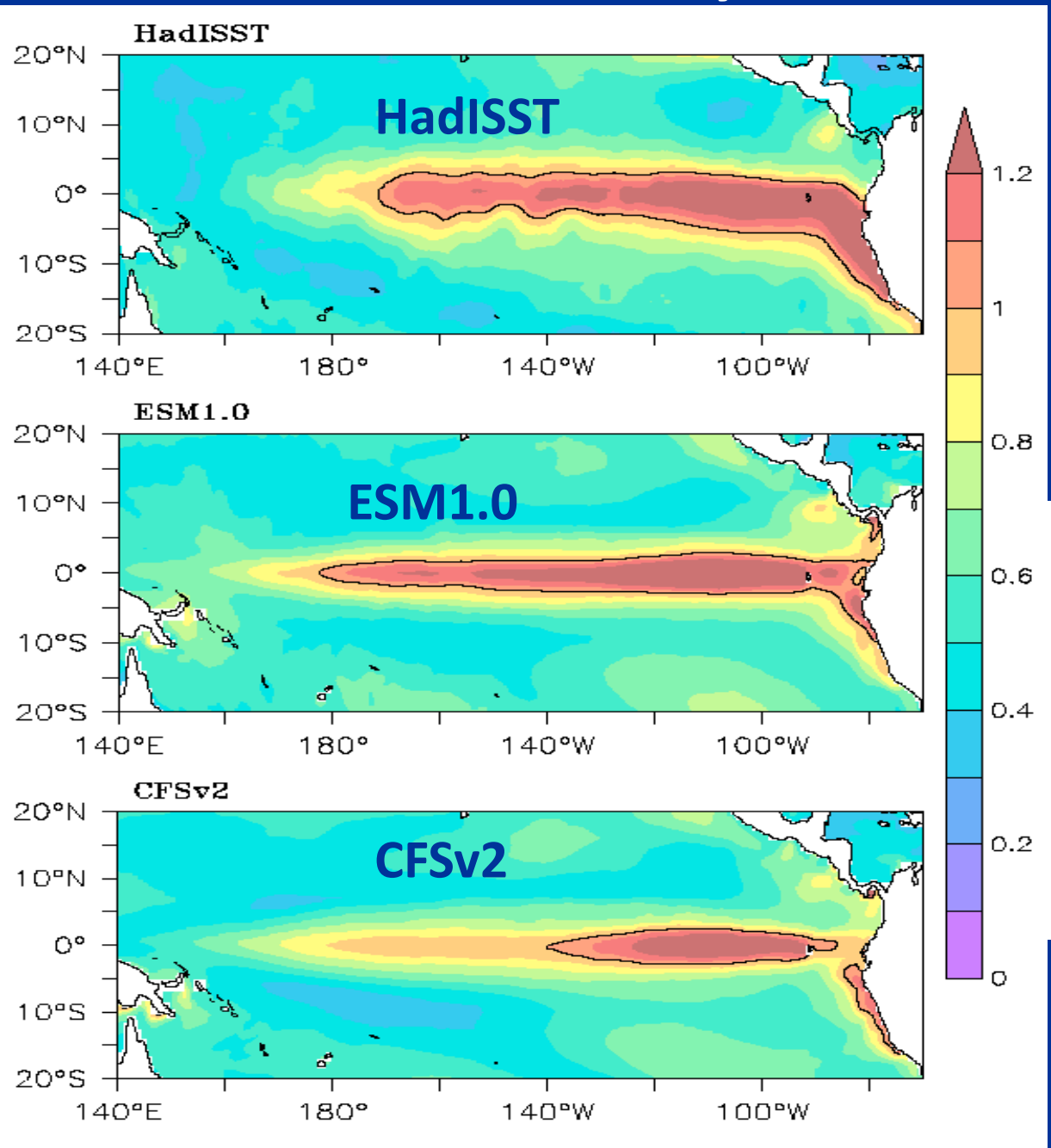
Coupled models drift towards a more equilibrated state. Initial rapid cooling of SST followed by warming trend. Significant subsurface drifts seen through multiple centuries of simulation. Vertical redistribution of heat with tendency of cooling in upper layers and warming in the sub-surface – Delworth et al. 2006



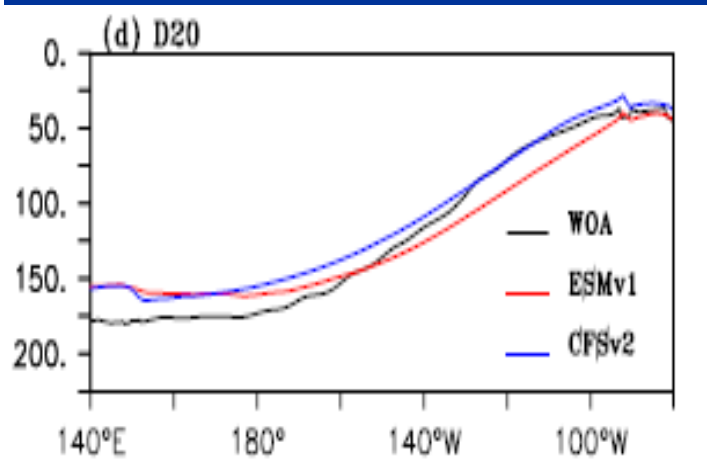


Differences between simulated and observed long-term global-mean ocean temperature as a function of depth and time.

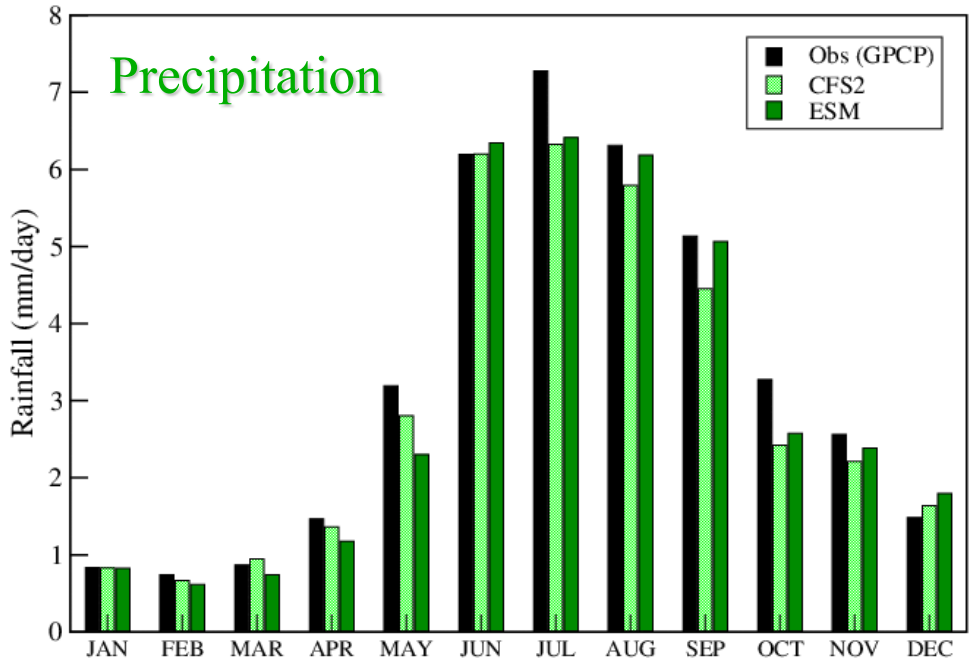
Interannual variability: Standard deviation of SST

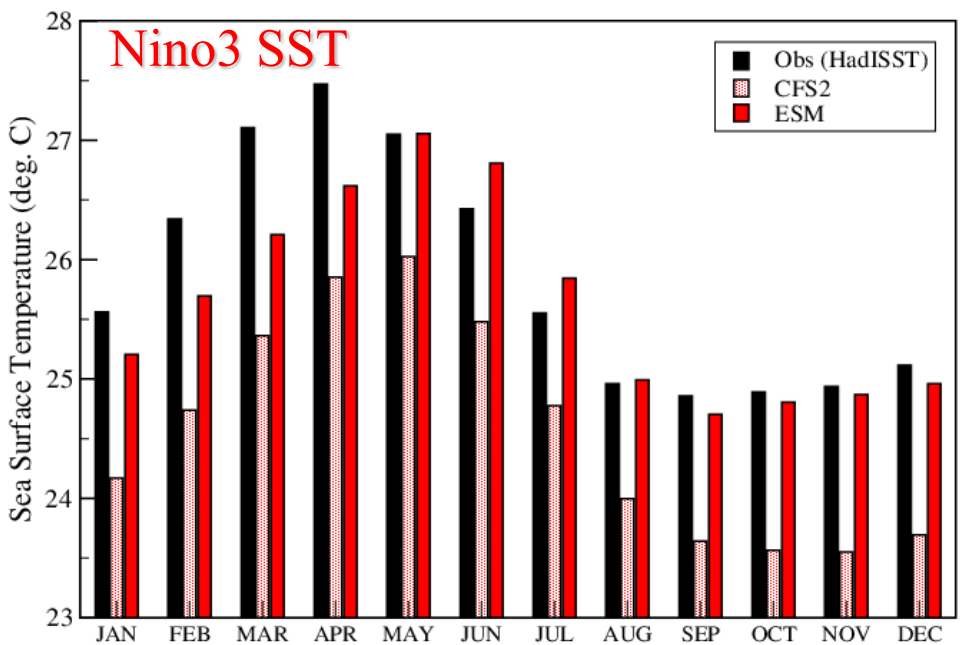


Interannual variability of Pacific SST in CFSv2 is mostly confined to the eastern equatorial Pacific; more realistic in ESM1.0



Courtesy: Swapna



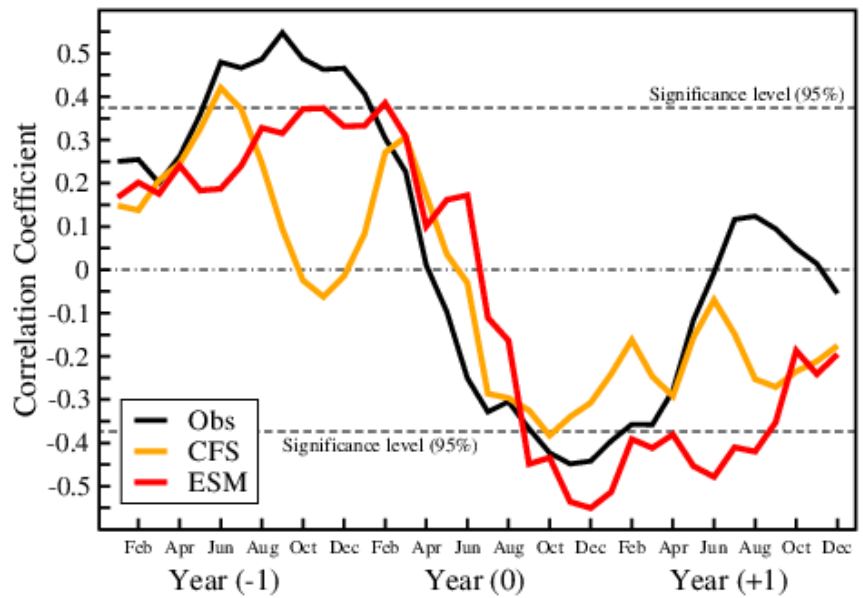


Precipitation

(5N-35N; 65E-95E)

Indian (land + ocean)

ENSO-Monsoon relationship

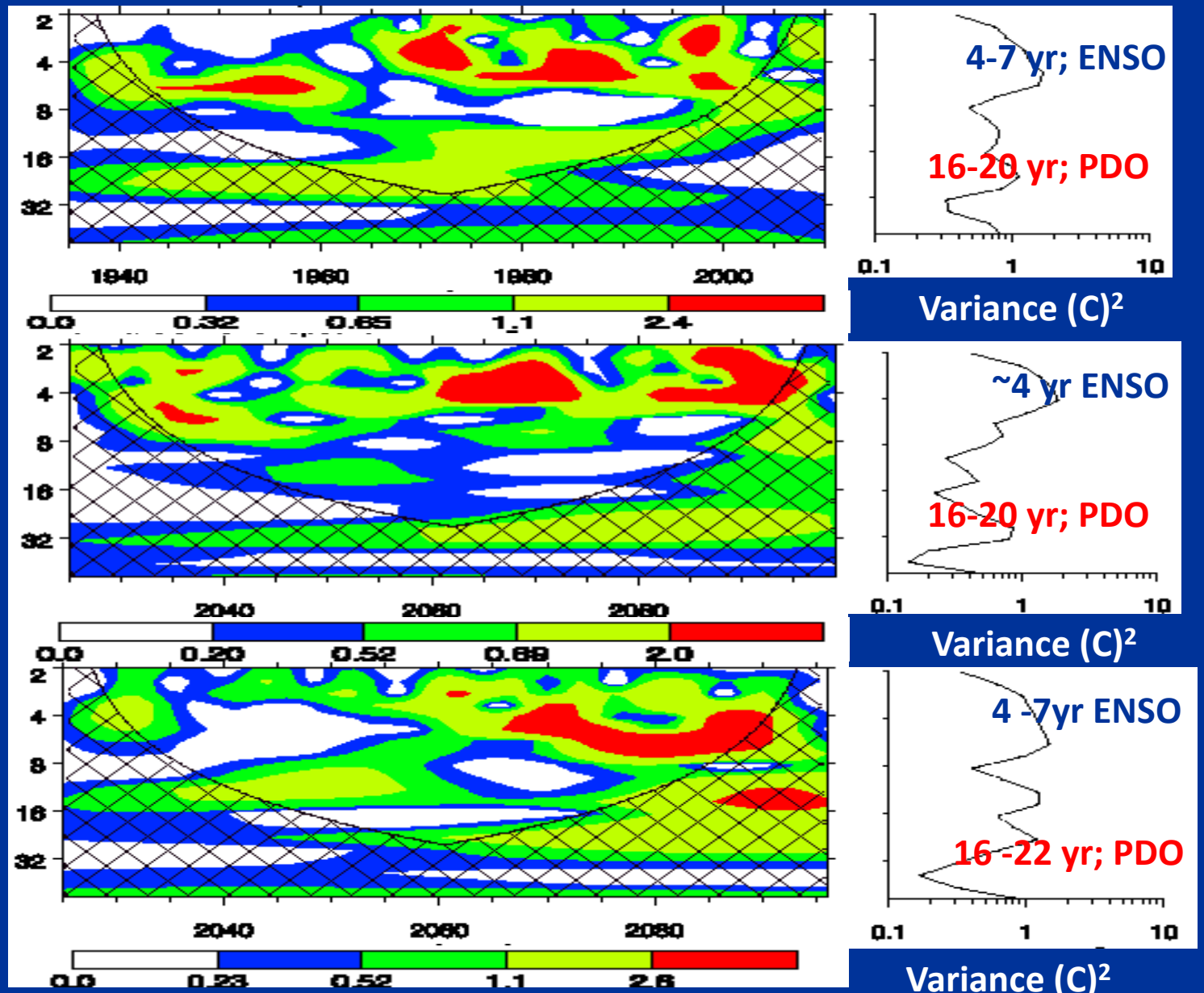


Lagged correlation between ISMR and Nino3 SST in the preceding/following months

CFS2 : 30 years (yr17-yr46)

ESM : 30 years (yr17-yr46)

Wavelet Power Spectrum of PC1 time-series. Power $(C)^2$ as a function of period and time



Courtesy: Swapna

Recent updates: IITM ESM Version 2

AGU100 ADVANCING EARTH AND SPACE SCIENCE

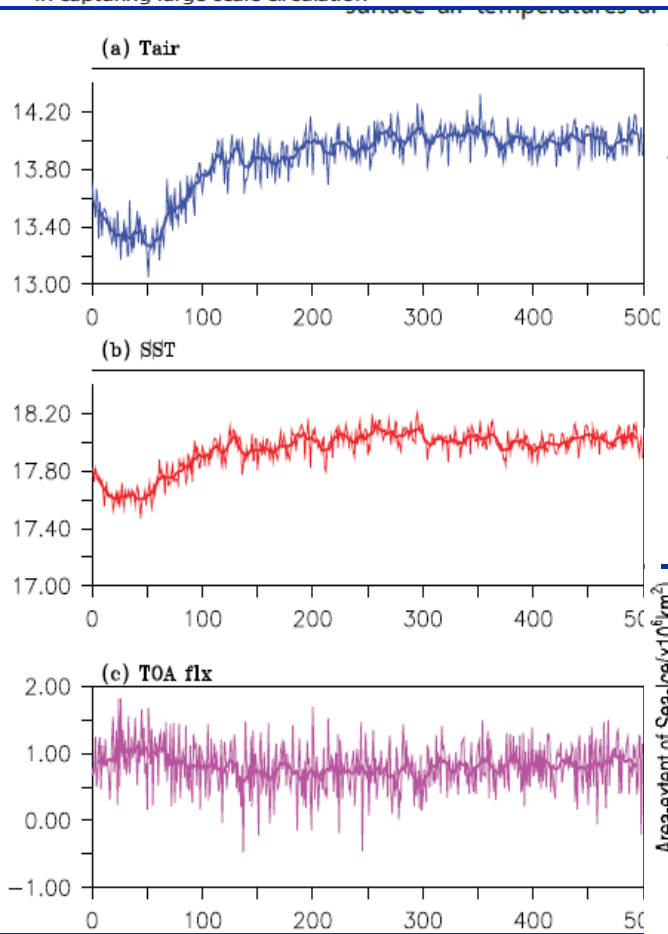
Journal of Advances in Modeling Earth Systems

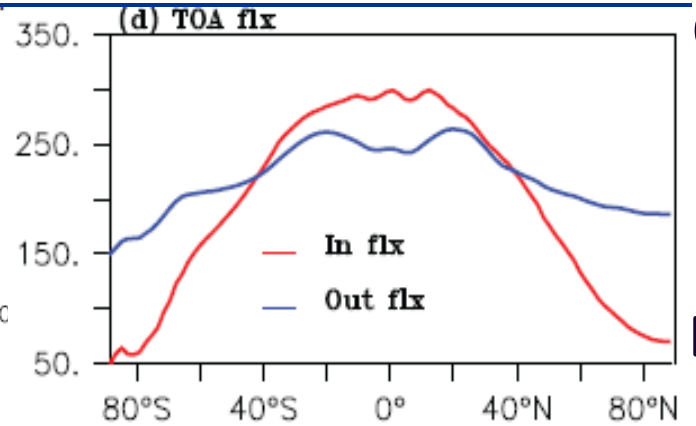
RESEARCH ARTICLE
10.1029/2017MS001262

Long-Term Climate Simulations Using the IITM Earth System Model (IITM-ESMv2) with Focus on the South Asian Monsoon

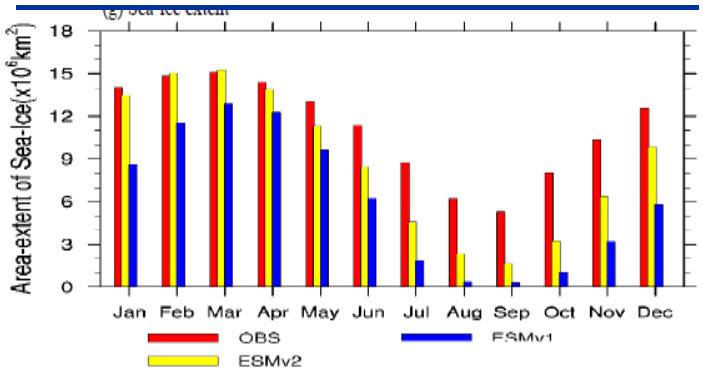
P. Swapna[1], R. Krishnan[1], N. Sandeep[1], A. G. Prajeesh[1], D. C. Ayantika[1], S. Manmeet[1], and R. Vellore[1]

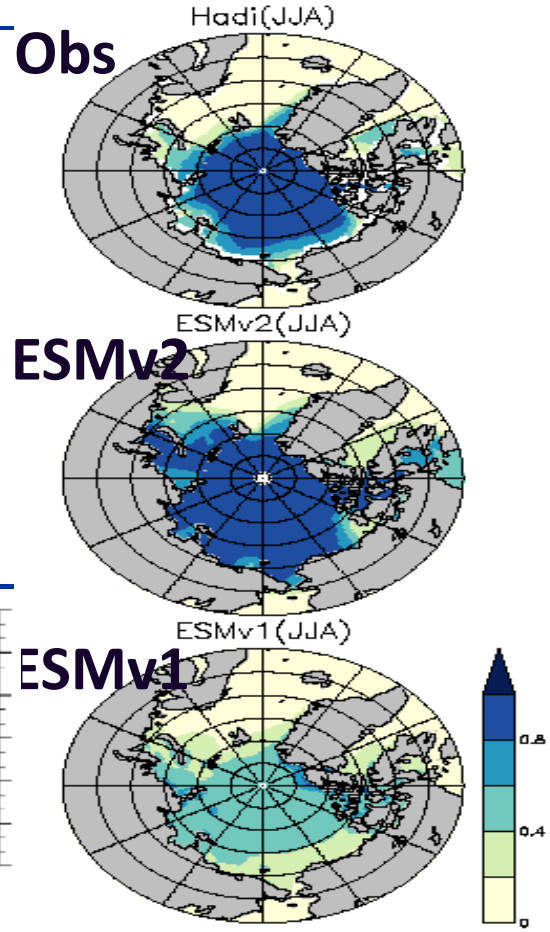
Key Points:
- IITM-ESMv2 simulations show fidelity in capturing large-scale circulation





Improved simulation of NH sea-ice during JJA





IITM-ESM for long-term climate change studies

Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune

Atmosphere : GFS (Global Forecast System)

T62 ; vertical: 64 sigma – pressure hybrid levels

Resolution ~200 km

Model top 0.2 mb

Prescribed MAC-v2 aerosols

Land surface : Noah LSM

Ocean: Modular Ocean Model v4p1 (MOM4p1)

Tripolar; 360x200 ; 1 deg poleward ; 0.33 deg near equator

50 levels ; Top grid cell 5m

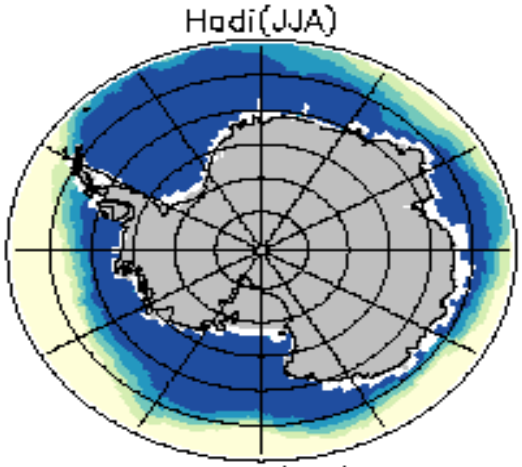
Ocean Biogeochemistry : TOPAZ

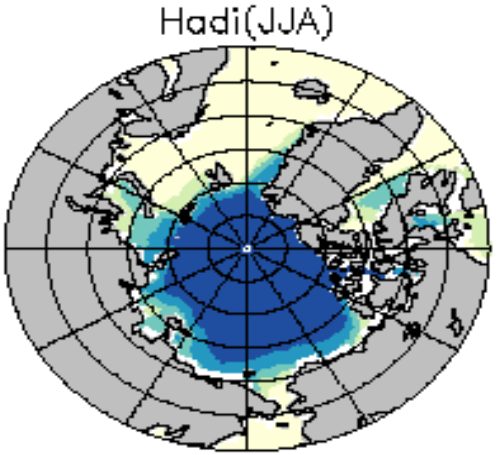
Ice Model : Sea Ice Simulator

Energy Balance in IITM ESM

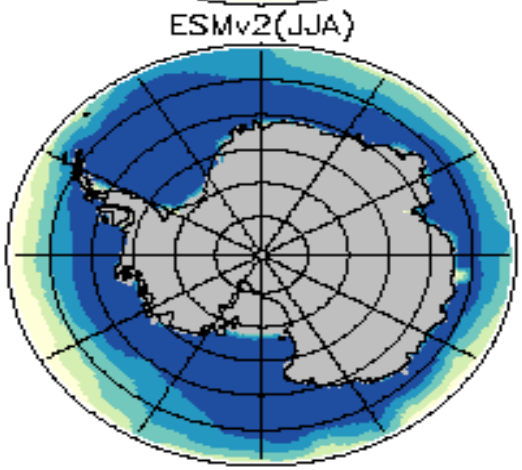
	Net flux TOA ($W\ m^{-2}$)	Net Flux Surface ($W\ m^{-2}$)	Difference ($W\ m^{-2}$)
ESMv1 (T126)	**6.6**	**1.2**	**5.4**
ESMv2 (T62)	**0.80**	**0.75**	**0.05**

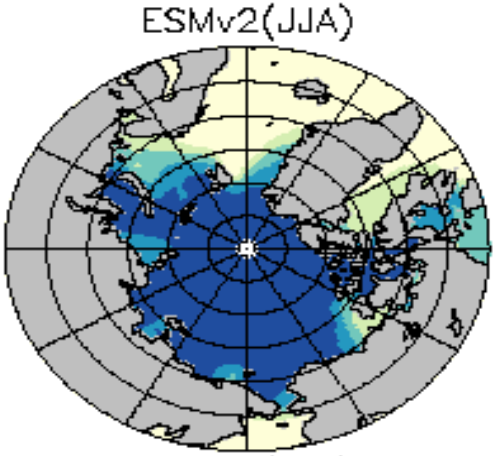
Sea-Ice concentration





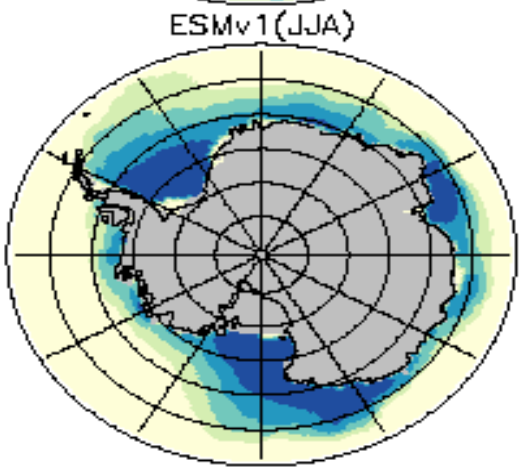
Obs

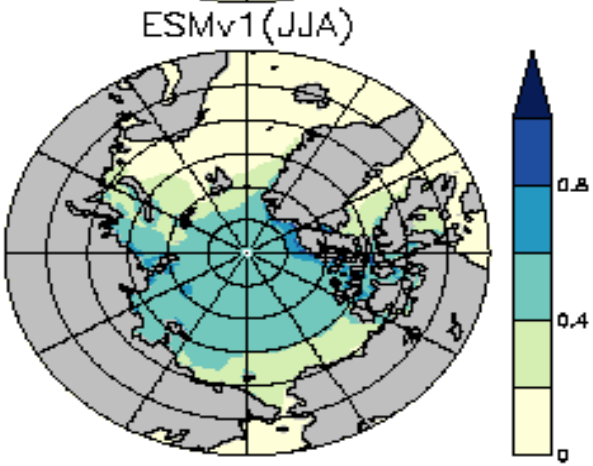




ESMv2

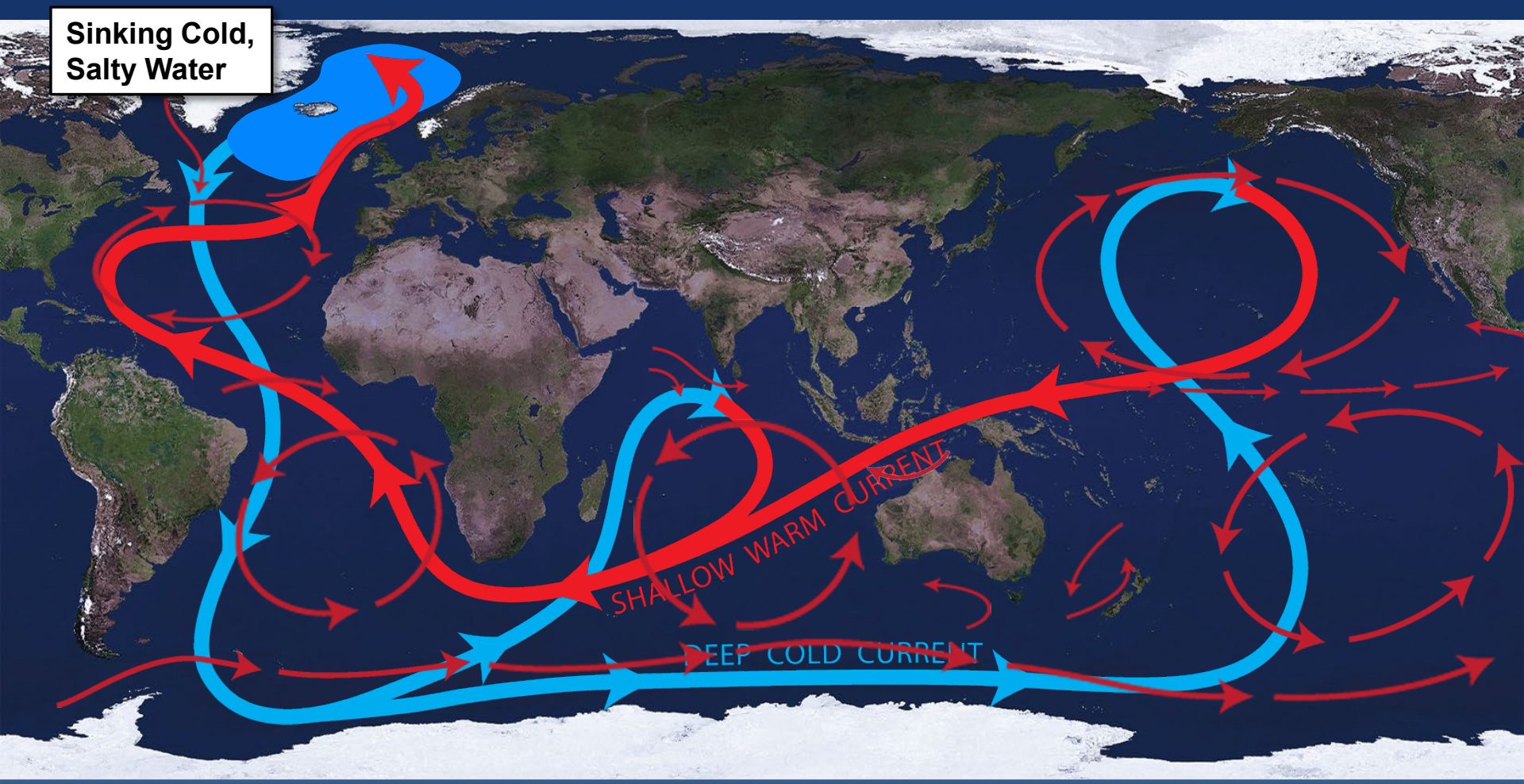
Improved simulation of NH sea-ice during JJA





ESMv1

Thermohaline Circulation (THC)
Global Conveyor Belt



Ocean-Atmosphere coupled feedbacks in IITM-ESM

Radiatively balanced coupled model framework

ESMv1: Flux computation over ice-covered regions in both GFS (atmosp) and MOM4p1 (Ocean).

ESMv2: Flux computation over ice-covered regions from MOM4p1 (Ocean)

ESMv2: Partial grid implementation for computation of fluxes atmosphere-Ocean-Ice

Improved representation of sea-ice

Reduced freshening in the North Atlantic

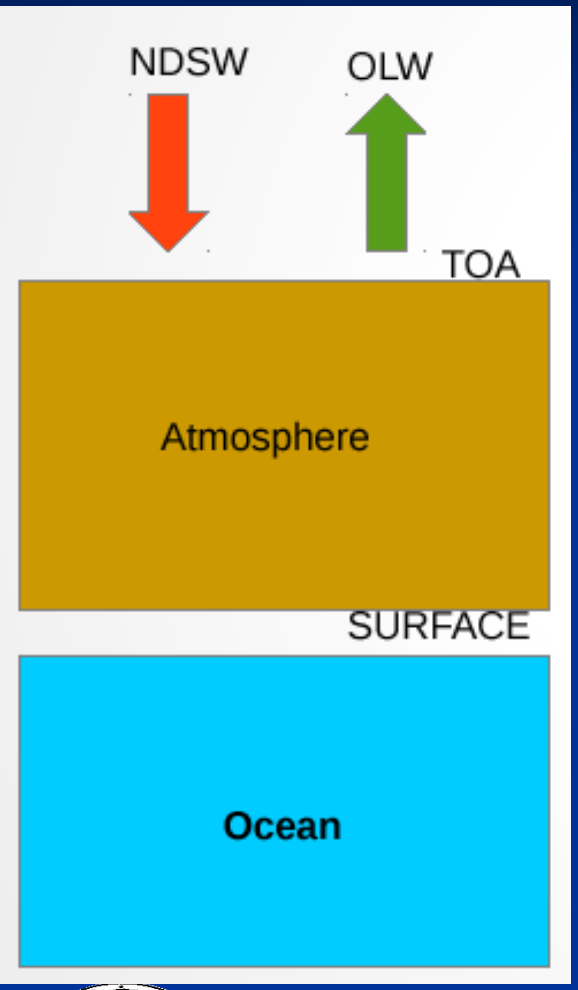
Realistic representation of AMOC

Improvement in the cross equatorial heat transport

Improved global mean circulation

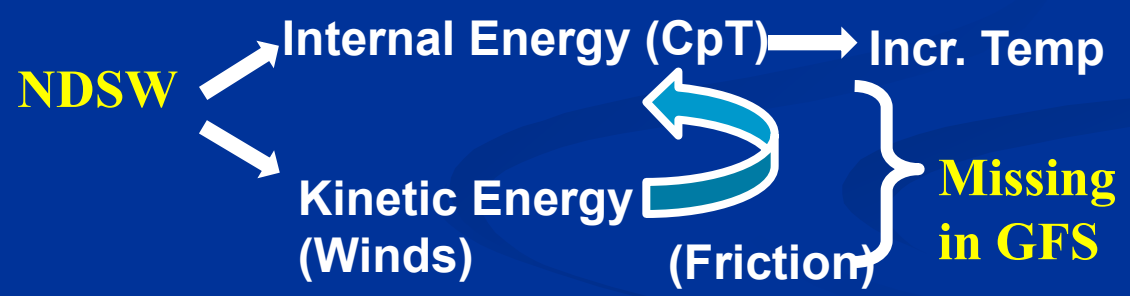
Courtesy: P. Swapna

TOA Energy Balance



NDSW – Net downward Short wave flux at TOA

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



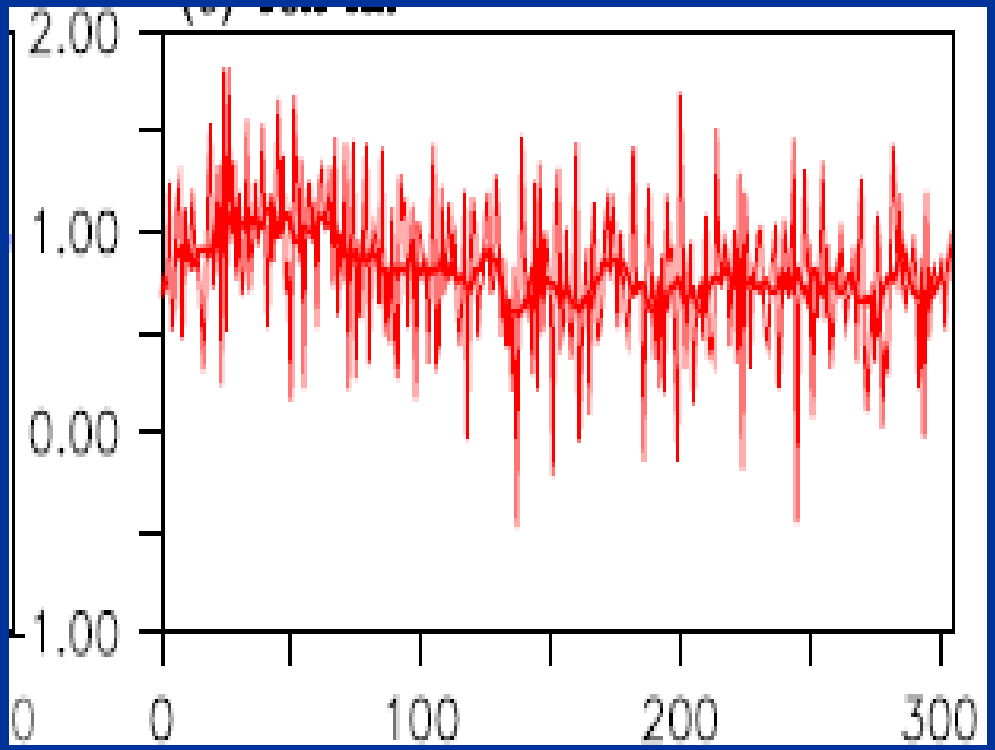
TKE dissipation heating (Han)

$$\varepsilon = \underbrace{-K_h \frac{g}{\theta_v}\frac{d\theta_v}{dz}}_{\text{buoyancy production}} + \underbrace{K_m \left|\frac{d\mathbf{u}}{dz}\right|^2}_{\text{shear production}}$$

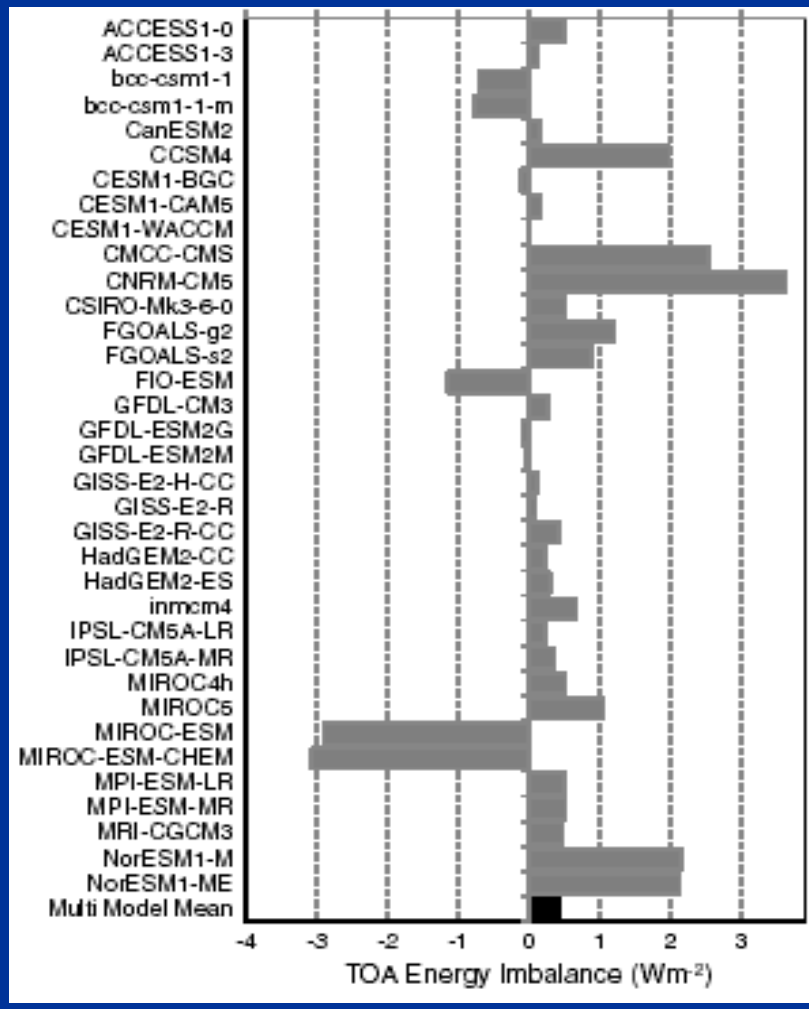
Minimize atmospheric energy loss – Bretherton et al. 2012

Courtesy: Prajeesh

Energy Balance in IITM ESMv2



TOA Energy Imbalance (CMIP5 Models)

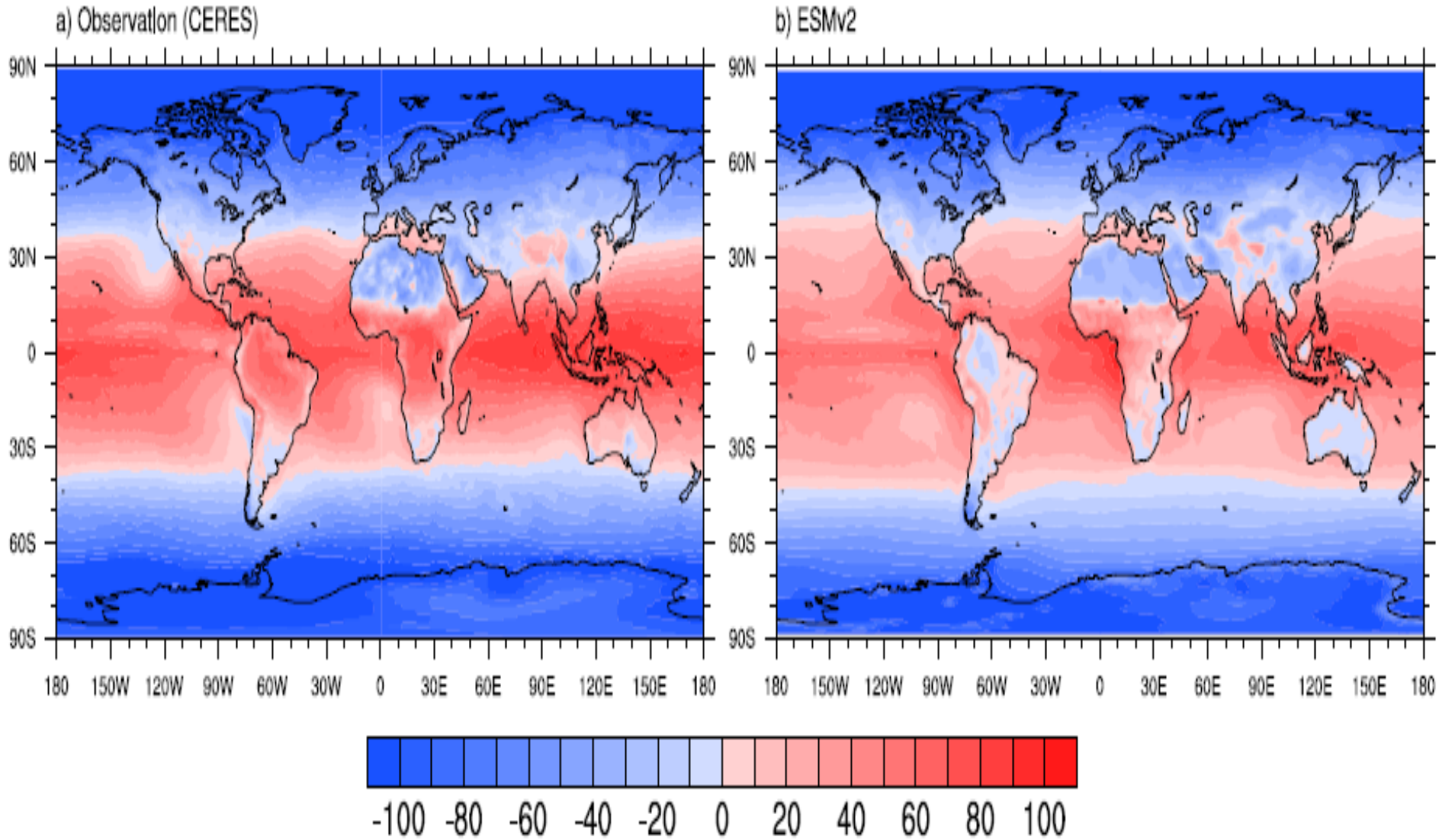


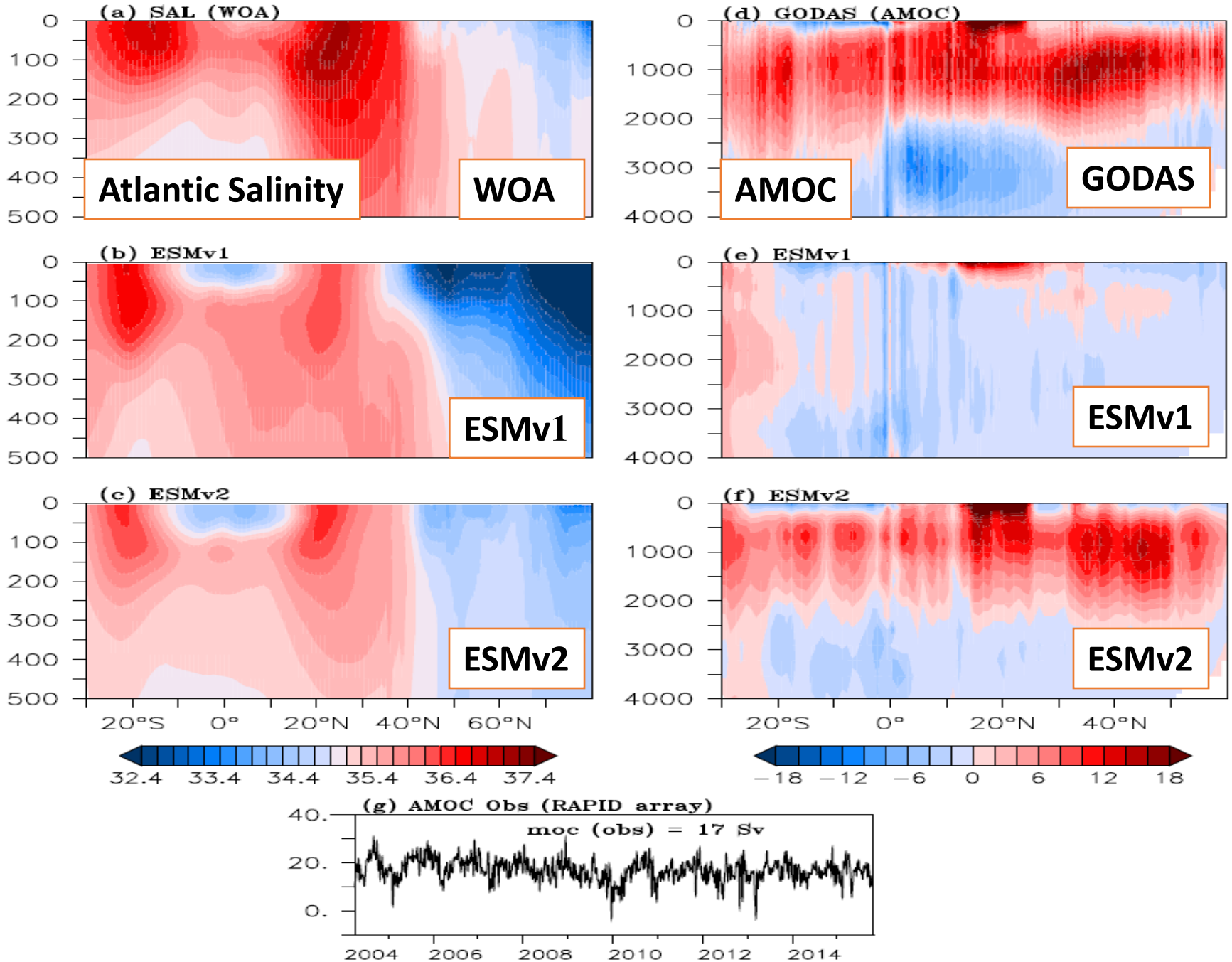
Preindustrial TOA (Wm^{-2}) Energy imbalance for CMIP5 Models (Forster et al., 2013)

Net Radiation (W m^{-2}) at TOA

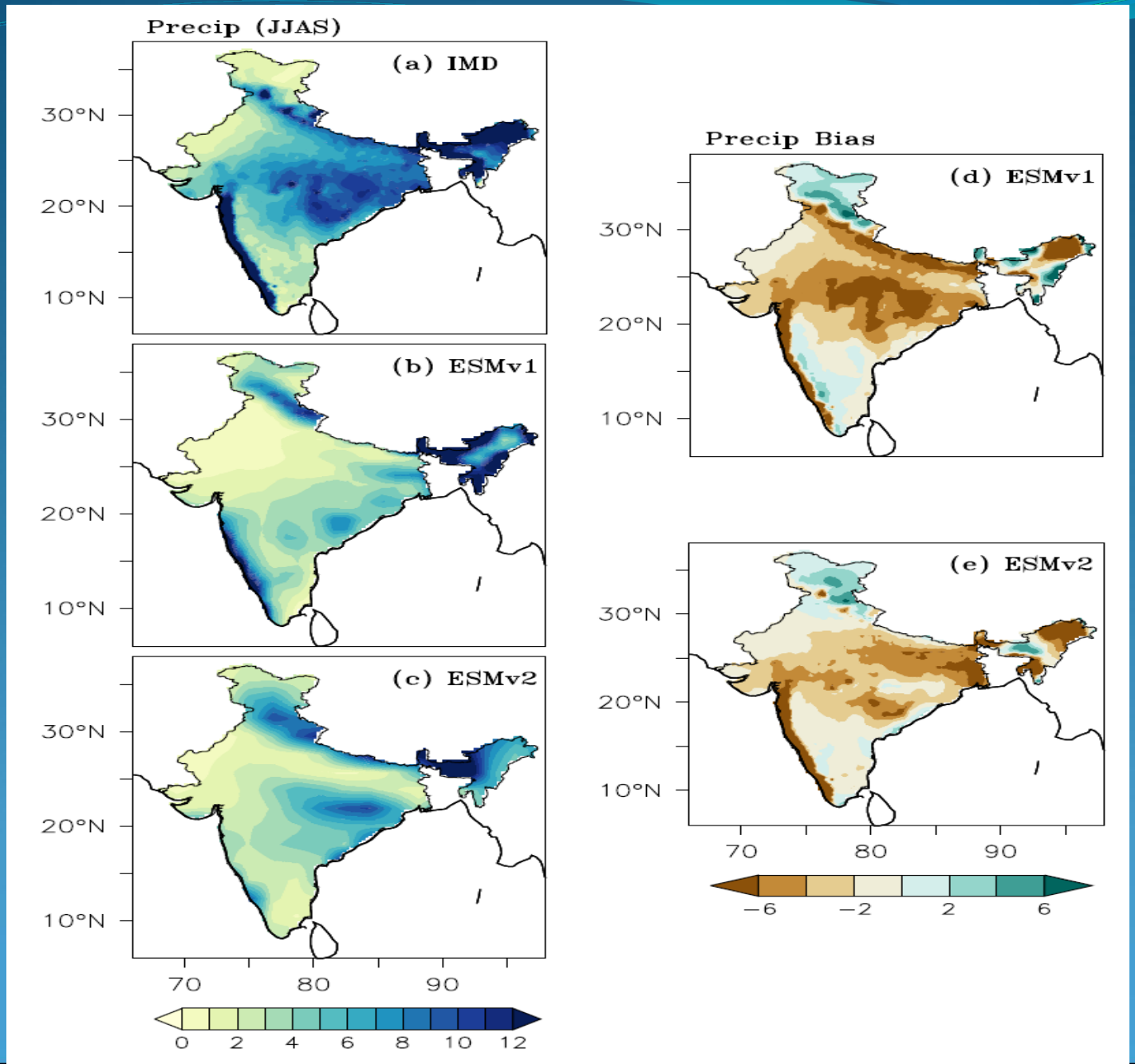
Obs (CERES)

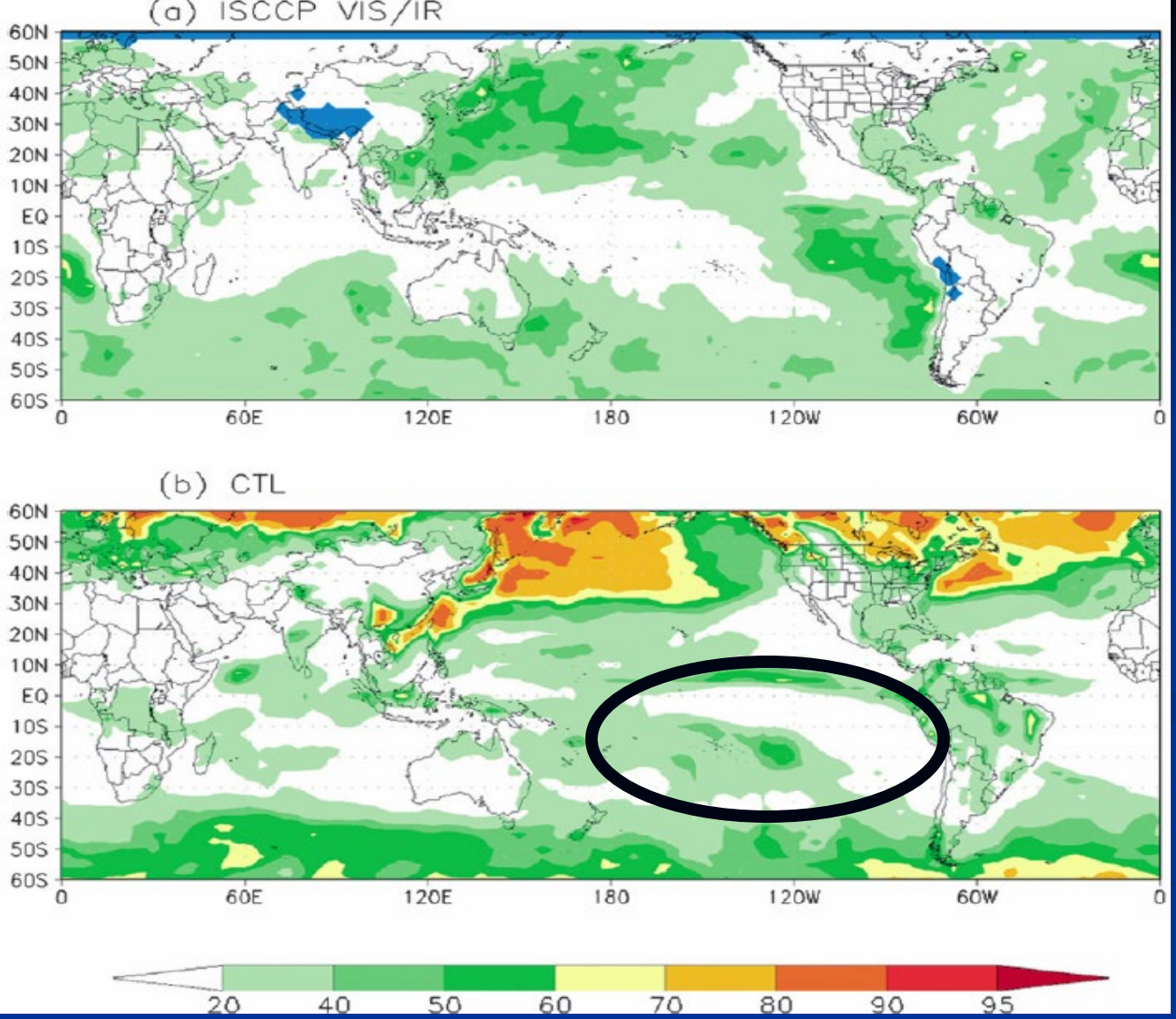
IITM-ESMv2




(a) SAL (WOA)
Atlantic Salinity
WOA
(b) ESMv1
ESMv1
(c) ESMv2
ESMv2
0
100
200
300
400
500
20°S
0°
20°N
40°N
60°N
32.4
33.4
34.4
35.4
36.4
37.4
(d) GODAS (AMOC)
AMOC
GODAS
(e) ESMv1
ESMv1
(f) ESMv2
ESMv2
0
1000
2000
3000
4000
20°S
0°
20°N
40°N
−18
−12
−6
0
6
12
18
(g) AMOC Obs (RAPID array)
moc (obs) = 17 Sv
40.
20.
0.
2004
2006
2008
2010
2012
2014

Precipitation Bias (June-Sept)





Monthly mean low cloud cover (%) for January 2003 from ISCCP (Rossow and Schiffer, 1991) VIS/IR satellite observations (blue color indicates 'no data' available).

Control simulation using the old shallow convection Scheme of NCEP GFS

Han and Pan, 2011

Long-standing problems in NCEP GFS: Systematic underestimation of stratocumulus clouds in the eastern Pacific and Atlantic Oceans; and the frequent occurrence of unrealistic excessive heavy precipitation, the so-called grid-point storms

Revision of Convection and Vertical Diffusion Schemes in the NCEP Global Forecast System

Han and Pan (2011): Weather and Forecasting

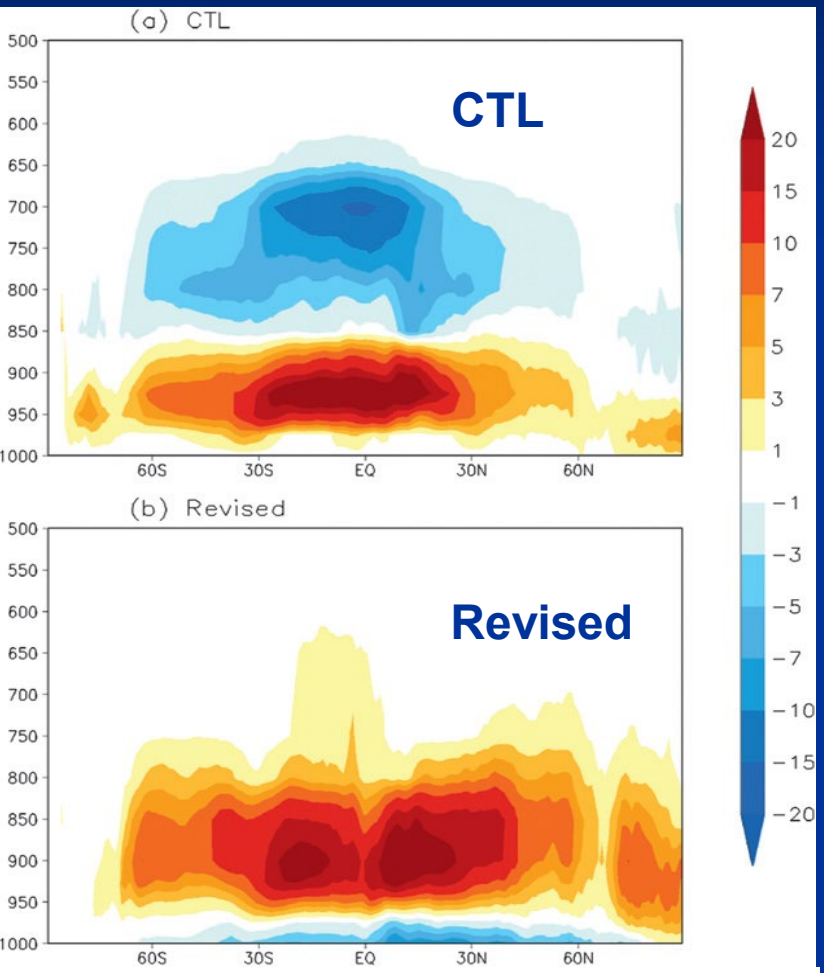


FIG. 4. Zonally averaged heating rates (10^{-6} K s^{-1}) due to the shallow convection for January 2003 from the (a) control and (b) revised model simulations.

Revised convection and planetary boundary layer (PBL) schemes in the NCEP's GFS.

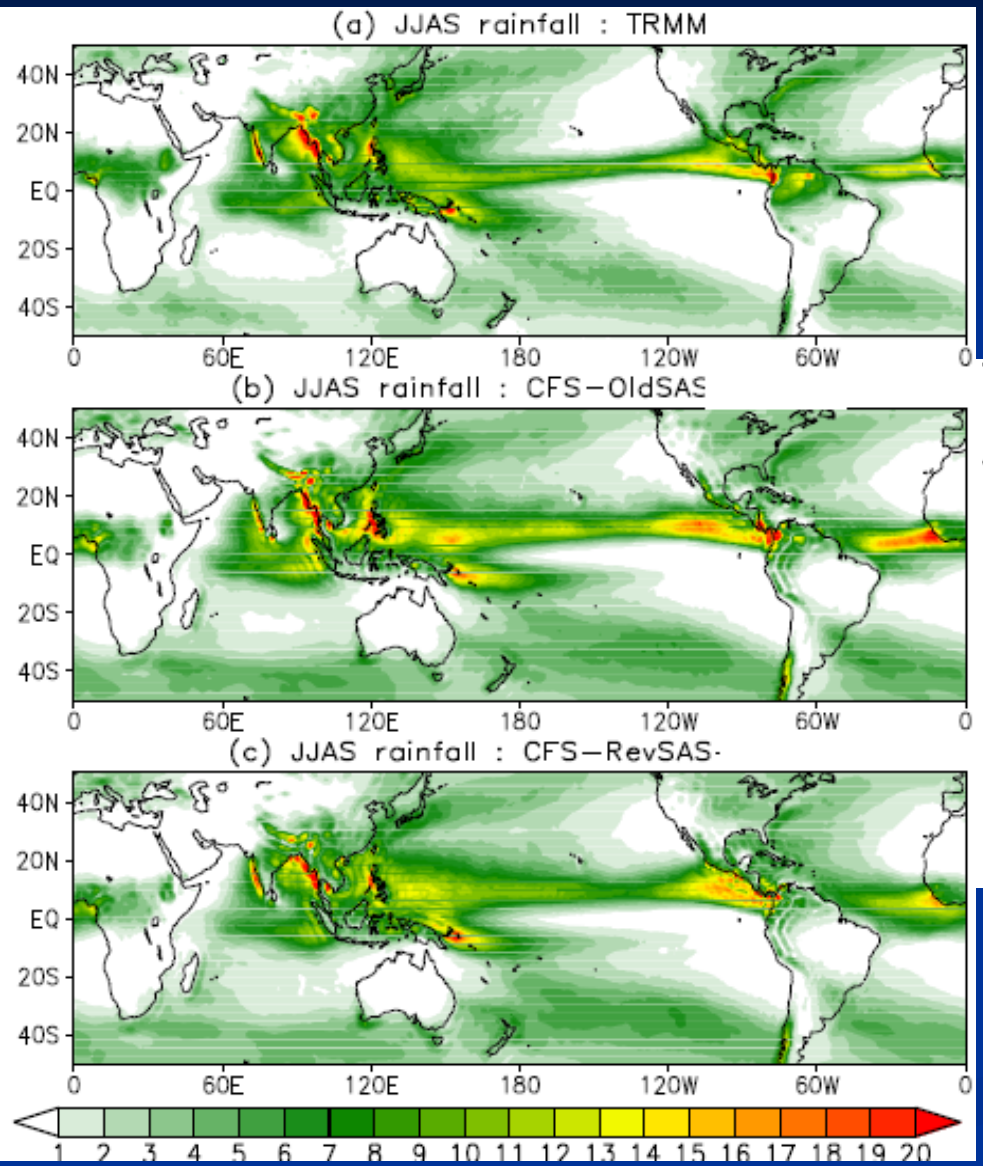
The shallow convection scheme in the revision employs a mass flux parameterization replacing the old turbulent diffusion-based approach. For deep convection, the scheme is revised to make cumulus convection stronger and deeper to deplete more instability in the atmospheric column and result in suppression of the excessive grid-scale precipitation.

The PBL model was revised to enhance turbulence diffusion in stratocumulus regions. A remarkable difference between the new and old SC schemes is seen in the heating or cooling behavior in lower-atmospheric layers above the PBL. While the old SC scheme produces a pair of layers in the lower atmosphere with cooling above and heating below, the new SC scheme using the mass-flux approach produces heating throughout the convection layers.

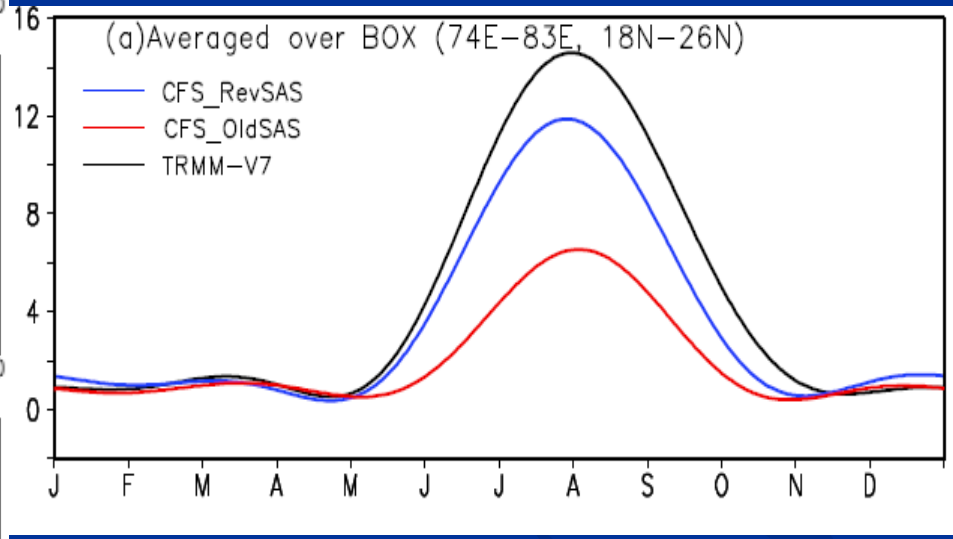
In particular, the new SC scheme does not destroy stratocumulus clouds off the west coasts of South America and Africa as the old scheme does. On the other hand, the revised deep convection scheme, having a larger cloud-base mass flux and higher cloud tops, appears to effectively eliminate the remaining instability in the atmospheric column that is responsible for the excessive grid-scale precipitation in the old scheme.

Impact of Revised SAS (Simplified Arakawa Schubert) convective parameterization on monsoon rainfall simulation in CFSv2 - Malay, G, Phani, R.M, P. Mukhopadhyay

Climate Dynamics (2014)

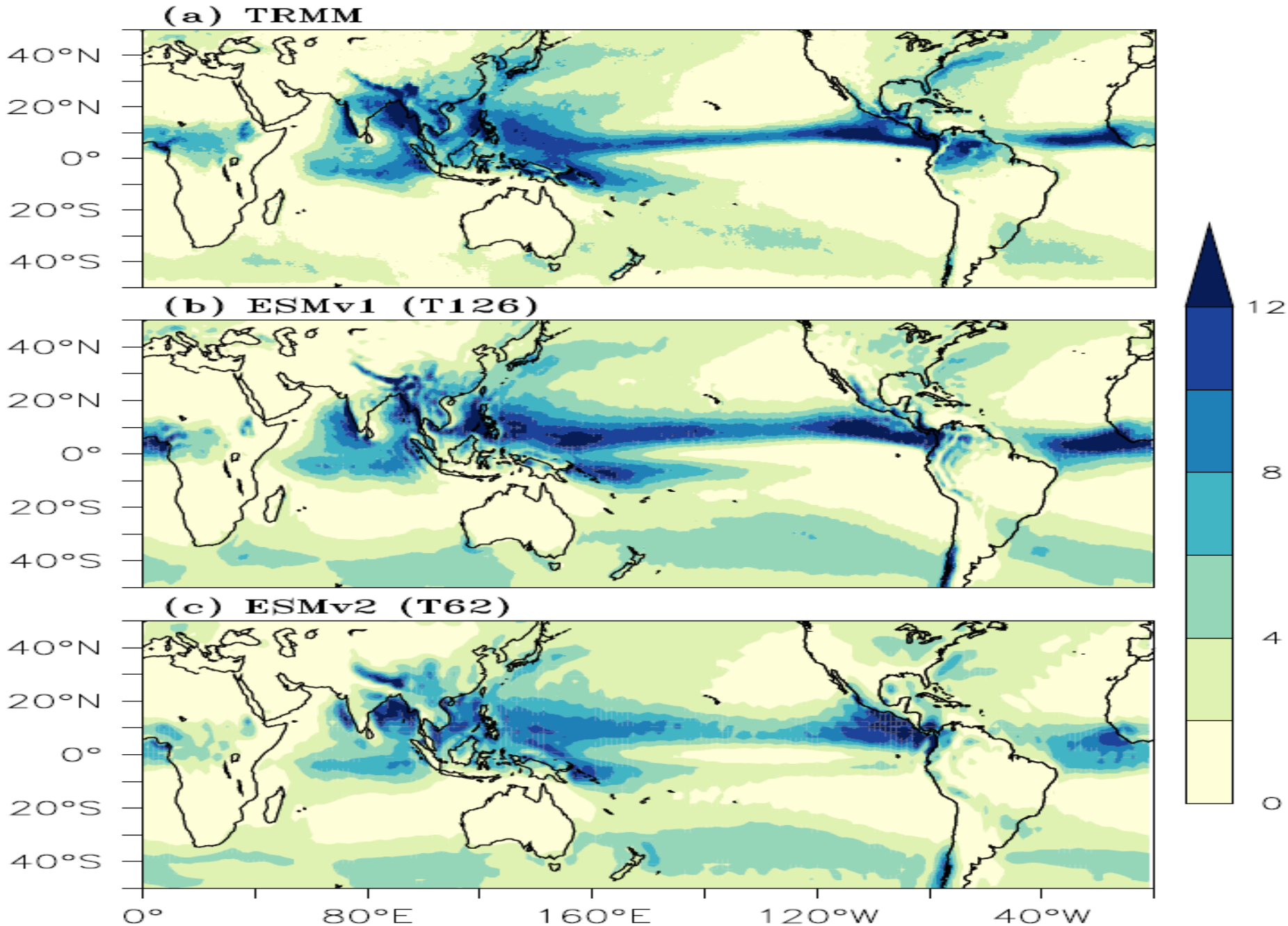


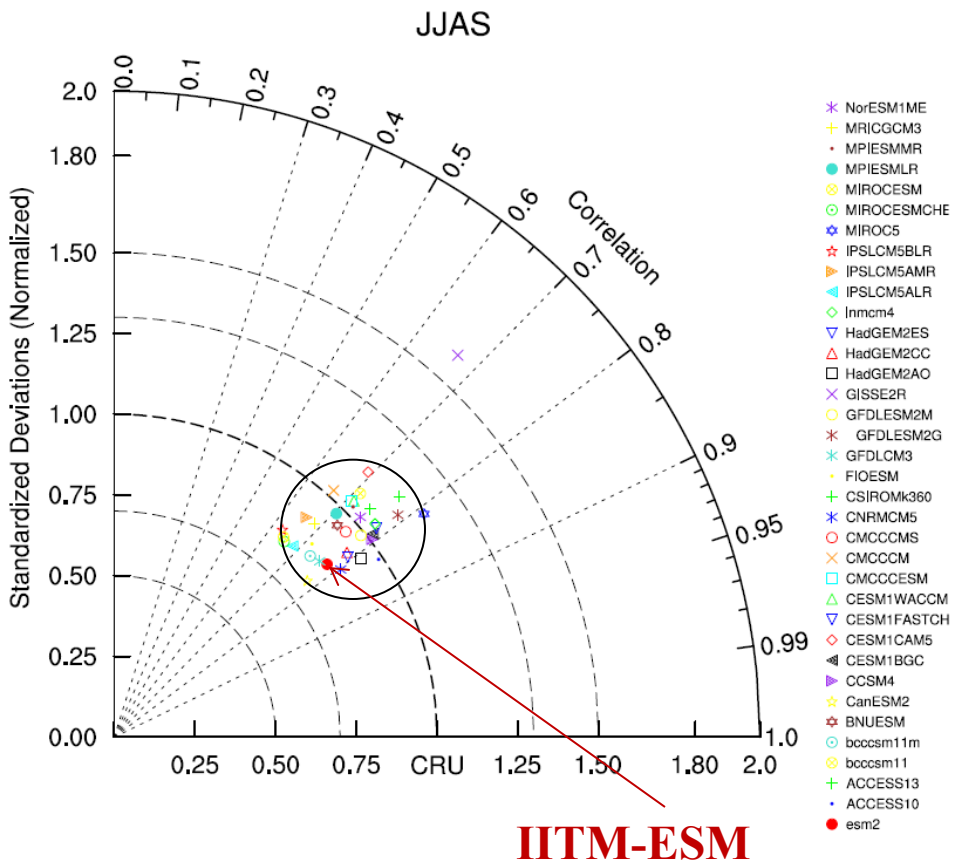
Annual cycle of rainfall over Indian region



CFSv2 T126 free run: 15 years - Courtesy: P. Mukhopadhyay, IITM

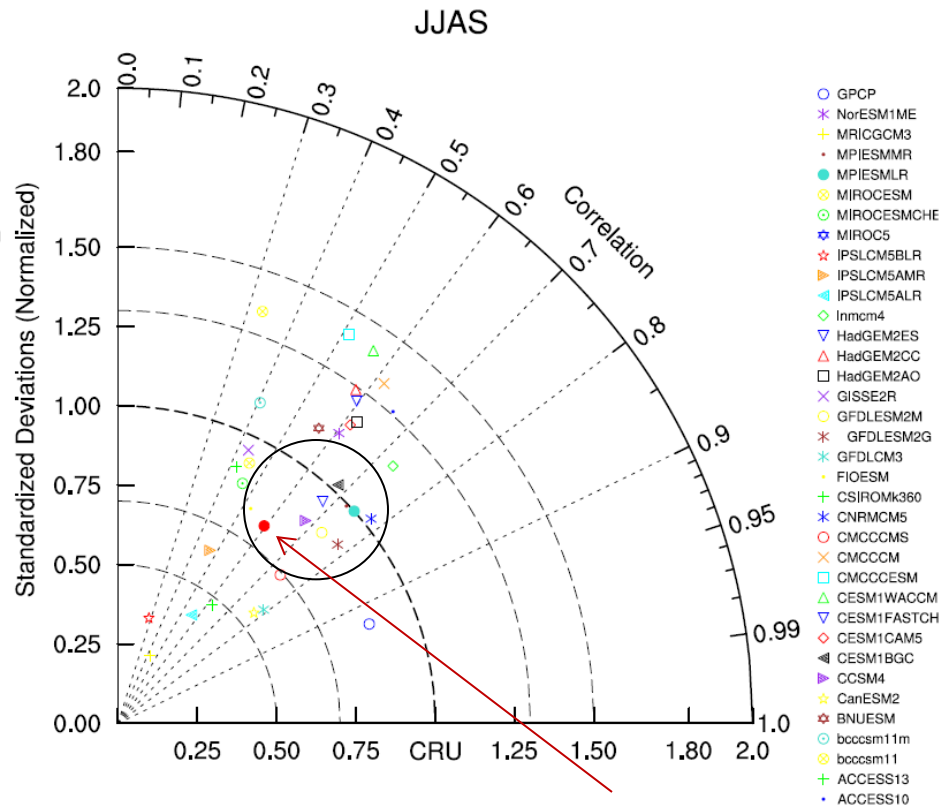
Mean summer rainfall (June-Sept)





IITM-ESM

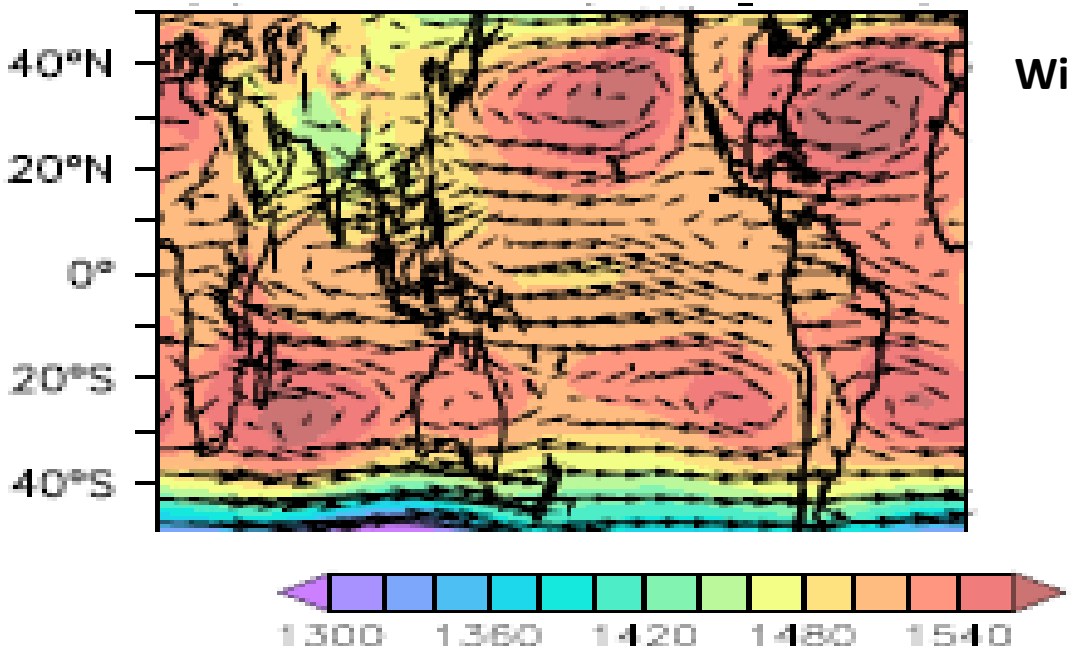
Indian region (JJAS precipitation)



IITM-ESM

Asian region (JJAS precipitation)

Courtesy: Swapna



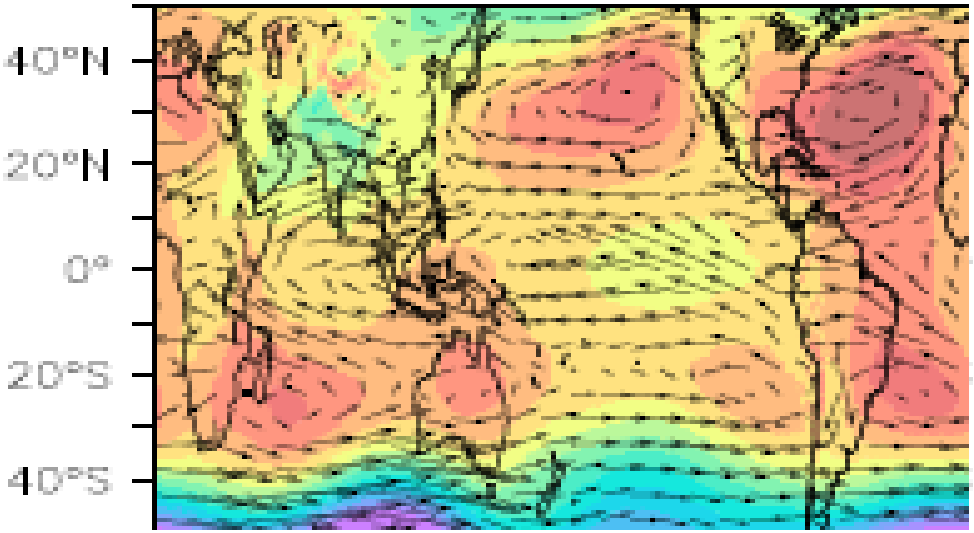
Winds & Geopotential Height: 850 hPa

JJAS

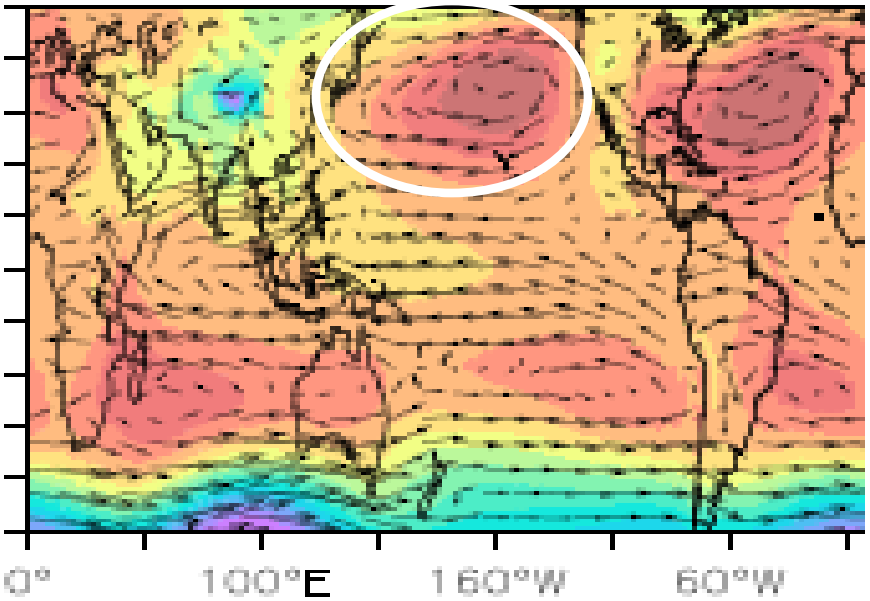
ERA-Interim

- Pacific sub-tropical anticyclone
- Easterly trade winds over Pacific

ESM-v1



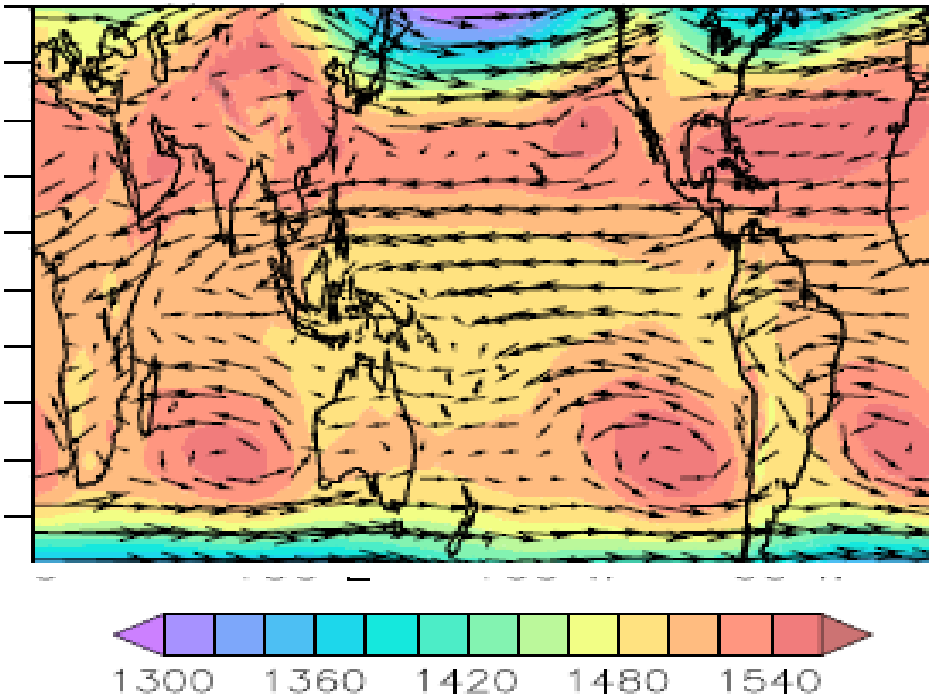
ESM-v2



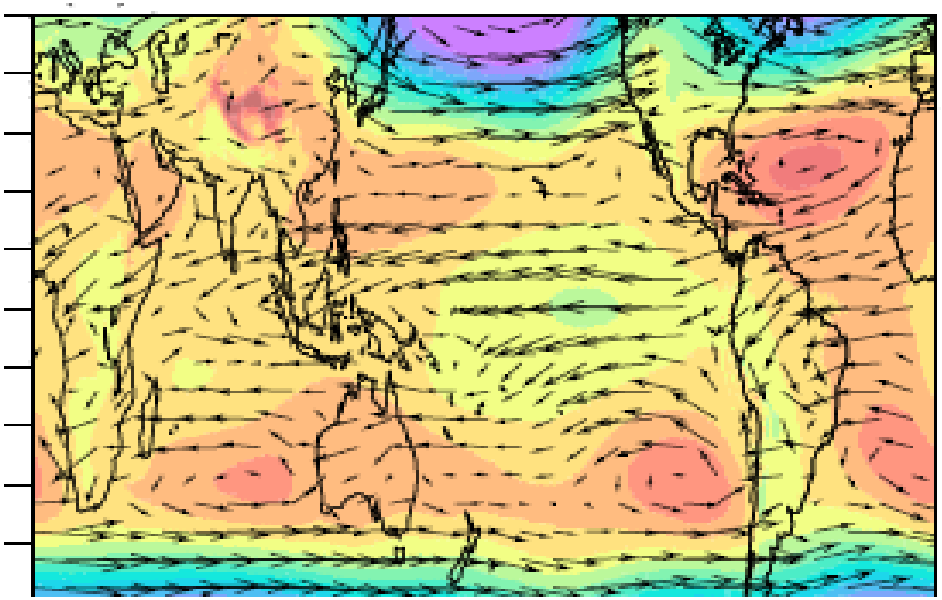
Winds & Geopotential Height: 850 hPa

DJF

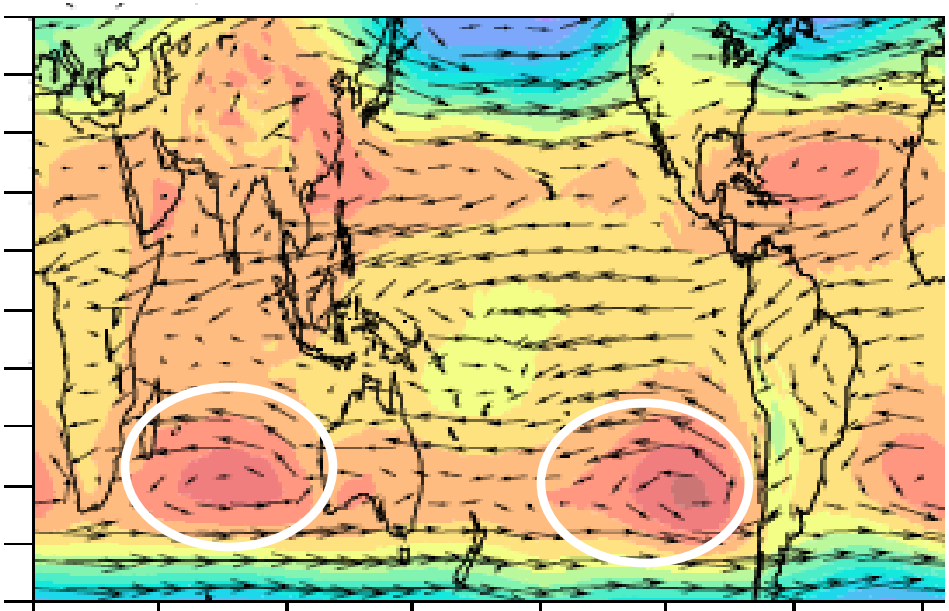
ERA-Interim



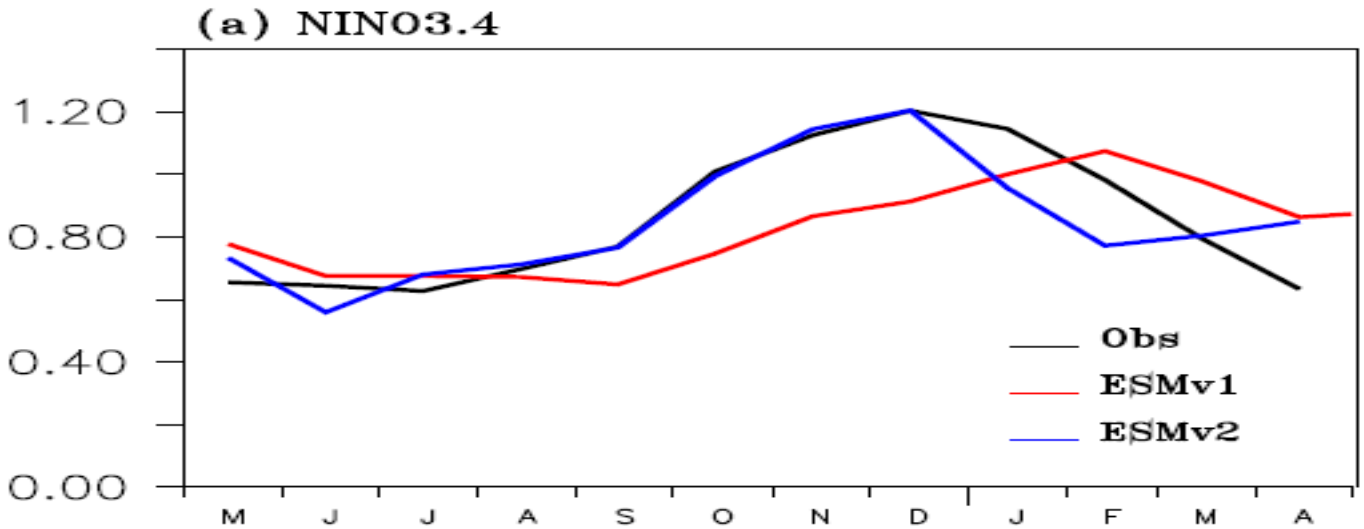
ESM-v1



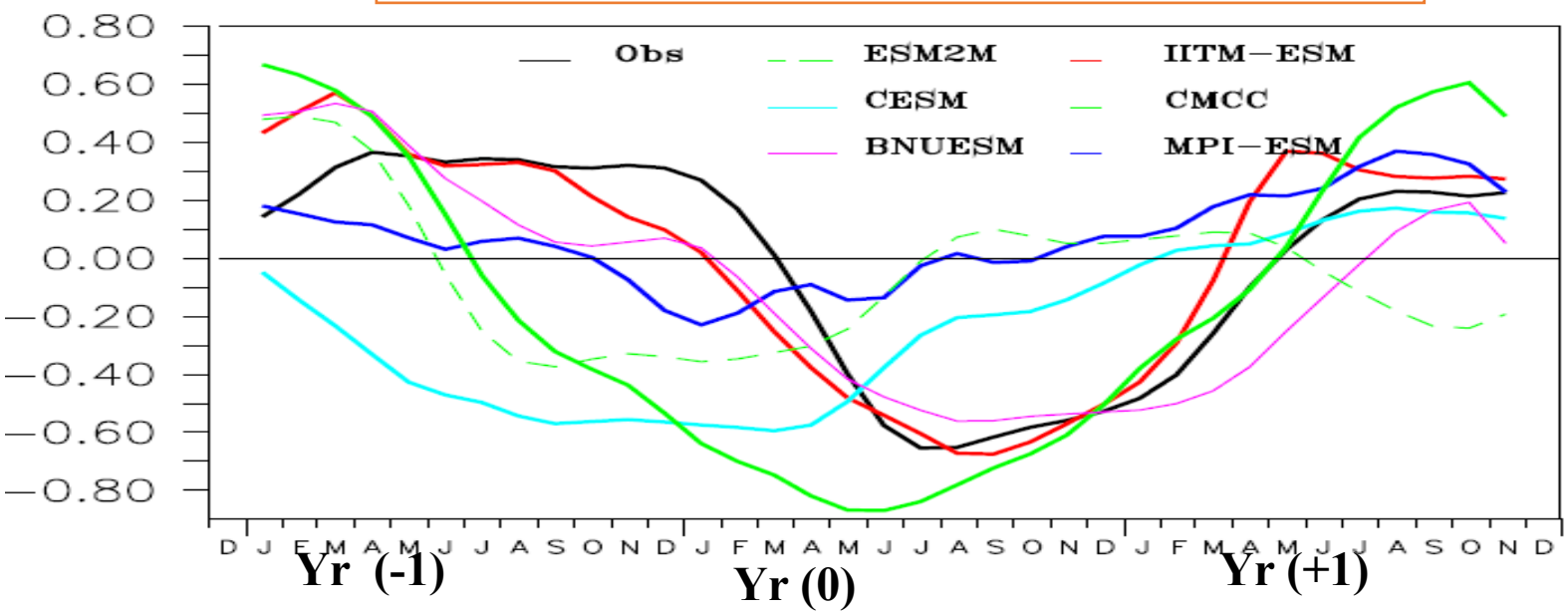
ESM-v2



Seasonal variability of NINO3.4



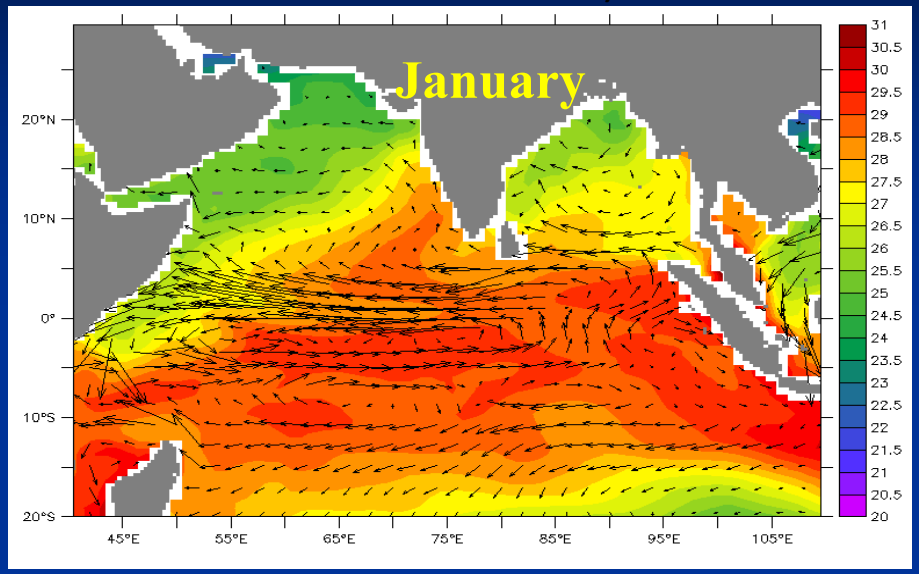
ENSO-Monsoon teleconnection



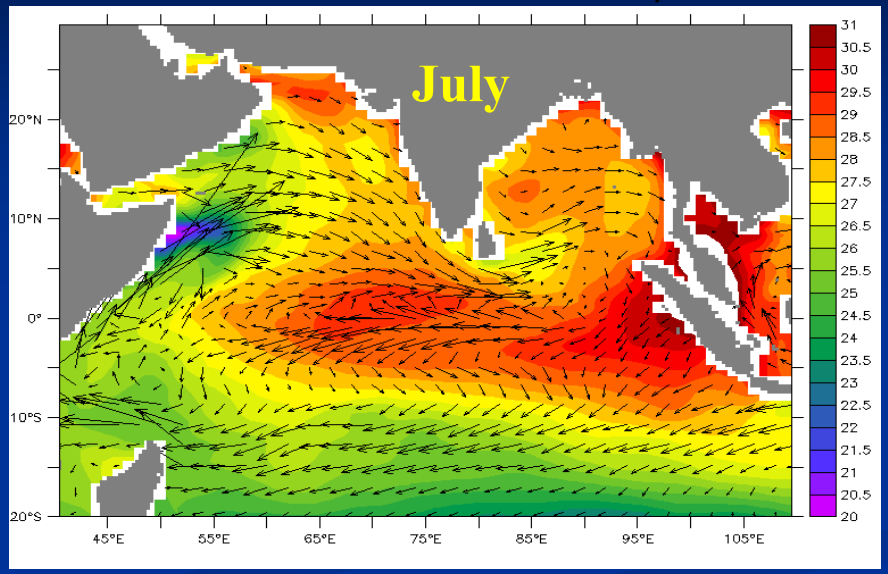
MOM4p1 forced ocean simulation – 130 year spin up

Physical and Biogeochemical Parameters for Tropical Indian Ocean

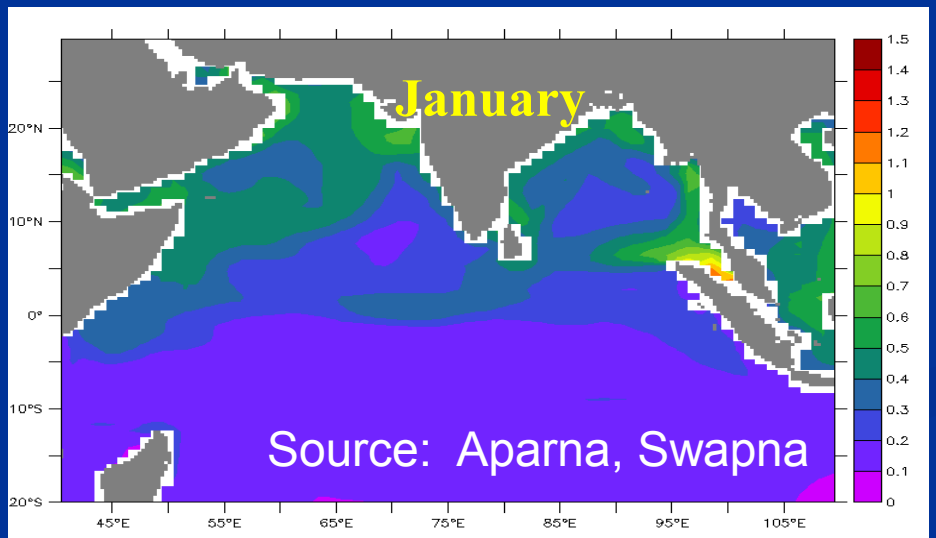
SST and currents)



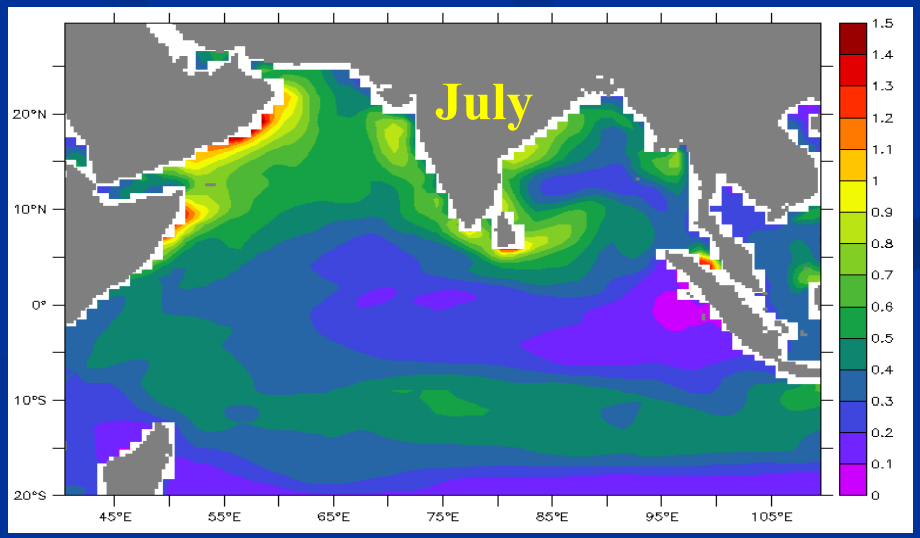
SST and currents)



Chlorophyll



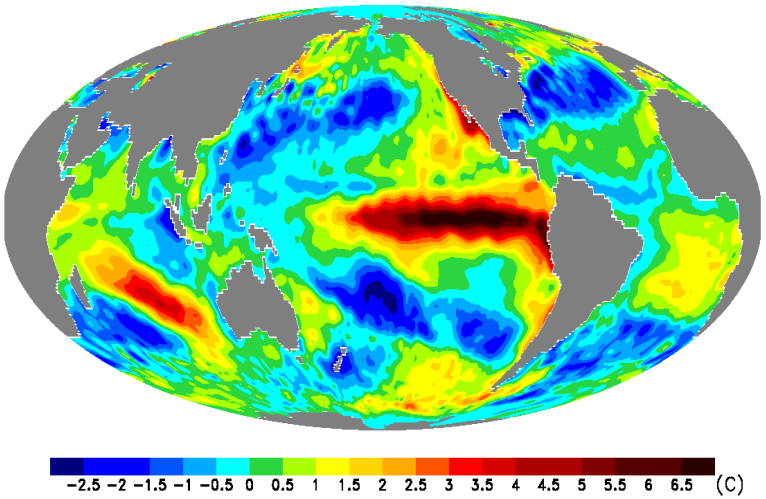
Chlorophyll



1997-98: Strongest El Niño ever recorded!

Sea Surface Temperature

Dec 1997 minus Dec 1998



In January 1998 (top right) the 1997-1998 El Nino event was at its height. Because of the weakness of the trade winds at this time, the upwelling of nutrient-rich water was suppressed in the equatorial Pacific. The absence of a green band along the equator in this image is indicative of relatively low chlorophyll concentrations there.

By July 1998 (bottom right) the trade winds had strengthened and equatorial upwelling had resumed giving rise to widespread phytoplankton blooms in the equatorial belt

(Ref: Wallace and Hobbs, 2006)

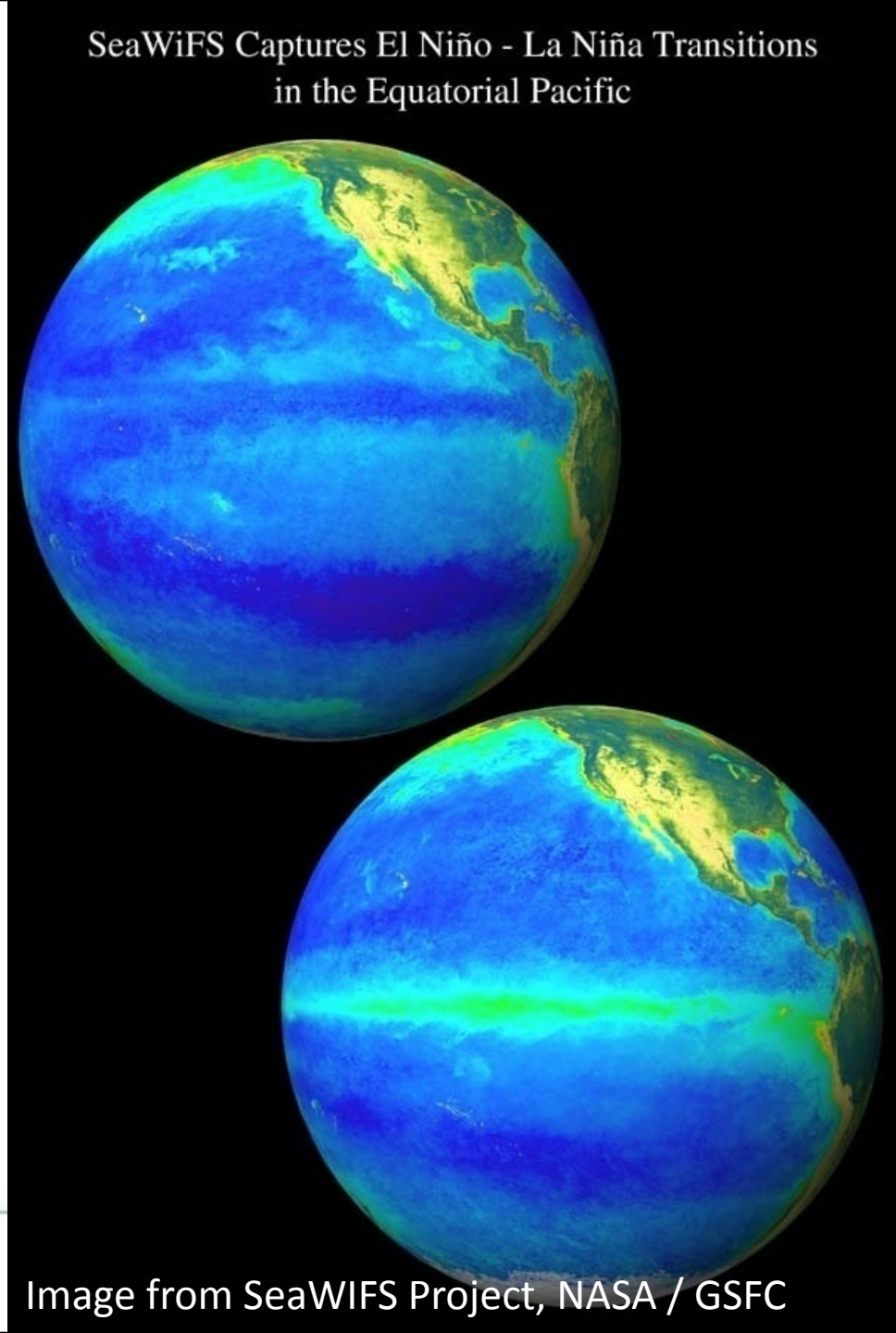
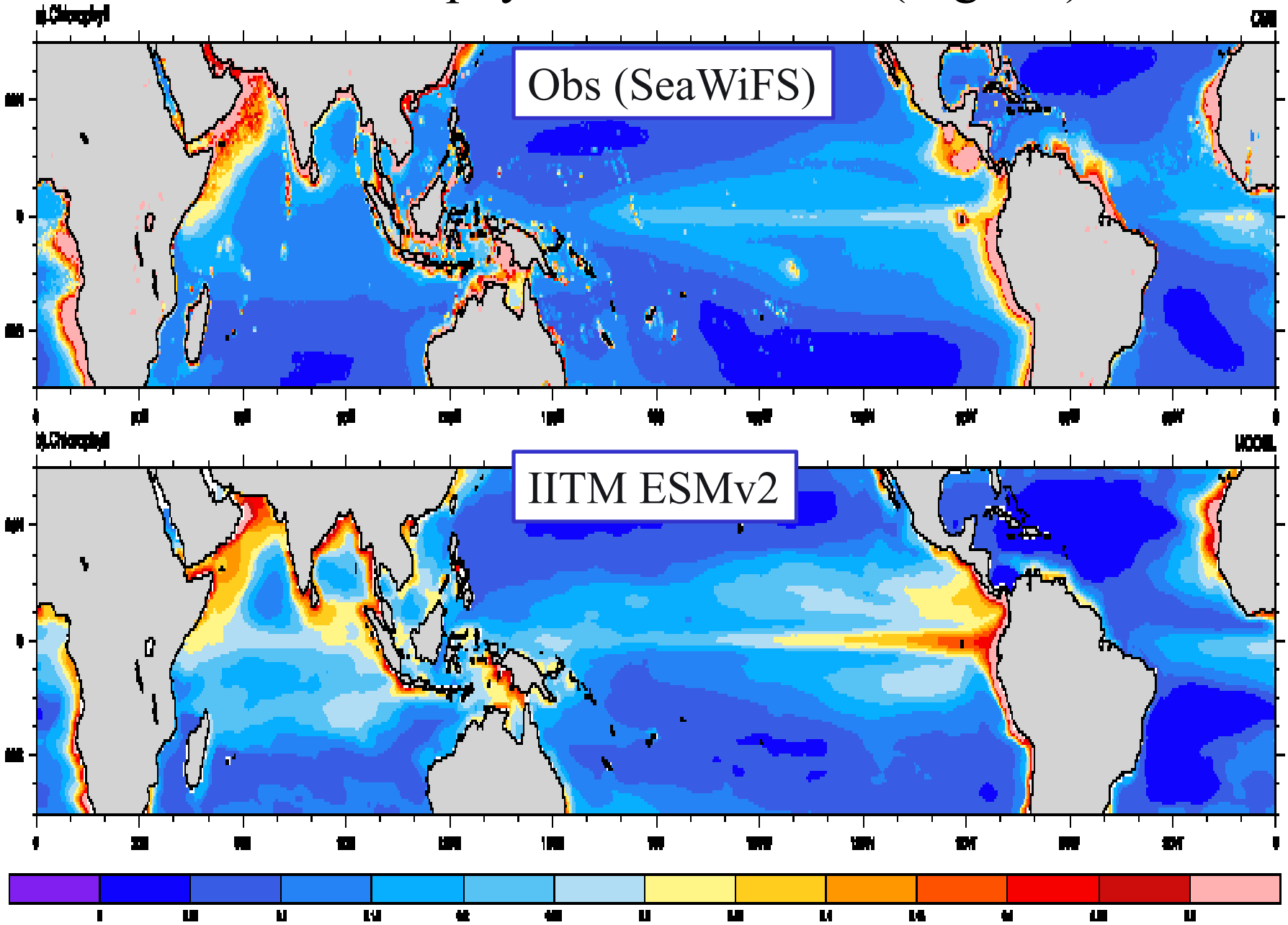


Image from SeaWIFS Project, NASA / GSFC

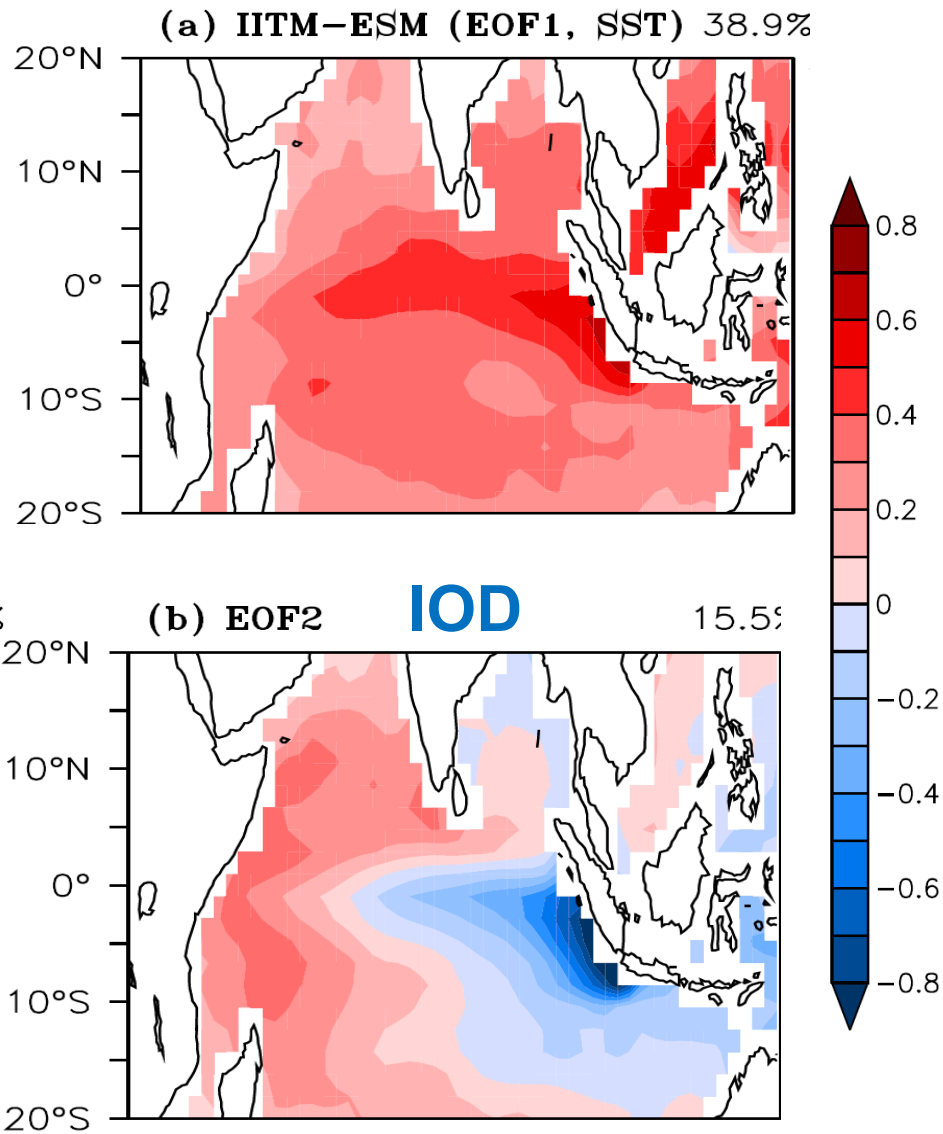
Chlorophyll Concentration (Mg m^{-3})

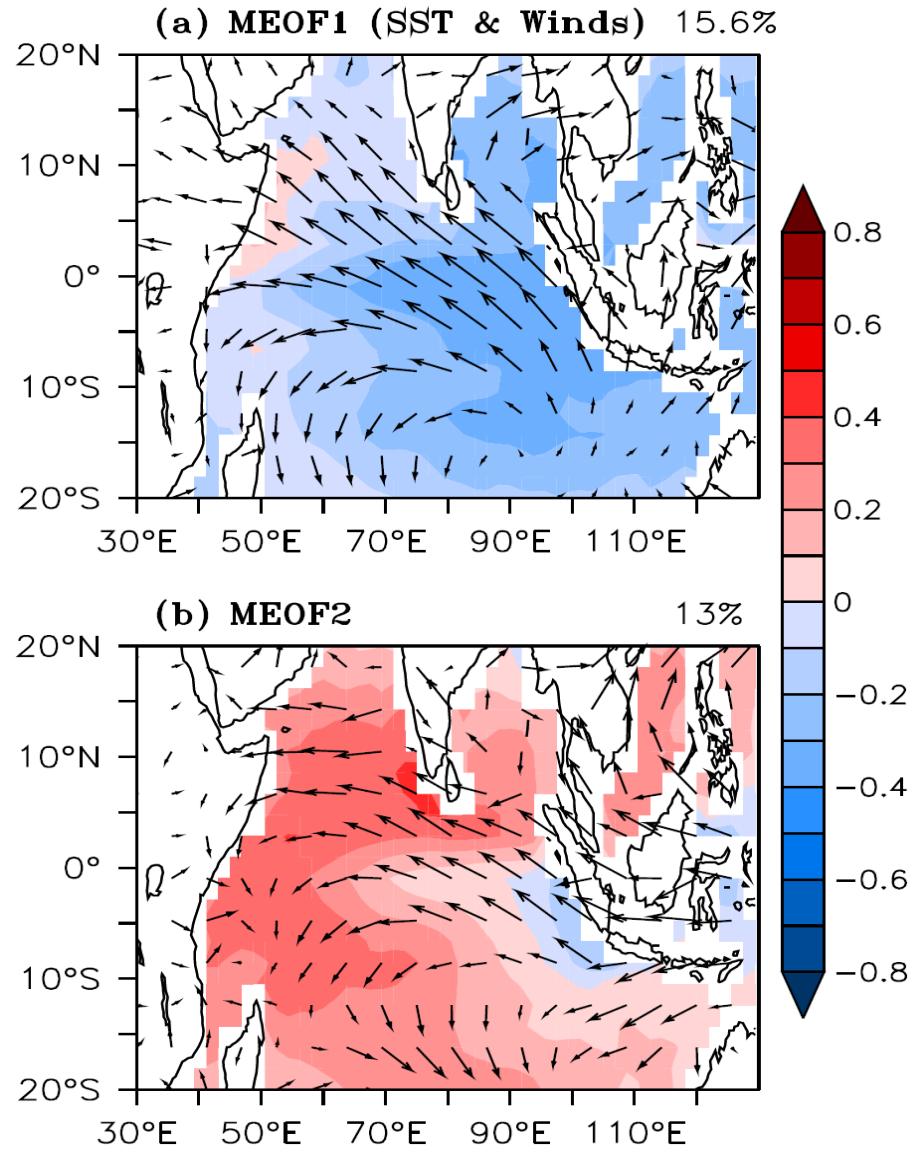


Courtesy: Sandeep, CCCR

Indian Ocean modes of variability in the IITM ESM

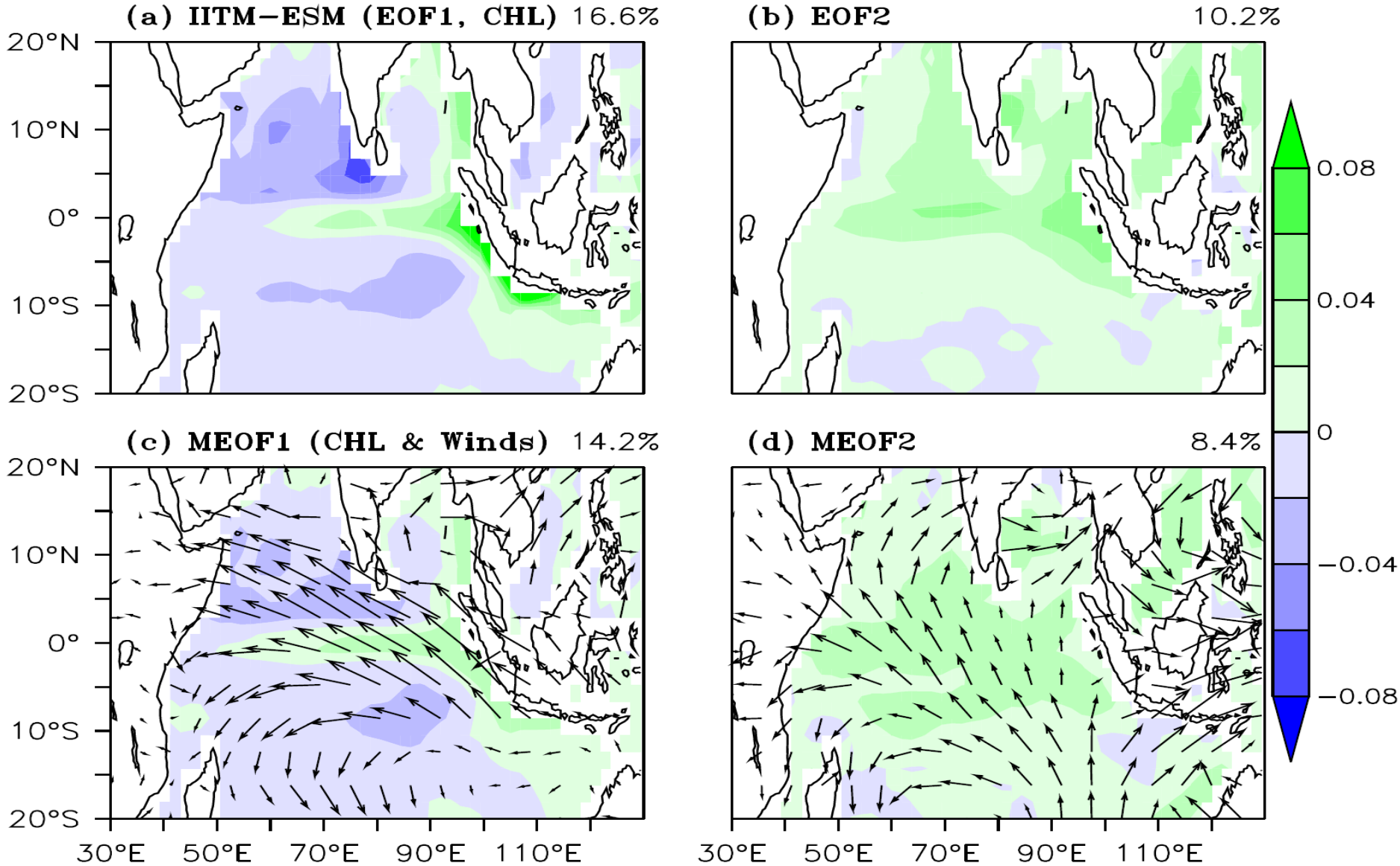
IO basin mode





Courtesy: Swapna and Prajeesh

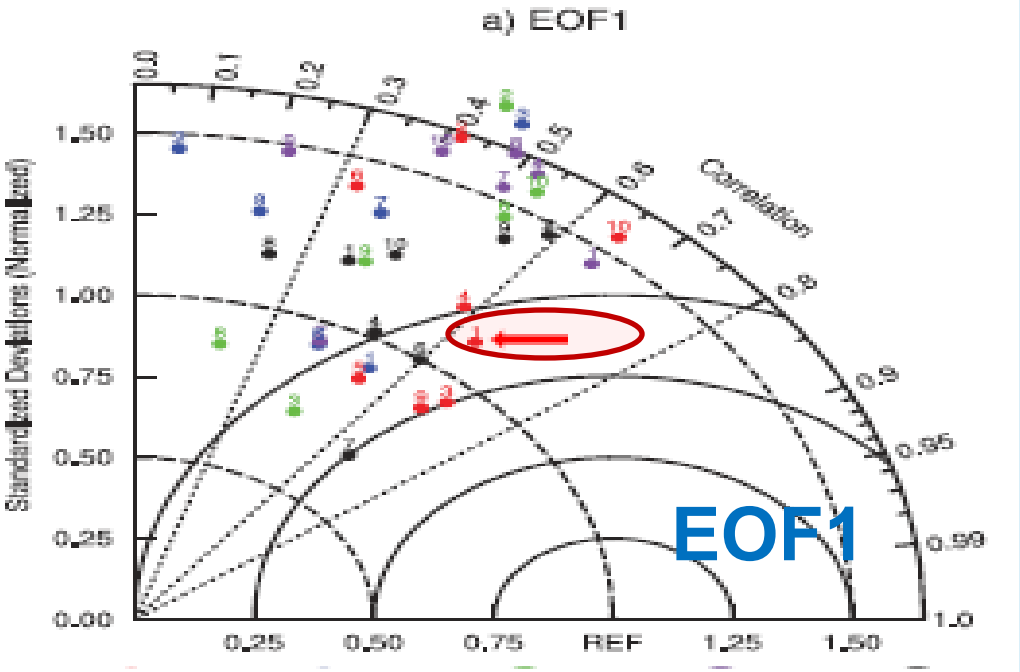
Leading modes of Chlorophyll variability in the IITM ESM

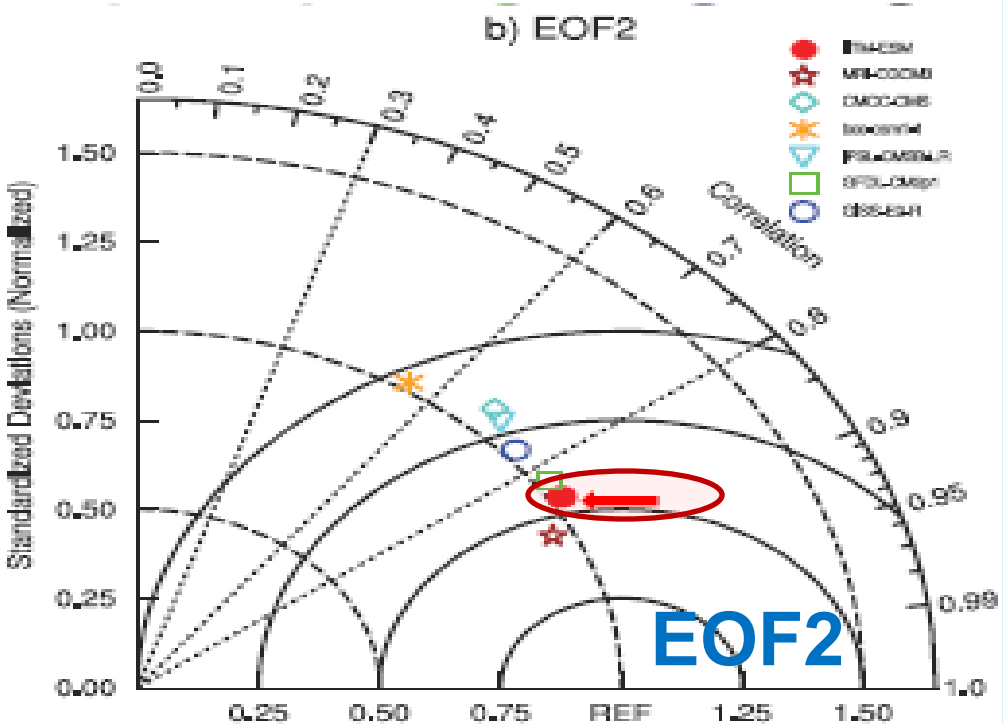


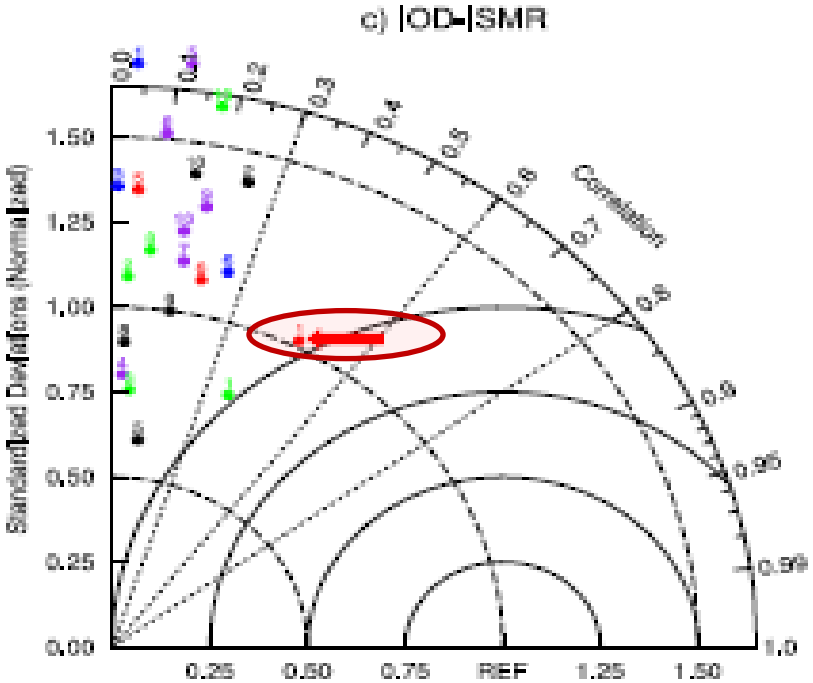
Courtesy: Swapna and Prajeesh

Pattern correlation of the leading modes of Indian Ocean SST variabil
- CMIP5 models & IITM ESM (red)

IOD-ISMR linkage



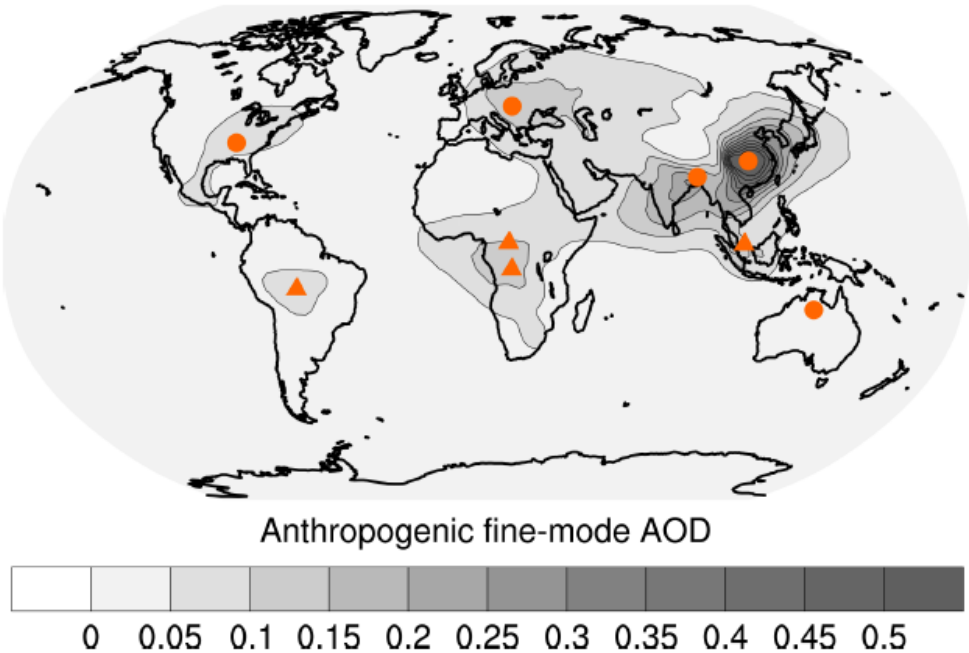




MACv2-SP: a parameterization of anthropogenic aerosol optical properties and an associated Twomey effect for use in CMIP6

Bjorn Stevens[1], Stephanie Fiedler[1], Stefan Kinne[1], Karsten Peters[1], Sebastian Rast[1], Jobst Müsse[1], Steven J. Smith[2], and Thorsten Mauritsen[1]

[1]Max Planck Institute for Meteorology, Hamburg, Germany
[2]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, USA



No.	Source region	Lat.	Long.	Type	Main features of annual cycle
1	Europe	49.4	20.6	Industrial	Amplitude 25 %, May max
2	North America	40.1	277.5	Industrial	Amplitude 30 %, July max
3	East Asia	30.0	114.0	Industrial	Amplitude 15 %, biharmonic, Oct and Apr max
4	South Asia	23.3	88.0	Industrial	Amplitude 10 %, maximum in mid-July
5	North Africa	3.5	22.5	Biomass	Non-harmonic, Dec max, Mar–Oct min
6	South America	−10.3	298.0	Biomass	Non-harmonic, Sep max, Jan–Jun min
7	Maritime Continent	−1.0	106.0	Biomass	Non-harmonic, Sep max, Jan–Jun min
8	South central Africa	−3.5	16.0	Biomass	Non-harmonic, Aug max, Jan–Dec min
9	Australia	−20.0	135.0	Industrial	Amplitude 60 %, Sep max

Figure 1. Global distribution of annually averaged anthropogenic aerosol optical depth τ_a at 550 nm. Also indicated are the locations of MACv2-SP plume centers. Industrial and biomass plumes are distinguished by the choice of symbol: circles for industrial plumes and triangles for biomass plumes.

Sensitivity experiments: 50 years of model integration

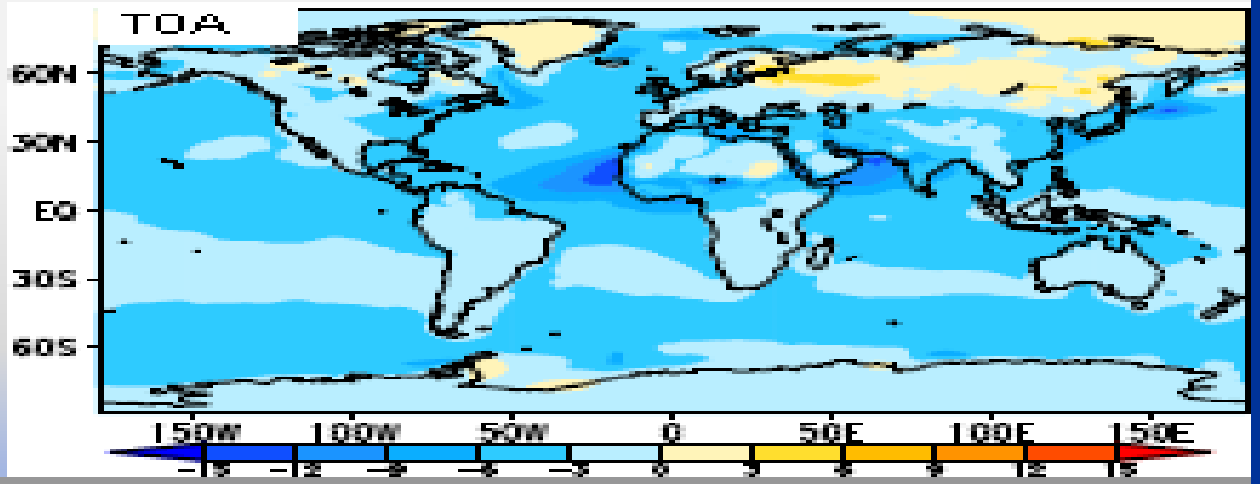
1) Pre-Industrial natural aerosols 2) No aerosols (clean environment)

Aerosol Radiative Forcing (ΔF=Faer-Fclean)

Faer is the net flux in the presence of natural aerosols
Fclean is the net flux reference atmospheric condition (clean)

ARF		Clear Sky (W/m²)	Total Sky (W/m²)
TOA	Net Total Radiation (SW+LW)	-2.63	-0.45
	Net Solar Radiation (SW)	-3.49	-0.89
ATM	Net Total Radiation (SW+LW)	2.47	2.39
	Net Solar Radiation (SW)	1.65	1.52
SFC	Net Total Radiation (SW+LW)	-5.11	-2.84
	Net Solar Radiation (SW)	-5.15	-2.39

Solar Radiative forcing for clear sky

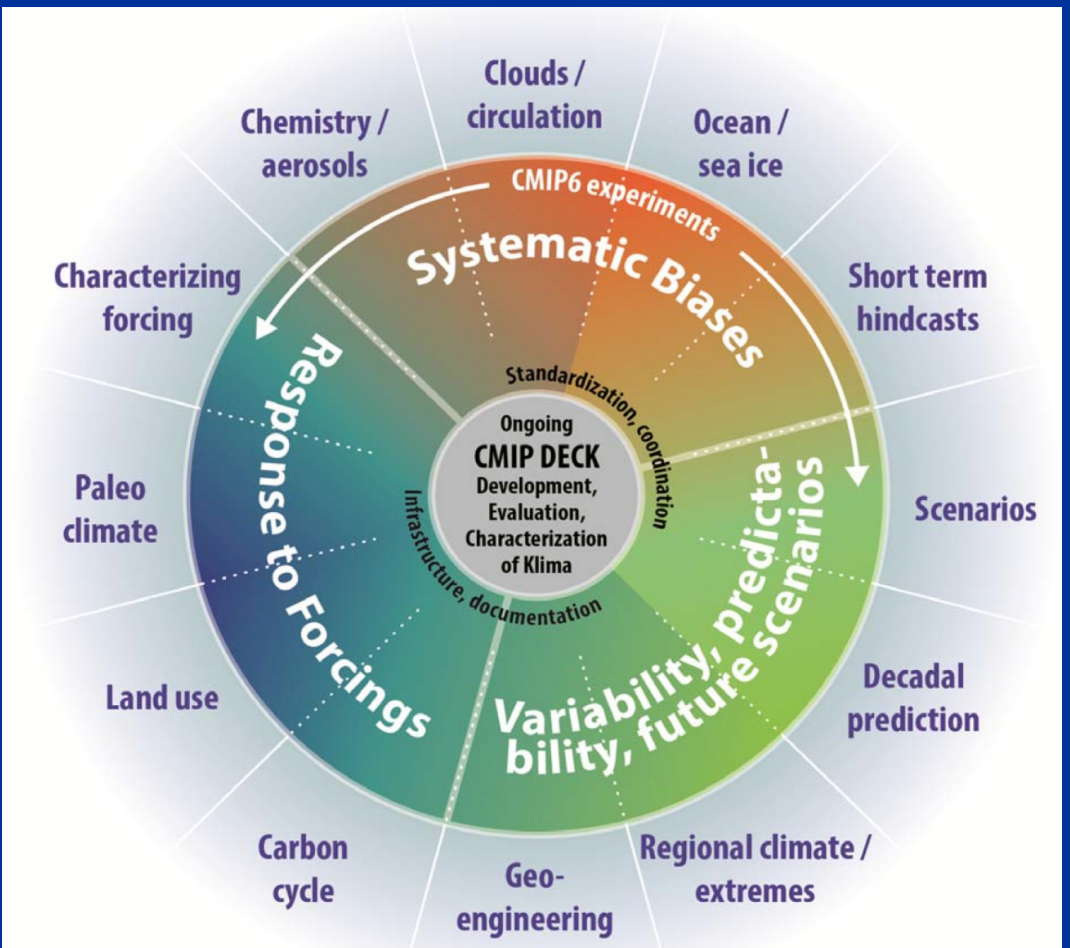


Time-varying aerosol distributions in IITM ESM

(Courtesy: Ayantika Dey Choudhury; Data source: Stefan Kinne, Bjorn Stevens, Max Planck)

CMIP6 Schematic: Participation in the 6th Intergovernmental Panel for Climate Change (IPCC)

CMIP6 experimental design



CMIP6 Concept: A Distributed Organization under the oversight of the CMIP Panel

IITM ESM will participate in the climate modeling CMIP6 experiments for the IPCC 6th Assessment Report

Status of IITM-ESM CMIP6 Simulations

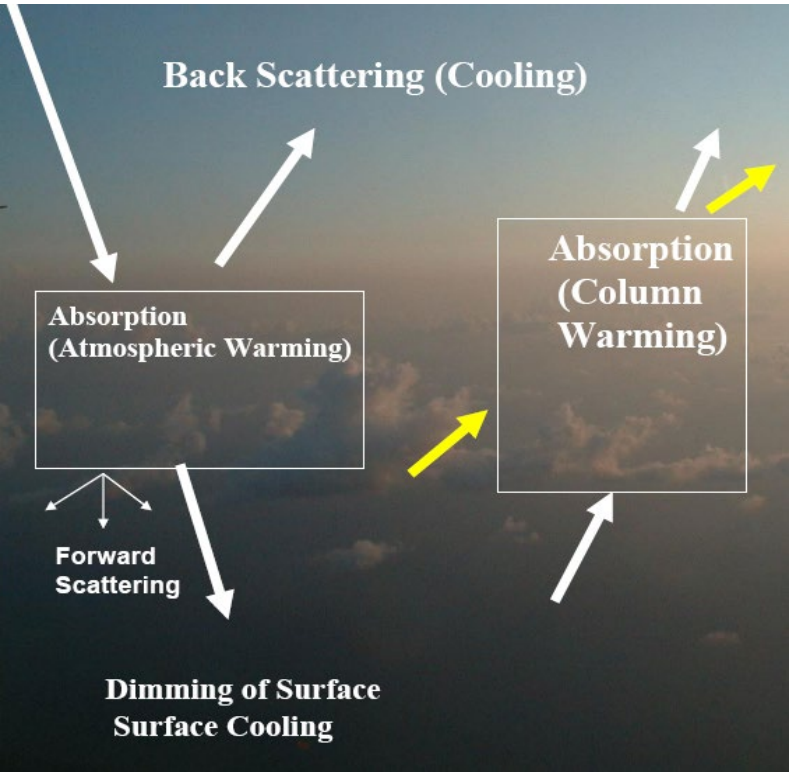
Experiments	Details of Simulation	No. of years of integration	Time period
PI-Control	Pre-industrial control simulation	**800 yrs** 300 year spin-up and 500 year PI-Control Simulation	Completed
Transient CO2 runs	1% /Yr increase in CO2 to quadrupling	**140 yrs**	Completed
	Abruptly Quadruple CO2 and fix	**140 yrs**	Completed
CMIP6	Historical	**165 yrs** Emission-or concentration-driven simulation of recent past	Completed
Global Monsoon MIP & AMIP Simulations	AMIP Simulation	` ~150 yrs of simulation	Completed
Future Scenario MIP	Future projections based on scenarios	400 years : Future scenario runs to start soon.	Expected to complete by August 2019

Summary

- **<u>IITM ESMv1:</u>** First version of IITM ESM has been successfully developed at CCCR, IITM by incorporating MOM4P1 (with ocean biogeochemistry) component in CFSv2. Major improvements are seen in IITM ESMv1 vis-à-vis CFSv2 :
  - Significant reduction of cold bias of global mean SST by ~0.8^{o}C
  - ENSO & PDO are robust and spatially more coherent in ESM1.0
  - ENSO and monsoon links are well-captured
  - The IITM Earth System Model: Transformation of a seasonal prediction model to a long term climate model - *Swapna et al. 2015 (Bulletin of American Meteorological Society)*
- **<u>IITM ESMv2</u>:** Further improvements are incorporated in IITM ESMv1
  - Reduced TOA radiation imbalance significantly
  - Improved mean monsoon precipitation over South Asia
  - Improved sea-ice distribution in the Arctic and Antarctic
  - Improved Atlantic Meridional Overturning Circulation (AMOC)
  - Interactive ocean biogeochemistry
  - Included time-varying aerosol properties (3D fields) for the CMIP experiments
  - Improved hydrological balance through discharge of runoff from land to ocean
- **IITM ESM** to participate in the upcoming CMIP6 activity & IPCC AR6 assessment

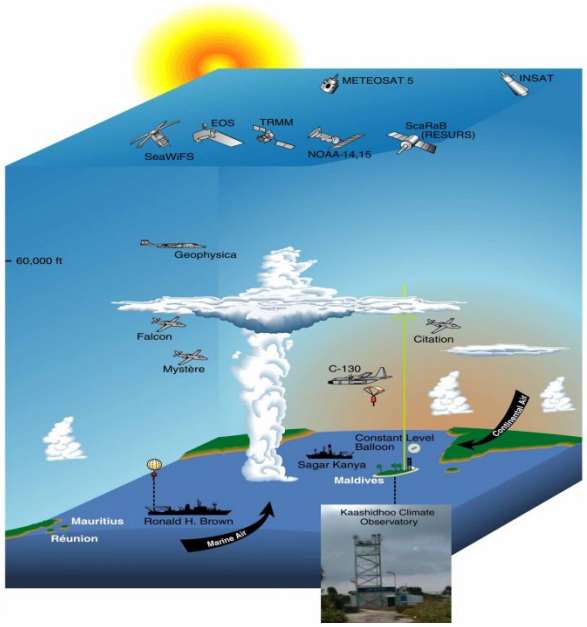
Part 2: Understanding the influence of climate change on the Indian summer monsoon using the IITM ESM

Atmospheric Brown Clouds (ABCs): How do they influence climate ?

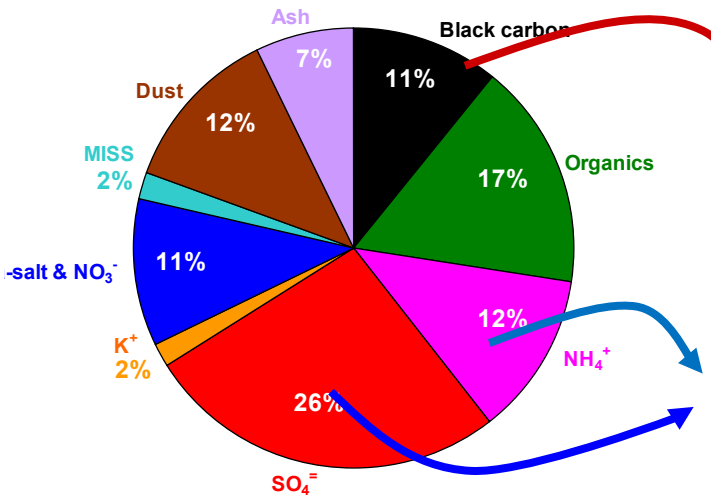


Indian Ocean Experiment - INDOEX
Lead PIs: Ramanathan, Crutzen and Mitra

Lead Agencies : NSF; ISRO; CSIR; Max Planck Inst



- **The absorption of solar radiation by the surface and the atmosphere is the fundamental driver for the physical climate system , for atmospheric chemistry, and for all life on the planet.**
- **ABCs have altered this forcing significantly**



Traps sunlight and heats the air

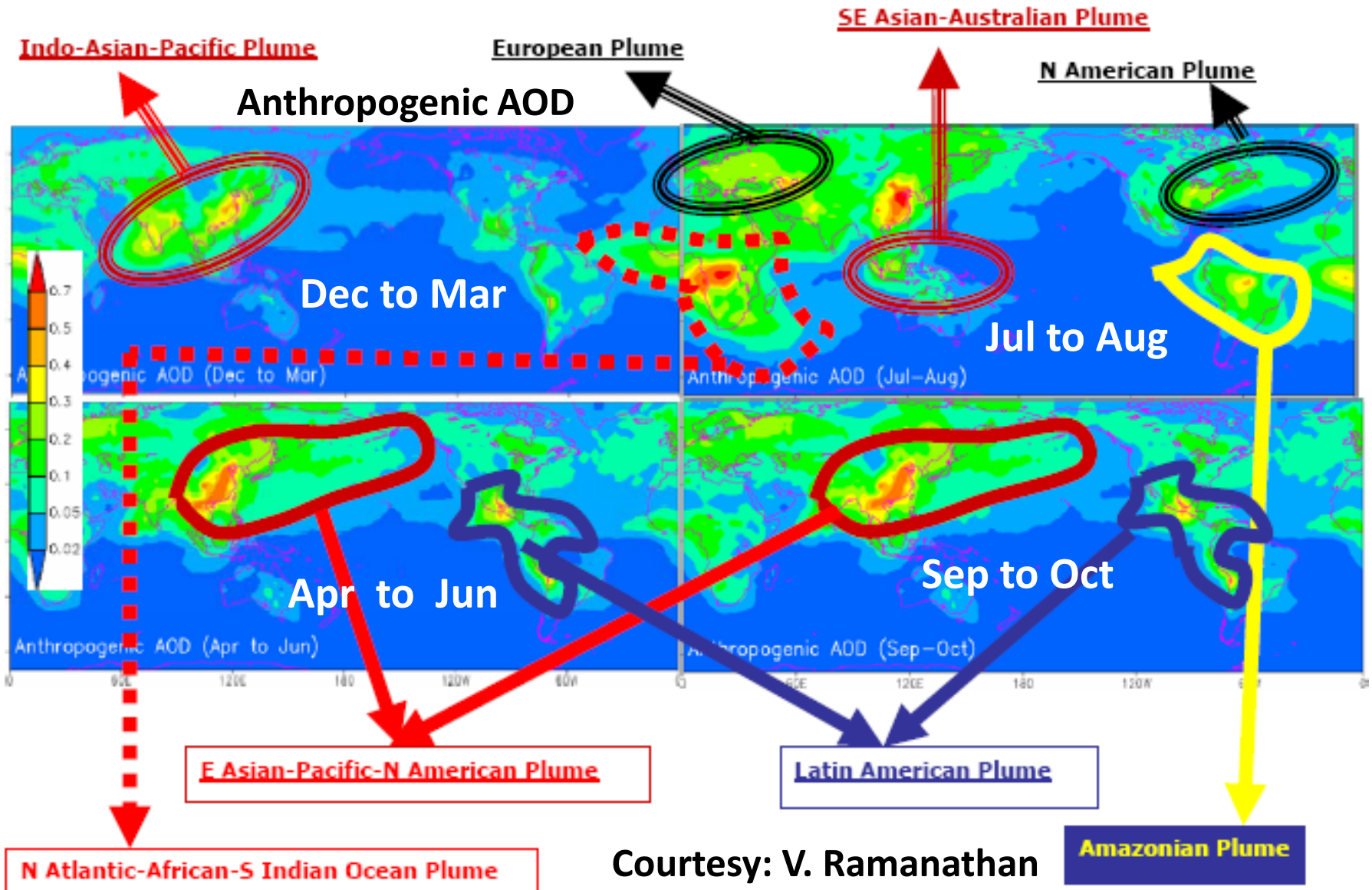
Reflects sunlight like mirrors and cool

Courtesy: V. Ramanathan

Atmospheric brown clouds: Hemispherical and regional variations in long-range transport, absorption, and radiative forcing

Ramanathan et al. JGR-2007

ABCs (eg. sulfate, organics, black carbon, ash, dust, sea-salt, etc) alter absorption and reflection of solar radiation and influence climate

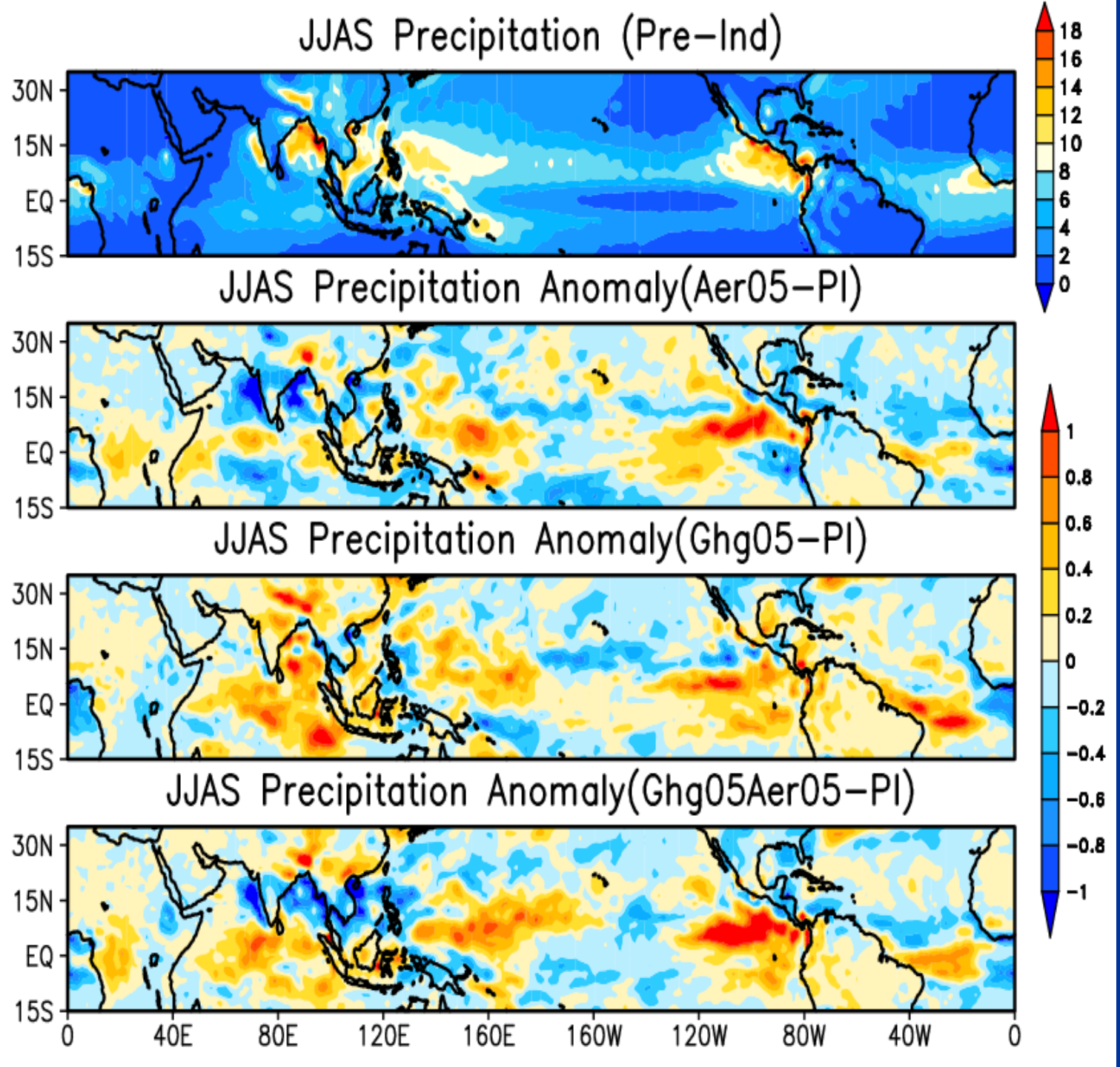


Courtesy: V. Ramanathan

Indian summer monsoon response to GHG & Aerosol forcing

Sensitivity experiments using the IITM ESMv2

Experiment	CO2	Aerosol	Integration
PI-CTL (1850 conditions)	284.2 ppmv	Natural	500 years
EXP1_(GHG2005+ AERO2005)	367.5 ppmv	Natural + Anthrop	50 years
EXP2_(AERO_2005)	284.2 ppmv	Natural + Anthrop	50 years
EXP3(GHG_2005)	367.5 ppmv	Natural	50 years

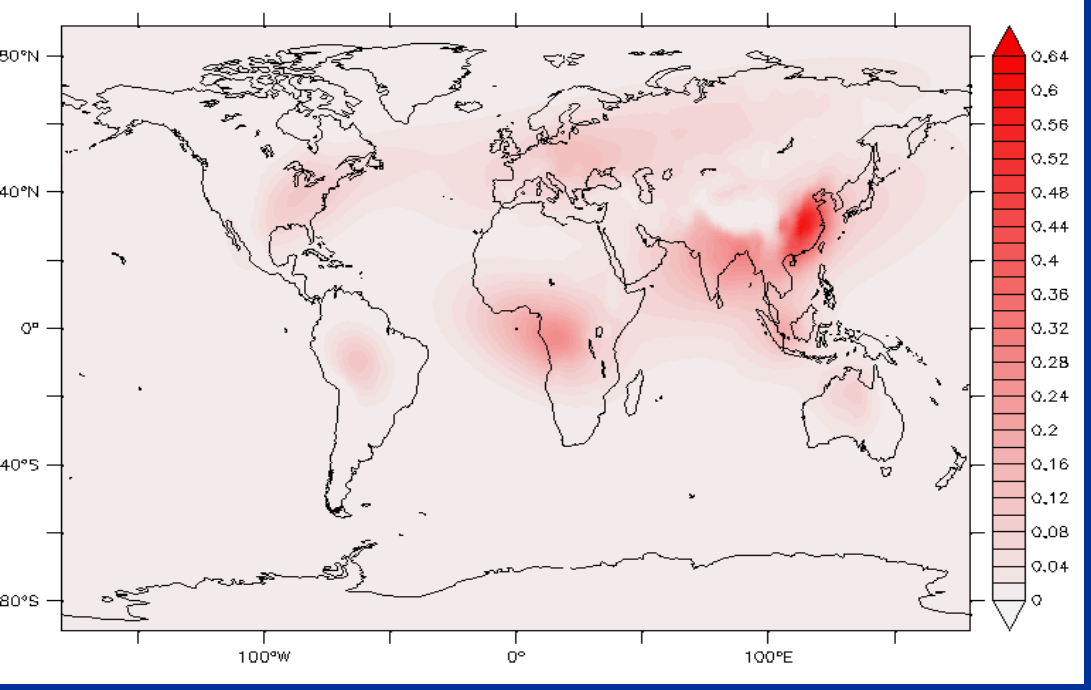


PI

EXP2 - PI

EXP3 - PI

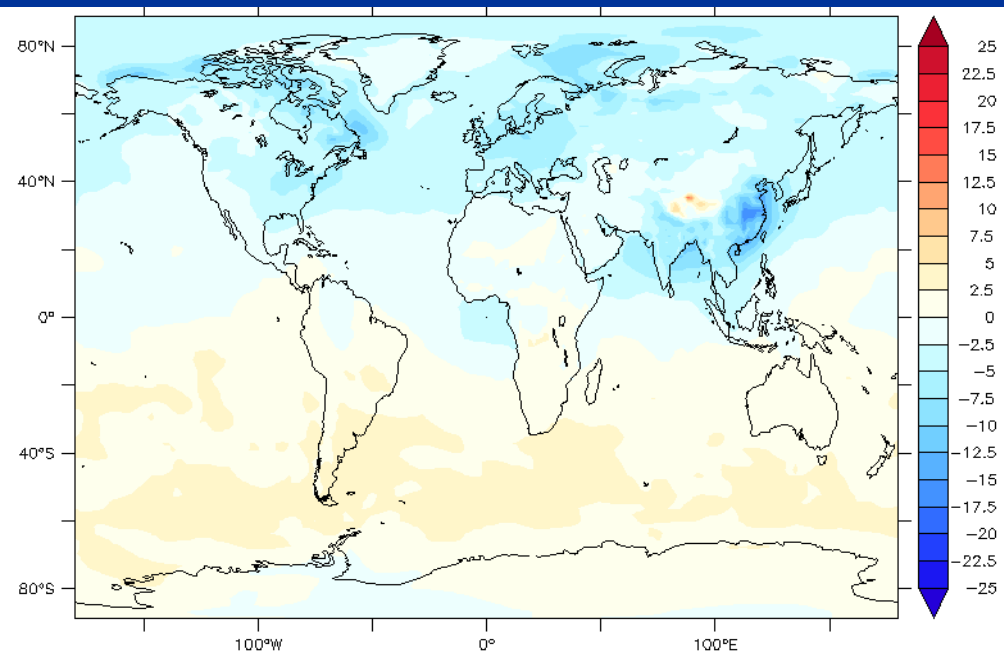
EXP1 - PI



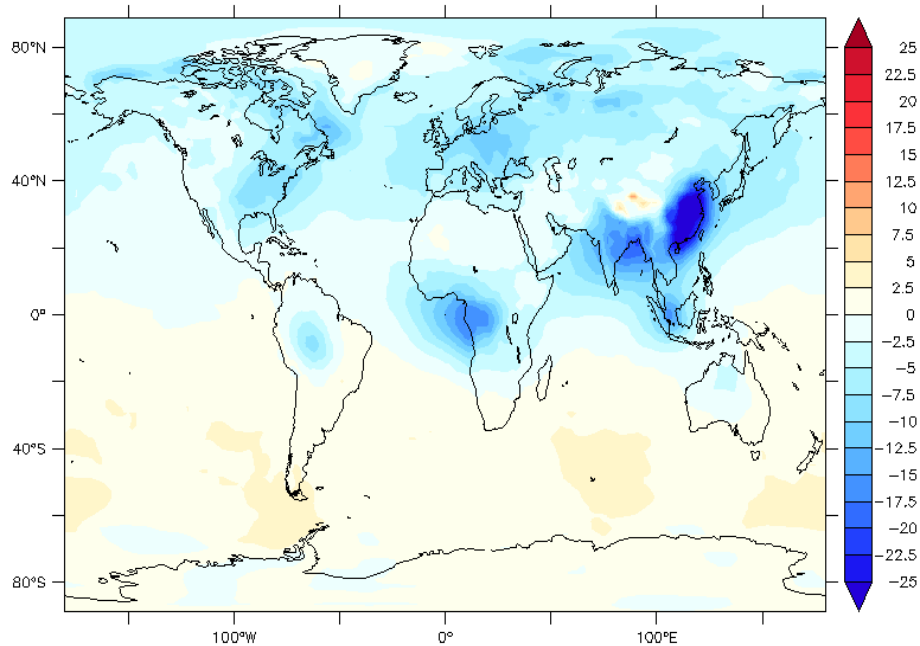
Anthropogenic Aerosol Optical Depth (550 nm)

Courtesy: Manmeet, Ayantika

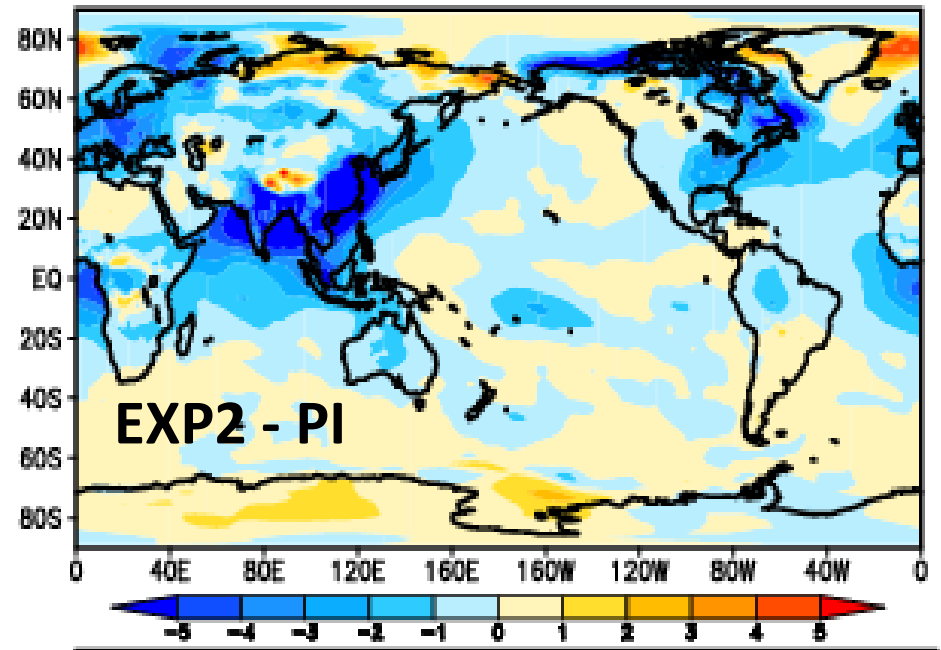
Anthropogenic Aerosol RF at TOA

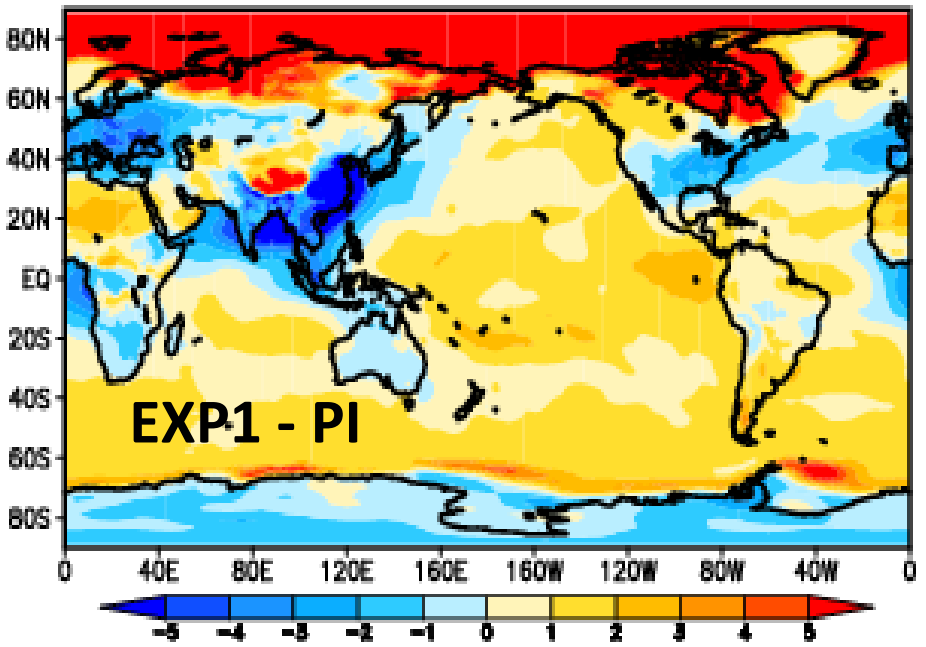


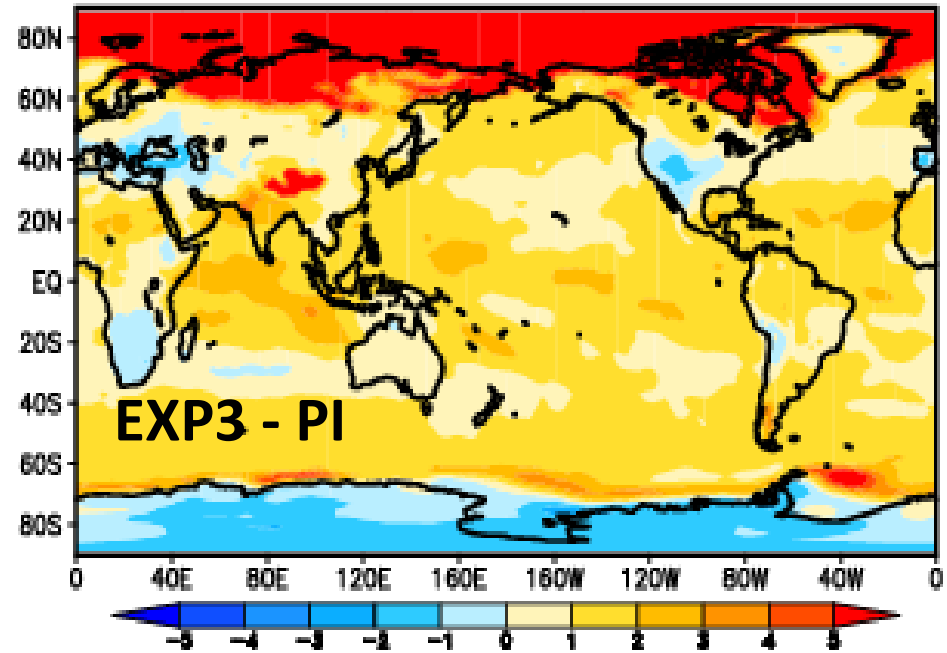
Anthropogenic Aerosol RF at Surface



Changes in Clear Sky Radiative Forcing (RF) @ TOA: (JJAS)

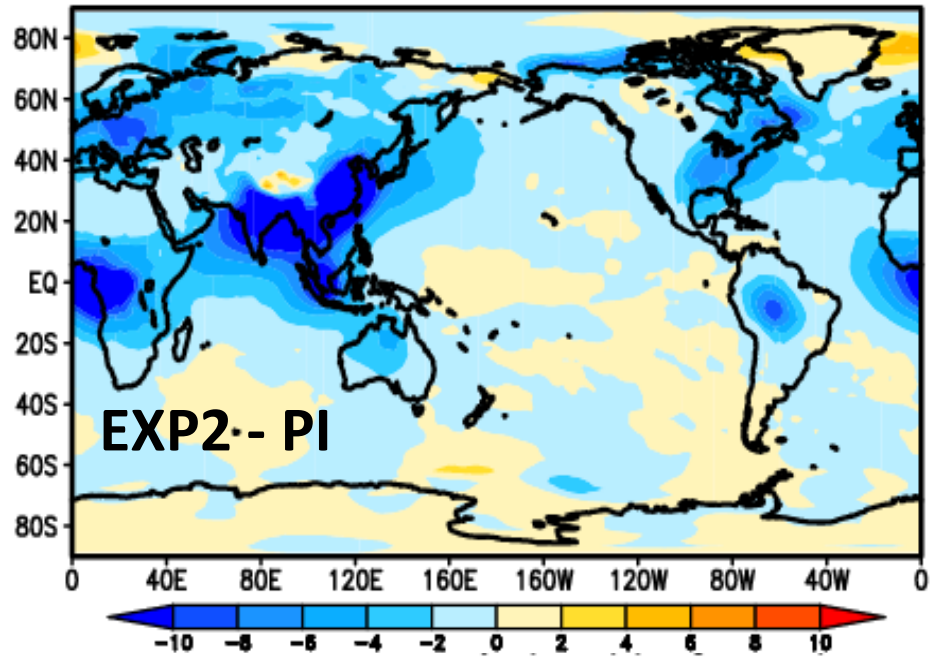


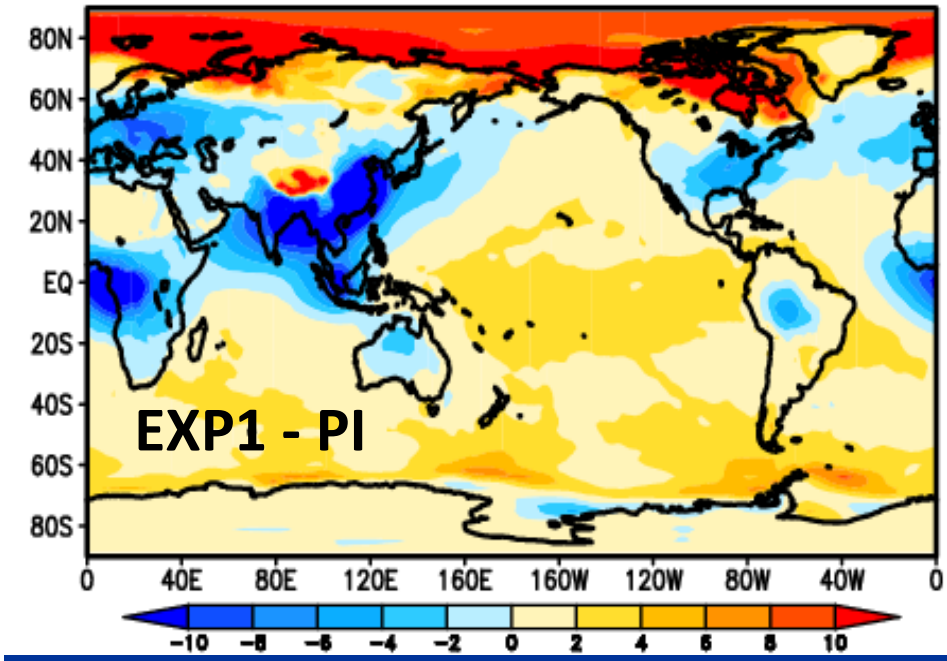


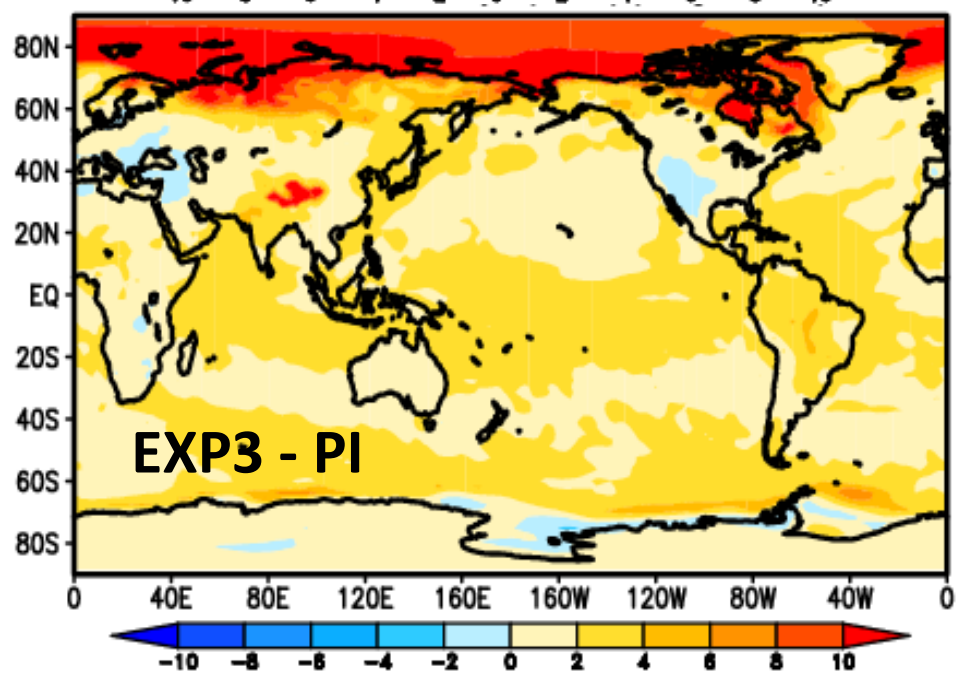


Courtesy: Ayantika

Changes in Clear Sky Radiative Forcing (RF) @ SFC: (JJAS)

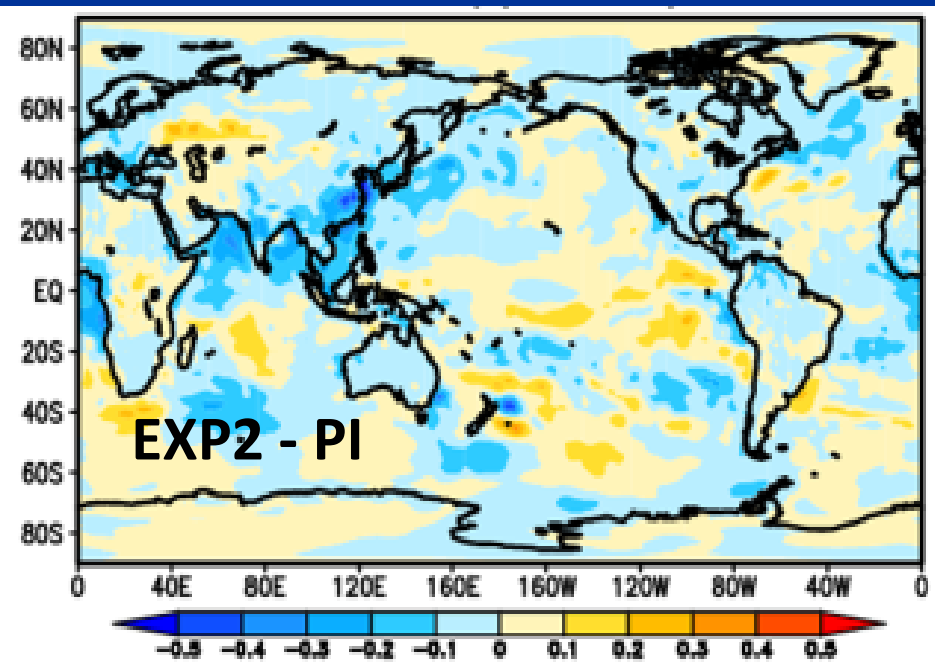


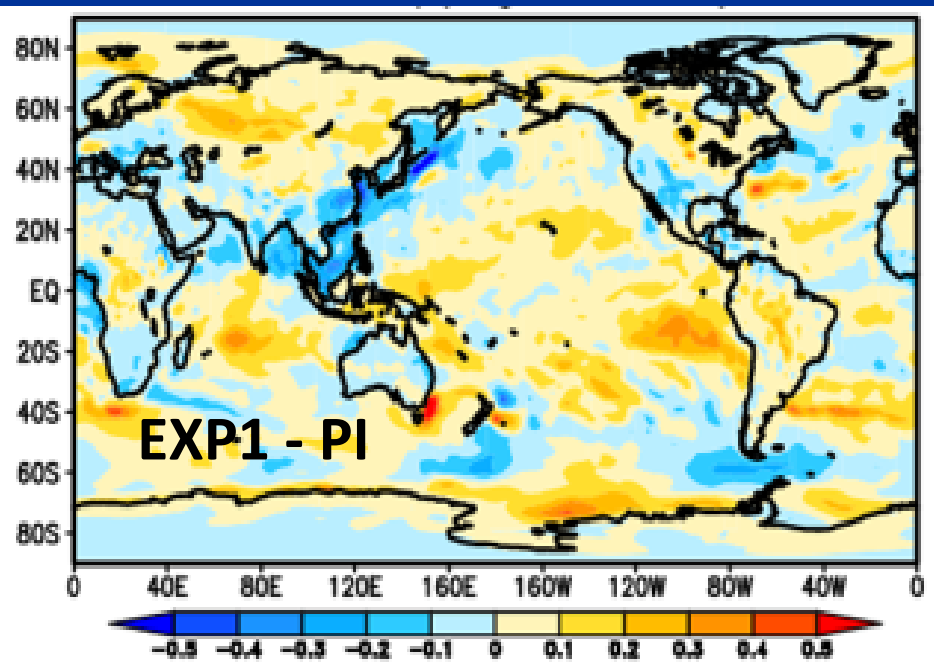


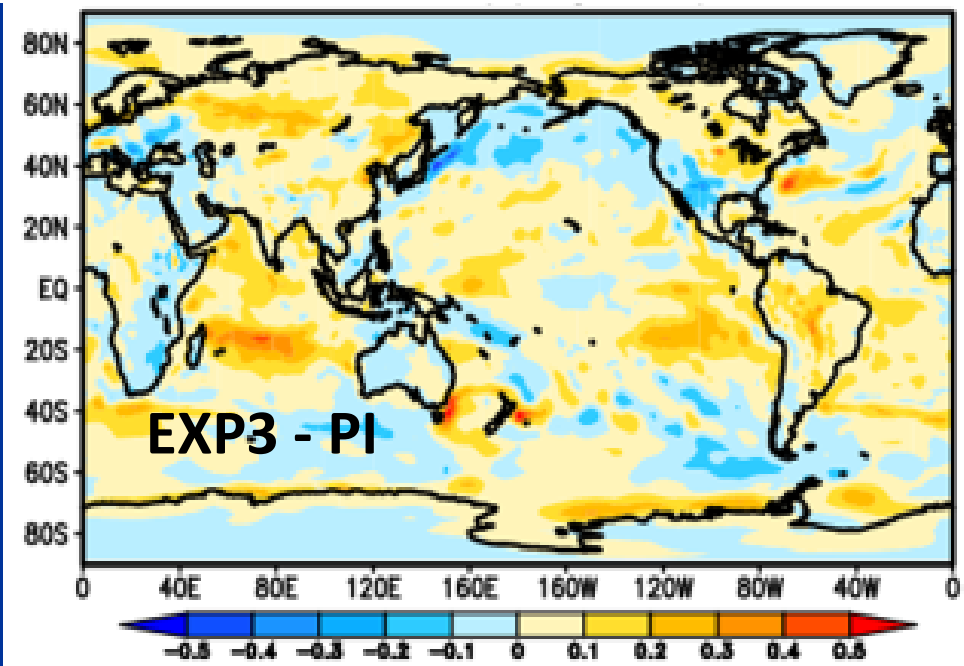


Courtesy: Ayantika

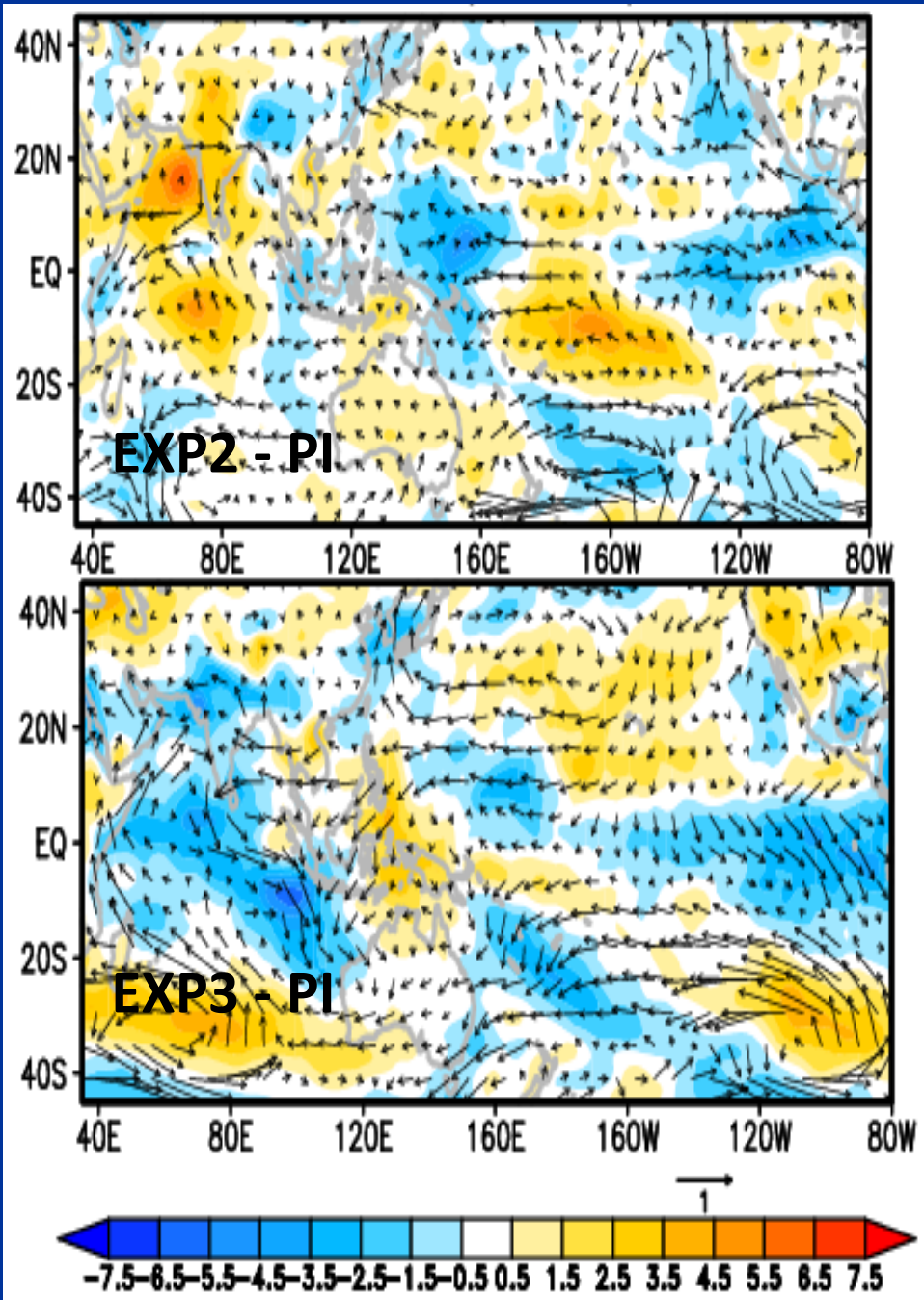
Changes in Evaporation: (JJAS)

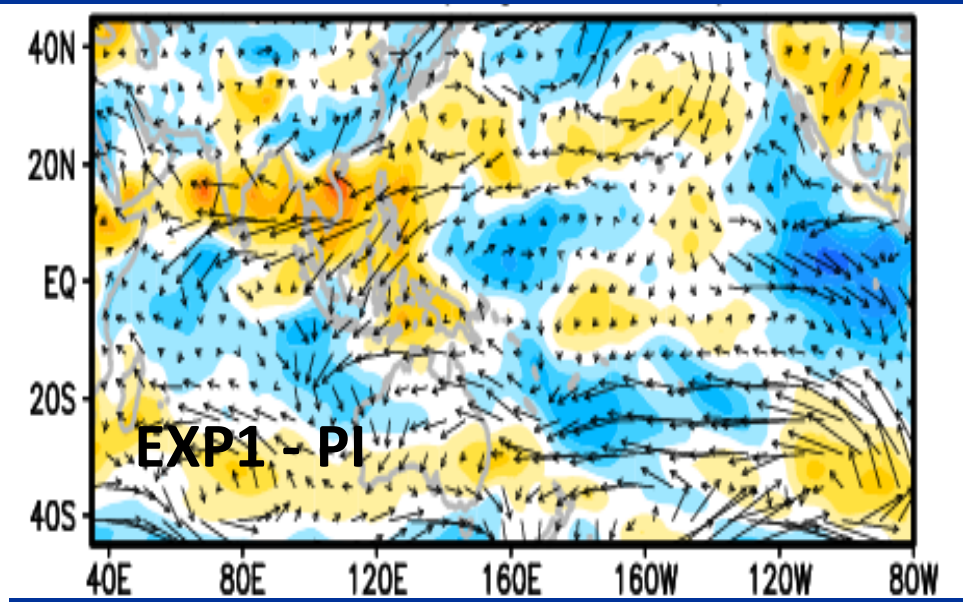




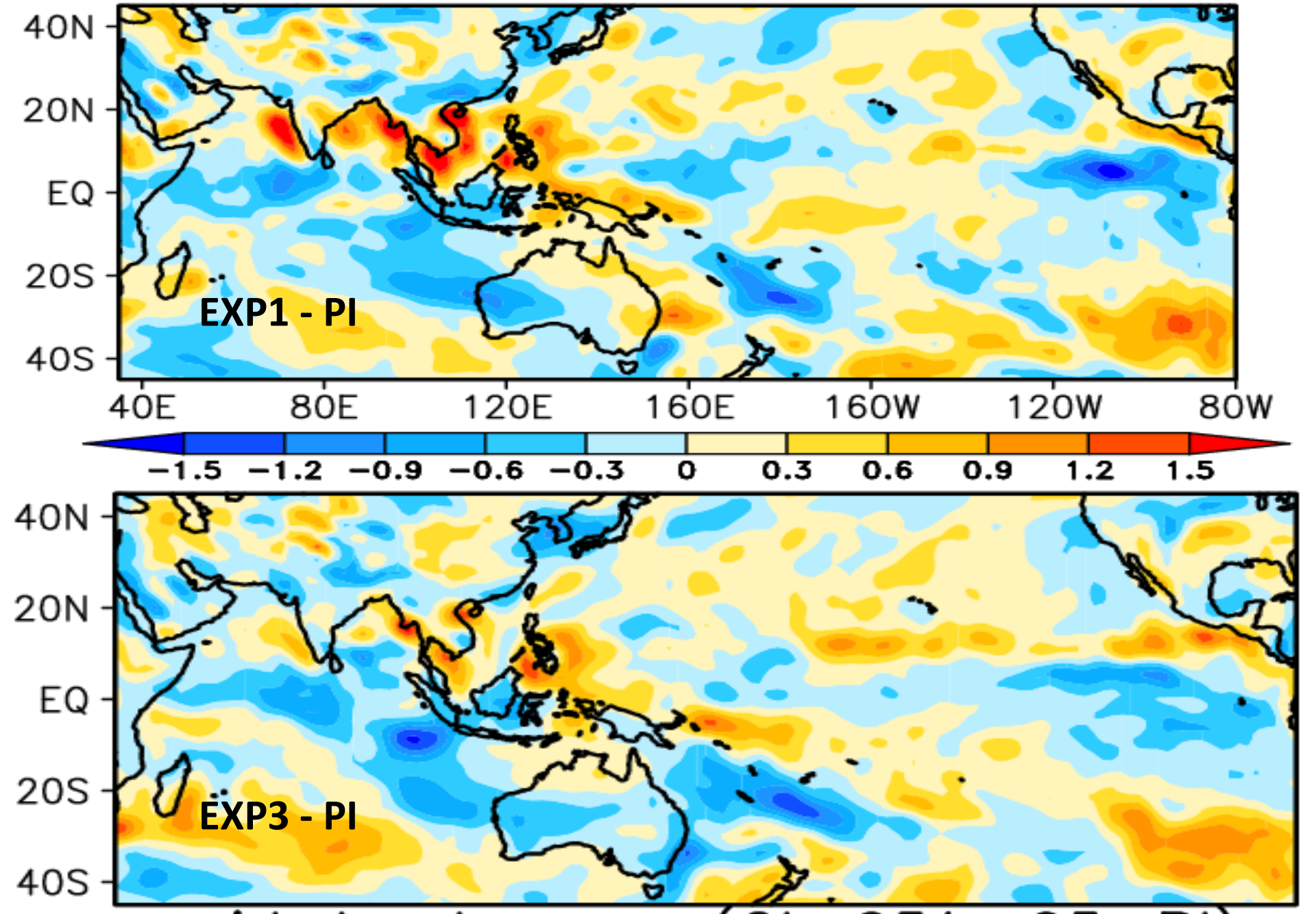


Changes in OLR and 850 hPa winds: (JJAS)

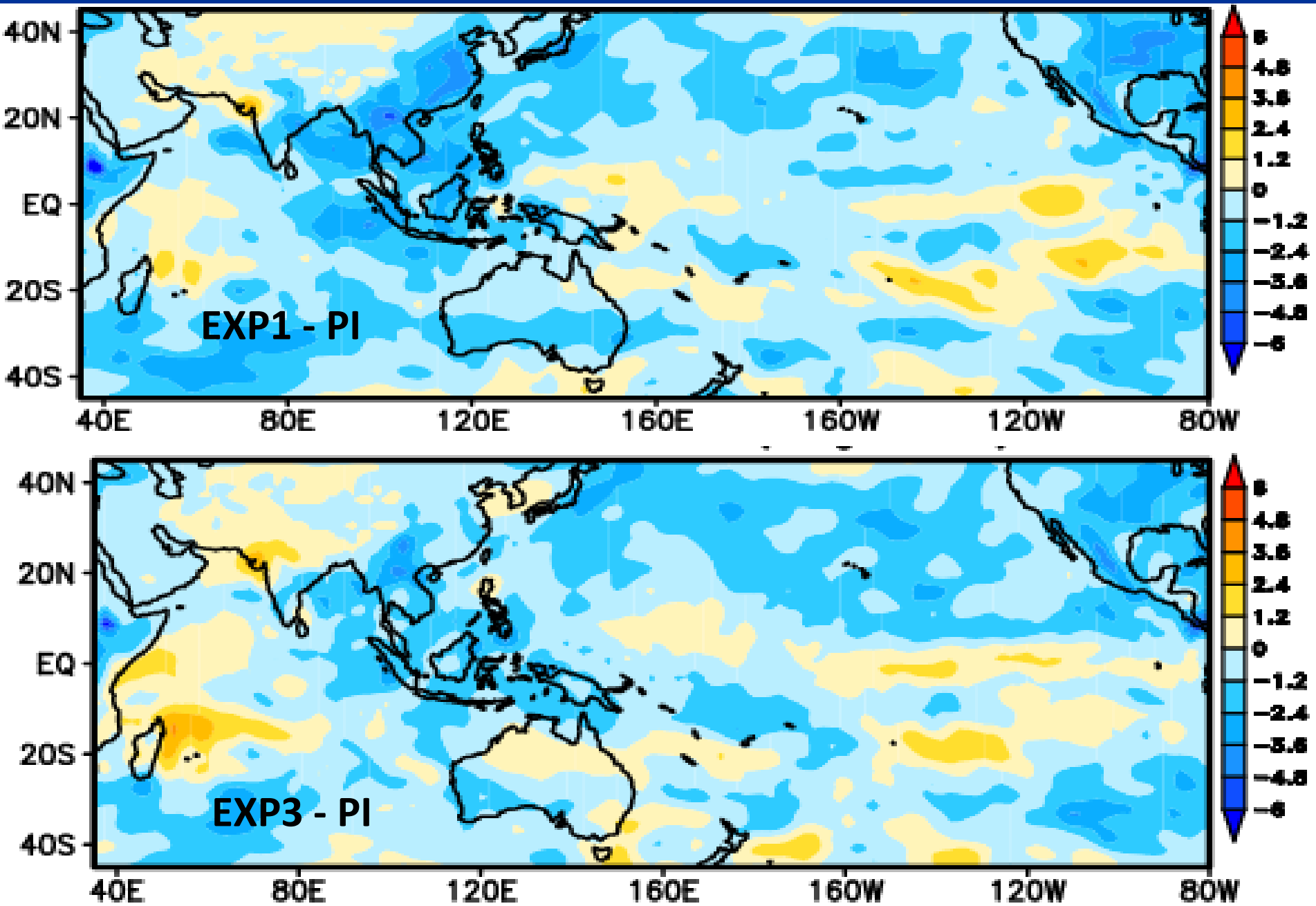




Changes in mid-tropospheric vertical velocity (JJAS)



Changes in low-level cloud cover (JJAS)



Summary

- Global Climate Change is Real. Its impact on the South Asian Monsoon Hydroclimate is evidenced from the IITM-ESM experiments.

- Decreasing trend of Indian monsoon precipitation in the post-1950s is captured by the model simulation in response to Anthropogenic Forcing. Recent monsoon decline largely forced by **Northern Hemispheric Anthropogenic Aerosols**

- Suppression of organized monsoon convection under the combined influence of anthropogenic aerosol and GHG forcing – as indicated by the IITM ESM experiments.

- Implications of changing regional monsoon precipitation distribution clearly demand adaptive strategies to enable a resilient South Asian population.

- Role of climate change on seasonal predictability of the monsoon ?

Why meteorological department's monsoon forecast is often inaccurate

Hindustan Times, 21 April 2019

Iailed monsoons play havoc with millions of farmers in central India leading to crippling poverty and soaring suicides. (AP file photo)

The India Meteorological Department's southwest monsoon forecasts provide critical information to at least 700 million people in India who depend, directly or indirectly, on agriculture for a livelihood. Yet, the predictions are, quite often, far from accurate. The reason: a very high variability in rainfall patterns.

And the predictions are not likely to get any better. Uncertainties associated with climate change mean that even the dynamic global models used to predict monsoon rainfall and distribution cannot significantly improve the accuracy of the forecasts,

IMD couldn't have forecast that rainfall will be below normal in 2018, said M Rajeevan, secretary, ministry of earth sciences, because "we didn't foresee the massive rainfall deficiency that the northeastern states would face.

For the first time ever, northeast India received less than 80% of LPA."

IMD is an arm of the ministry of earth sciences.

"No natural phenomenon can be predicted accurately; it's even more difficult when climate change causes aberrations," said DS Pai, senior scientist at IMD, Pune.

The large uncertainty of global models in predicting the impact of climate change on the monsoon has led a team from the Indian Institute of Tropical Meteorology (IITM) to develop an IITM Earth System Model (IITM-ESM) that will be used for seasonal monsoon forecasts. It will also contribute to the Intergovernmental Panel on Climate Change's (IPCC) sixth Assessment Report on how the world is being affected by climate change, to be released in 2020.

The IITM model projections have indicated that there has been a weakening of the Indian monsoon in recent decades, leading to an overall decrease in rainfall.

This trend has been supported by long-term monsoon data from the IMD, but the model also shows that in future there will be a perceptible enhancement in overall monsoon rainfall as well as increase in extreme weather events like floods and droughts associated with climate change.

Future Plans: High resolution (27 km grid) global climate model (T574)

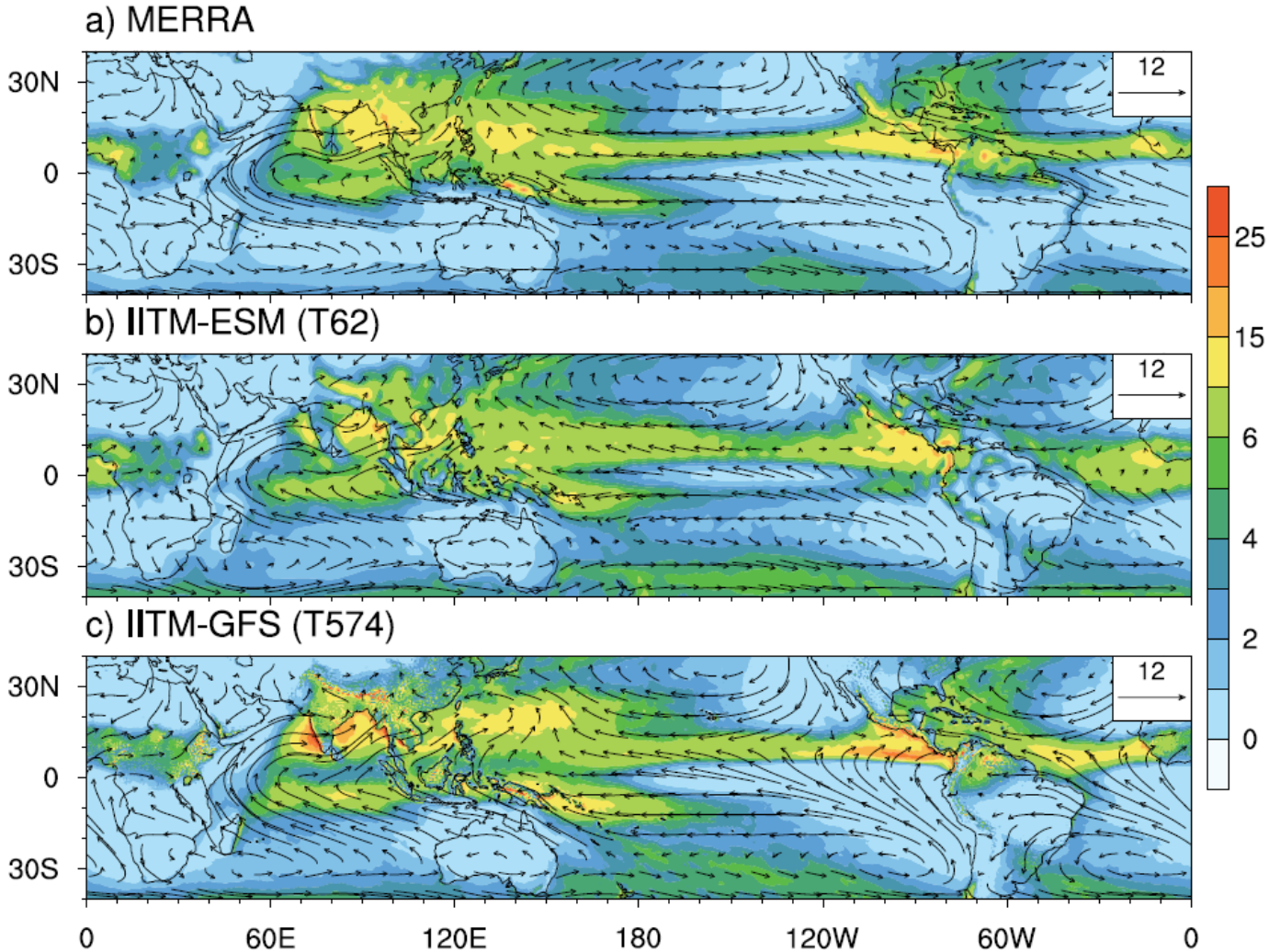


Figure. Spatial maps of climatological mean precipitation (mm day^{-1}) and 850 hPa winds during the boreal summer monsoon (June – September) season **(a)** TRMM precipitation and MERRA reanalysis winds **(b)** IITM-ESMv2 (PI control simulation) and **(c)** High-resolution (T574: 27 km grid) atmospheric-only version of IITM-ESMv2. The simulated means are based on the last 50 years of the PI Control experiment and 10 years from high-resolution atmospheric-only version of IITM-ESMv2.

Thanks for your kind attention!