The IITM Earth System Model: Development and Future Road Map

Swapna Panickal

Centre for Climate Change Research
Indian Institute of Tropical Meteorology (IITM)

ESM Team: R. Krishnan, V. Prajeesh, D.C. Ayantika , N. Sandeep, S. Manmeet, M. Aditi and V. Ramesh

ICTP TTA: Monsoon in a changing climate, Italy, 31st-4th August 2017

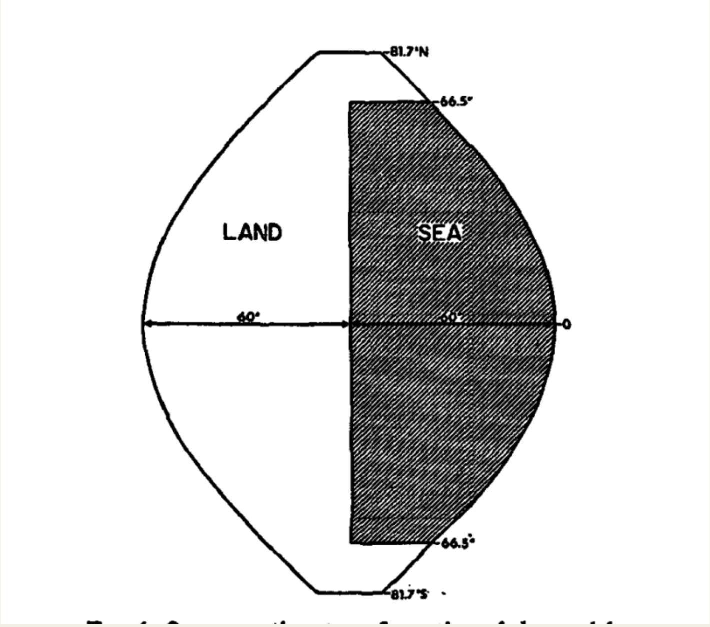
Outline

- **Climate Modeling : brief history**
- **Need for Improving Monsoon Simulation**
- **Overview of IITM-ESM**
- **Step towards Earth System Modeling frame-work**
- **Future Road Map**

Manabe and Brian (1969)

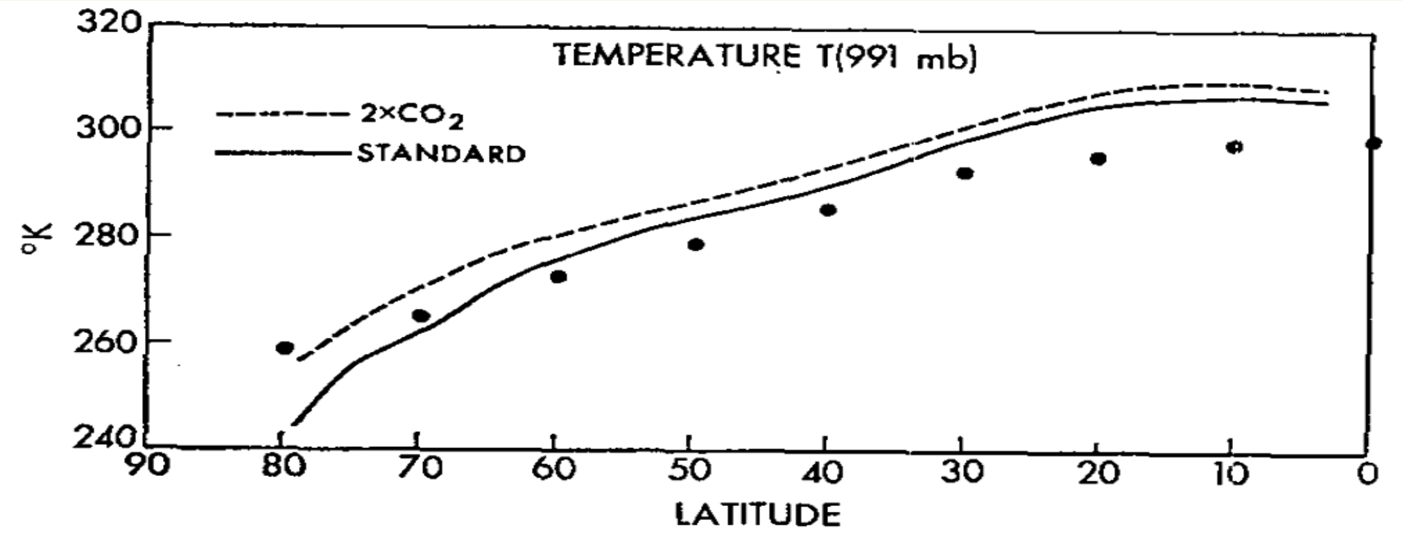
Climate Calculations with a Combined Ocean-Atmosphere Model

- Recognized as a “milestone in scientific computing”, Nature (2006).
- Sector model of 120°
- 1 atmospheric year coupled to
- 100 ocean years
- 1200h for 1 simulated year
- (0.02 SYPD) on Univac 1108



- ➢ **Empirical evidence indicates that poleward heat transport by ocean currents is of same order of magnitude as poleward transport of energy in the atmosphere (Sverdrup, 1975)**
- ➢ **Serious attempt to calculate climate must take into account atmosphere and hydrosphere**

Atmospheric response to doubled CO2



Manabe and Wetherald (1975): A foundational document of climate modeling

- Estimated the temperature changes resulting from doubling CO_2 concentration
- Simplified three-dimensional general circulation model.
- A limited computational domain, an idealized topography, no beat transport by ocean currents, and fixed cloudiness.
- The CO2 increase raises the temperature of the model troposphere and significantly increases the intensity of the hydrologic cycle

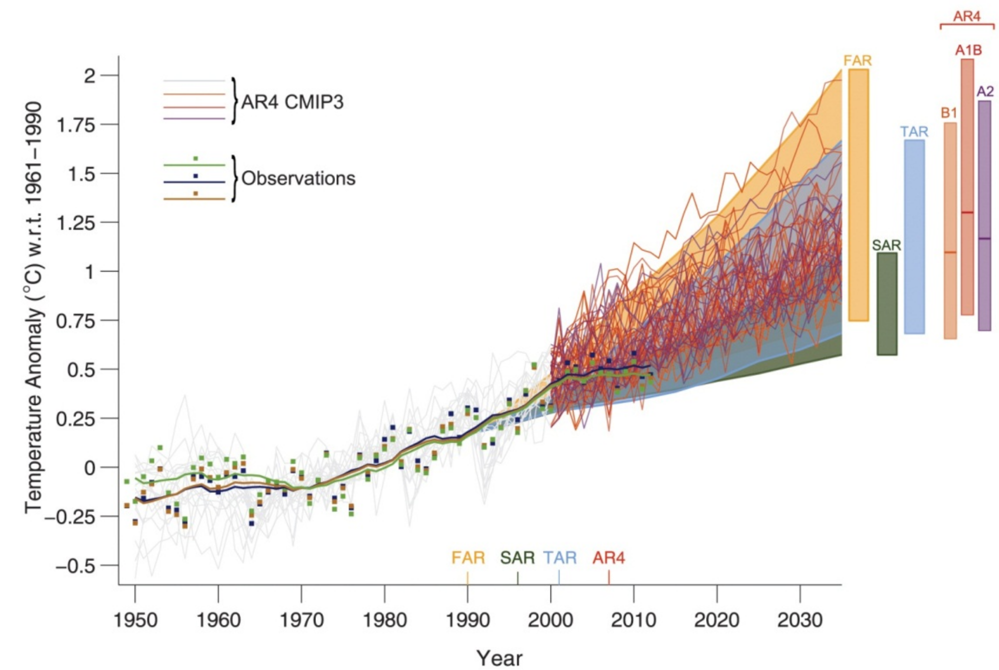
The Charney Report (1979)

"Carbon dioxide and climate: A Scientific Assessment."

- Precursor to the IPCC Assessment Reports.
- Based on 5 model runs: 3 from Manabe (GFDL), 2 from Hansen (GISS).

- Conclusions:
  - Direct radiative effects due to doubling of CO_2: 4 W/m^2
  - Feedbacks: water vapor (Clausius-Clapeyron), snow-ice albedo feedback.
  - Cloud effects: "How important the cloud effects are, is, however, an extremely difficult question to answer. The cloud distribution is a property of the entire climate system, in which many other feedbacks are involved."
  - "We believe, therefore, that the equilibrium surface warming will be in the range of 1.5-4.5C, with the most probable value near 3C."

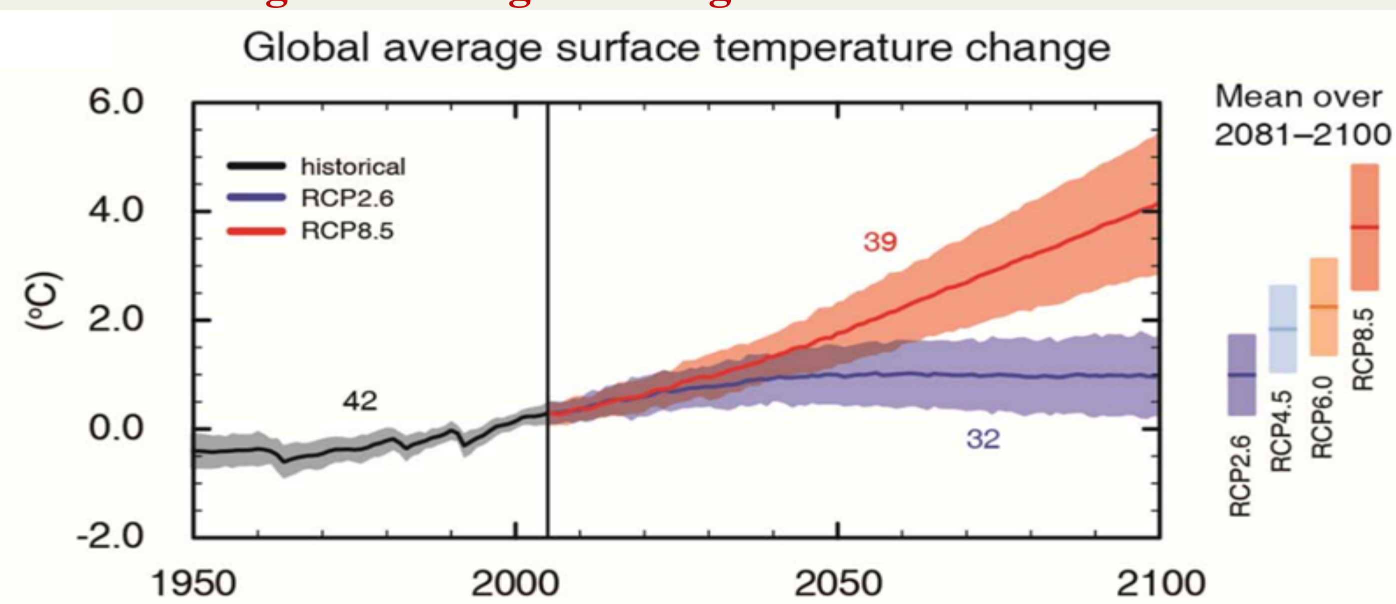
Climate Modeling Today...



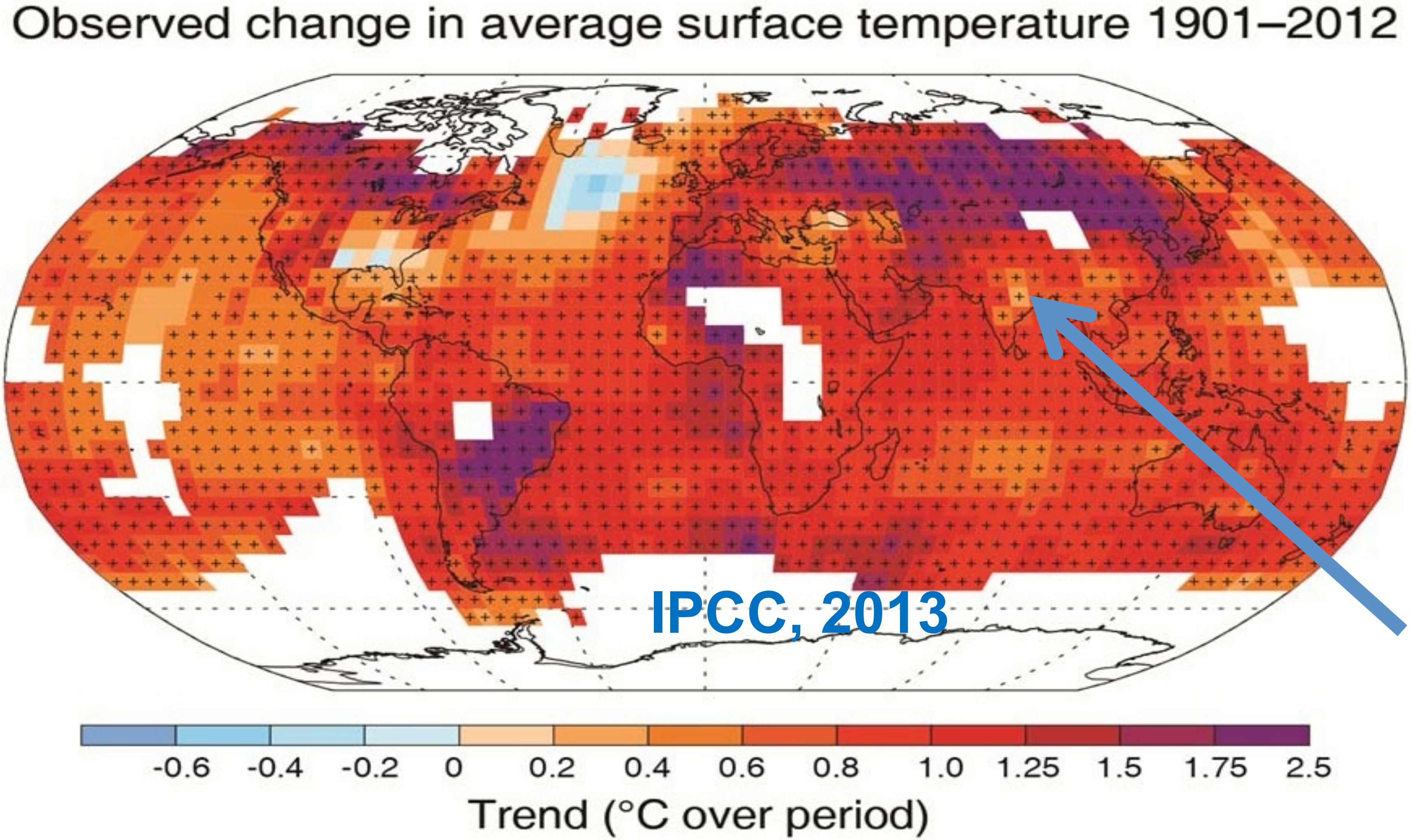
IPCC AR5 SPM:

- Warming of the climate system is unequivocal
- Last three decades has been successively warmer than any preceding decade since 1850

IPCC AR5. 20th century warming cannot be explained without greenhouse gas forcings



Recent Climate Change Report



Planet has warmed by 0.85 K over 1880-2012

Climate Change 2013: WG1 contribution to IPCC Fifth Assessment Report

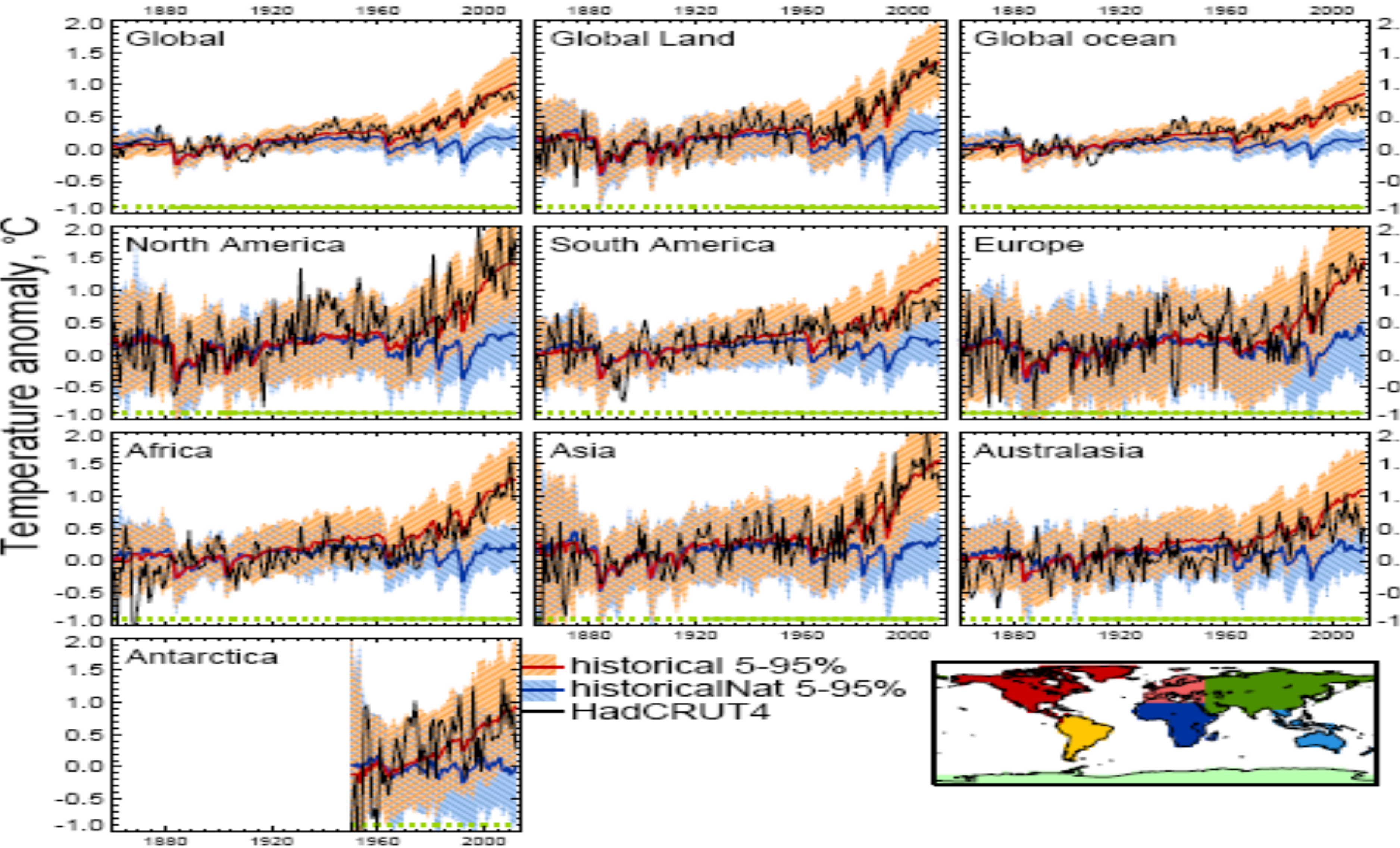
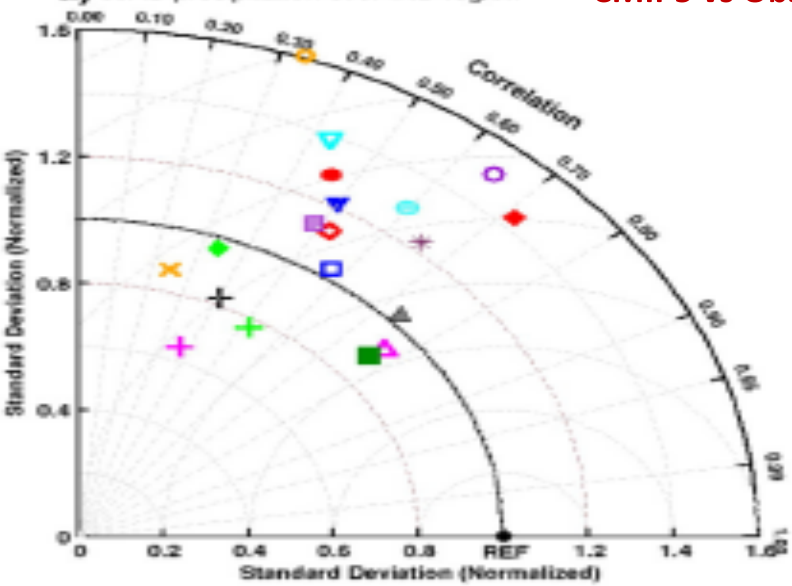


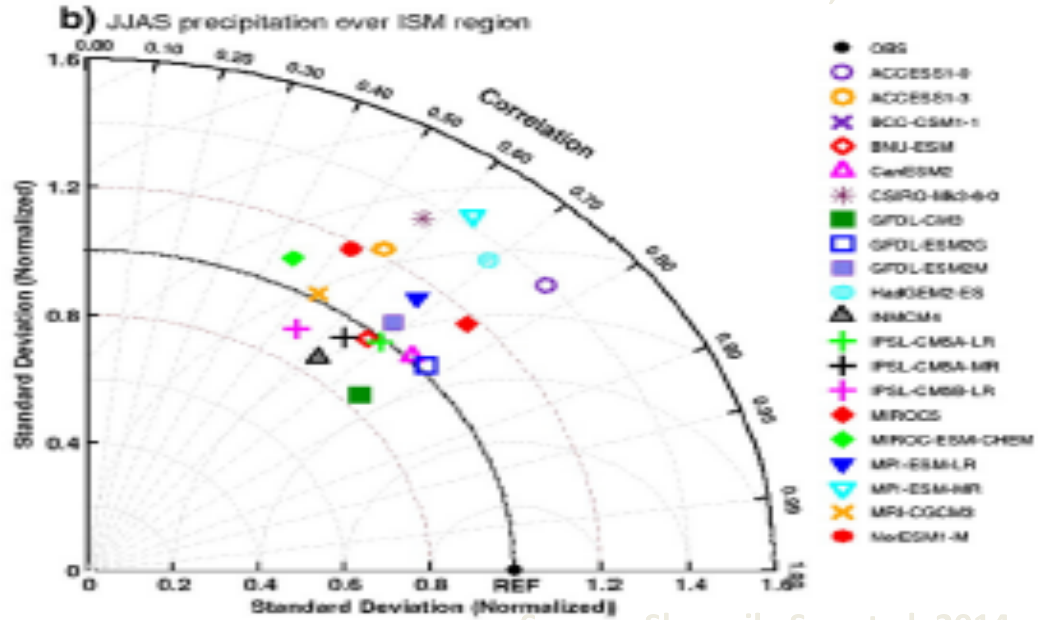
Figure 10.7: Global, land, ocean and continental annual mean temperatures for CMIP3 and CMIP5 historical (red) and historicalNat (blue) simulations (multi-model means shown as thick lines, and 5–95% ranges shown as thin light lines) and for HadCRUT4 (black). Mean temperatures are shown for Antarctica and six continental regions formed by combining the sub-continental scale regions defined by Seneviratne et al. (2012). Temperatures are shown with respect to 1880–1919 for all regions apart from Antarctica where temperatures are shown with respect to 1950–2010. Adapted from Jones et al. (2013).

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

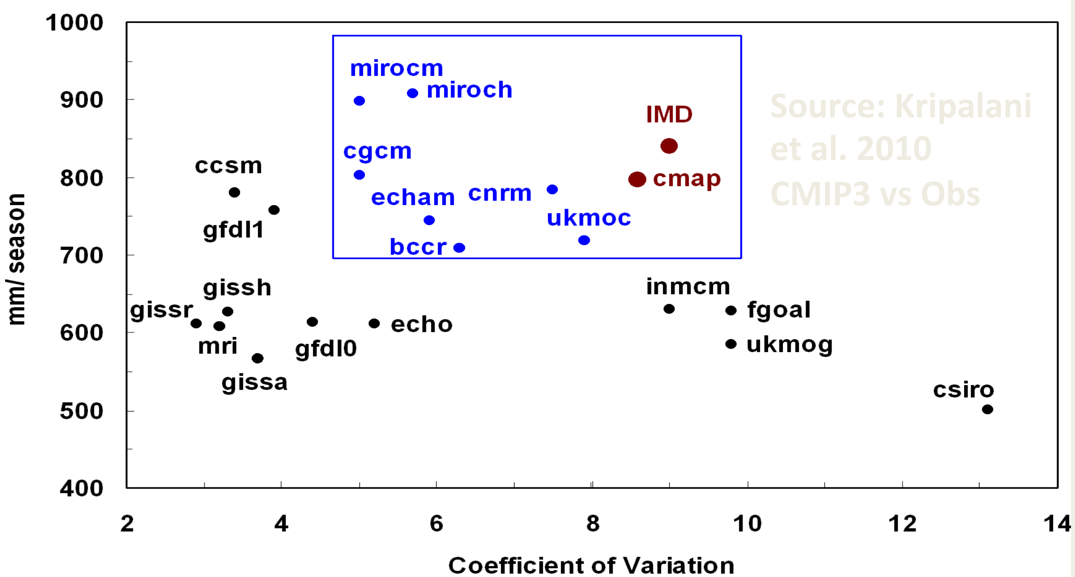
Indian Land: CMIP5 vs Obs



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



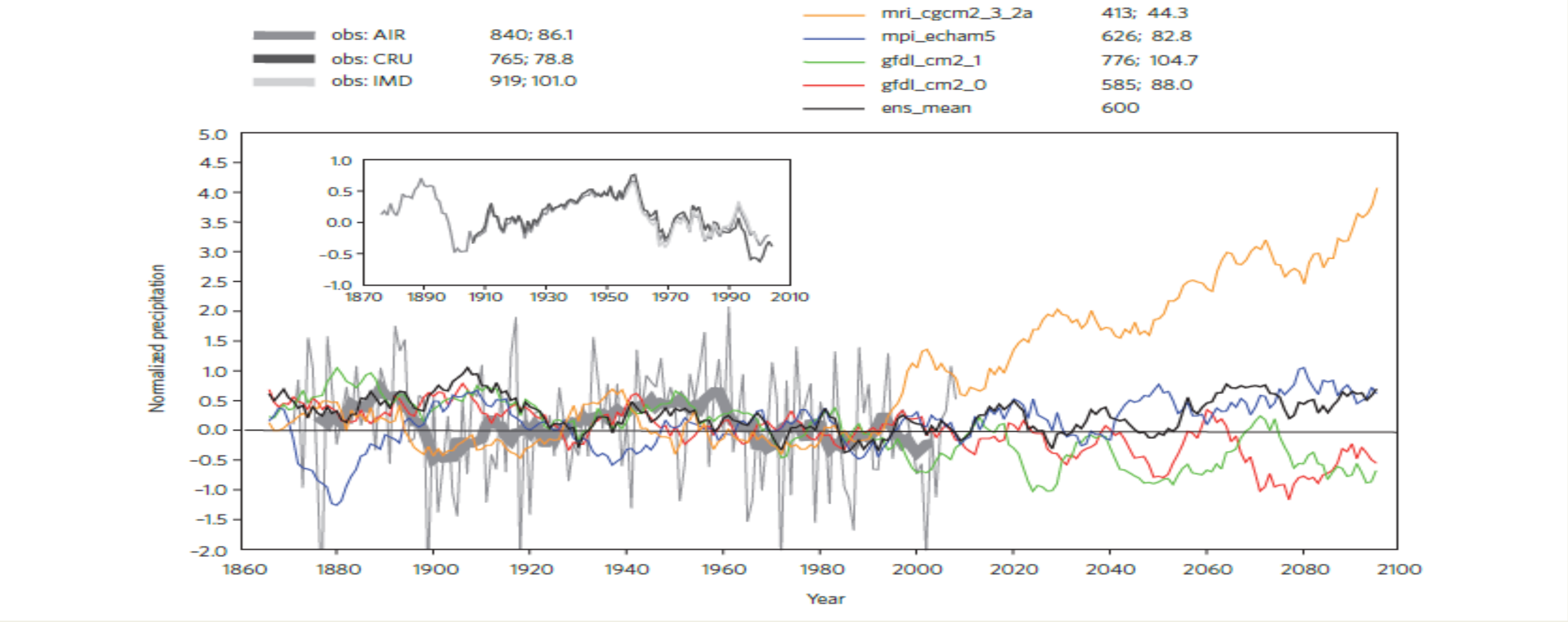
Source: Sharmila Sur et al. 2014



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

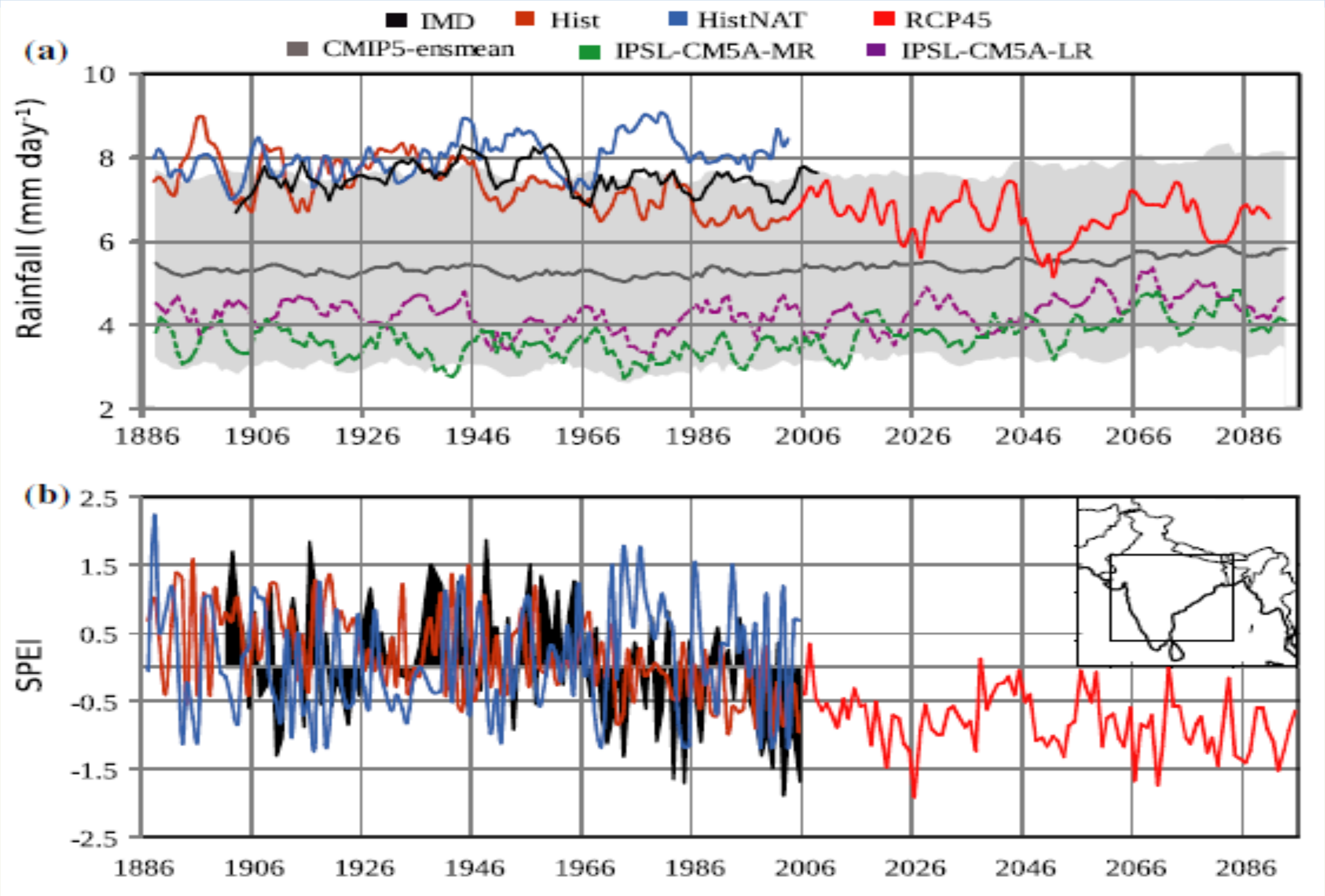
Trend in All India Summer Monsoon Rainfall



Historical and SRES A1B projection of South Asian monsoon rainfall [Turner and Annamalai, 2012]

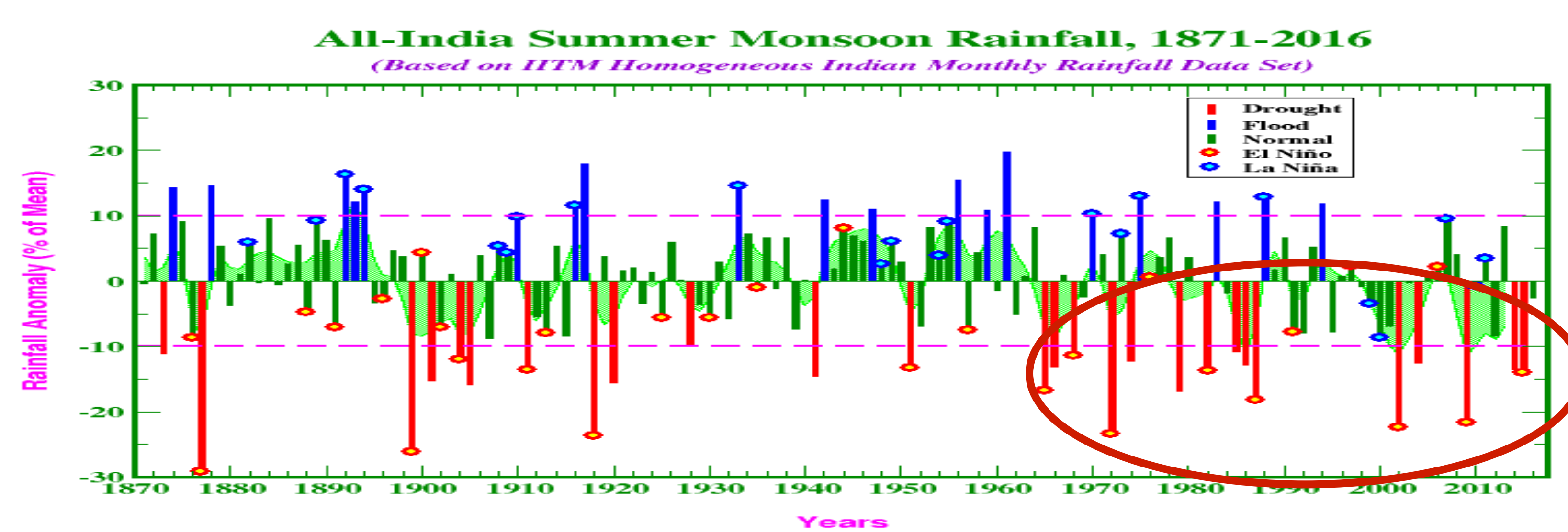
- **Observed data shows a negative trend in precipitation since 1950.**
- **Decadal variability dominates & considerable uncertainty in precipitation between the models**

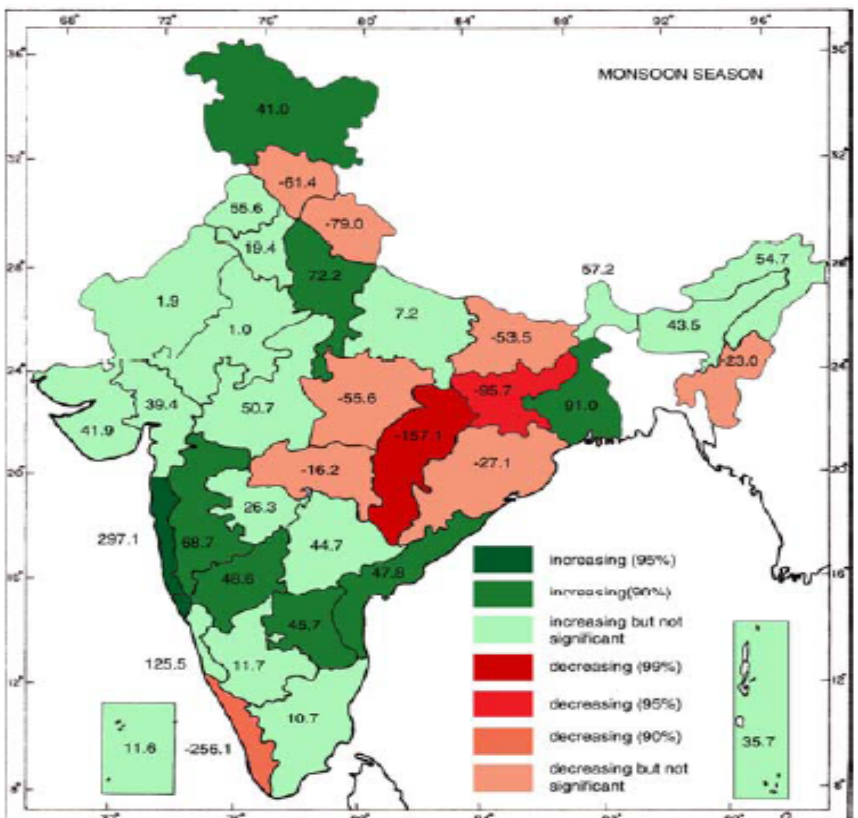
Temporal evolution of monsoon hydro-climatic signals



Krishnan et al. 2016

- **Decreasing trend of monsoon precipitation during the later part of 20th century**
- **The aridity index (SPEI , Standard Precipitation-Evaporation Index] indicates a marked increase in propensity of monsoon droughts**





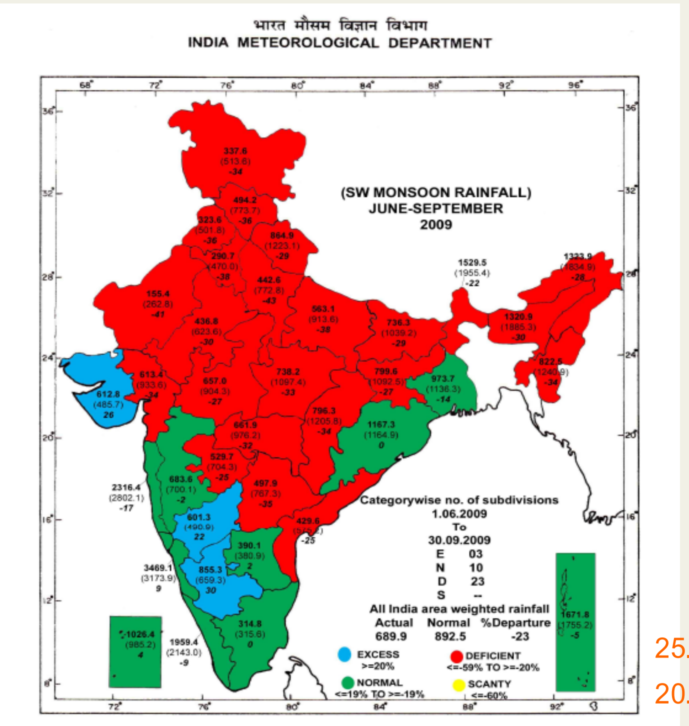
The 142-yr (1871-2012) record of all-India monsoon rainfall indicates a 40% increase in the frequency of monsoon-droughts during the second half relative to the first half of the period

Long-term trends in the Indian monsoon rainfall

Guhathakurtha and Rajeevan, 2006: Trends in monsoon rainfall over India (1901-2003)

Significant negative trends: Kerala, Jharkhand, Chattisgarh

Summer Monsoon Rainfall and Crop Production



Rainfall - 2009

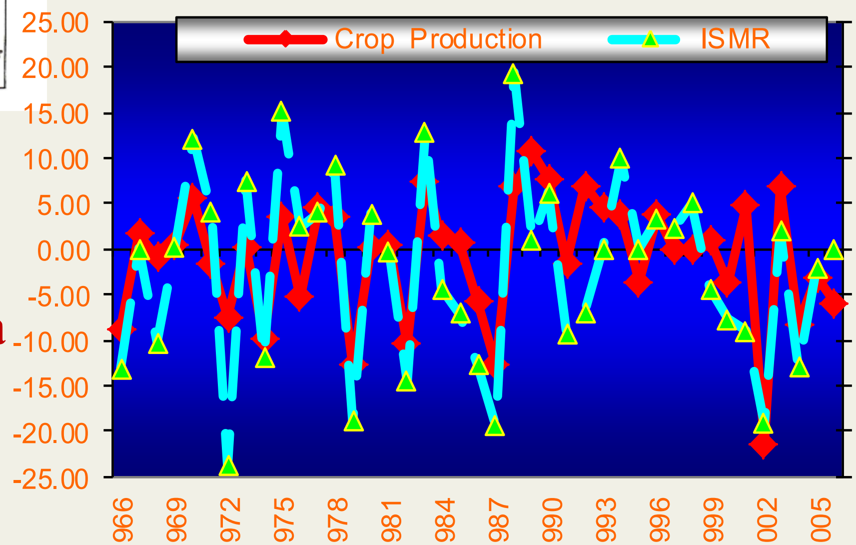
DRYING GRAIN BOWL

- Haryana, with **34%** rain deficit so far, heading for **6th drought in 11 years**
- Punjab's deficit at **36%, 5th drought** in 11 years likely
- In 17 years since 1998, monsoon in Haryana has been **10%** or more in **deficit in 12 years**
- In Punjab, such deficits seen in **11 out of 17 years**
- Droughts do not lead to huge drops in crop output in both states but put **severe strain on groundwater**

GROUNDWATER CRISIS

- Punjab on average draws **45%** more groundwater than is replenished. Haryana **9%**
- A 2009 NASA study said groundwater in Punjab, Haryana & Raj had decreased by more than 88 million acre-feet in 10 yrs — nearly 8 **times the water held in Lake Mead**, the largest water body in US

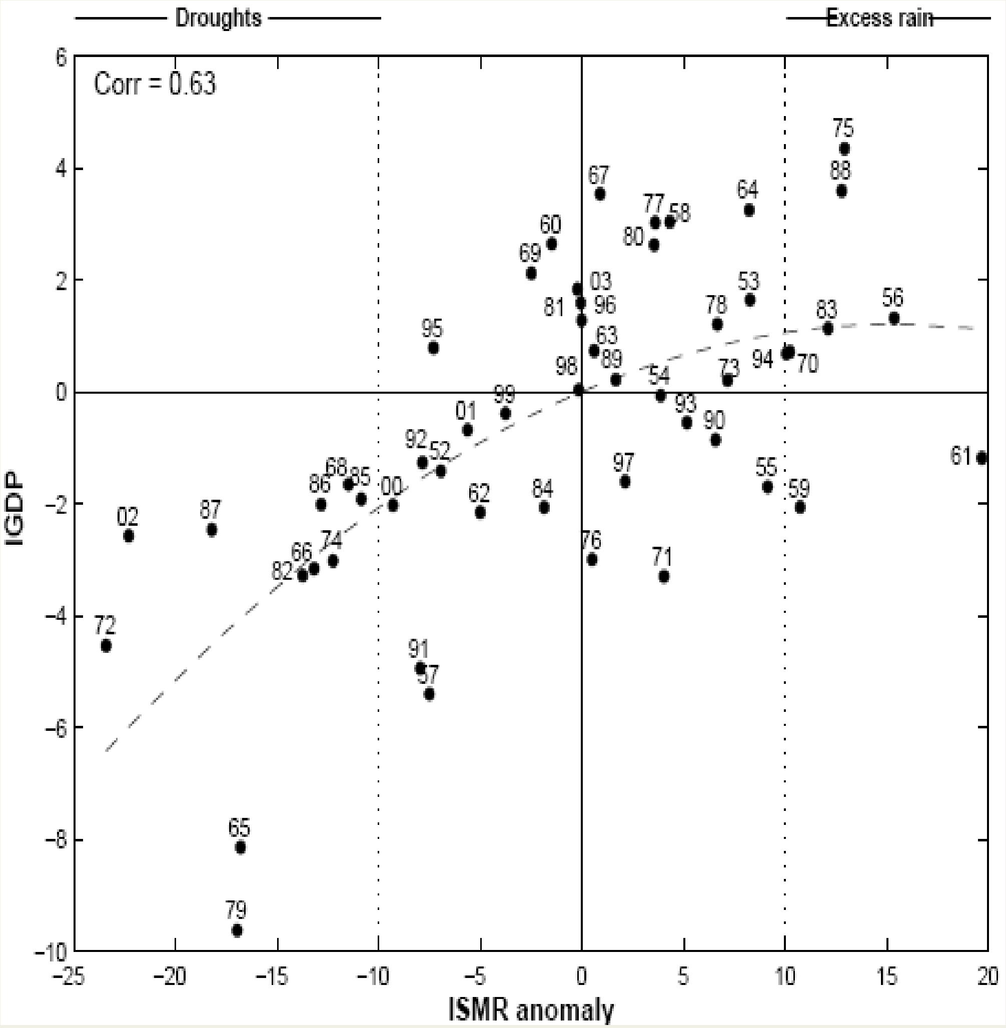
Detrended All India Kharif Production Anomaly (NCC, IMD)



GDP and Indian Monsoon Rainfall

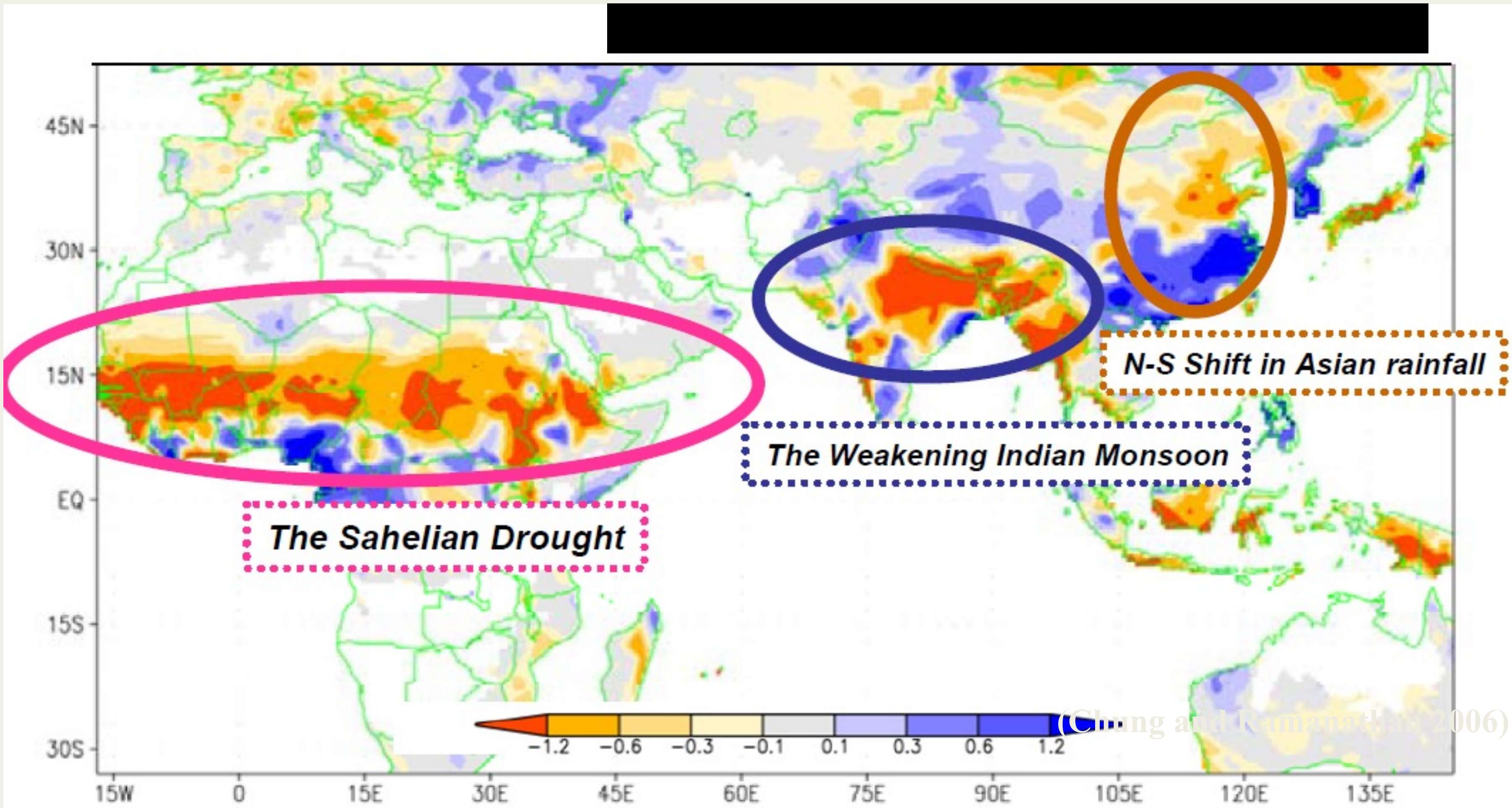
Impact of a severe drought on GDP remains 2 to 5% throughout, despite the substantial decrease in the contribution of agriculture to GDP over the five decades.

Two-thirds of the workforce is in agriculture



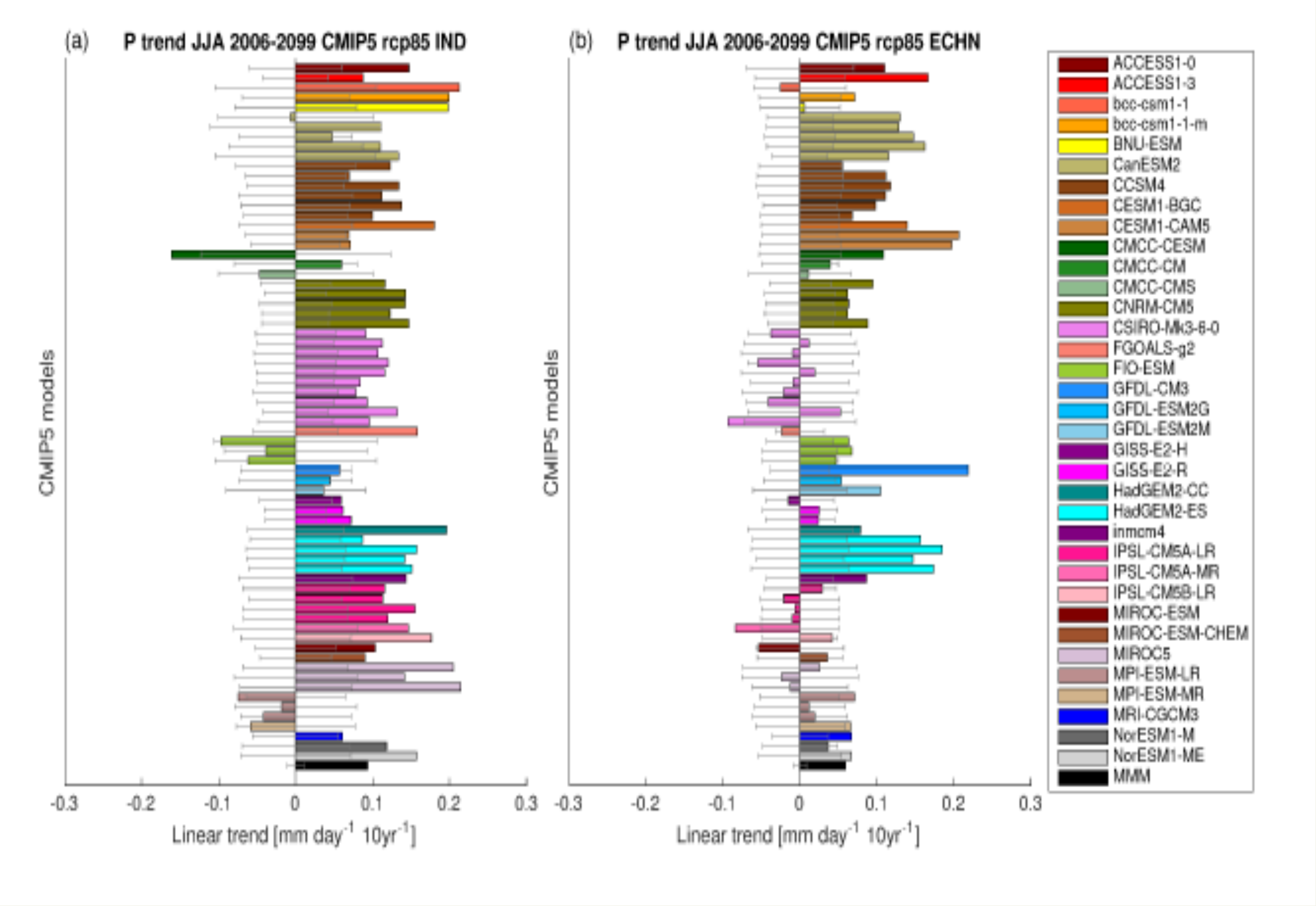
Gadgil and Gadgil (2006)

Observed Trend in Summer Rainfall 1950 to 2002



The observed linear trend shows widespread decrease in rainfall over the IGP and mountainous west-coast. The increasing trend over southeastern China and adjoining areas is also observed. The prominent drought over the Sahel region is also evident from the decreasing trend.

The linear trend of area averaged land precipitation from 2006 to 2099 for India and eastern China from CMIP5 Models



- **Most models show an intensified Asian monsoon rainfall,**
- **There is substantial model spread.** **(Li and Ting, 2016)**

Why there are uncertainty in regional precipitation response ?

- **In a warmer climate, as a consequence of the increase in tropospheric water vapor, the global hydrological cycle will become more intensified (Held and Soden 2006).**

- **The rate of precipitation increase is less than the rate of water vapor, and tropical atmospheric circulation weakens as climate warms (Vecchi and Soden 2007, Krishnan et al., 2015)**

- **The atmospheric circulation is the major source of uncertainty in regional rainfall projection (Xie et al. 2015)**

Science of climate change

Detection, attribution & projection of global climate and regional monsoons

Roadmap for Earth System Model (ESM) development

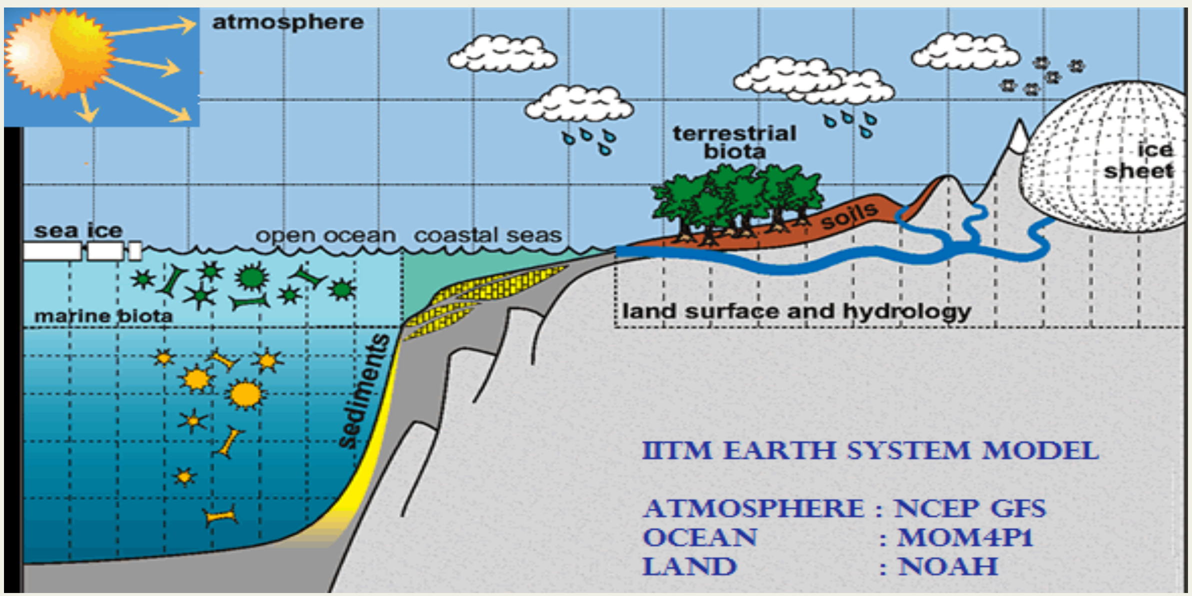
- **Start with an atmosphere-ocean coupled model with realistic mean climate**
  - Fidelity in capturing the global and monsoon climate
  - Realistic representation of monsoon interannual variability
  - Features of ocean-atmosphere coupled interactions
  - …
- **Include components / modules of the ESM**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

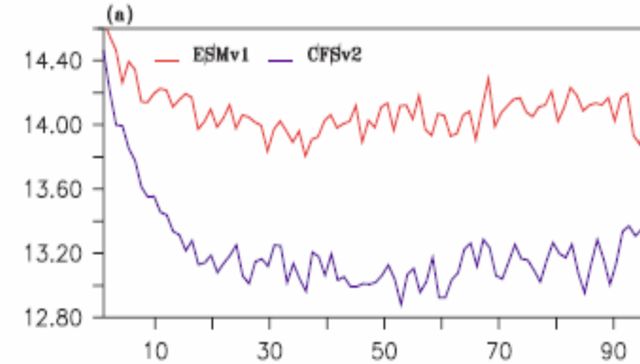
THE IITM EARTH SYSTEM MODEL

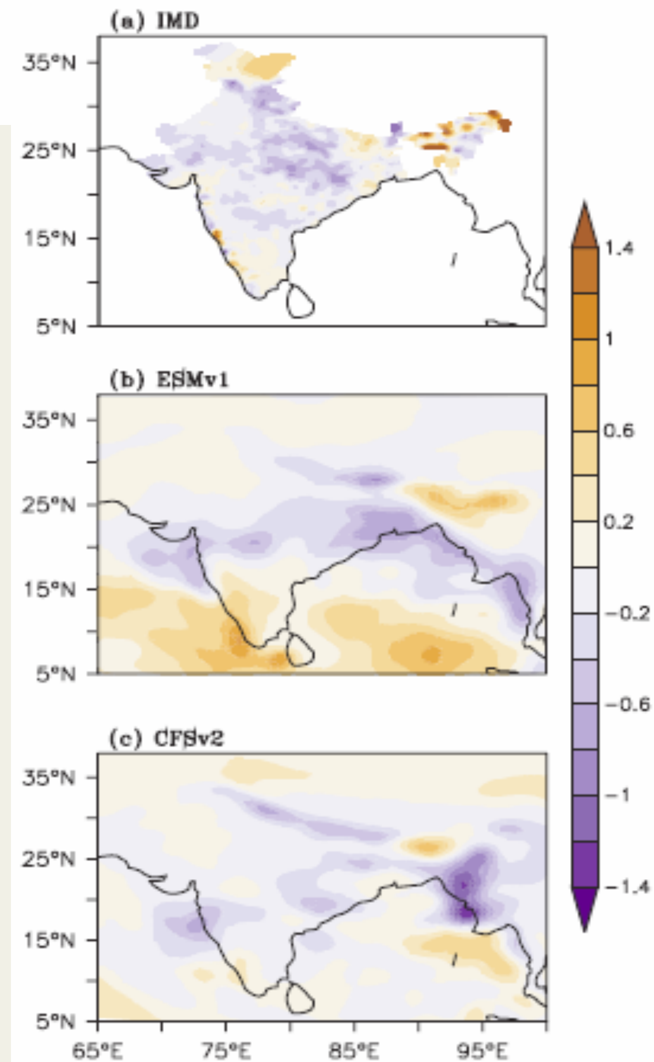
Transformation of a Seasonal Prediction Model to a Long-Term Climate Model

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.







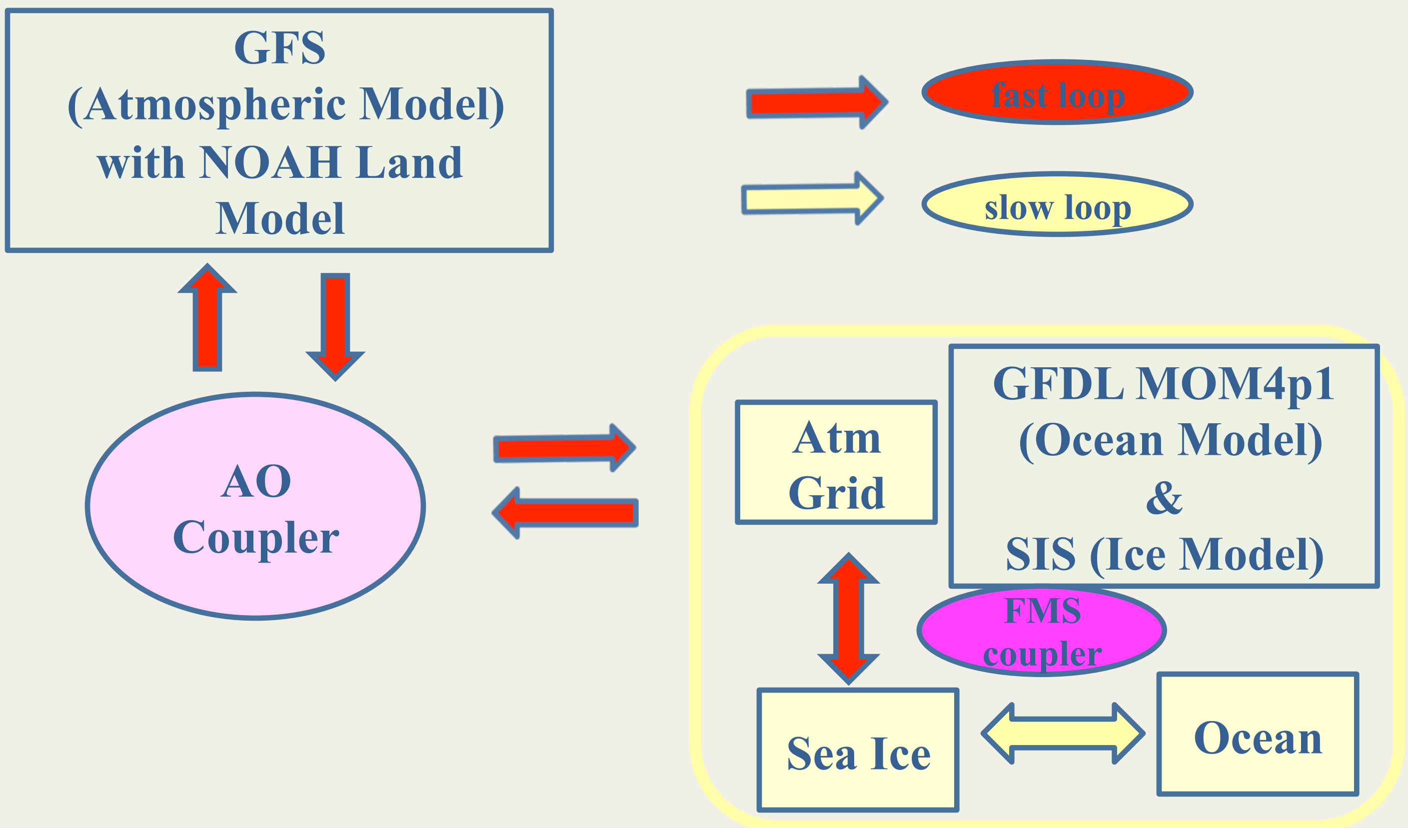
Atmosphere: T126 spectral (~ 190 km), 64 vertical levels – ESMv1

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

IITM Earth System Model (IITM ESM) Based on Coupled Forecast System (CFS) T62L64

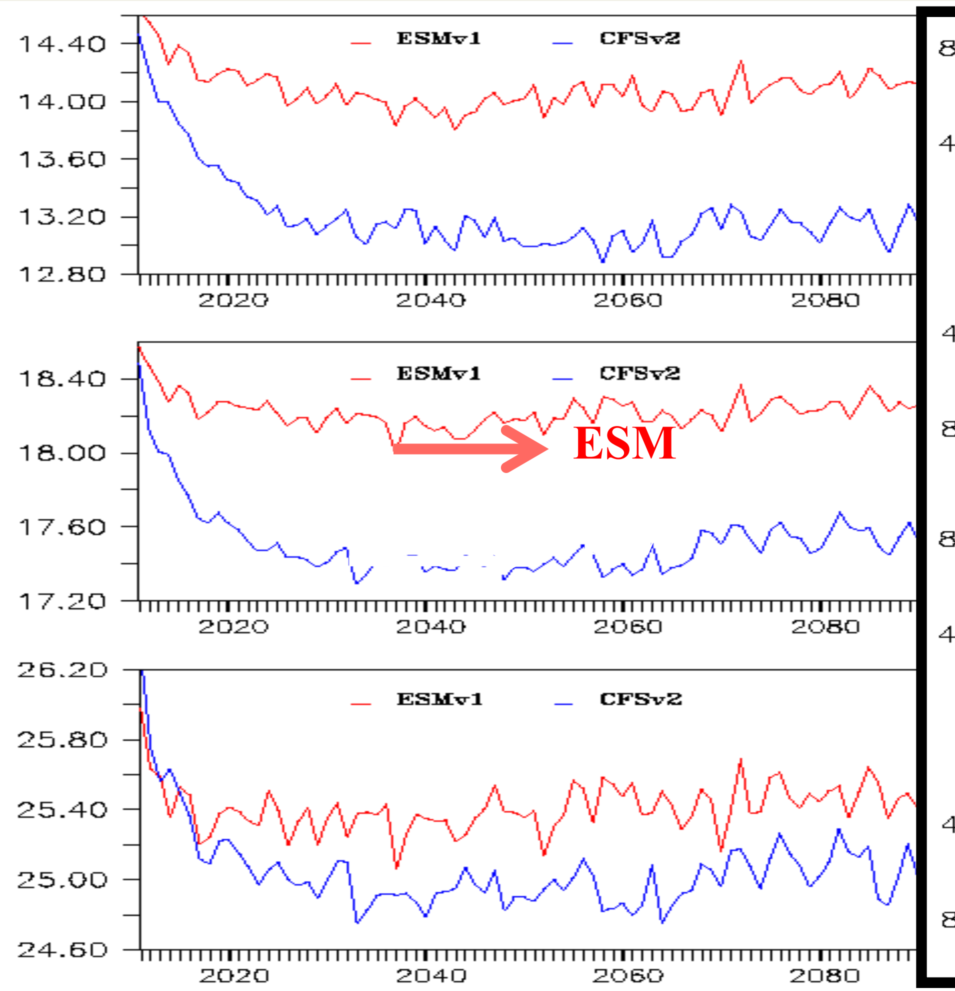
- The **NCEP CFS** Components
- Atmospheric **GFS (Global Forecast System) model**
  - T62 ; vertical: 64 sigma – pressure hybrid levels
  - Model top 0.2 mb
  - **Revised Simplified Arakawa-Schubert convection (Han & Pan)**
  - Non-local PBL (Pan & Hong)
  - SW radiation (Chou, modifications by Y. Hou)
  - Prognostic cloud water (Moorthi, Hou & Zhao)
  - LW radiation (GFDL, AER in operational wx model)
  - Land surface processes (Noah land model)
- Interactive Ocean: **GFDL MOM4p1** (Modular Ocean Model-4p1)
  - 1.0 deg poleward of 10^{o}N and 10^{o}S; and 0.33 deg near equator (10^{o}S – 10^{o}N)
  - 50 levels
  - **Interactive sea-ice**
  - **Interactive ocean biogeochemistry**

Schematic of IITM ESM

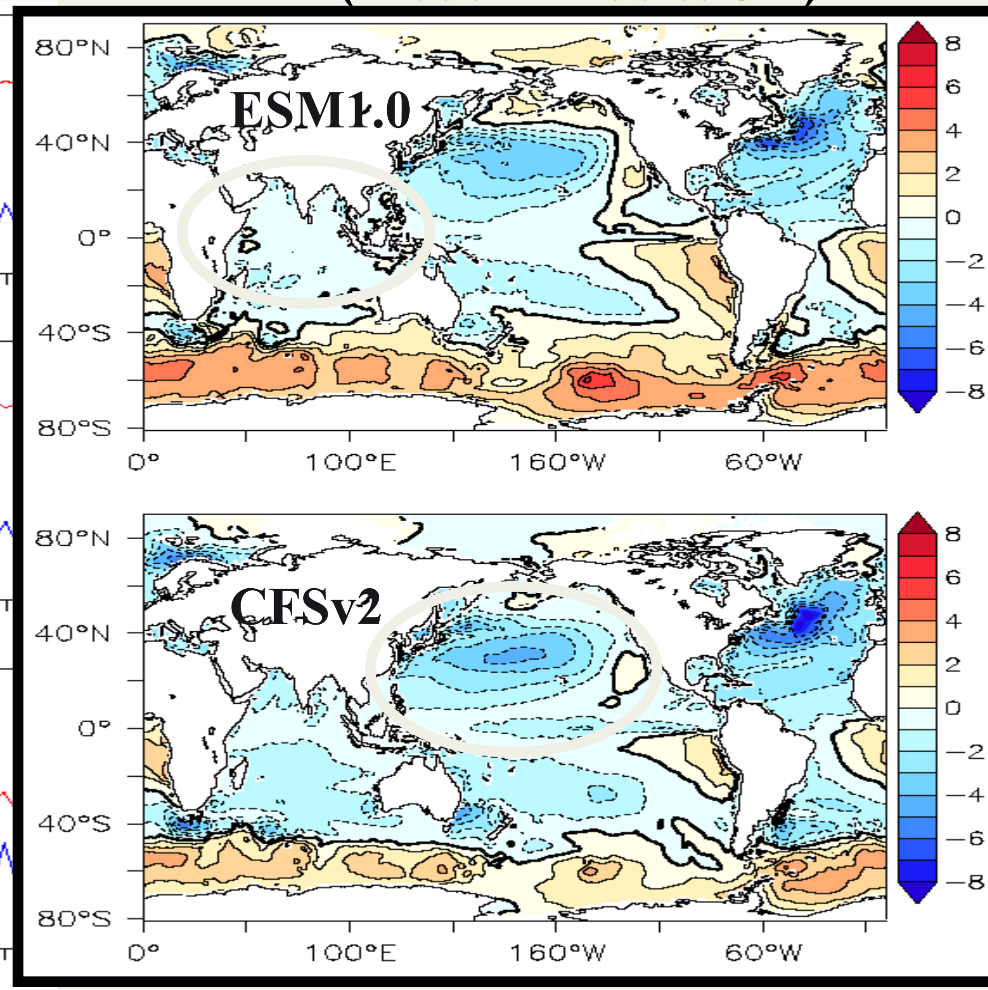


Scalability : 8 SYPD

Global mean surface (2m) temperature



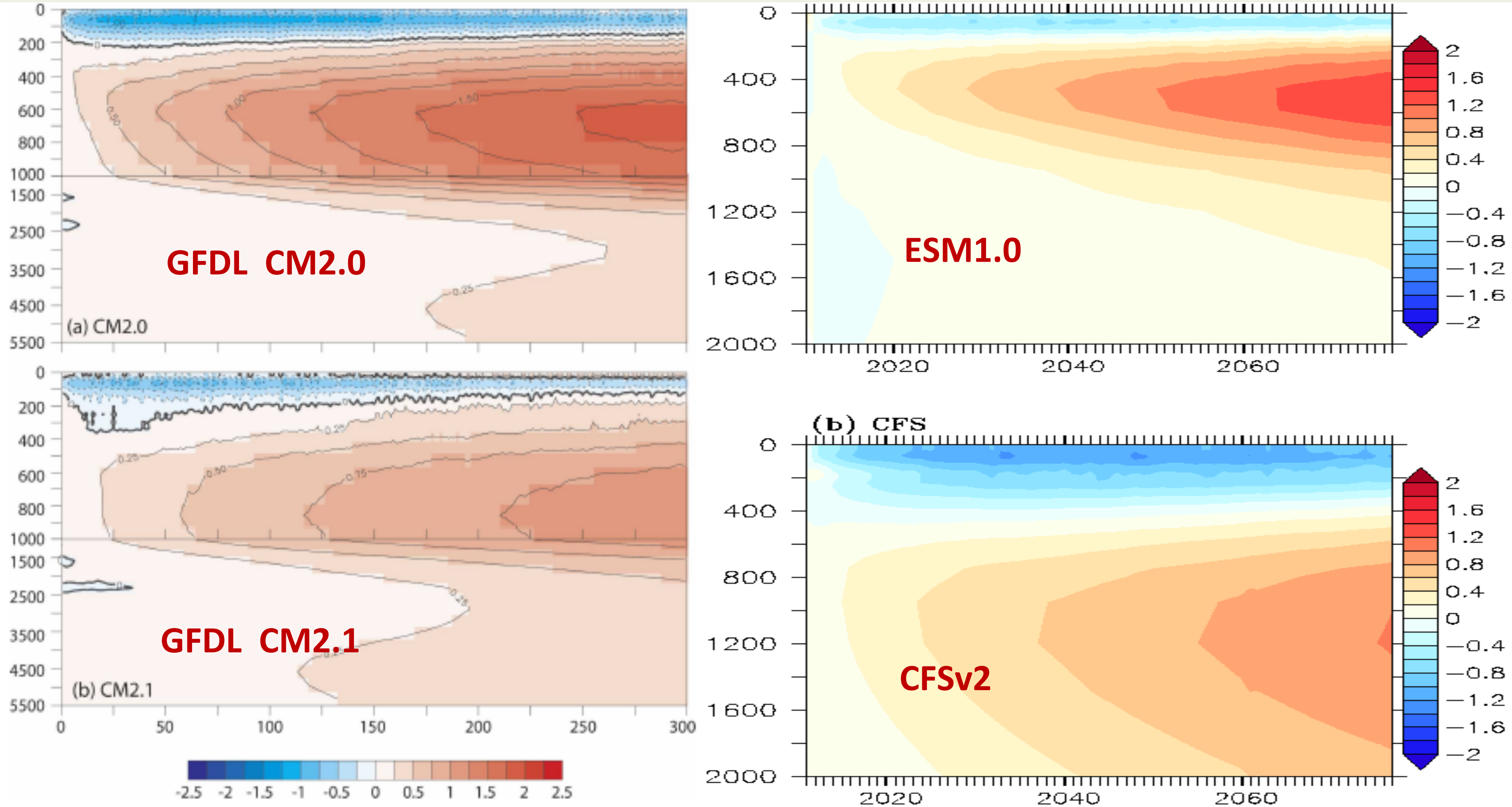
Annual mean SST difference (Model minus WOA)



The drift in surface temperature and SST is minimum in IITM ESMv1 (red line) compared to CFSv2 (blue line).

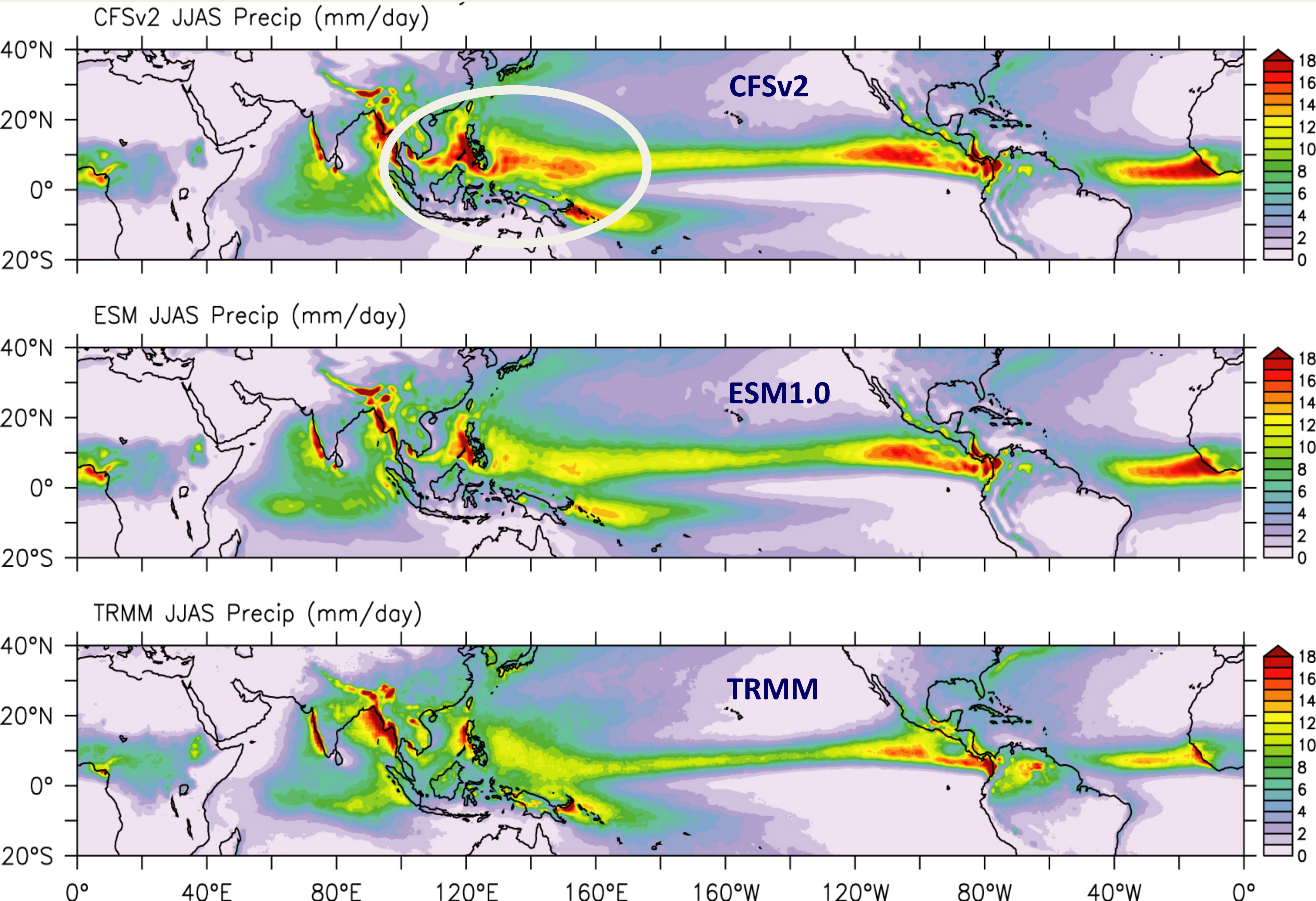
Significant reduction in cold SST bias in tropical IO and subtropical Pacific

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

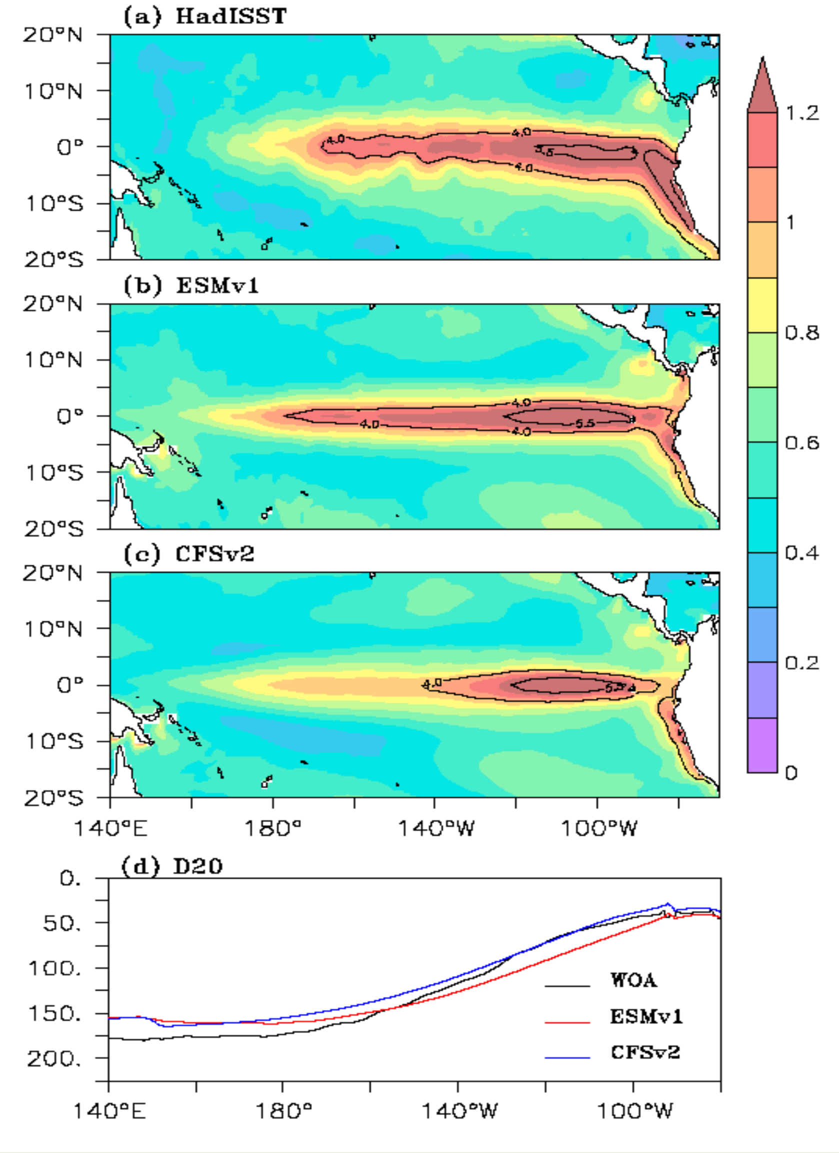


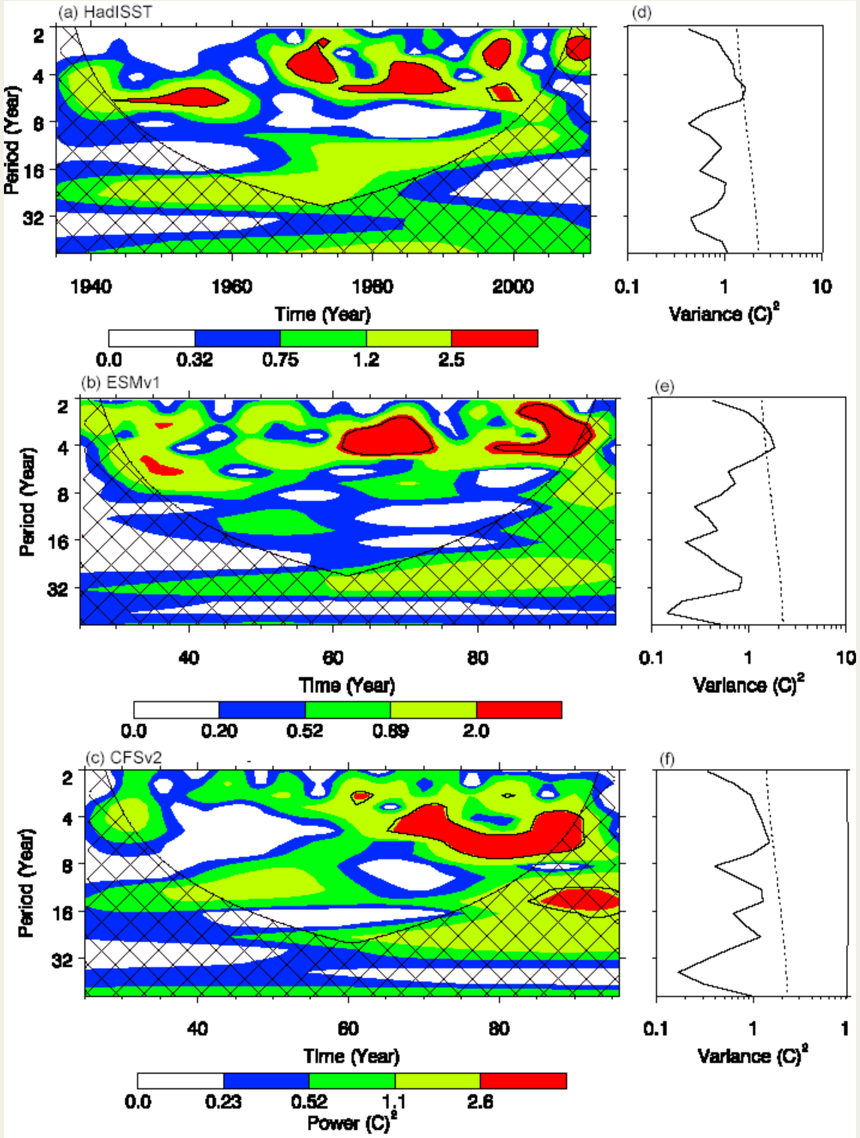
Differences between simulated and observed long-term global-mean ocean temperature as a function of depth and time.

Precipitation (mm day^{-1}): JJAS mean

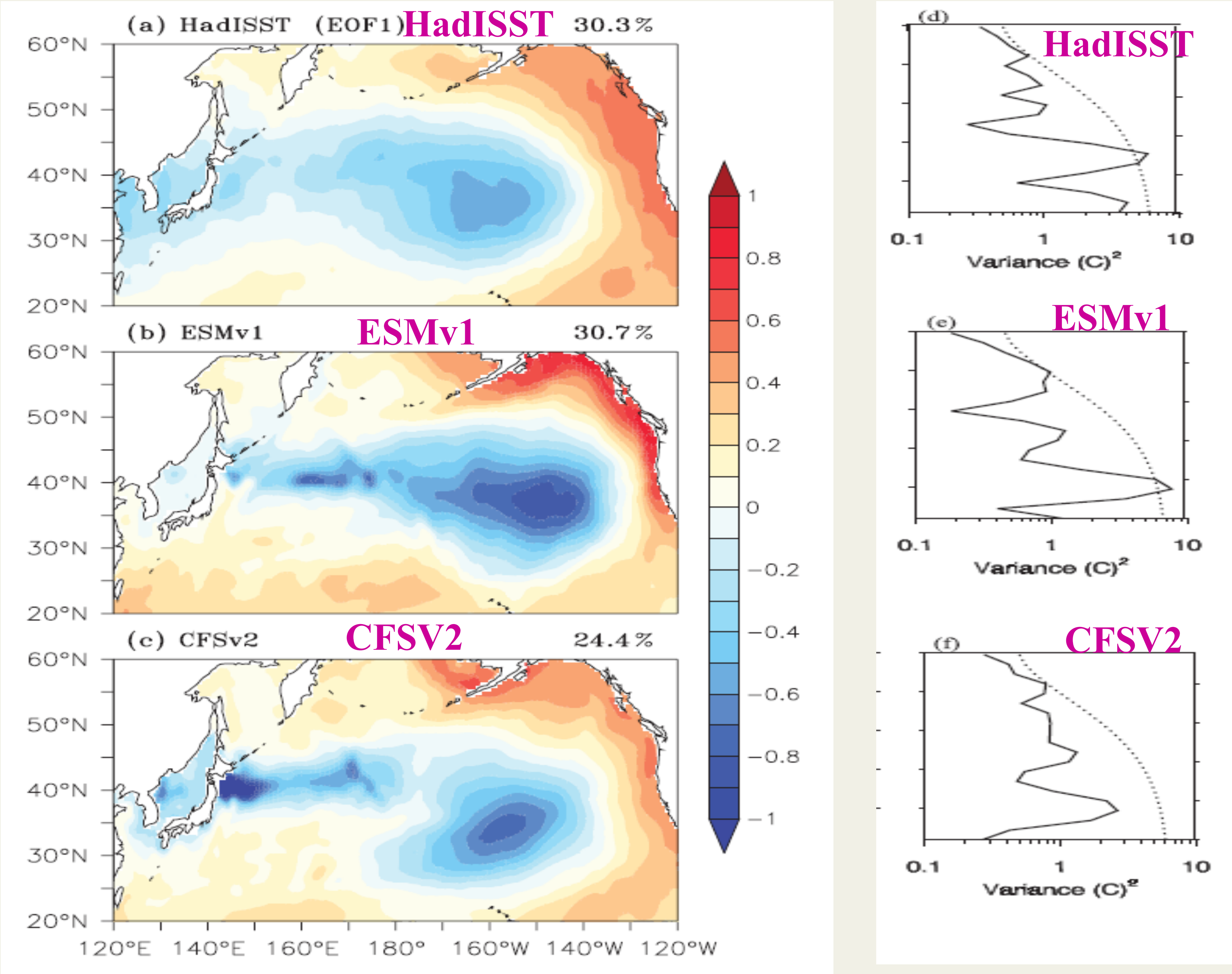


Inter-annual variability

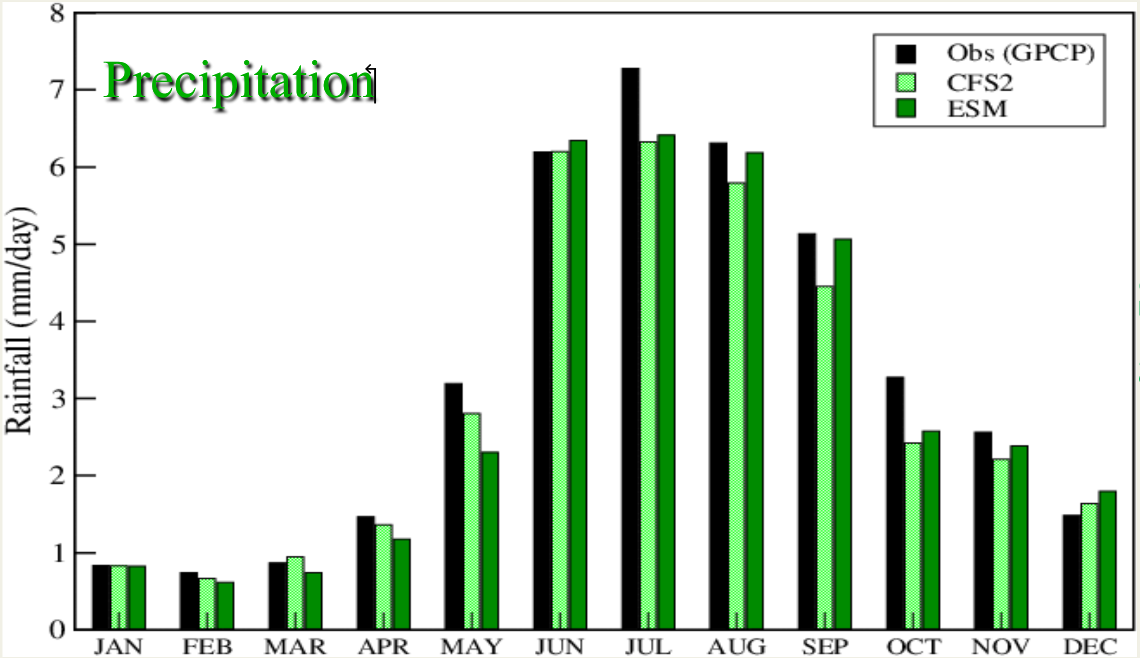




PDO - IITM ESM



(a) HadISST (EOF1) HadISST 30.3%
(b) ESMv1 ESMv1 30.7%
(c) CFSv2 CFSV2 24.4%
60°N
50°N
40°N
30°N
20°N
120°E 140°E 160°E 180° 160°W 140°W 120°W
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
(d) HadISST
(e) ESMv1
(f) CFSV2
0.1 1 10
Variance (C)²

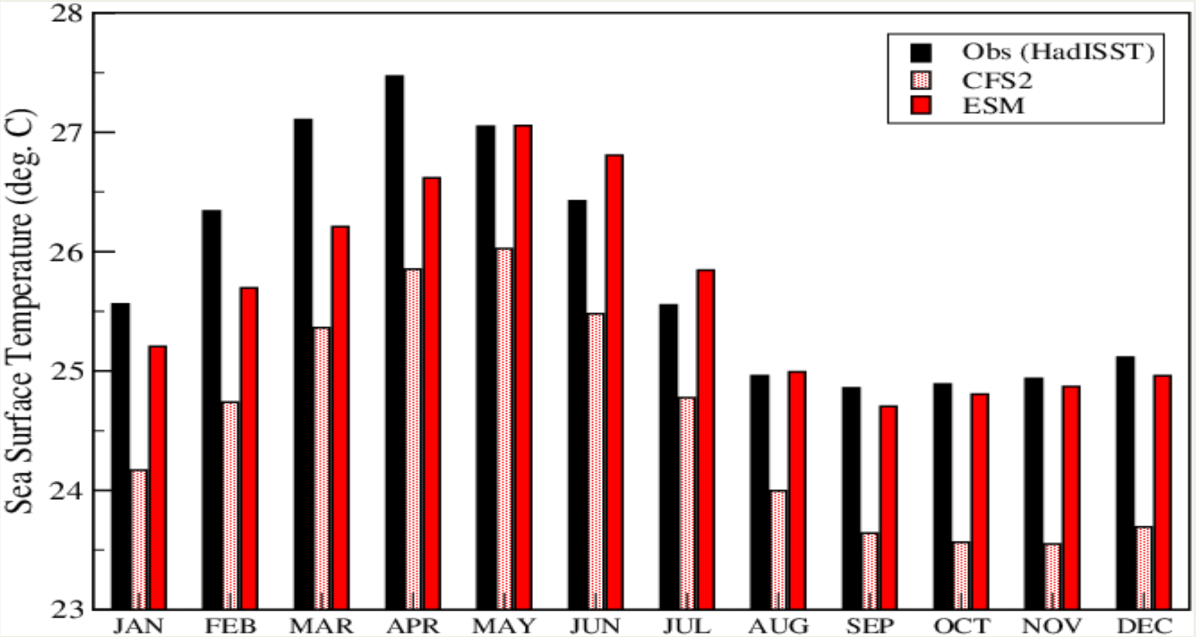


Precipitation

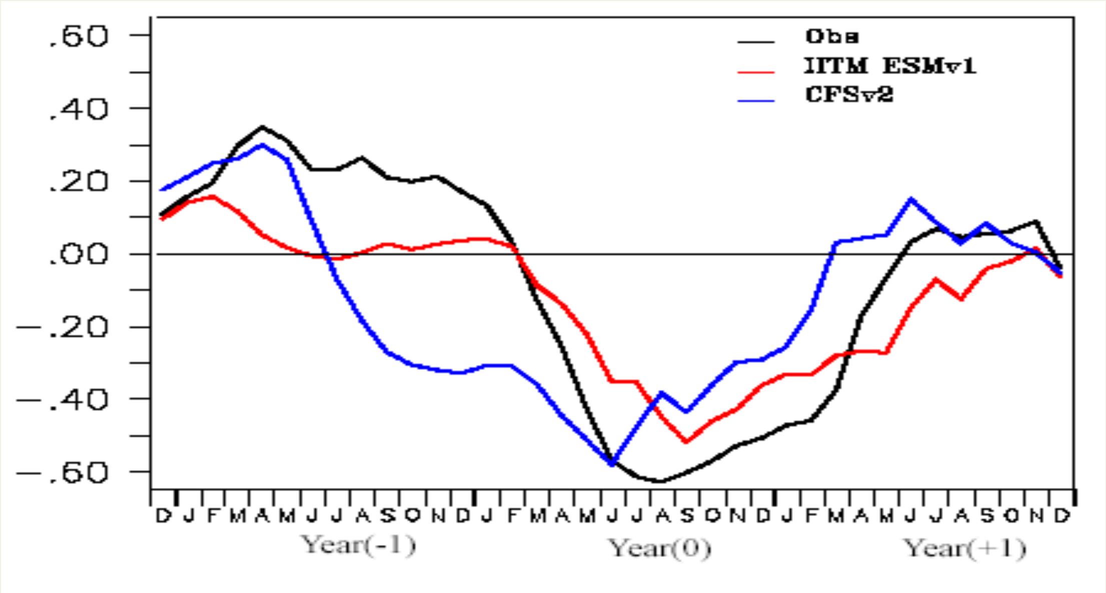
(5N-35N; 65E-95E)

Seasonal cycle of precipitation and Nino 3 SST is captured in ESM & CFSv2

Nino3 SST

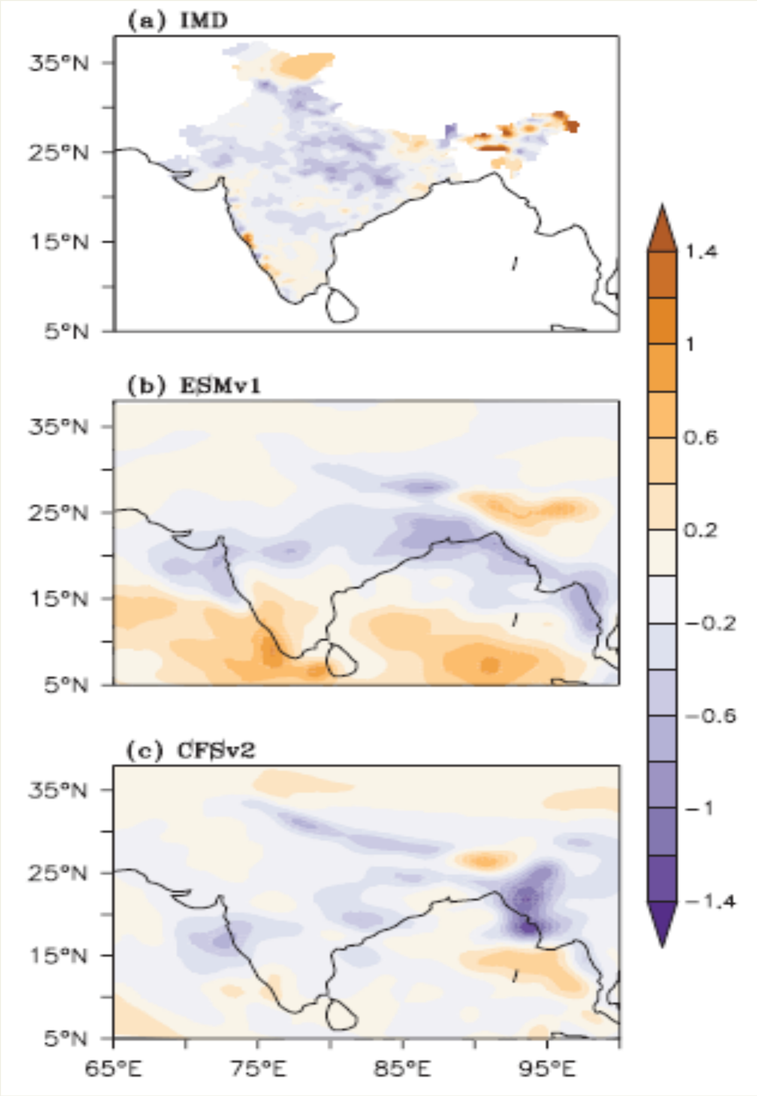


ENSO-Monsoon relationship



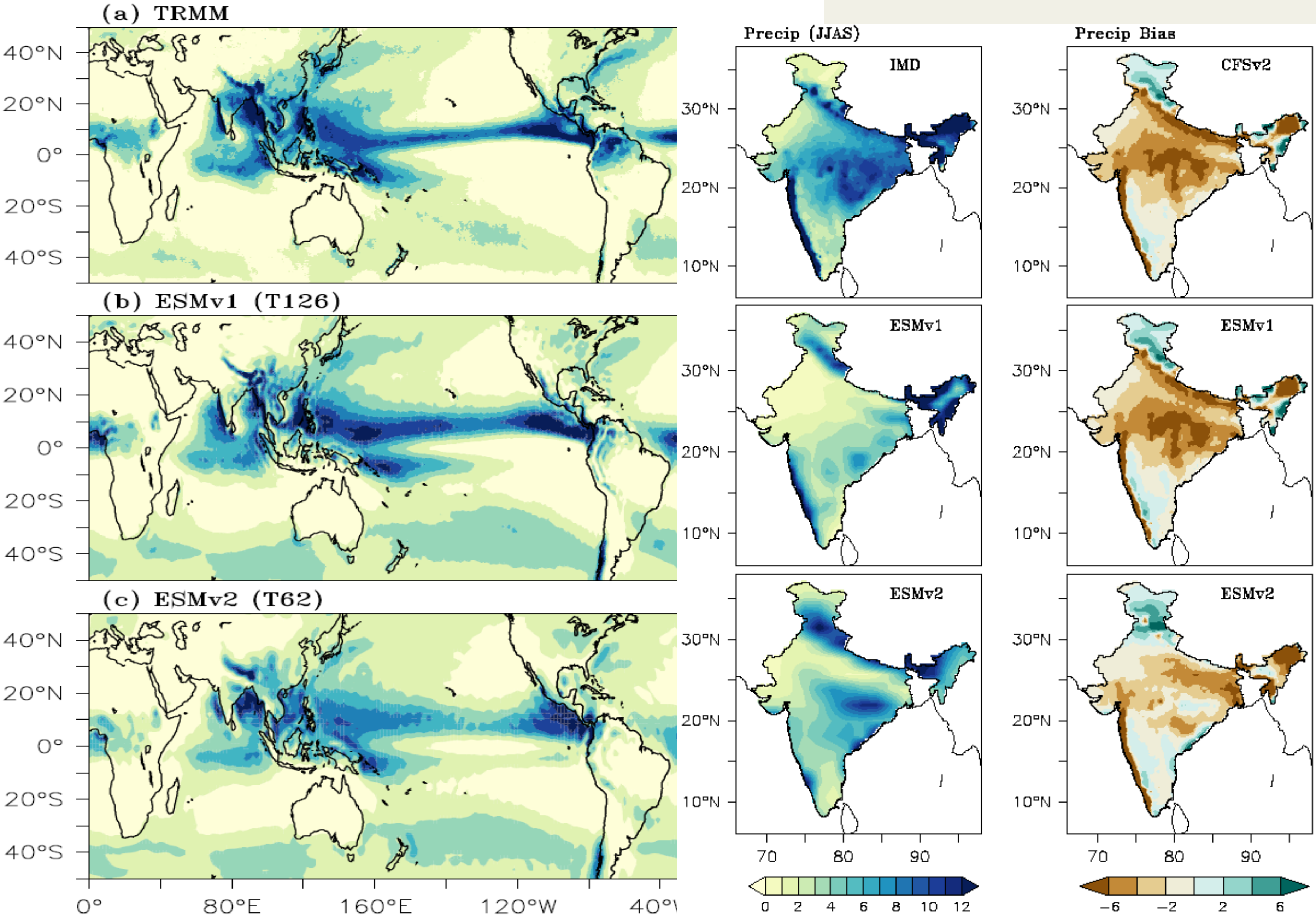
Lagged correlation between ISMR and Nino3 SST in the preceding/following months are captured well in IITM ESM as compared to CFSv2

PDO-Monsoon relationship

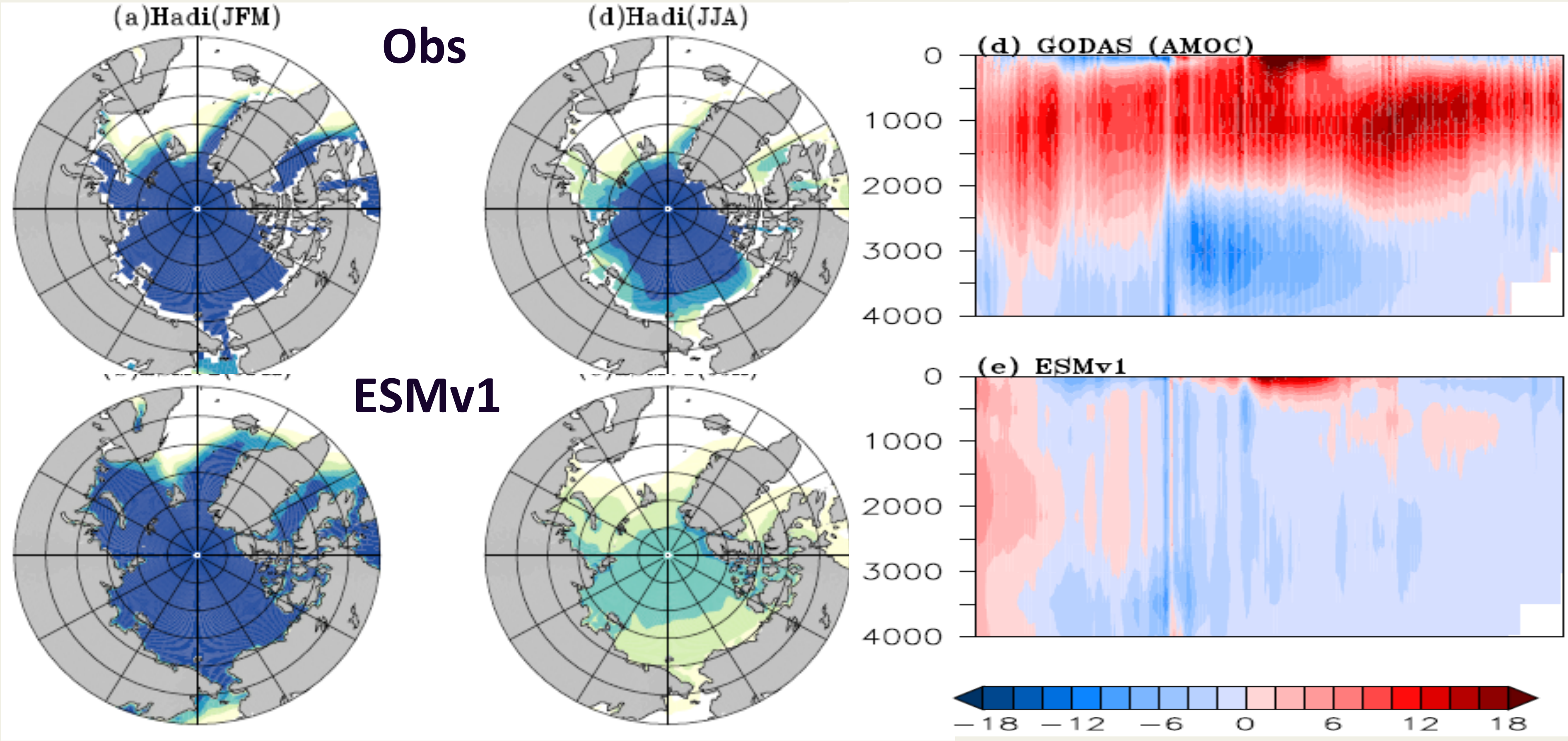


Recent improvements in IITM ESM

Boreal summer monsoon (JJAS) precipitation and bias



Sea-Ice concentration & AMOC

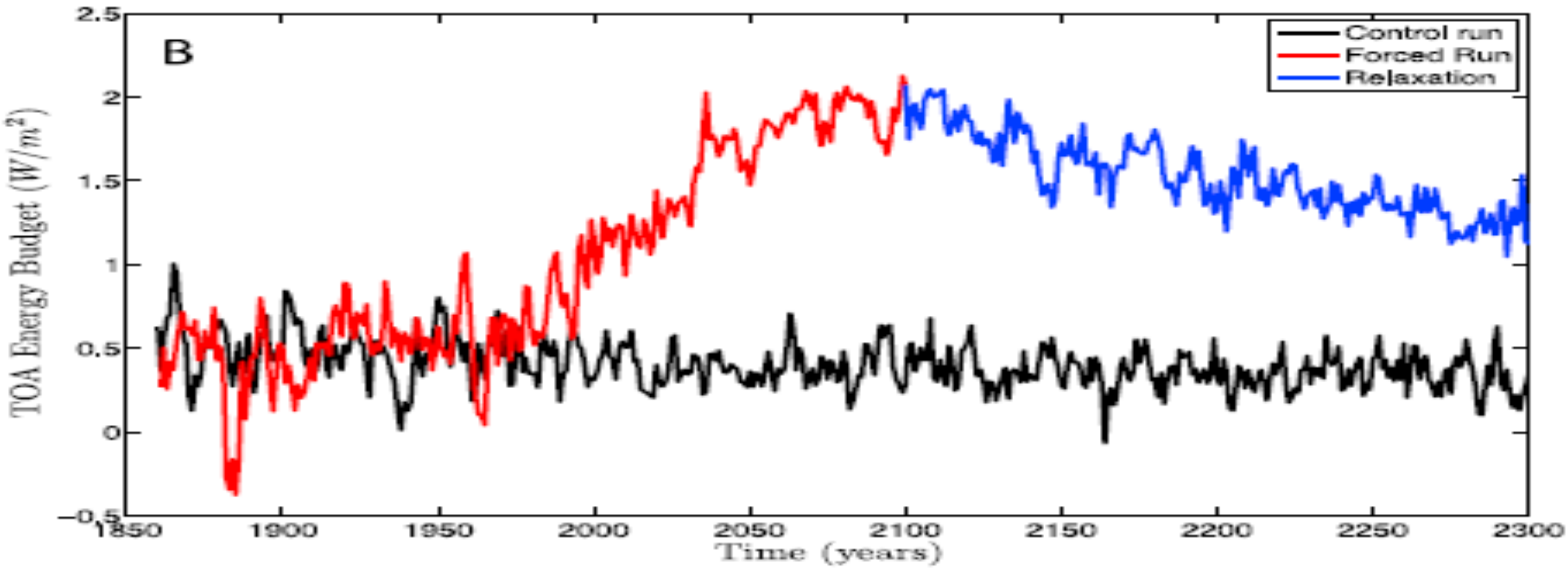


Depletion of NH sea-ice during Jan-Mar

Weakening of AMOC

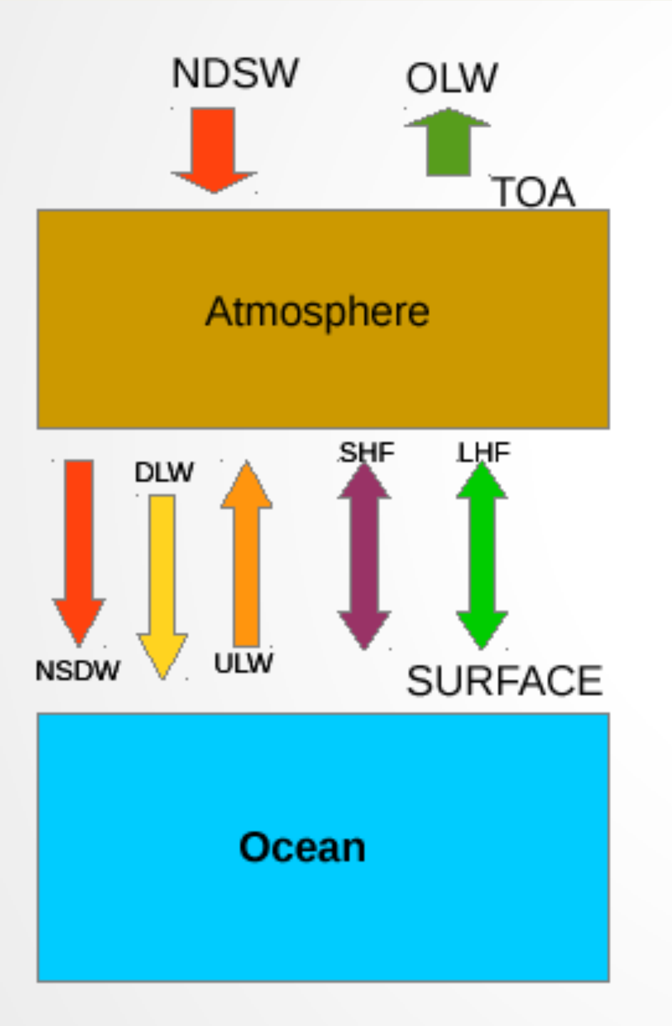
Time-series of TOA energy budget (GFDL2.1 CM9)

– V. Lucarini, F. Ragone, 2011, Rev. Geophy



Black line is the preindustrial run. The red line shows the 20th century simulation and the 21st century portion of the SRES A1B simulation (stared from the end of the 20th century simulation. The blue line shows the 22nd and 23rd century SRES A1B simulation

Energy Balance of the Coupled System



NDSW – Net downward Short wave radiation

OLW- Outgoing Long wave radiation

DLW- Downward Long wave (depends on T of Atm)

ULW – Upward long wave (depends on T of Ocean)

SHF – Sensible heat flux

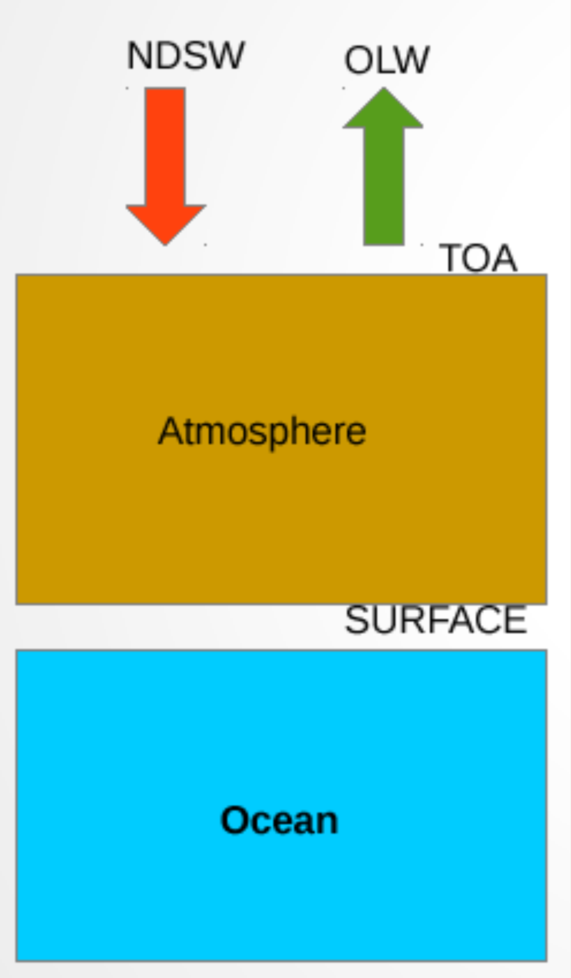
LHF – Latent heat flux

Surface Flux = NDSW – DLW +ULW +SHF+LHF

Net flux = TOA – Surface flux

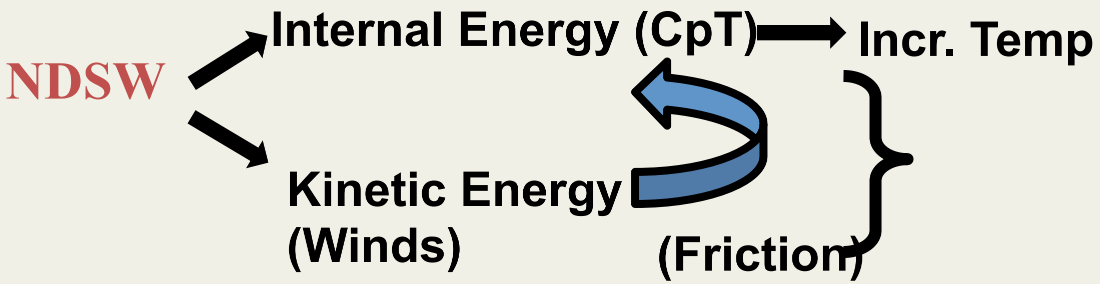
Courtesy: Prajeesh

TOA Energy Balance



NDSW – Net downward Short wave flux at TOA

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

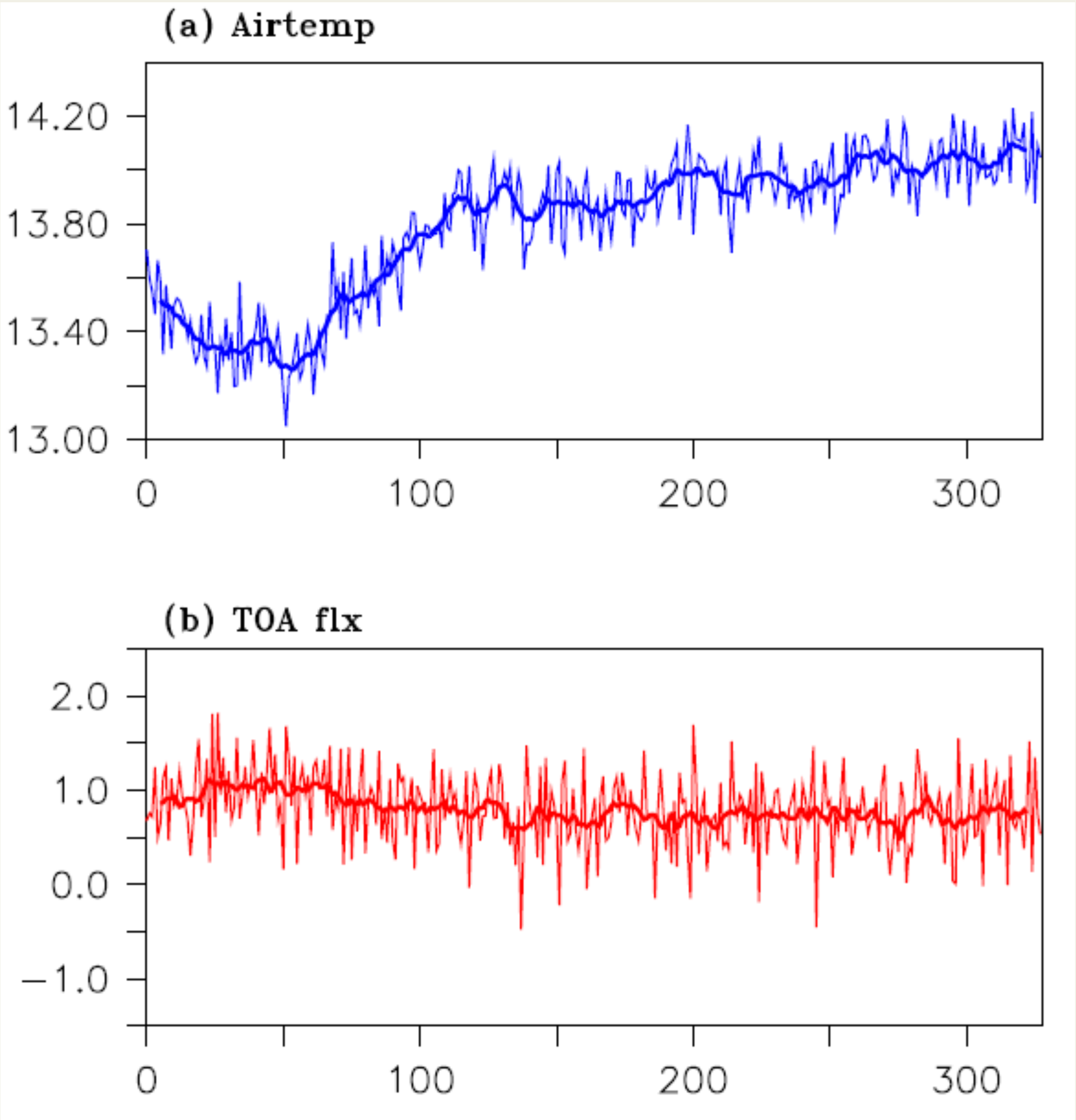


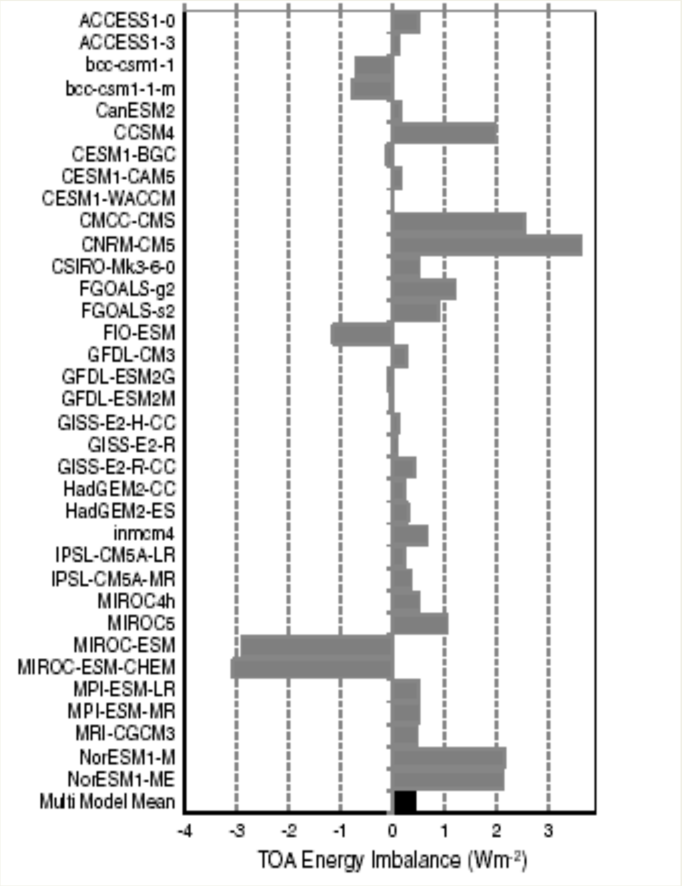
TKE dissipation heating (Han)

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

Minimize atmospheric energy loss – Bretherton et al. 2012

Energy Balance in IITM ESM



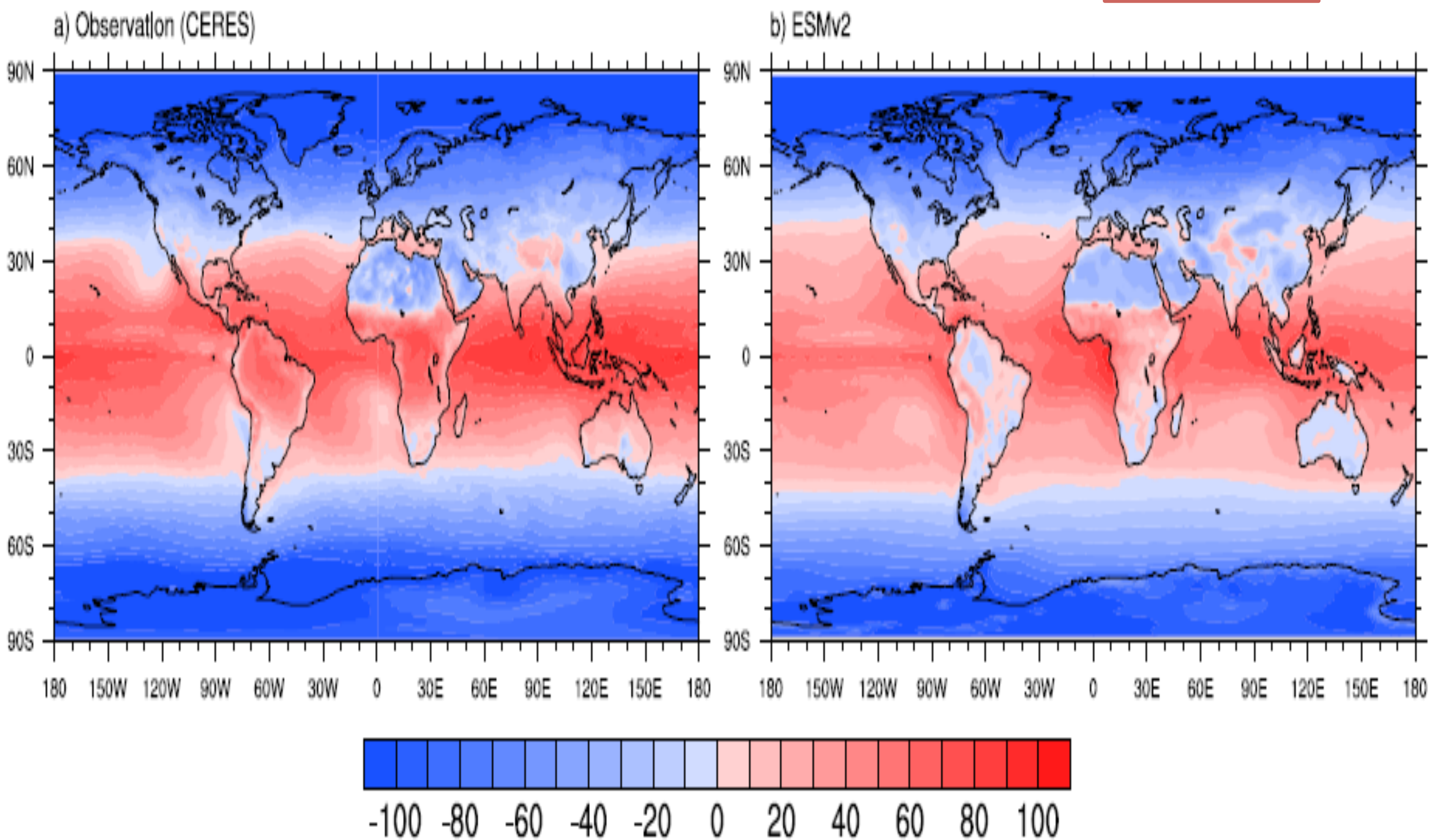


Preindustrial TOA (Wm^{-2}) Energy imbalance for CMIP5 Models (Forster et al., 2013)

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

Obs (CERES)

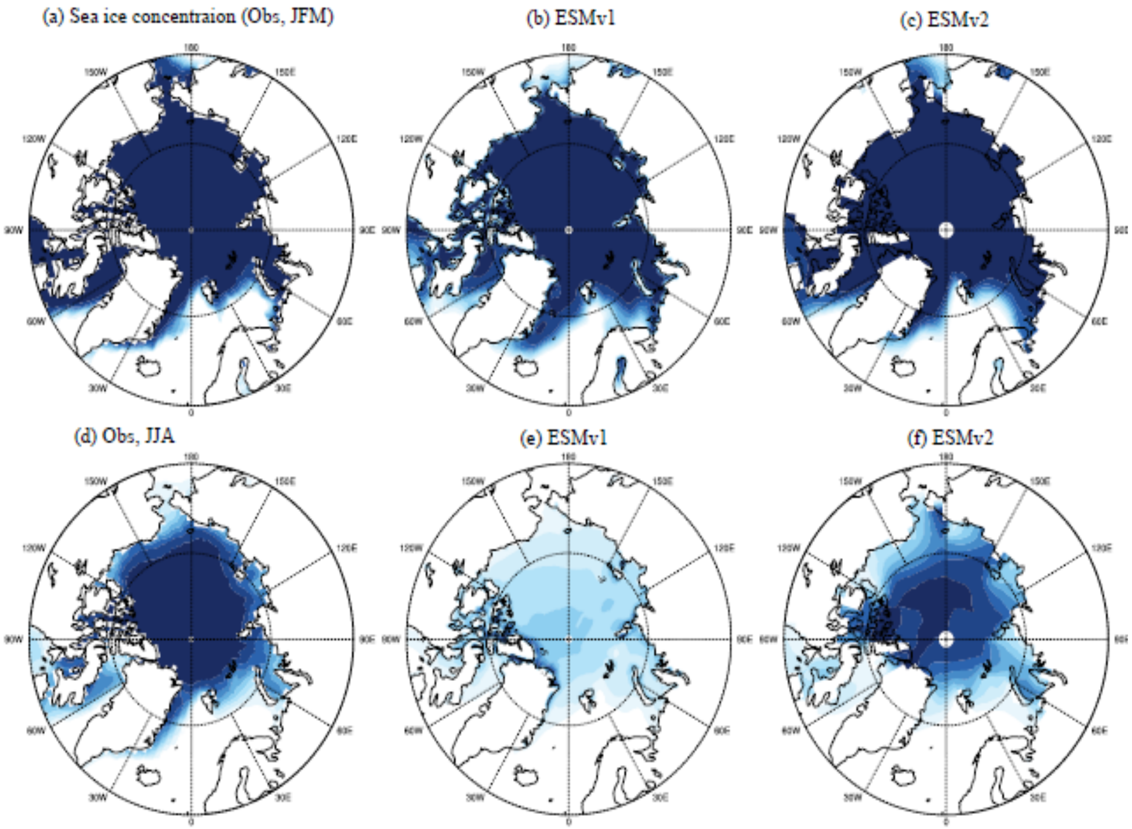
IITM-ESMv2

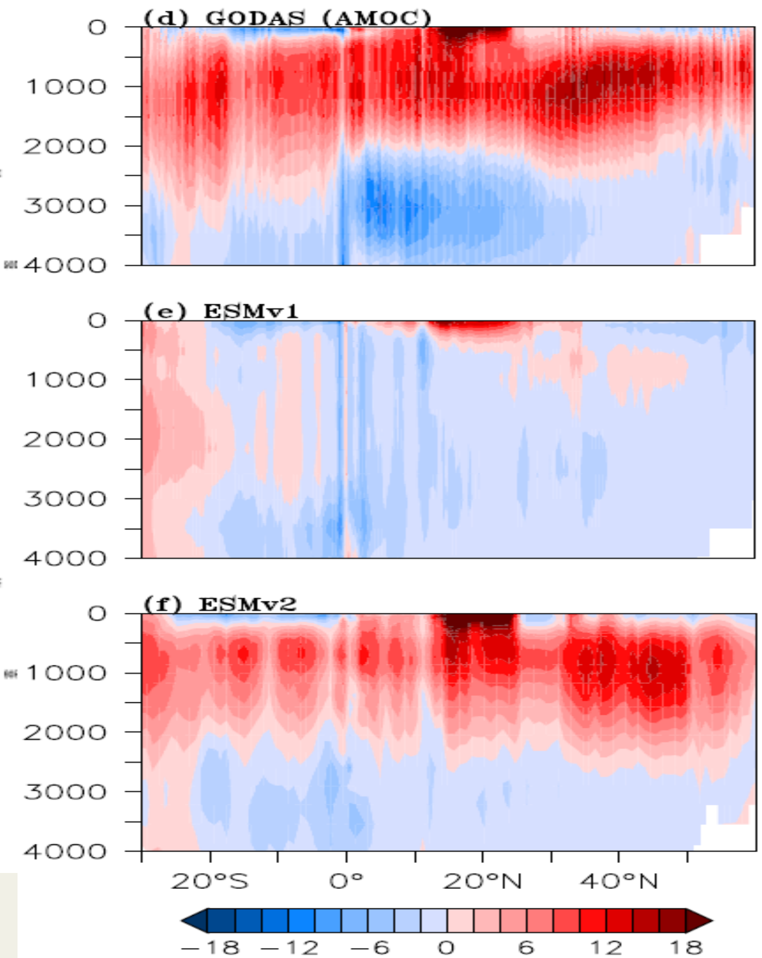


Energy Balance in IITM ESM

	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	0.81	0.01

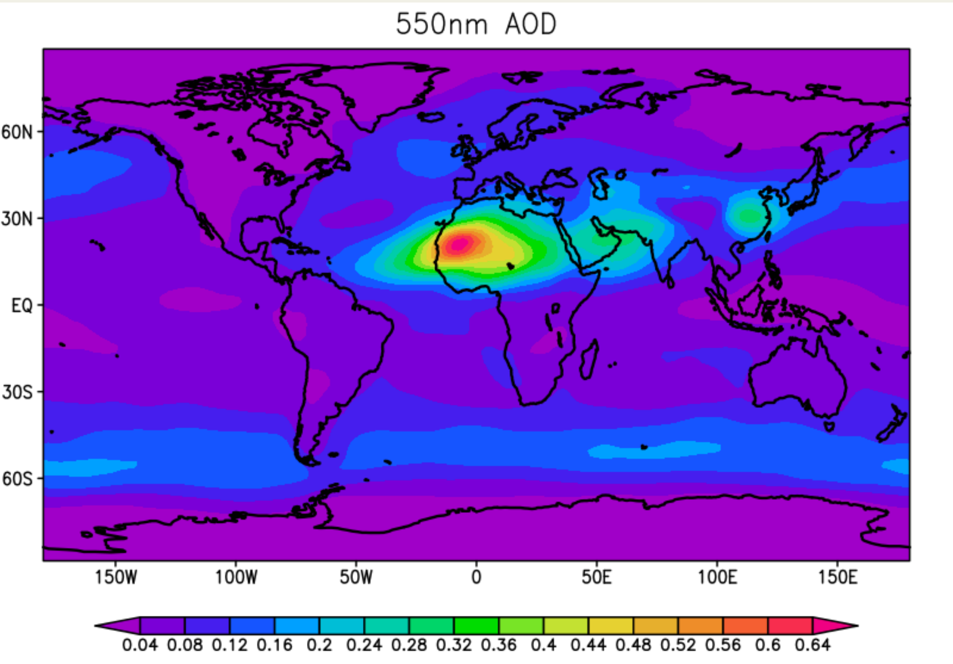
Sea-Ice concentration and AMOC in IITM ESMv2





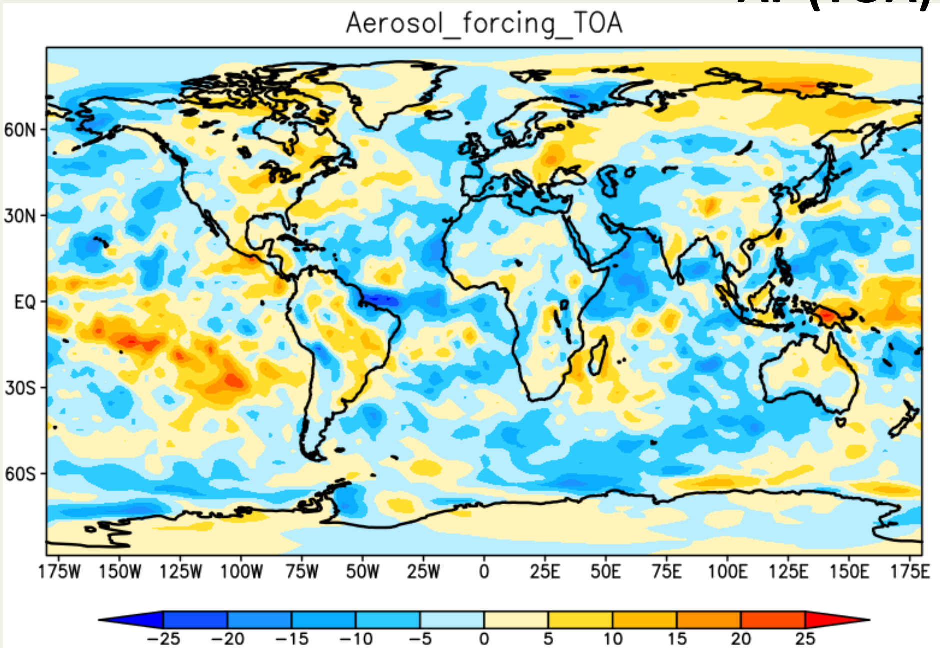
Aerosol forcing in IITM ESM

Prescribed time-varying aerosol distributions in IITM ESM from CMIP

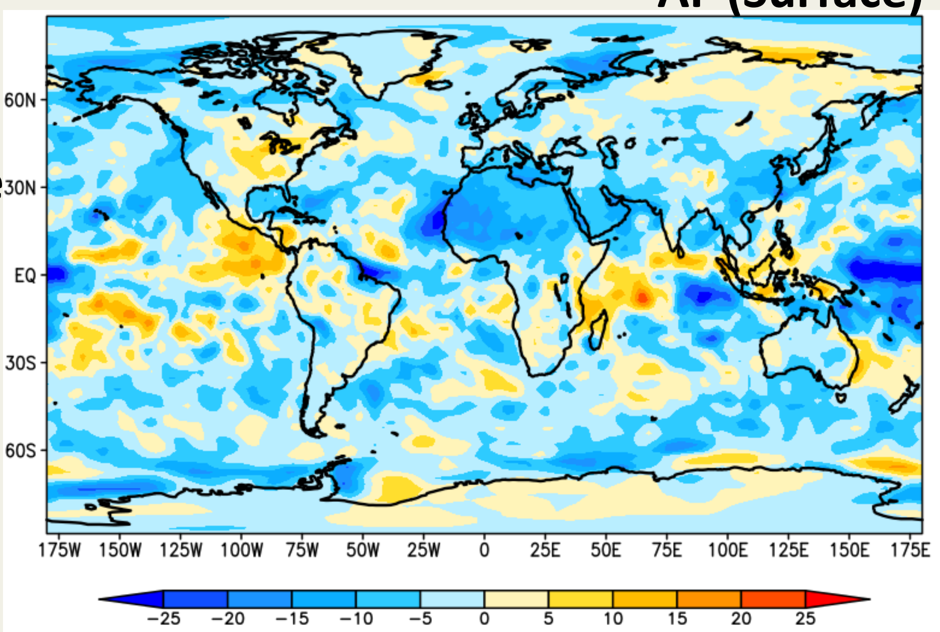


Data Courtesy : Bjorn Stevens, Stefan Kinne (Max Planck)

AF (TOA)



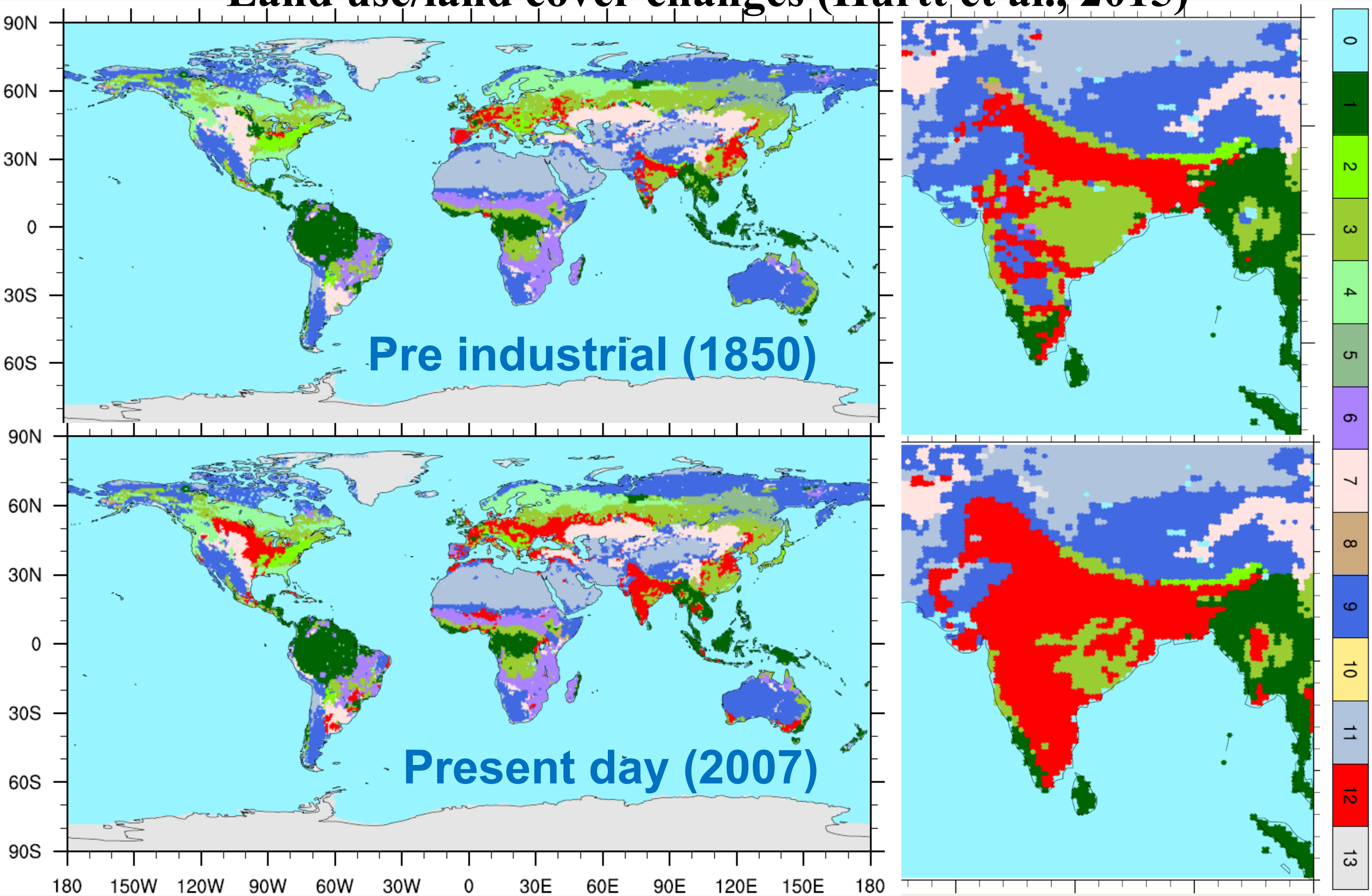
AF (Surface)



Aerosol TOA forcing (total sky)= -0.9

Courtesy: Ayantika, CCCR

Land use/land cover changes (Hurtt et al., 2015)



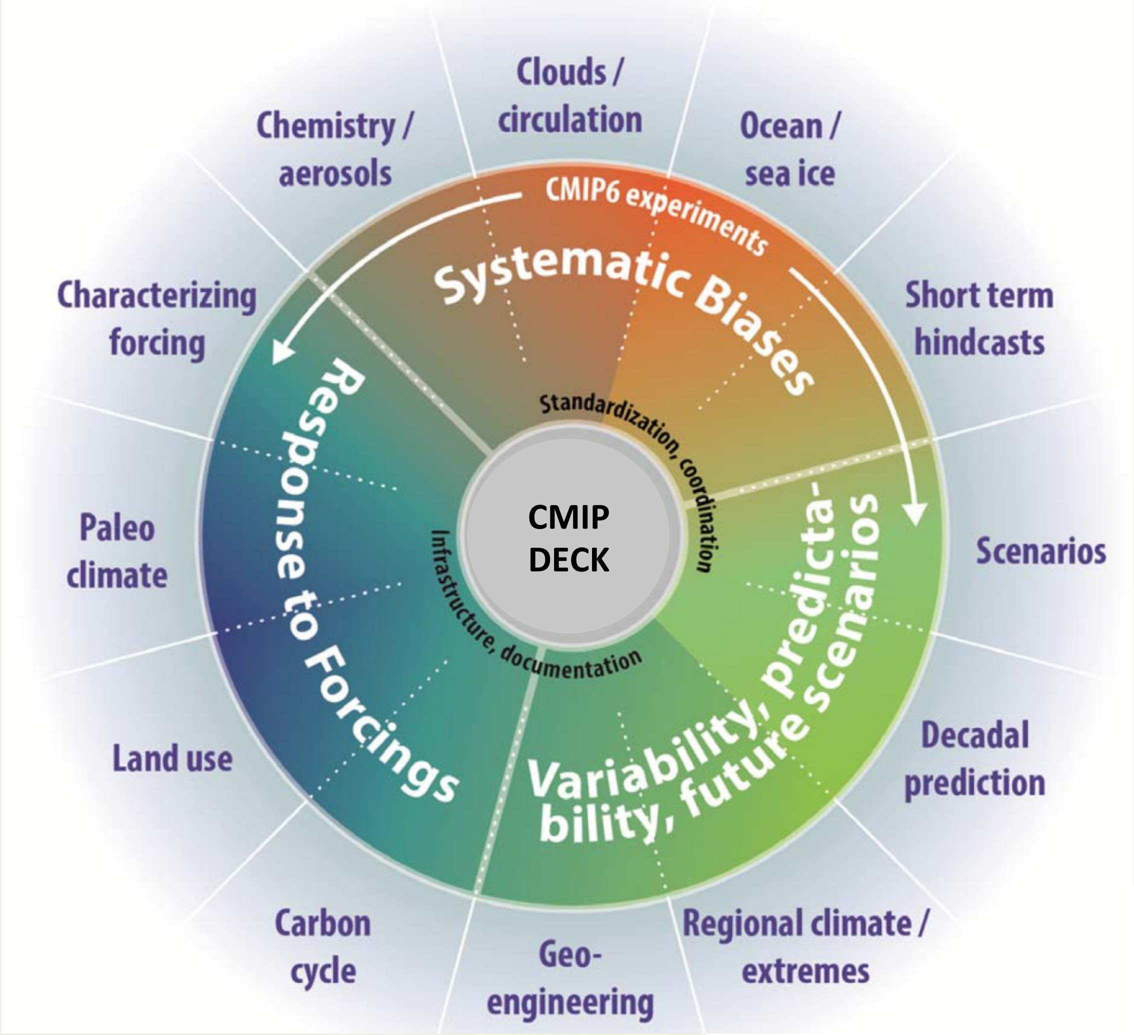
0 waterbodies	3 mixedforests	6 savannas	9 openshrubs	12 crops
1 Evergreen Broad	4 Evergreen Needle	7 grasslands	10 Tundra	13 snowice
2 DeciduousBroad	5 Deciduous Needle	8 shrubs	11 Barre	

Courtesy: Sandeep, CCCR

CMIP6 Schematic

CMIP6 experimental design

Meehl et al., 2014: Climate Model Intercomparisons: Preparing for the Next Phase, Eos Trans. AGU, 95,77-84.



CMIP6 Concept:

A Distributed Organization under the oversight of the CMIP Panel

"DECK":

Development

Evaluation

Characterisation of

Klima (German for 'climate')

CMIP6 Experiments

Experiment	CMIP6 label	Experiment Description	Forcing methods	Start Year	End Year	Minimum # Years	Major purpose
Historical AMIP	amip	Observed SSTs and SICs prescribed	CO_2 concentration-driven	1979	2014	36	Evaluation
Pre-industrial control	piControl	Coupled atmosphere/ocean pre-industrial control run (concentration driven)	CO_2 emission- or concentration-driven	1850	n/a	500	Evaluation, unforced variability
1 %/yr CO_2	1pctCO2	CO_2 prescribed to increase at 1%/yr until concentrations have quadrupled, and then (optionally) extended 160 years with CO_2 concentration held constant	CO_2 concentration-driven	n/a	n/a	140	Climate sensitivity, feedbacks
Quadruple CO_2 abruptly, then hold fixed	abrupt4xCO2	CO_2 abruptly quadrupled and then held constant	CO_2 concentration-driven	n/a	n/a	150	Climate sensitivity, feedbacks, fast responses
Past ~1.5 centuries	historical	Simulation of the recent past	CO_2 emission- or concentration-driven	1850	2014	165	Evaluation

Summary

IITM ESMv1

- Significant reduction of cold bias of global mean SST by ~0.8^{o}C
- ENSO & PDO are robust and spatially more coherent in IITM ESM
- 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. (BAMS, 2015).

IITM ESMv2

- ➢ Reduced the TOA energy imbalance
- ➢ Improved the mean precipitation over Asian region
- ➢ Improved the sea ice distribution
- ➢ Included time-varying aerosol concentration
- ➢ Corrected the hydrology imbalance
- ➢ Improved representation of ocean BGC

Future Roadmap

- Development of High Resolution Global Model (~grid size 27 km) Atmospheric version of IITM-ESM for dynamical downscaling. Generation of high resolution global climate and monsoon projections.

- High-resolution IITM-ESM coupled model (atmosphere grid size: 27 km, ocean grid: 0.5 deg x 0.5 deg and 0.25 deg x 0.25 deg near equator) for long-term climate.

- Development of next-generation IITM-ESM coupled model, to include new components (eg., interactive aerosols, chemistry, carbon cycle).


Thank You