The IITM Earth System Model (ESM)

Development and Future Roadmap

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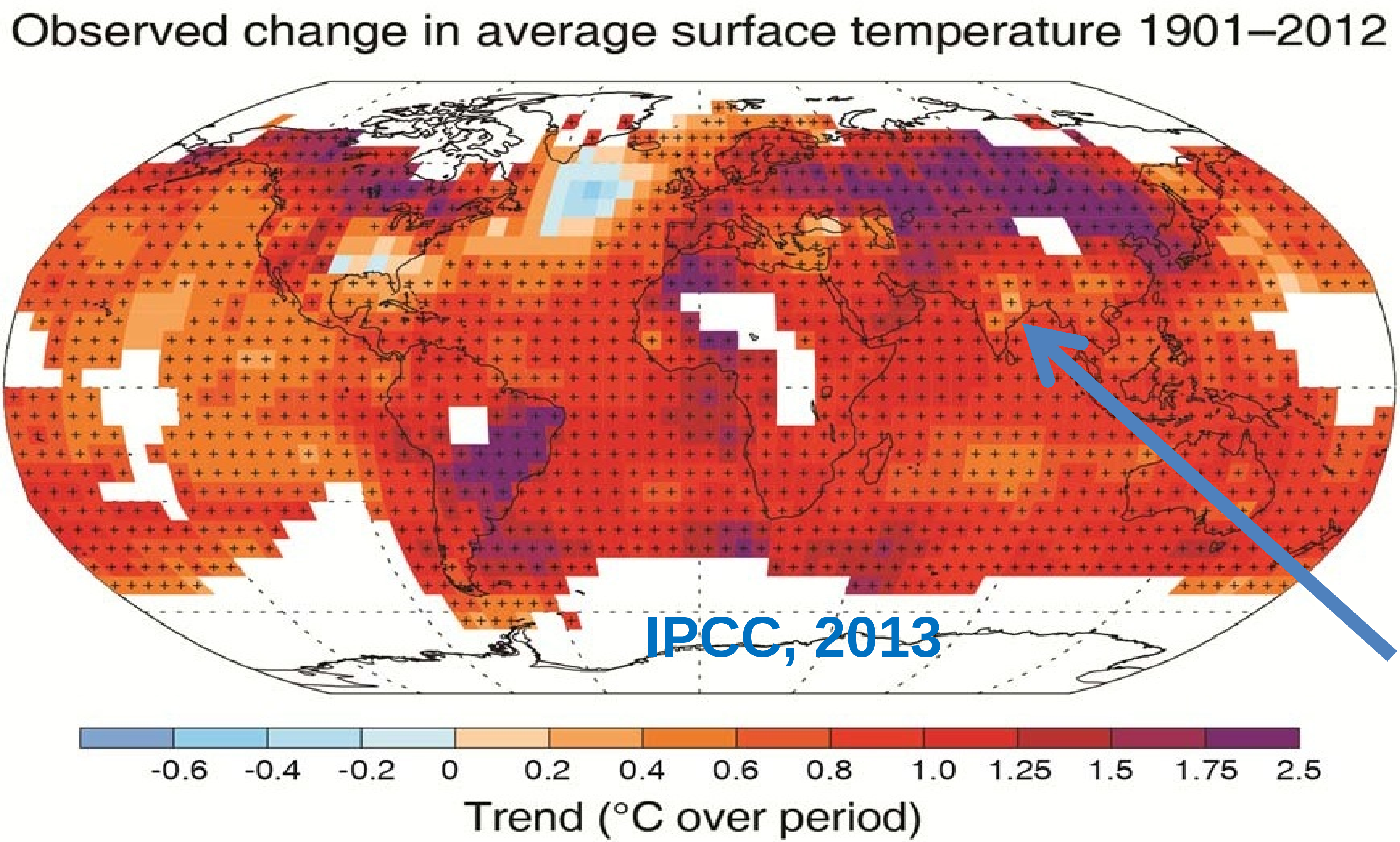
ESM Team: P. Swapna, D.C.Ayantika , Prajeesh, Sandeep Narayansetti, Manmeet Singh, M.K. Roxy, A. Modi, Ramesh Vellore

Diagnostics: M. Mujumdar, B. Preethi, Sabade

INTROSPECT 2017: *International Workshop on Representation of Physical Processes in Weather and Climate Model*

13 – 16 February 2017, IITM, Pune

Recent climate change report



Planet has warmed by 0.85 K over 1880-2012

Climate Change 2013: WG1 contribution to IPCC Fifth Assessment Report

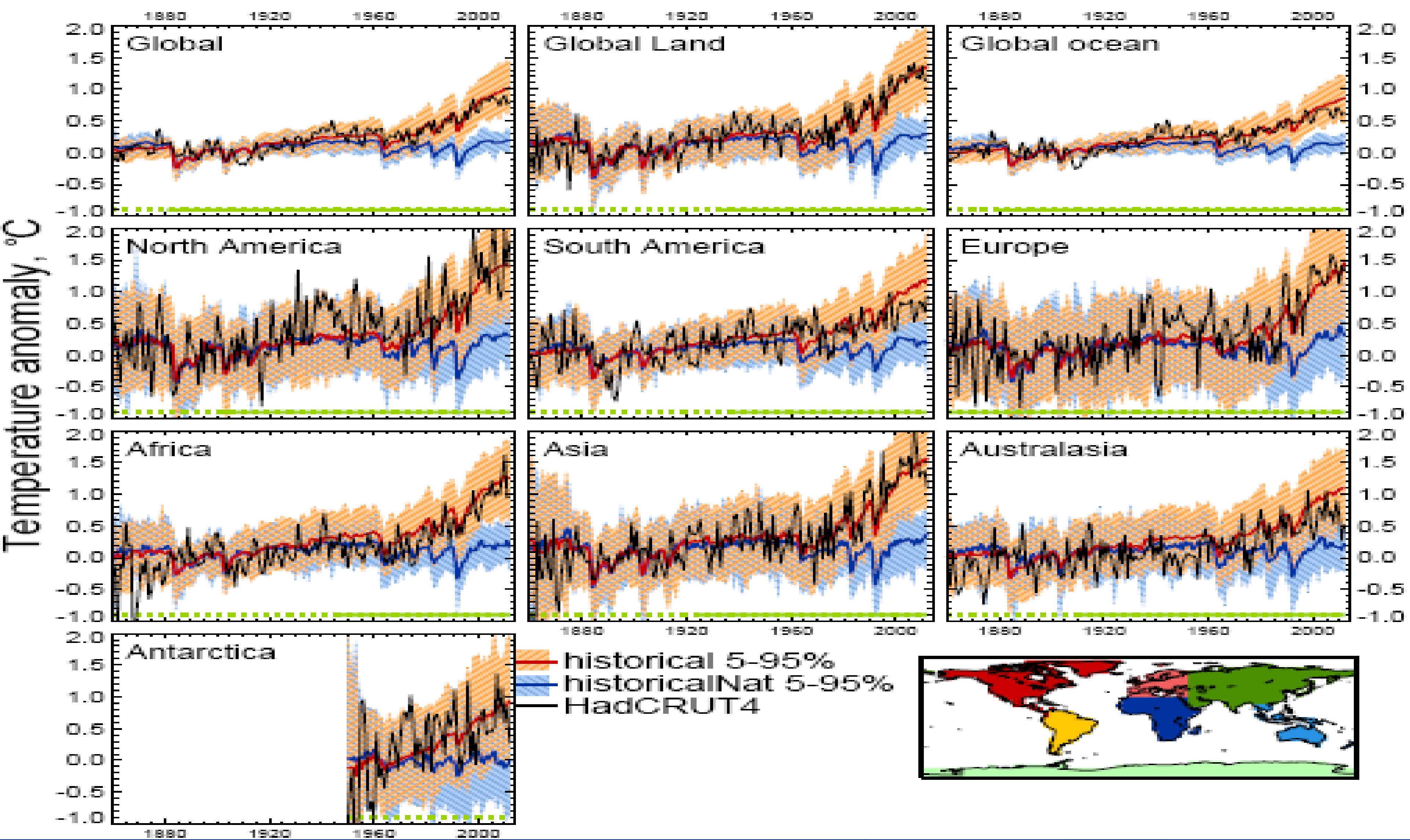
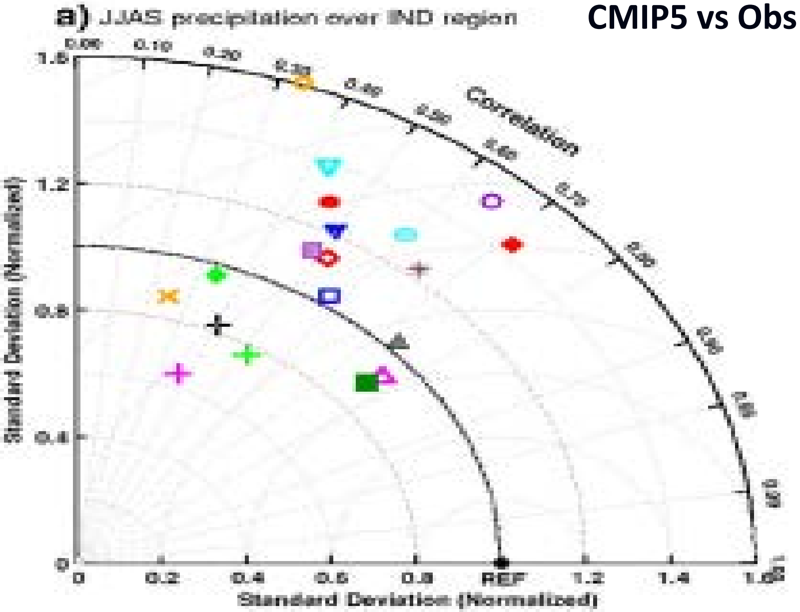


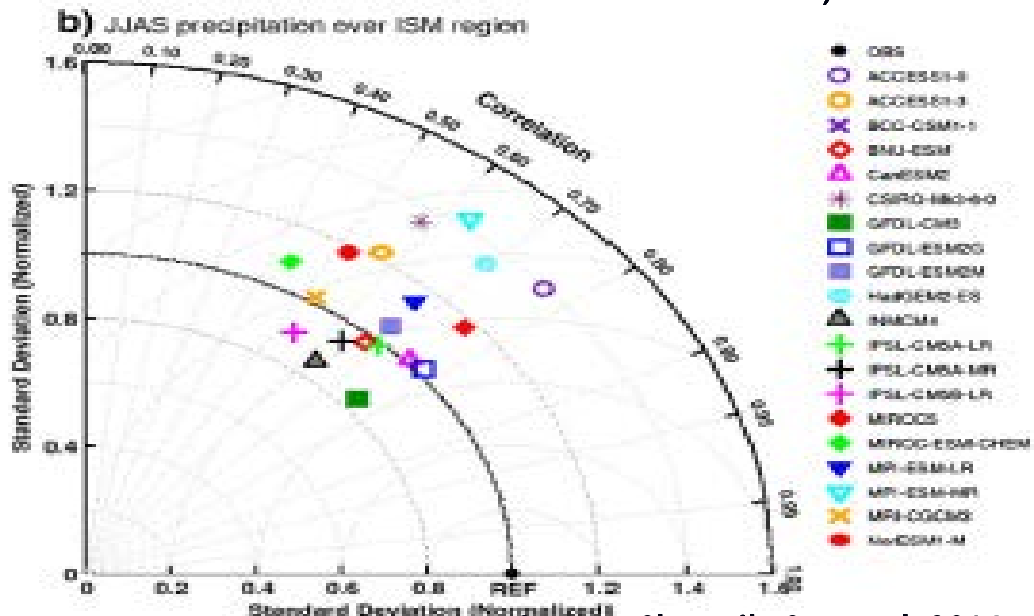
Figure 10.7: Global, land, ocean and continental annual mean temperatures for CMIP3 and CMIP5 historical (red) and historicalNat (blue) simulations (multi-model means shown as thick lines, and 5–95% ranges shown as thin light lines) and for HadCRUT4 (black). Mean temperatures are shown for Antarctica 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

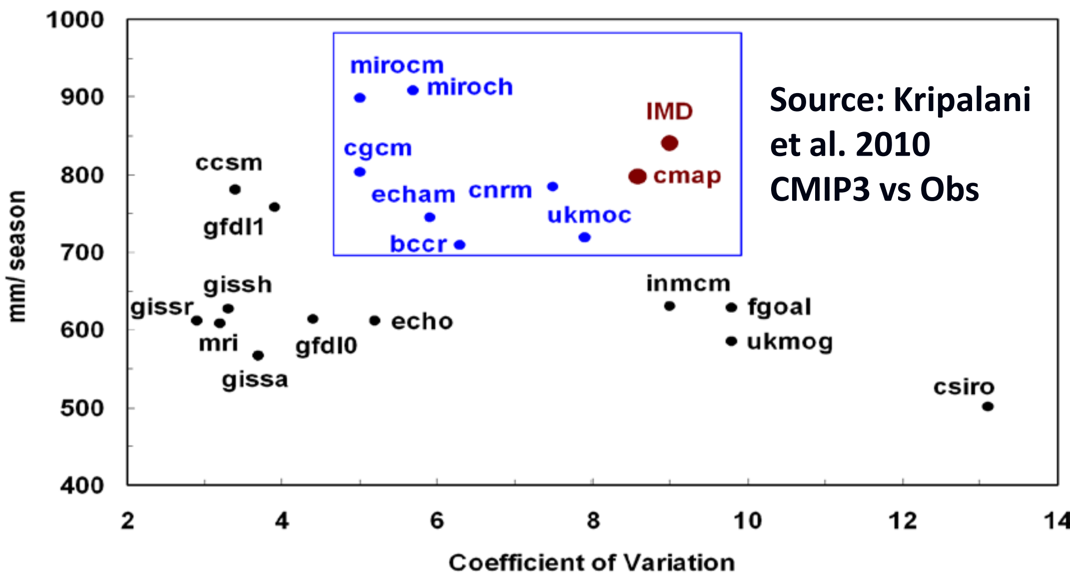
Indian Land:
CMIP5 vs Obs



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

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.

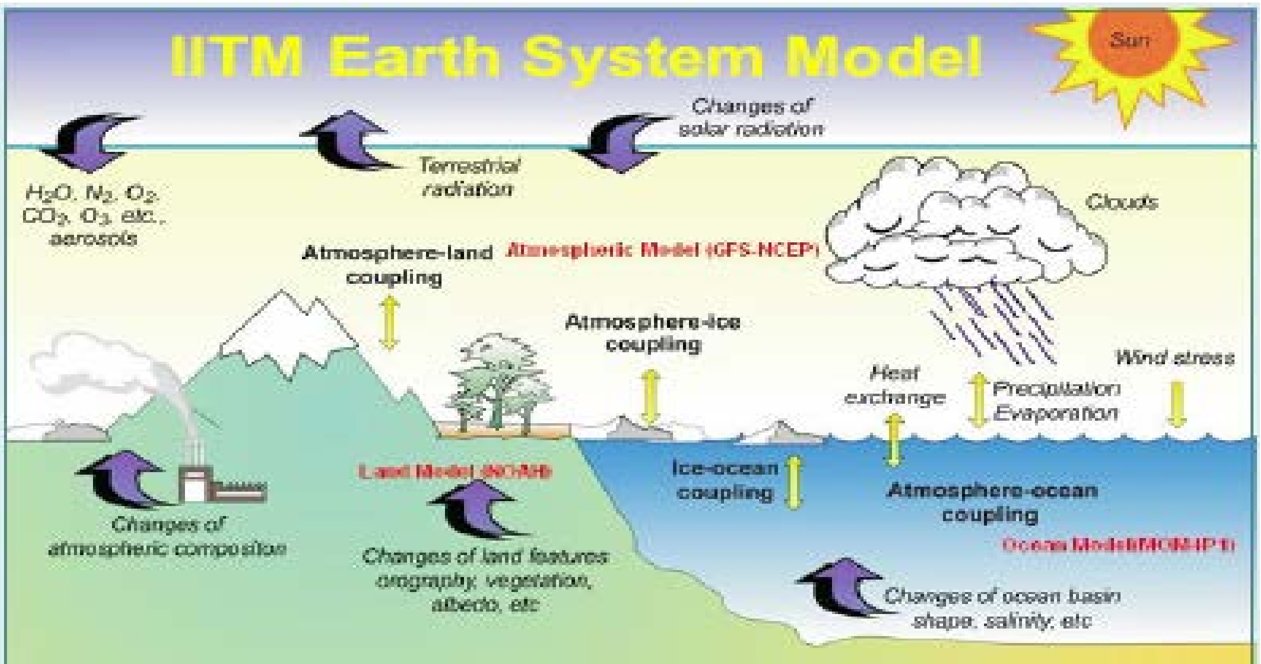
- The **NCEP CFS** Components
- Atmospheric **GFS (Global Forecast System) model**
  - – T126 ~ 110 km; vertical: 64 sigma – pressure hybrid levels
  - – Model top 0.2 mb
  - – Simplified Arakawa-Schubert convection (Pan)
  - – Non-local PBL (Pan & Hong)
  - – SW radiation (Chou, modifications by Y. 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^{o}N and 10^{o}S; and 0.25 deg near equator (10^{o}S – 10^{o}N)
  - – 40 levels
  - – Interactive sea-ice

THE IITM EARTH SYSTEM MODEL

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

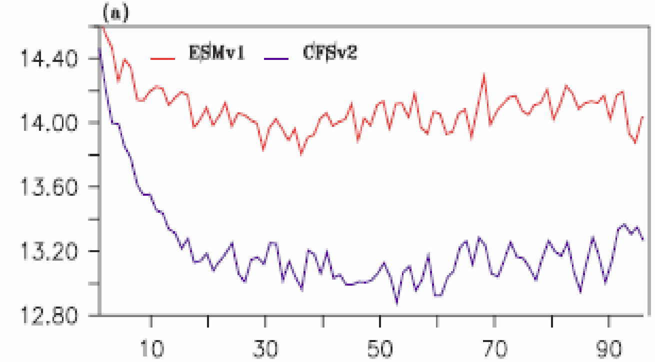
BY P. SWAPNA, M. K. ROXY, K. APARNA, K. KULKARNI, A. G. PRAJEESH, K. ASHOK, R. KRISHNAN, S. MOORTHI, A. KUMAR, AND B. N. GOSWAMI

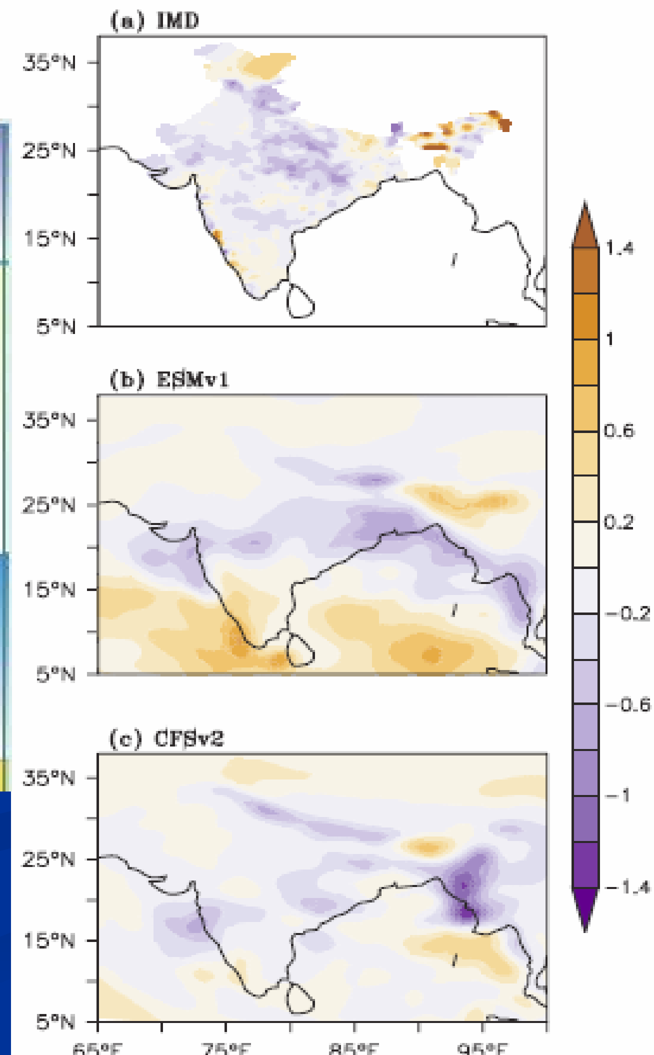
This work documents the fidelity of the newly developed Indian Institute of Tropical Meteorology climate model simulations and demonstrates its suitability to address the climate variability and change issues relevant to the South Asian monsoon.



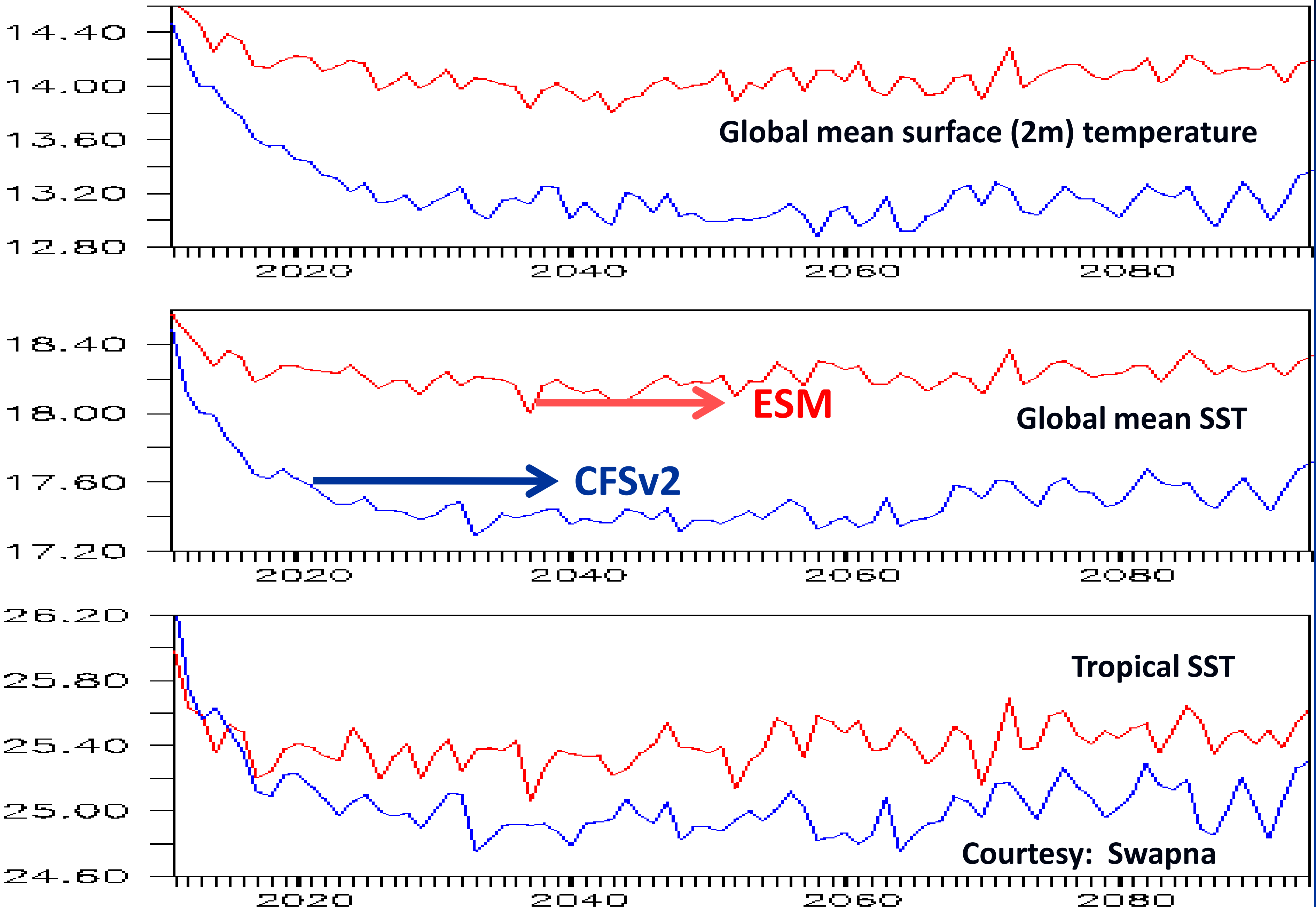
Atmosphere: T126 spectral (~ 190 km), 64 vertical levels – ESMv1

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

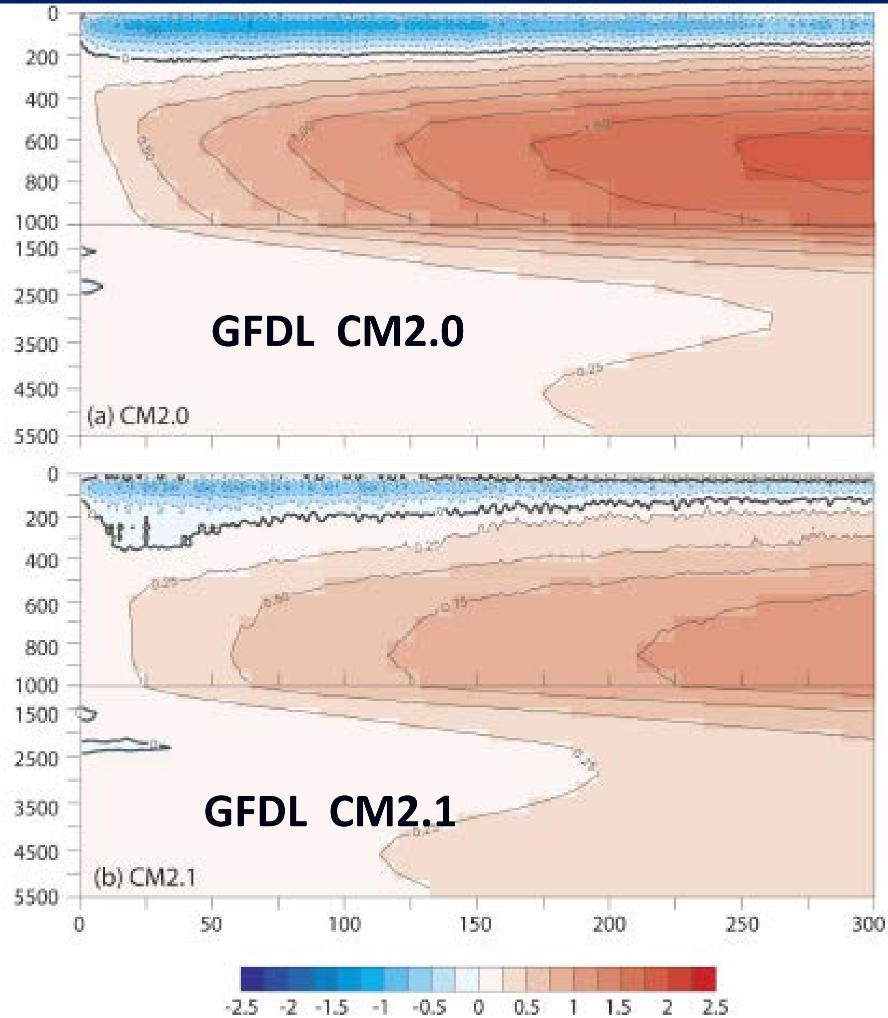


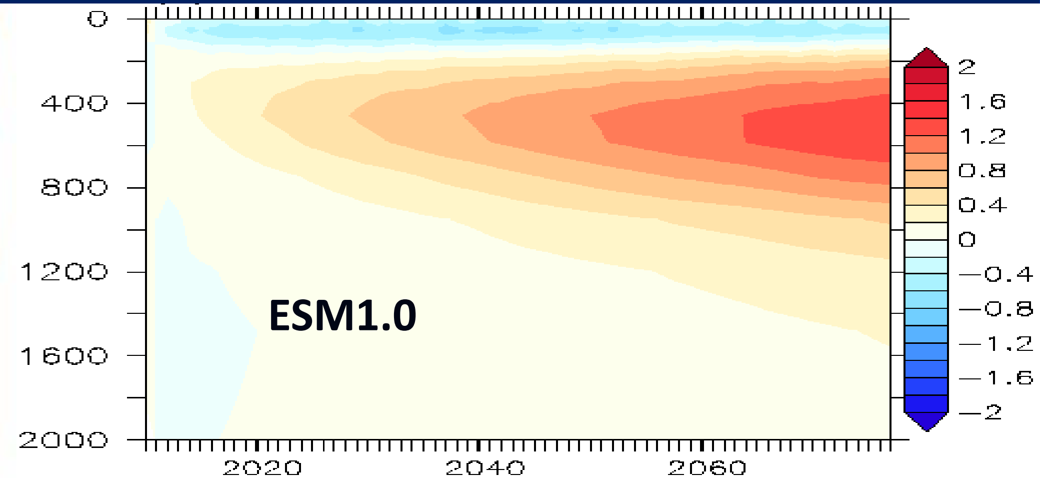


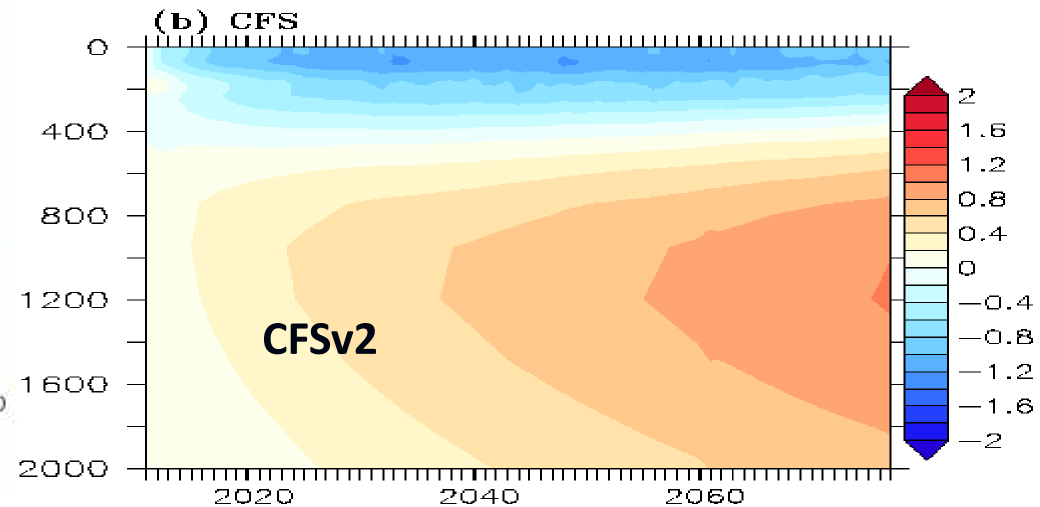
Annual mean temperature



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

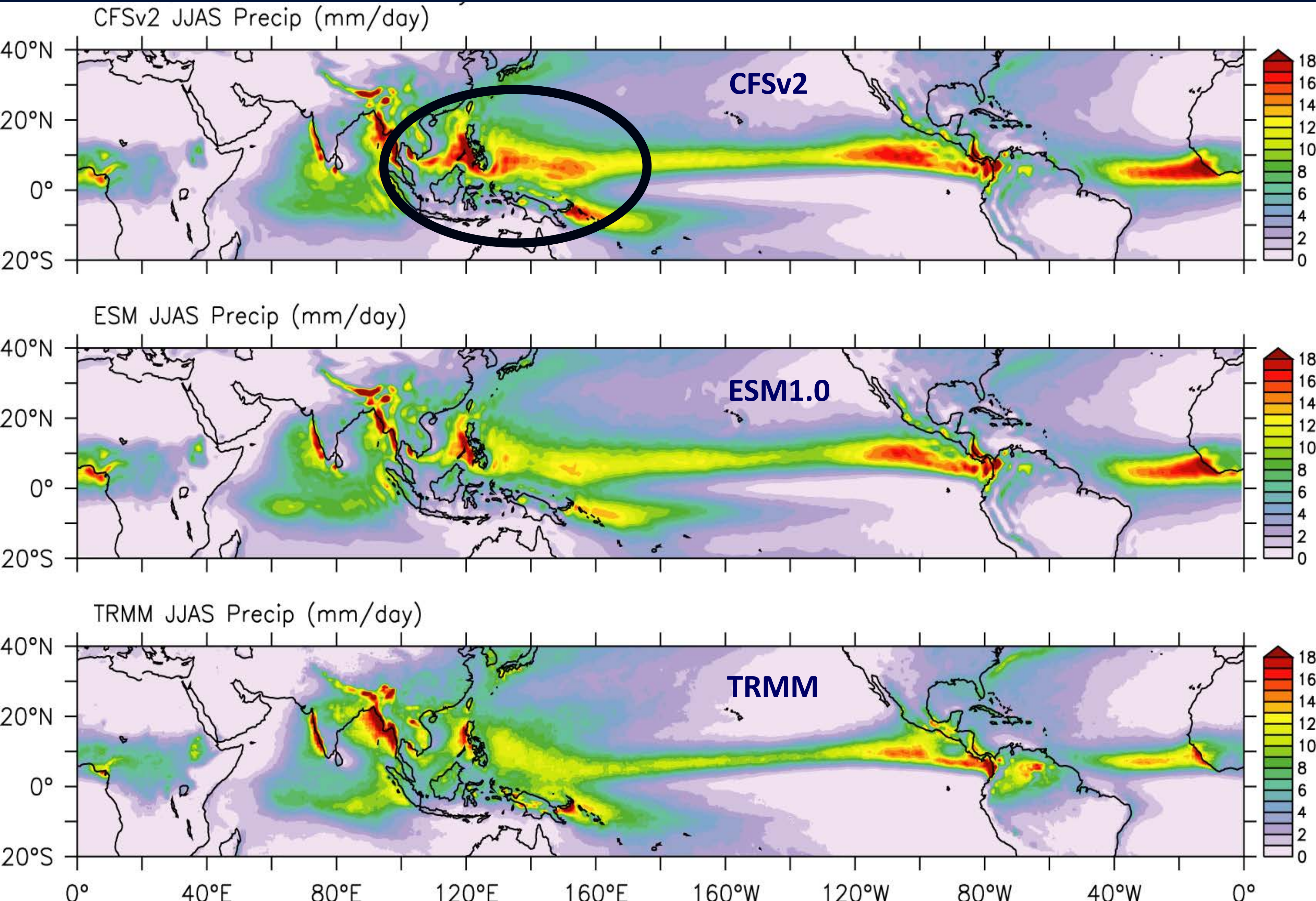




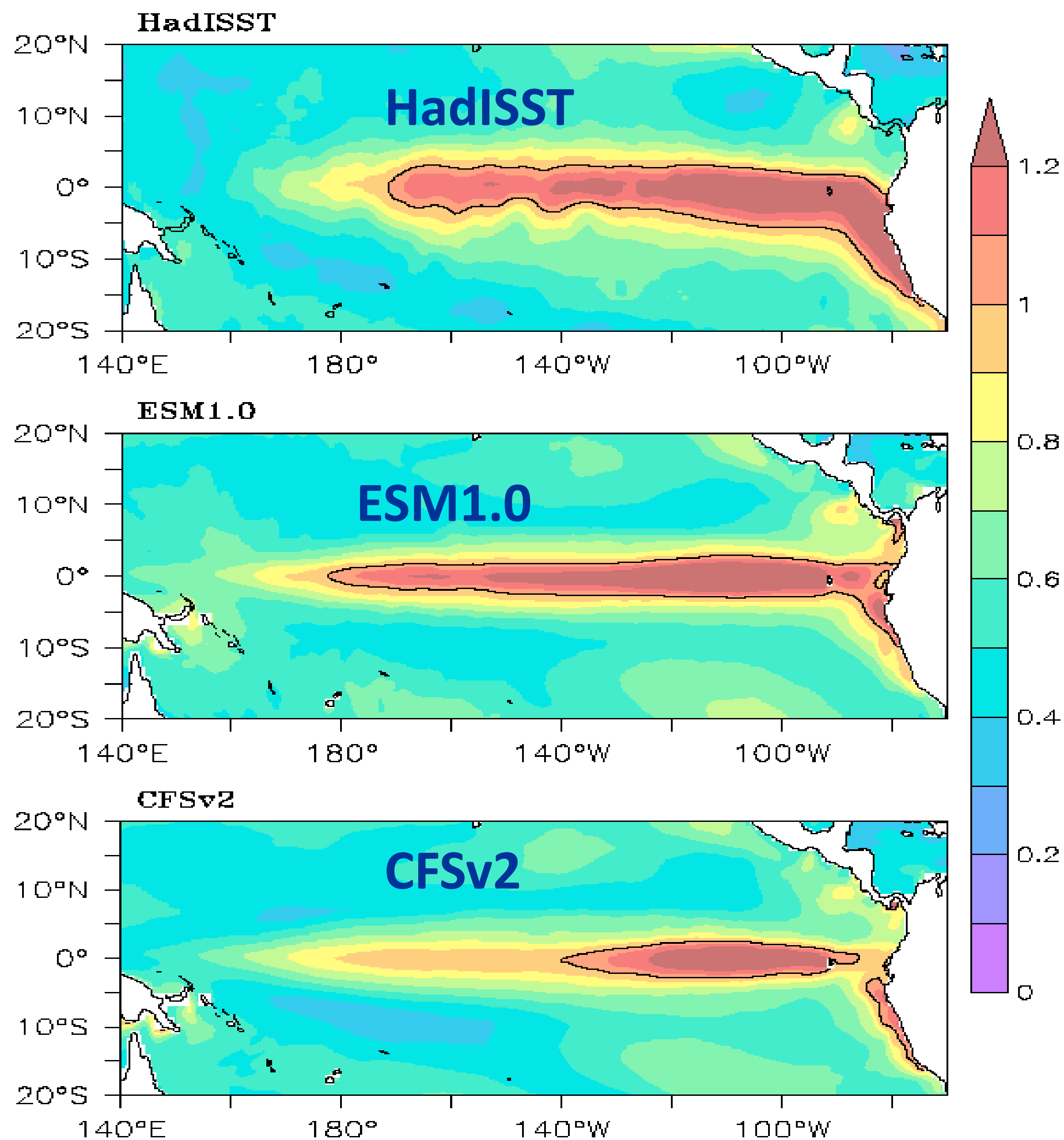


Differences between simulated and observed long-term global-mean ocean temperature as a function of depth and time.

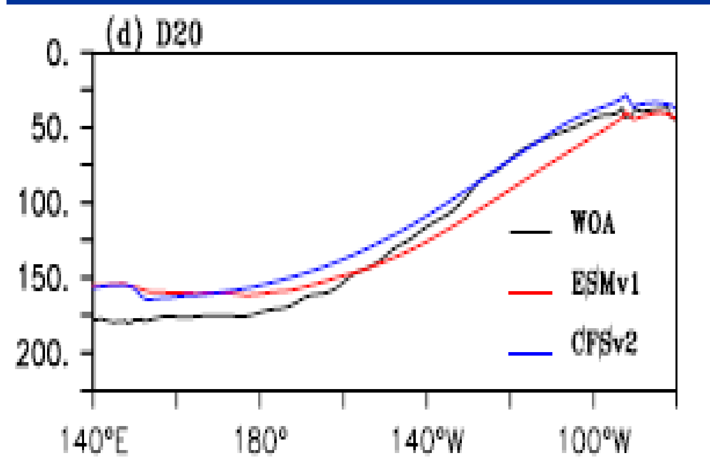
Precipitation (mm day^{-1}): JJAS mean



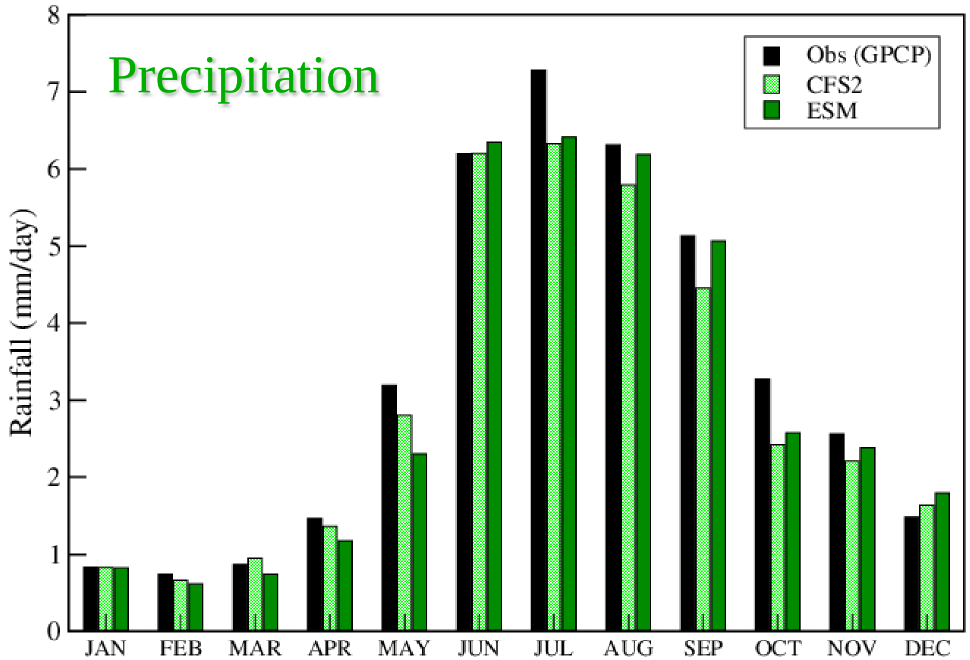
Interannual variability: Standard deviation of SST



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



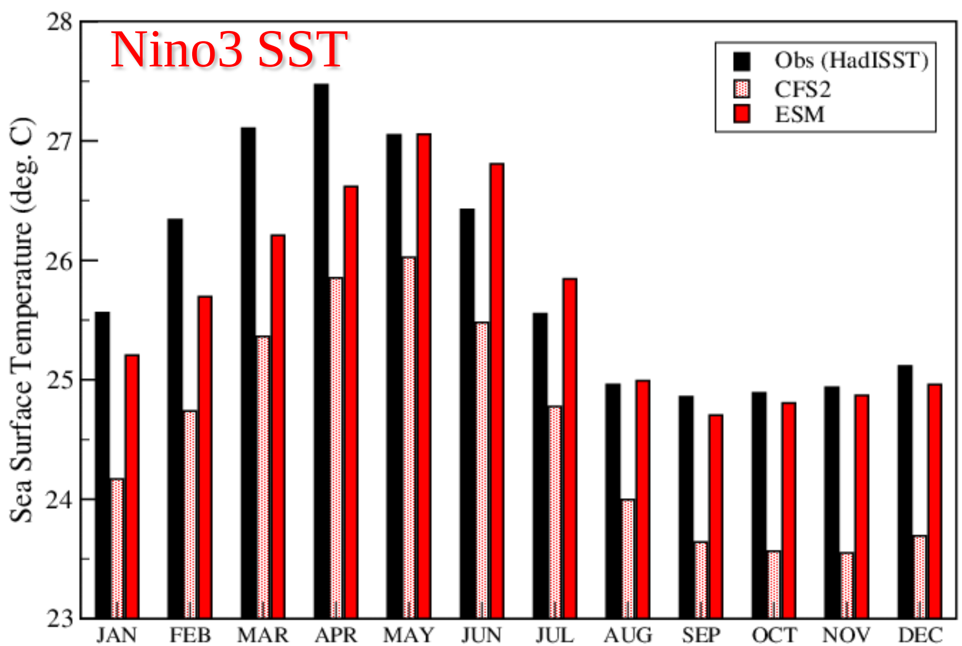
Courtesy: Swapna



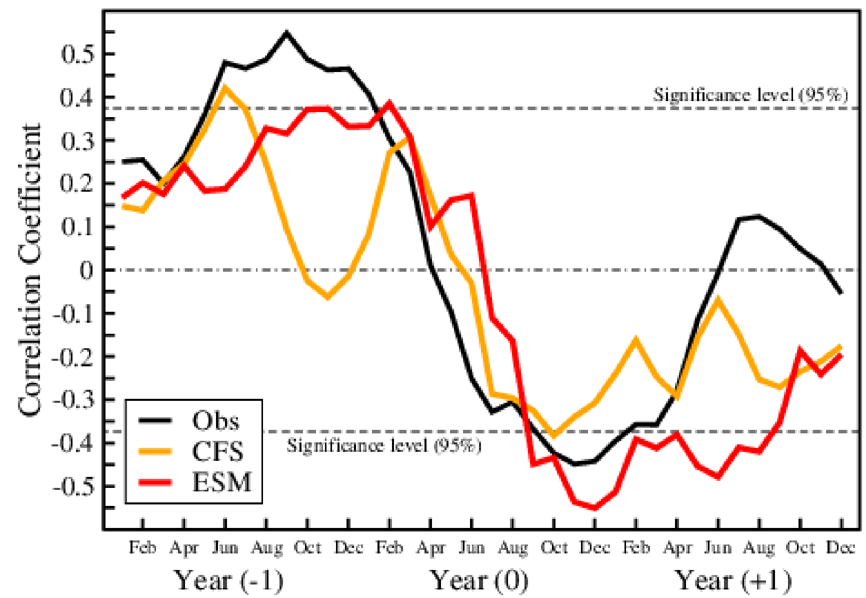
Precipitation

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

Indian (land + ocean)



ENSO-Monsoon relationship

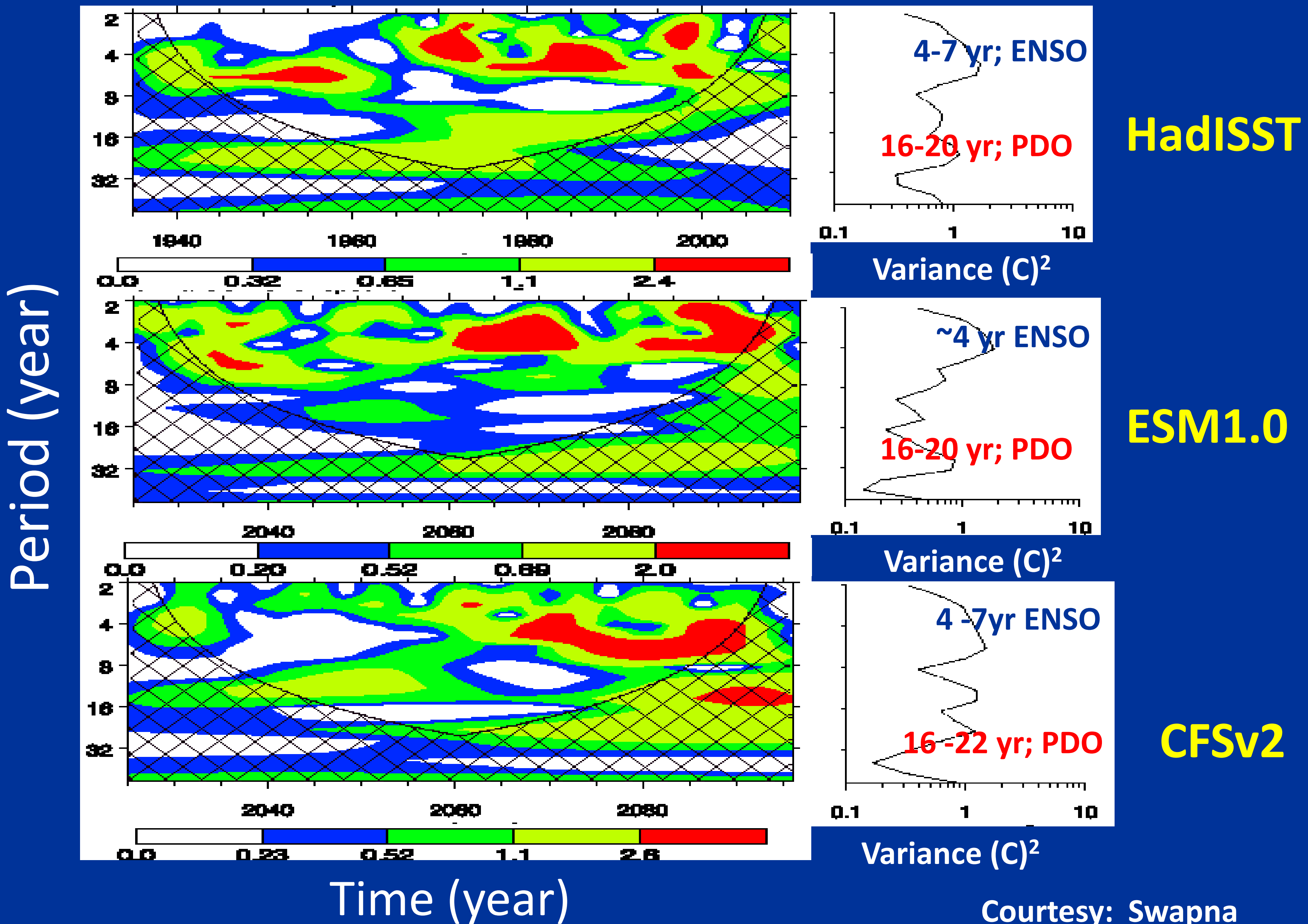


Lagged correlation between ISMR and Nino3 SST in the preceding/following months

CFS2 : 30 years (yr17-yr46)

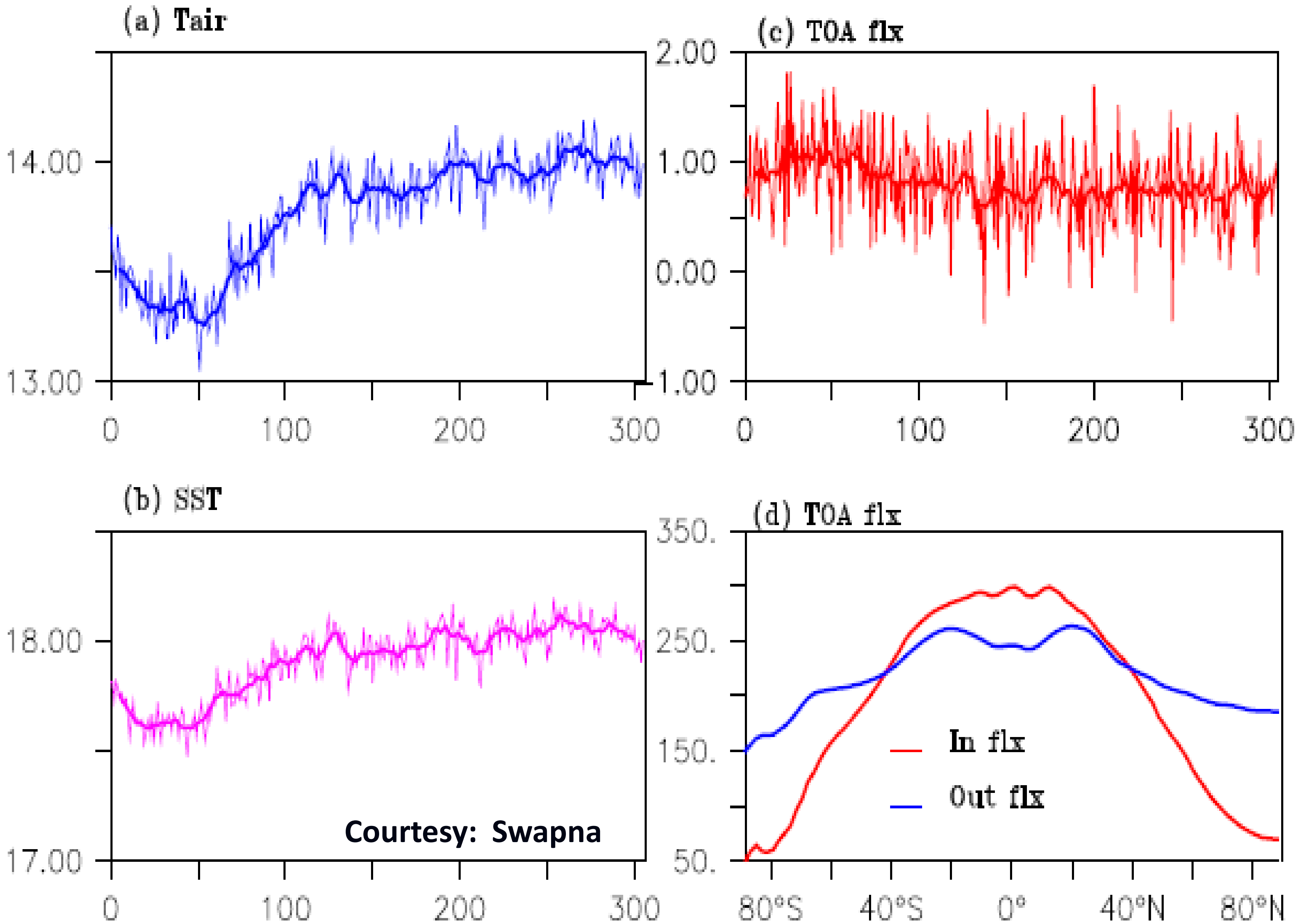
ESM : 30 years (yr17-yr46)

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



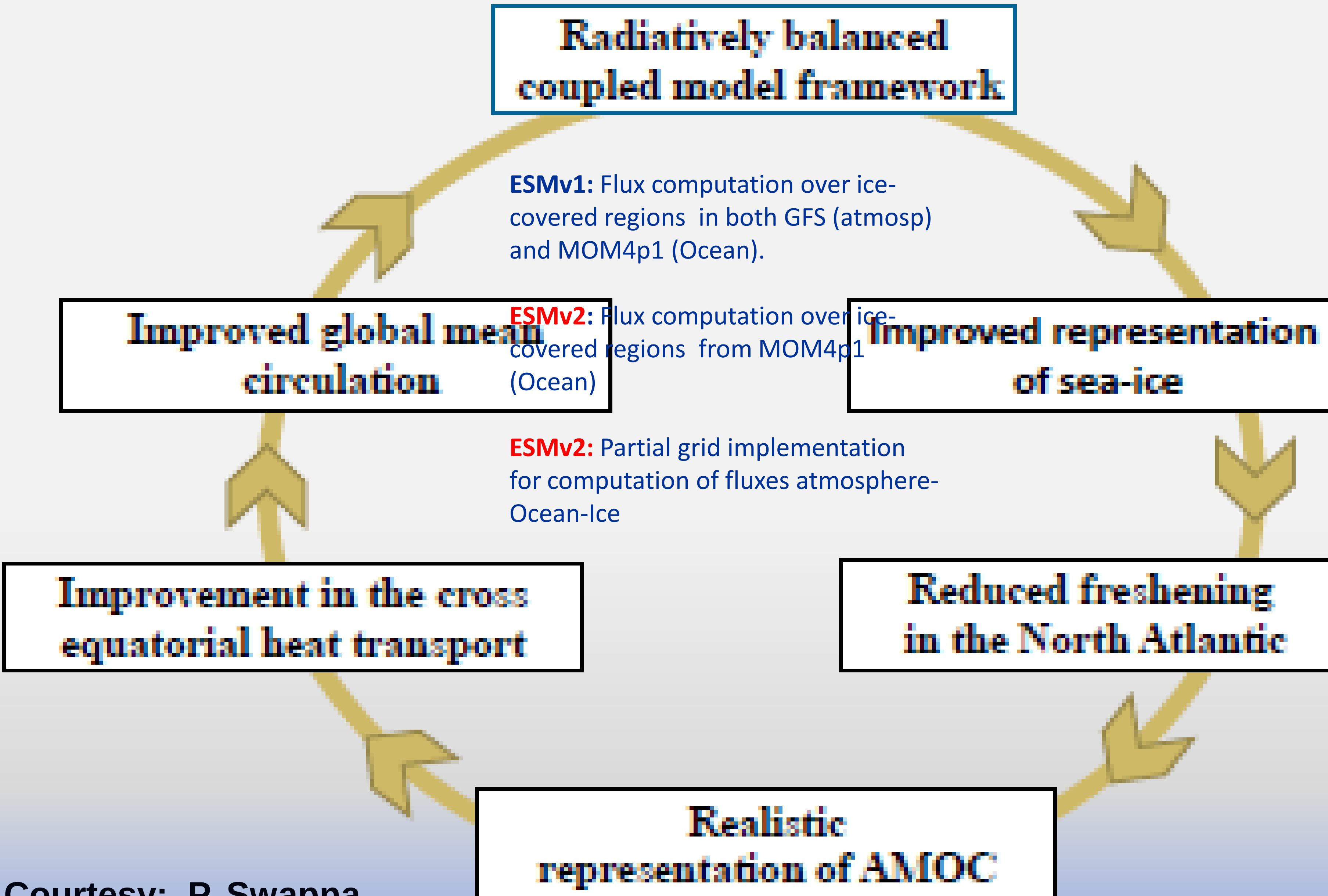
Courtesy: Swapna

Recent improvements in IITM ESM



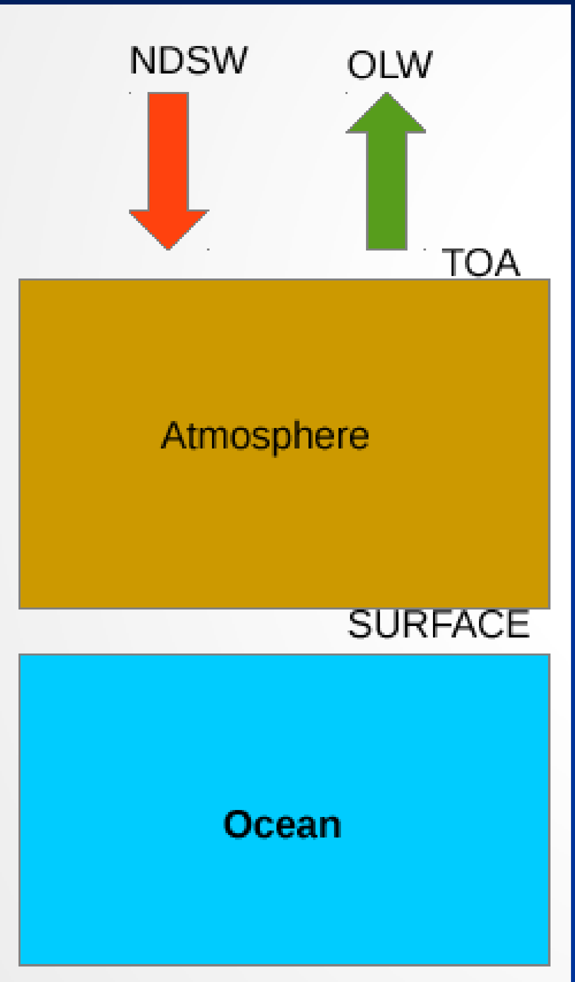
(a) Tair
14.00
13.00
0
100
200
300
(b) SST
18.00
17.00
0
100
200
300
Courtesy: Swapna
(c) TOA flx
2.00
1.00
0.00
-1.00
0
100
200
300
(d) TOA flx
350.
250.
150.
50.
80°S
40°S
0°
40°N
80°N
In flx
Out flx

Ocean-Atmosphere coupled feedbacks in IITM-ESM



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)

NDSW → **Internal Energy (CpT)** → **Incr. Temp**

NDSW → **Kinetic Energy (Winds)**

(Friction)

Missing in GFS

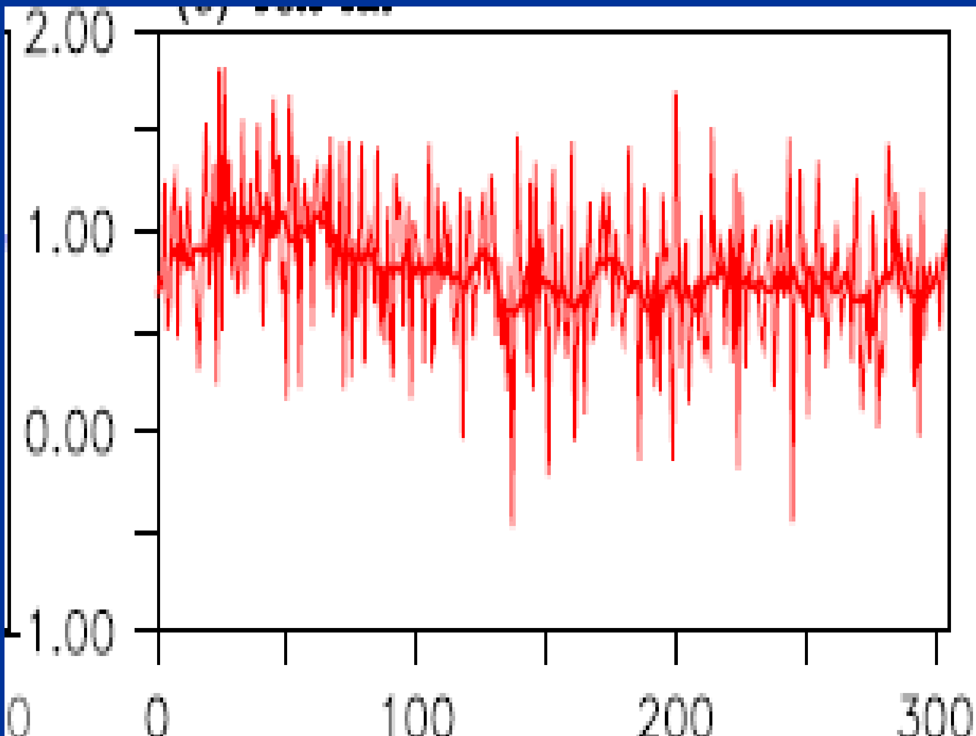
TKE dissipation heating (Han)

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

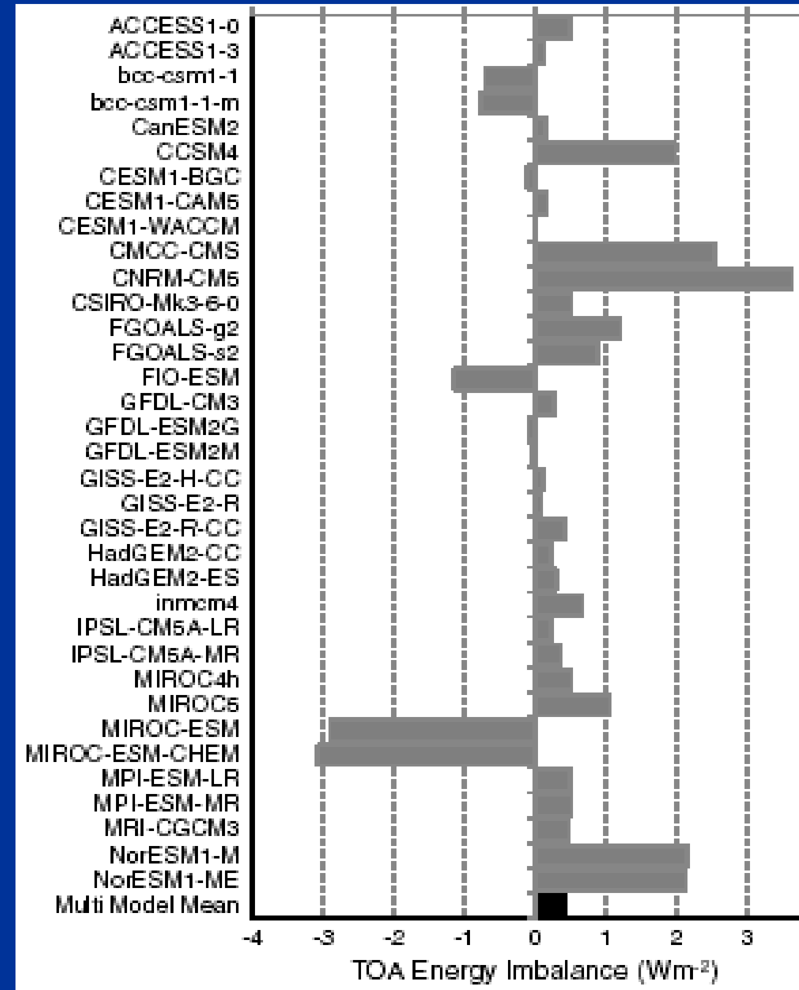
Minimize atmospheric energy loss – Bretherton et al. 2012

Courtesy: Prajeesh

Energy Balance in IITM ESMv2

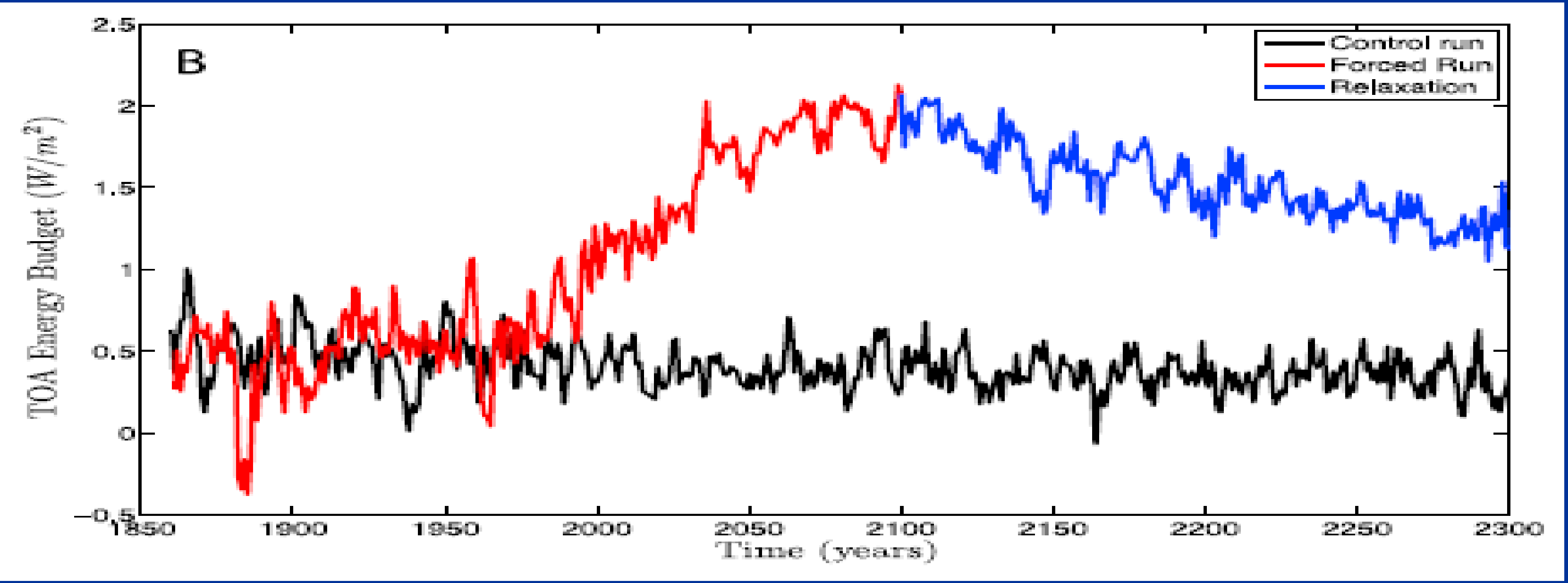


TOA Energy Imbalance (CMIP5 Models)



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

Time-series of TOA energy budget (GFDL2.1 CM9) – V. Lucarini, F. Ragone, 2011, Rev. Geophy

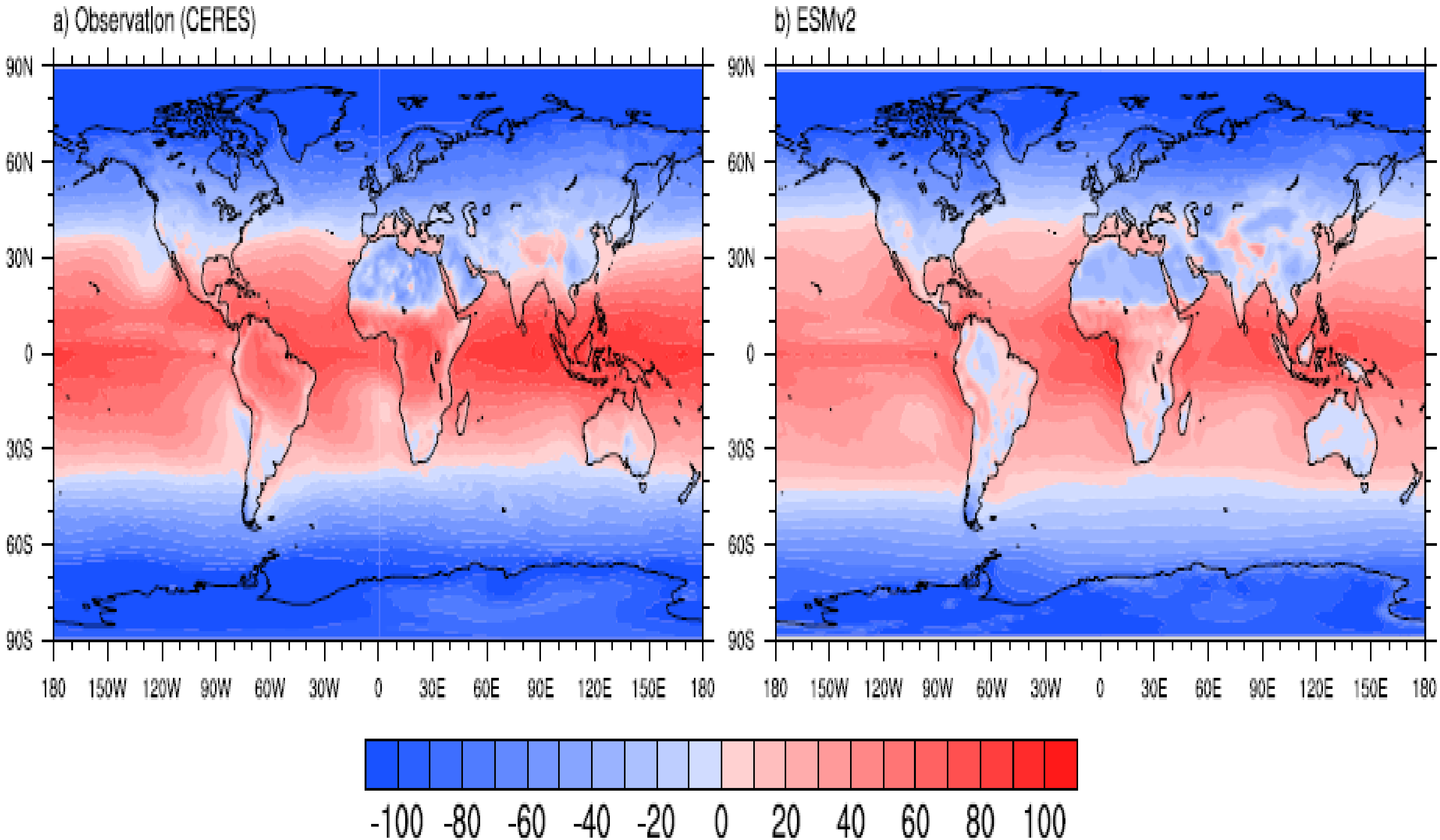


Black line is the preindustrial run. The red line shows the 20th century simulation and the 21st century portion of the SRES A1B simulation (stared from the end of the 20th century simulation. The blue line shows the 22nd and 23rd century SRES A1B simulation

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	0.75	0.05

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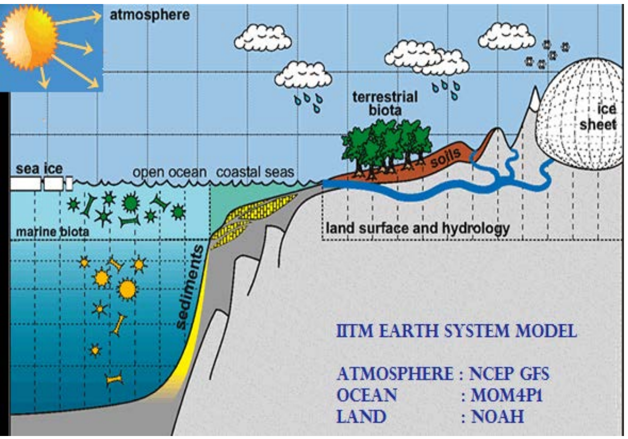
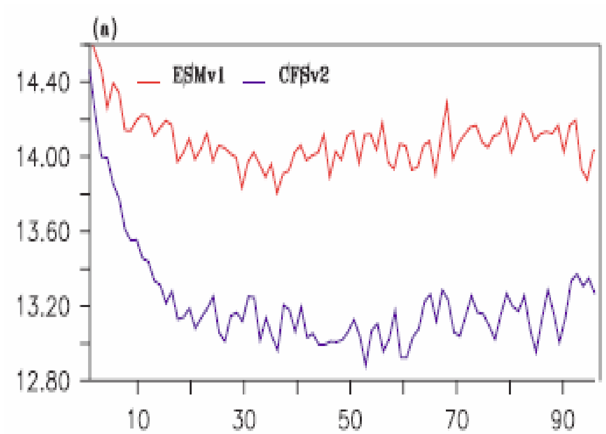
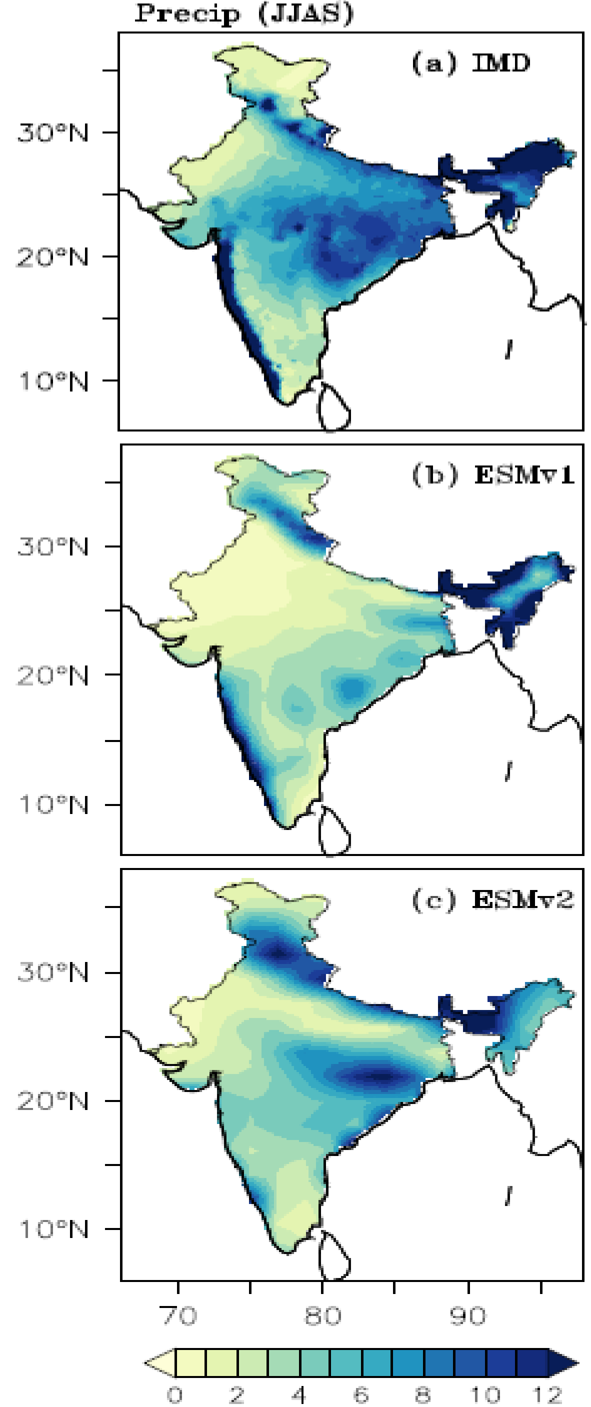
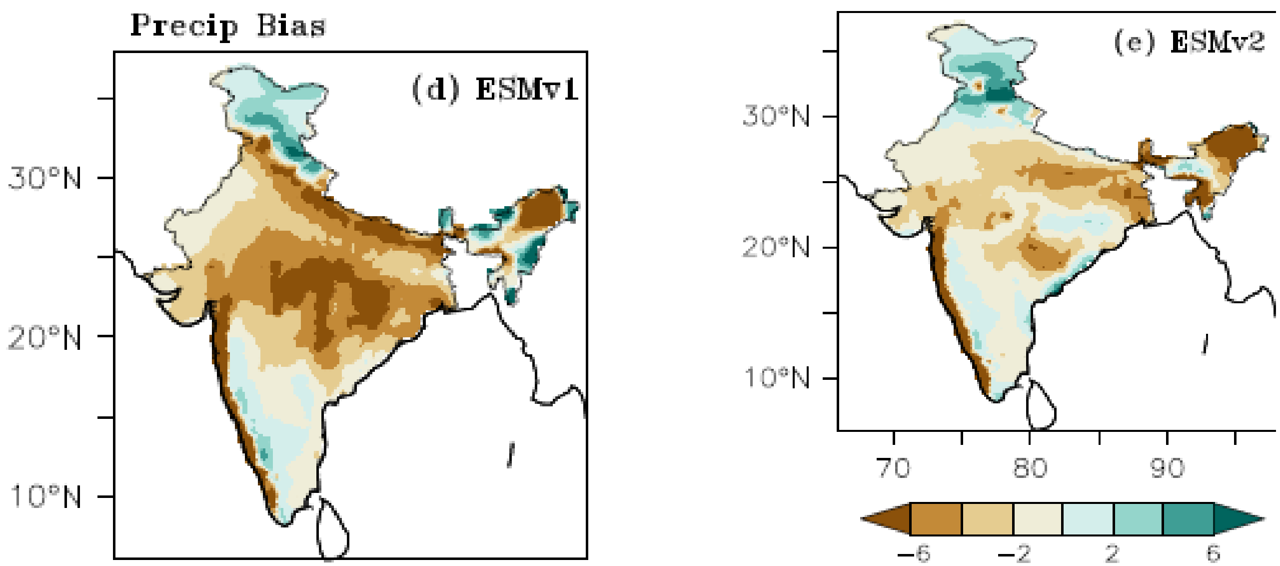
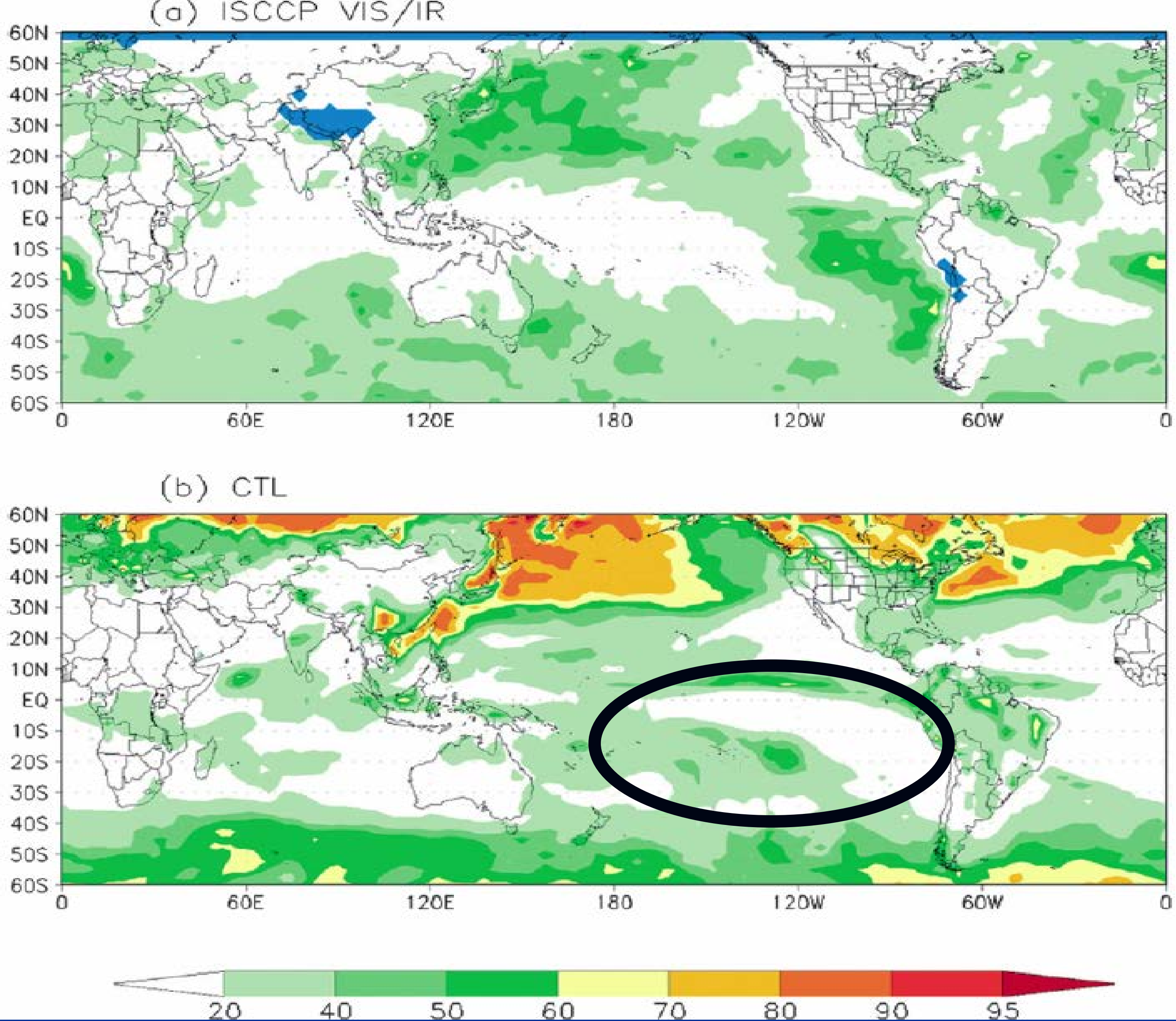










Monthly mean low cloud cover (%) for January 2003 from ISCCP (Rossow and Schiffer, 1991) VIS/IR satellite observations (blue color indicates 'no data' available).

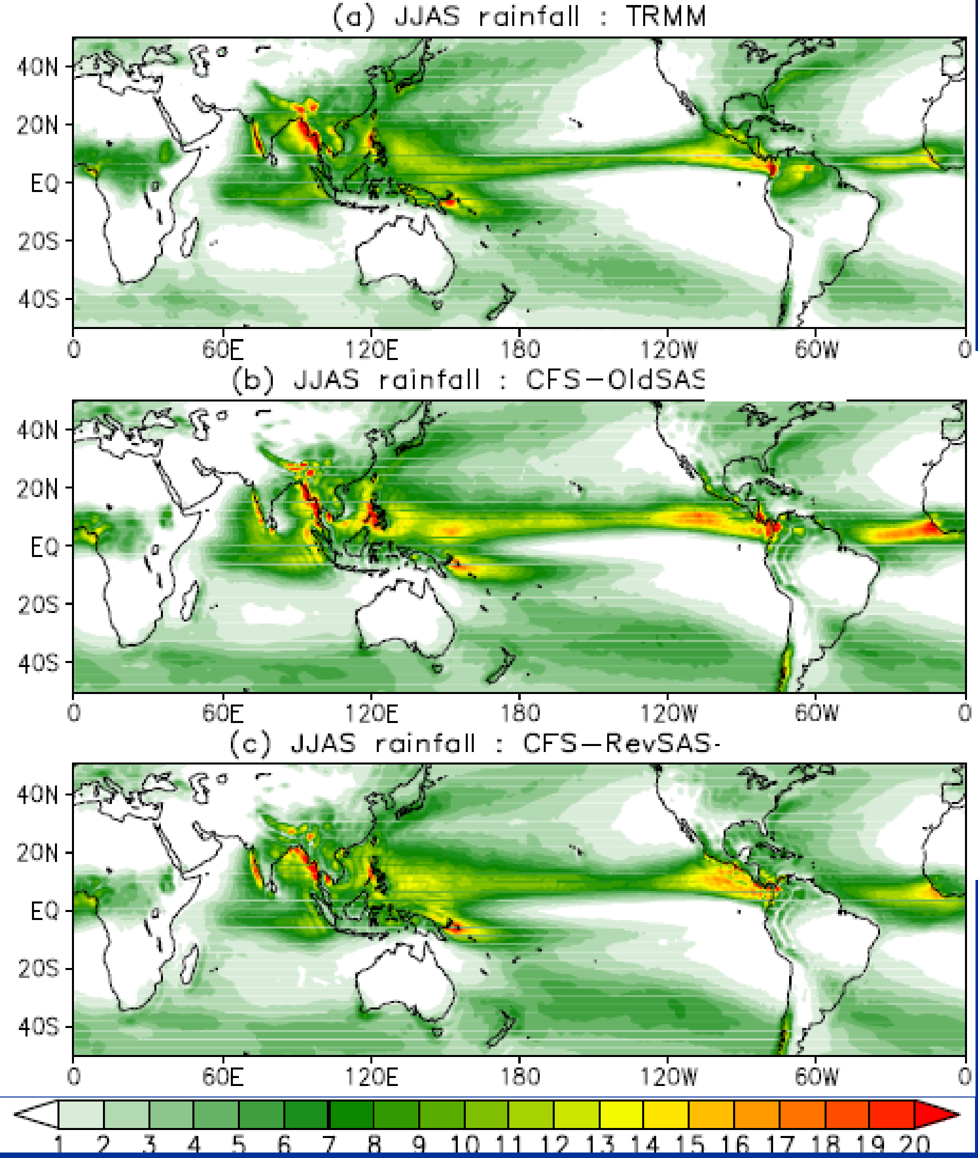
Control simulation using the old shallow convection Scheme of NCEP GFS

Han and Pan, 2011

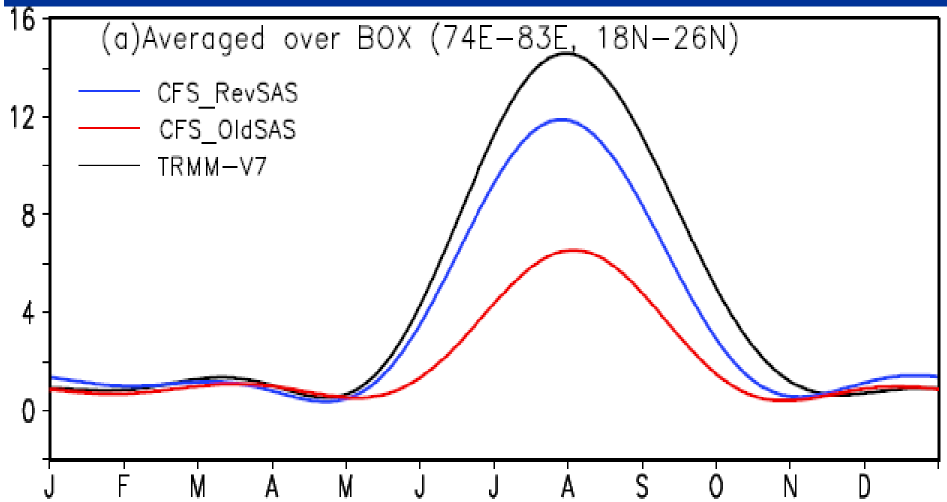
Long-standing problems in NCEP GFS: Systematic underestimation of stratocumulus clouds in the eastern Pacific and Atlantic Oceans; and the frequent occurrence of unrealistic excessive heavy precipitation, the so-called grid-point storms

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

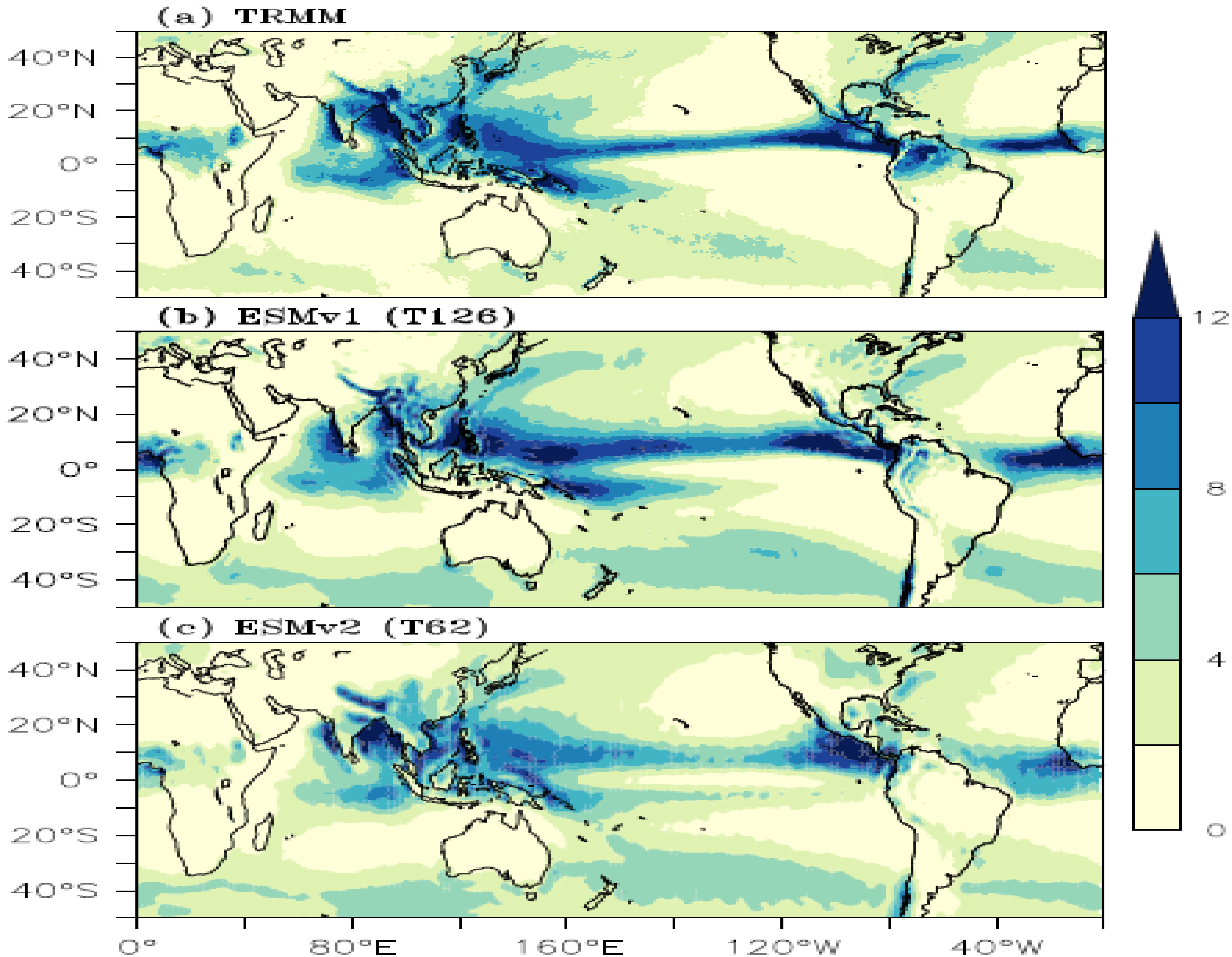
Climate Dynamics (2014)



Annual cycle of rainfall over Indian region



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

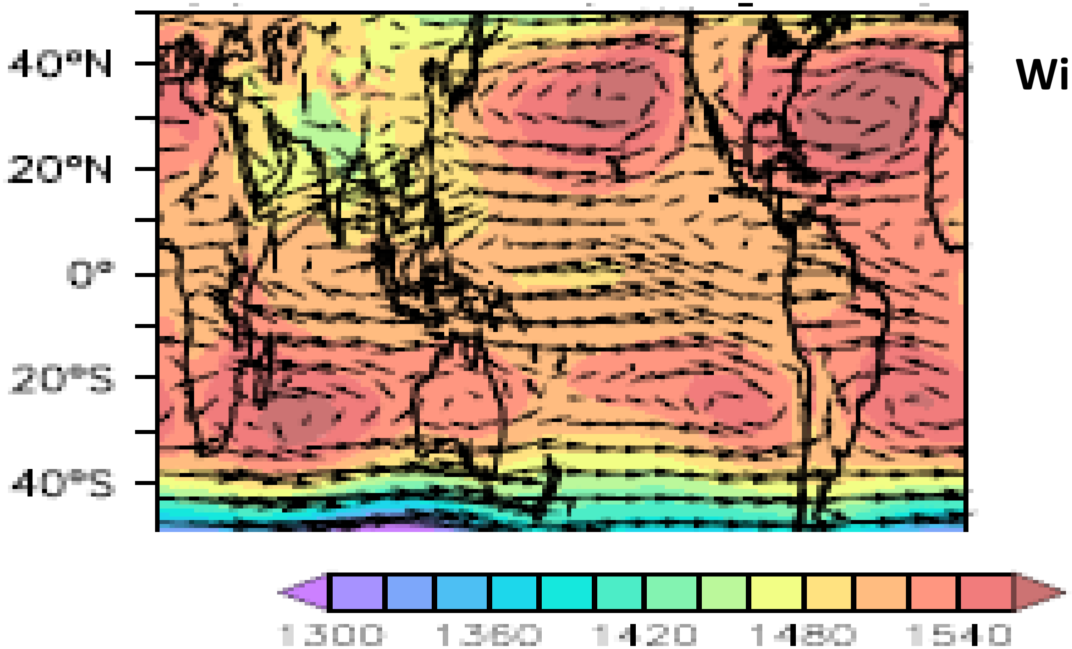


(a) TRMM
(b) ESMv1 (T126)
(c) ESMv2 (T62)
40°N
20°N
0°
20°S
40°S
0°
80°E
160°E
120°W
40°W
12
8
4
0

Winds & Geopotential Height: 850 hPa

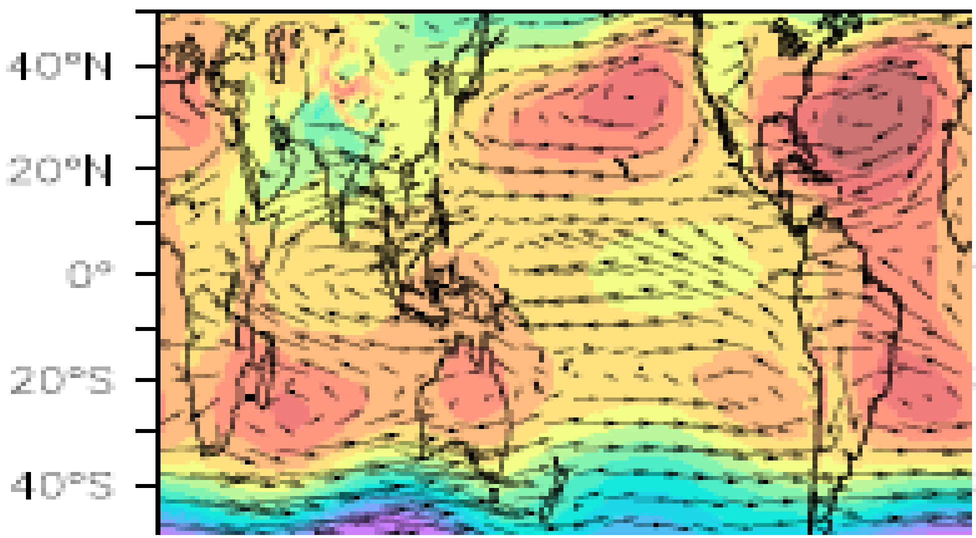
JJAS

ERA-Interim

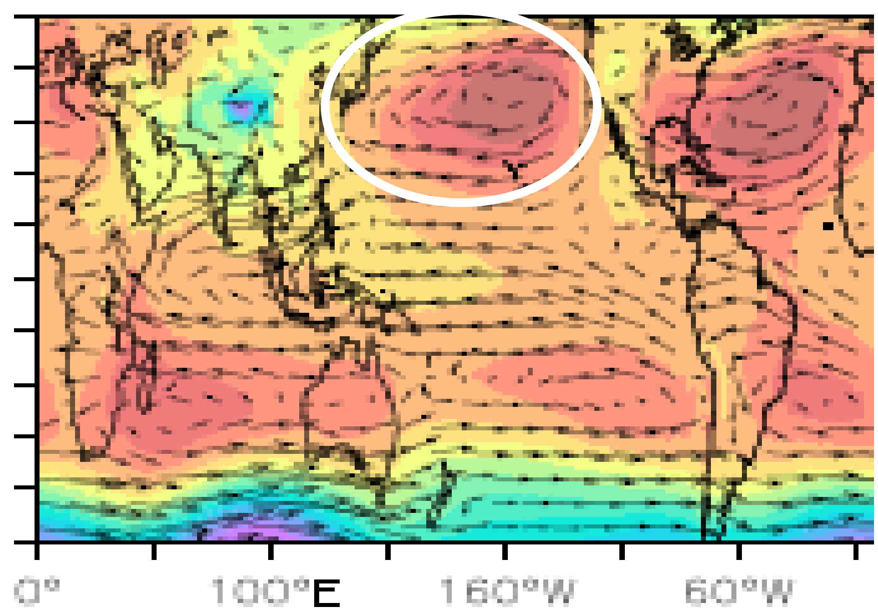


- Pacific sub-tropical anticyclone
- Easterly trade winds over Pacific

ESM-v1



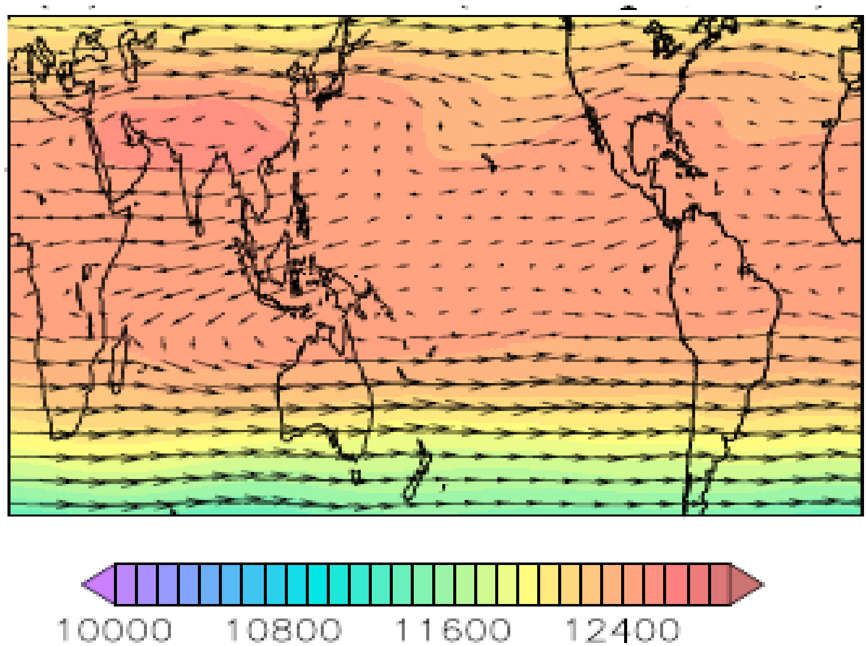
ESM-v2



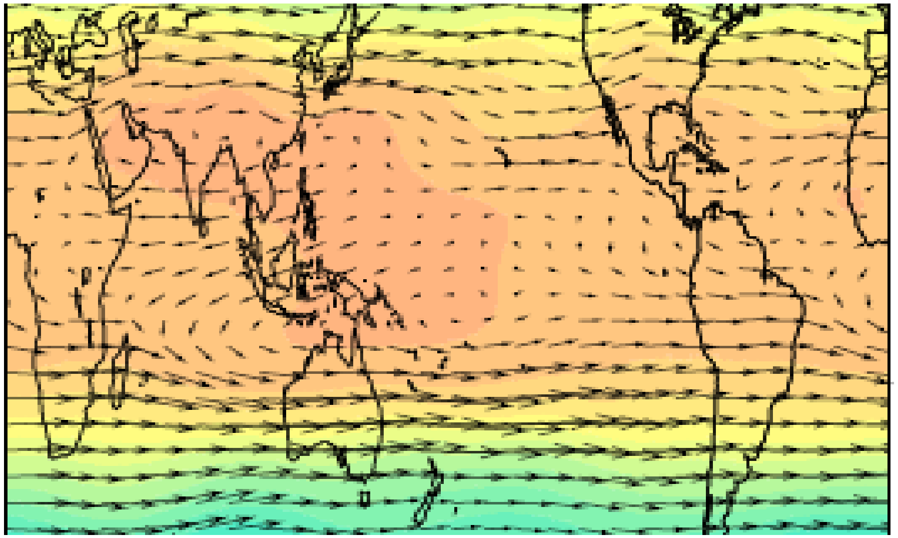
Winds & Geopotential Height: 200 hPa

JJAS

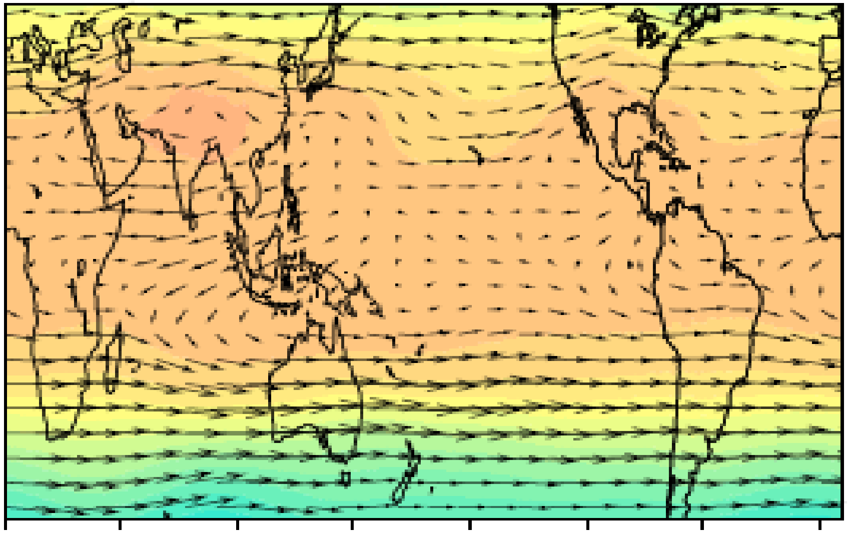
ERA-Interim



ESM-v1



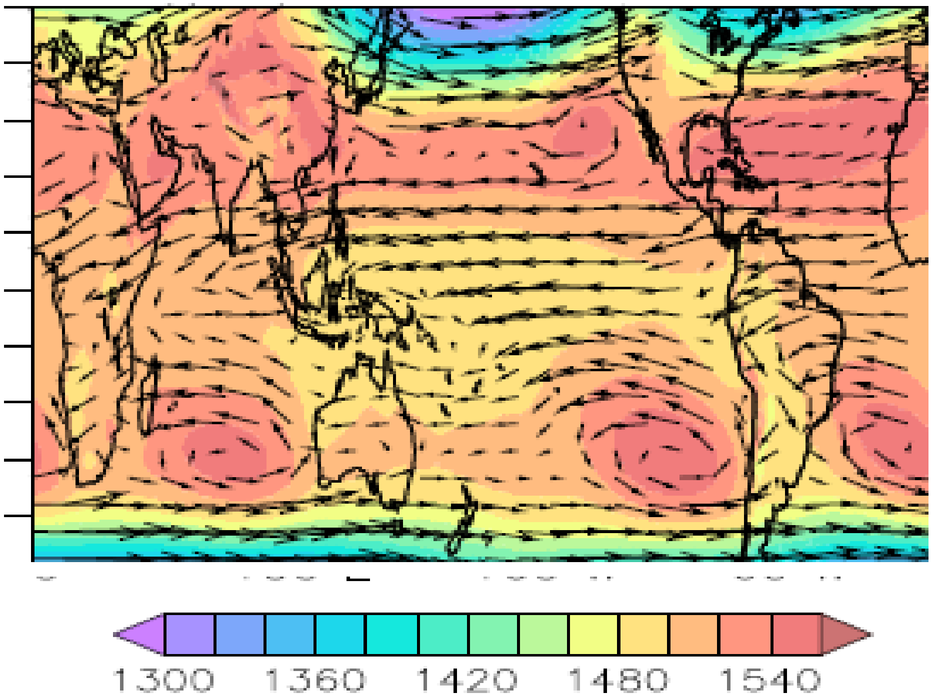
ESM-v2



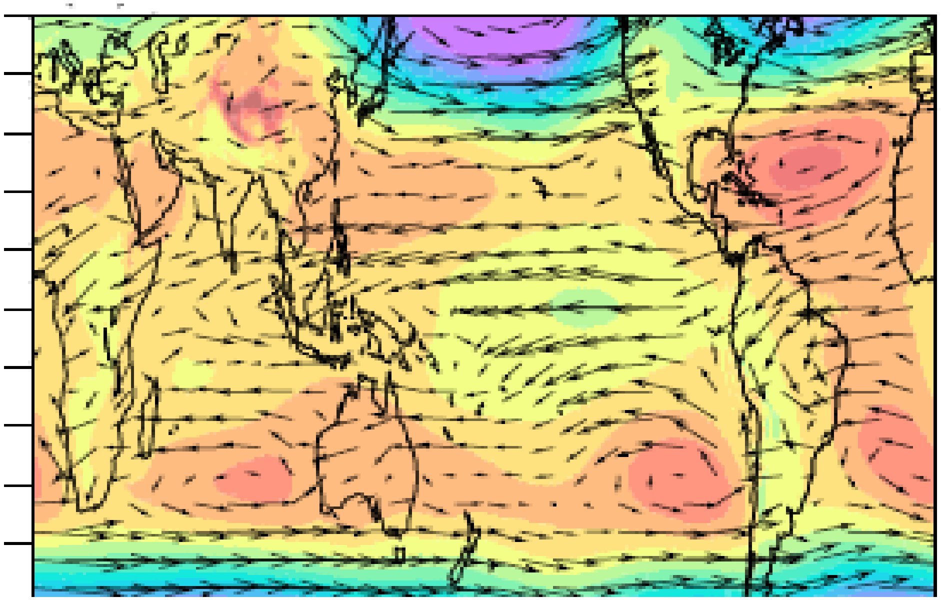
Winds & Geopotential Height: 850 hPa

DJF

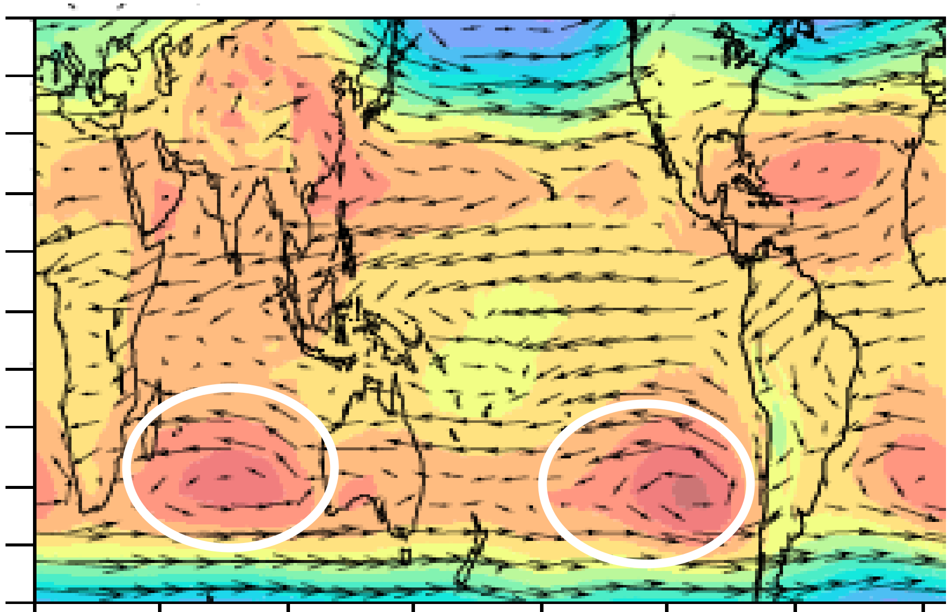
ERA-Interim



ESM-v1



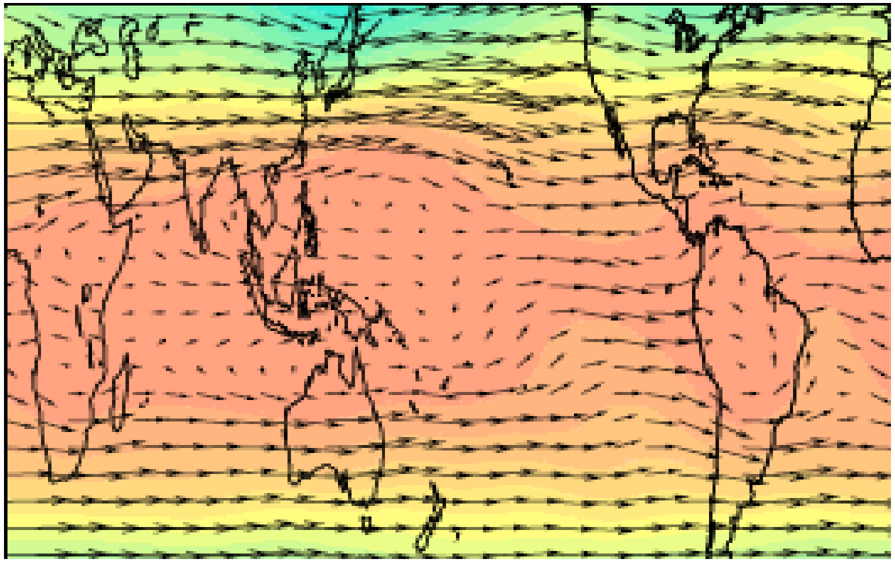
ESM-v2

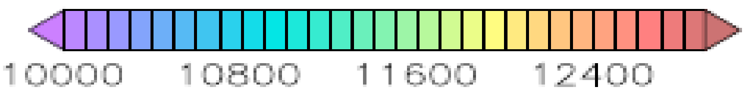


Winds & Geopotential Height: 200 hPa

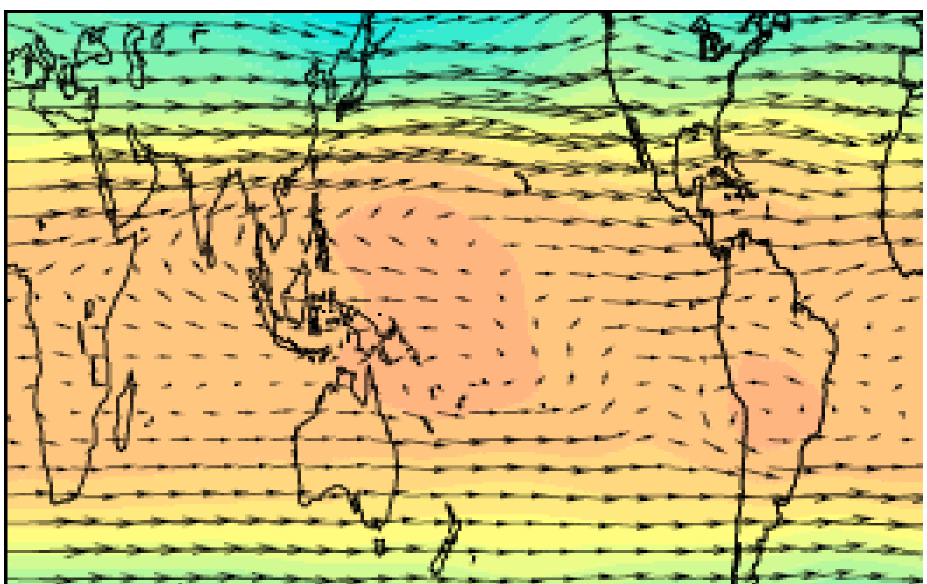
DJF

ERA-Interim

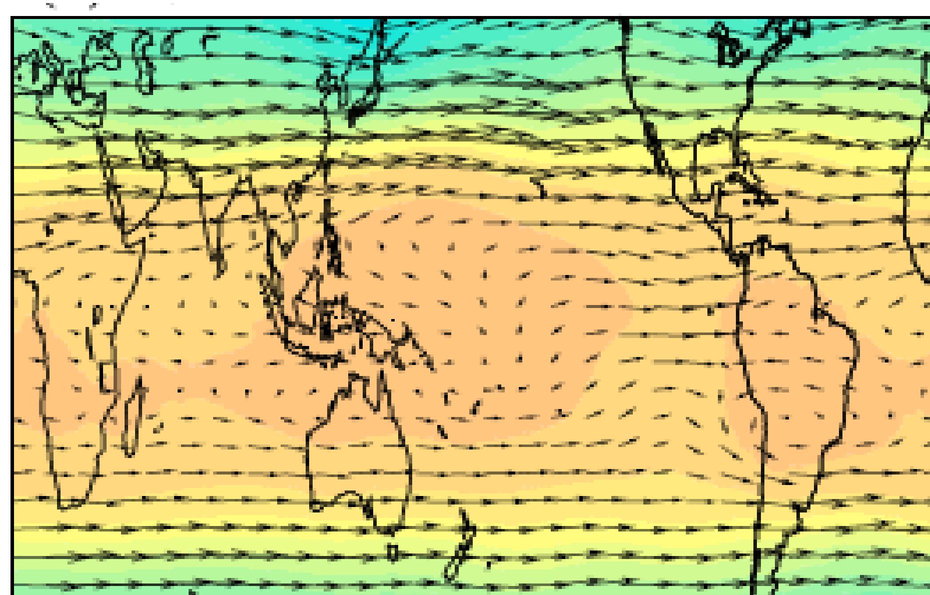




ESM-v1



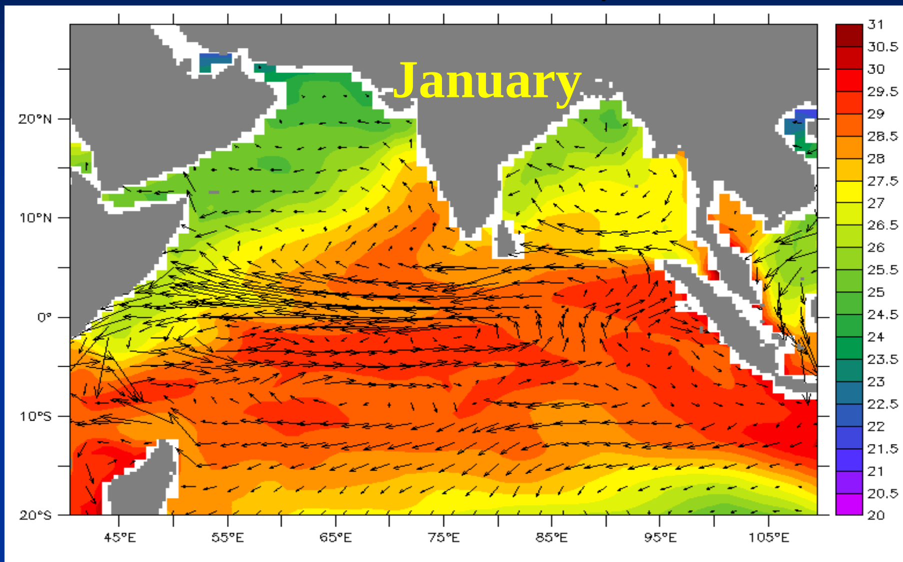
ESM-v2



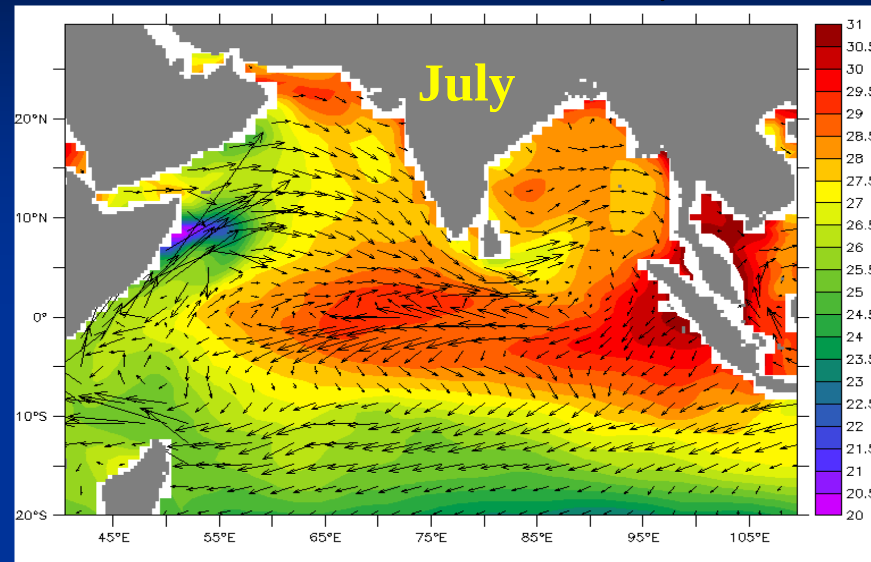
MOM4p1 forced ocean simulation – 130 year spin up

Physical and Biogeochemical Parameters for Tropical Indian Ocean

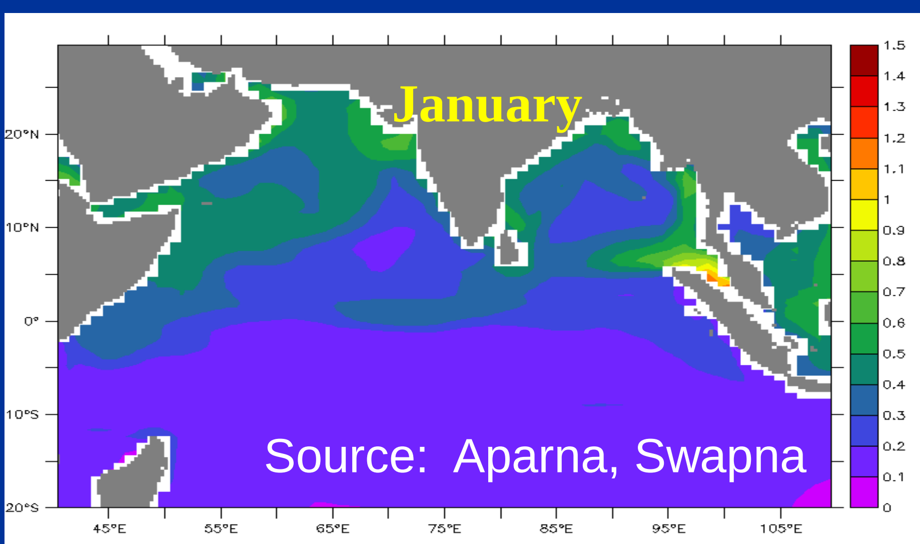
SST and currents)



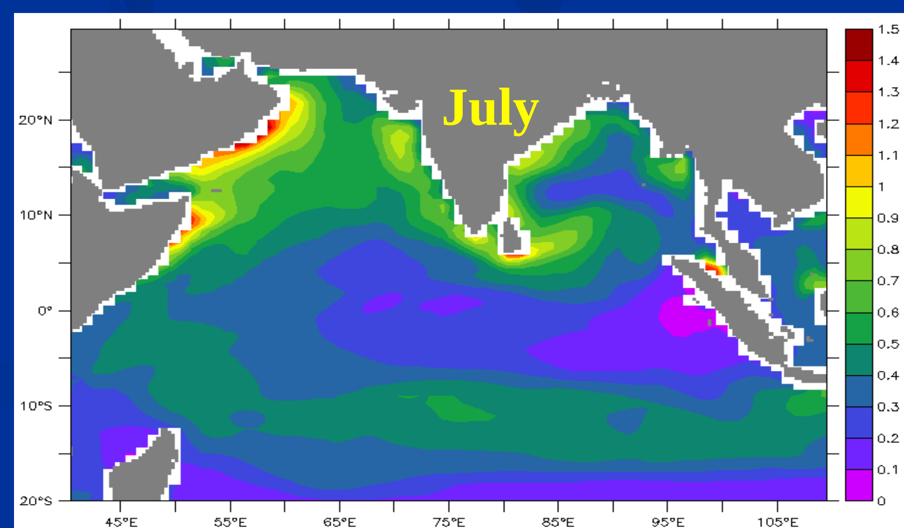
SST and currents)



Chlorophyll



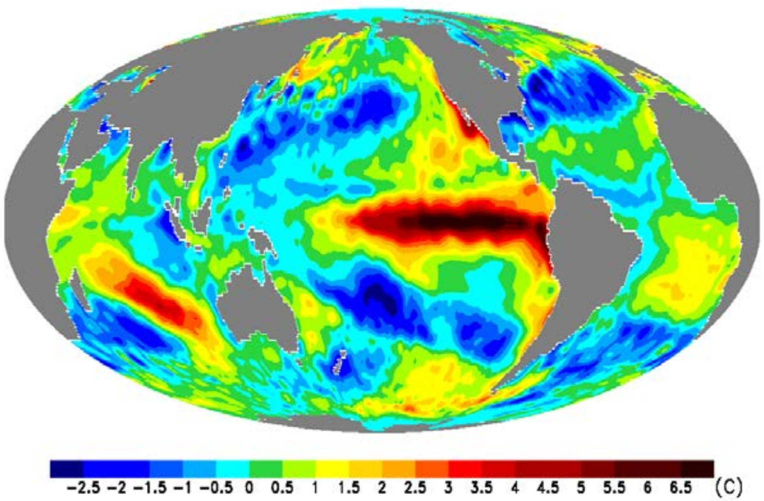
Chlorophyll



1997-98: Strongest El Niño ever recorded!

Sea Surface Temperature

Dec 1997 minus Dec 1998



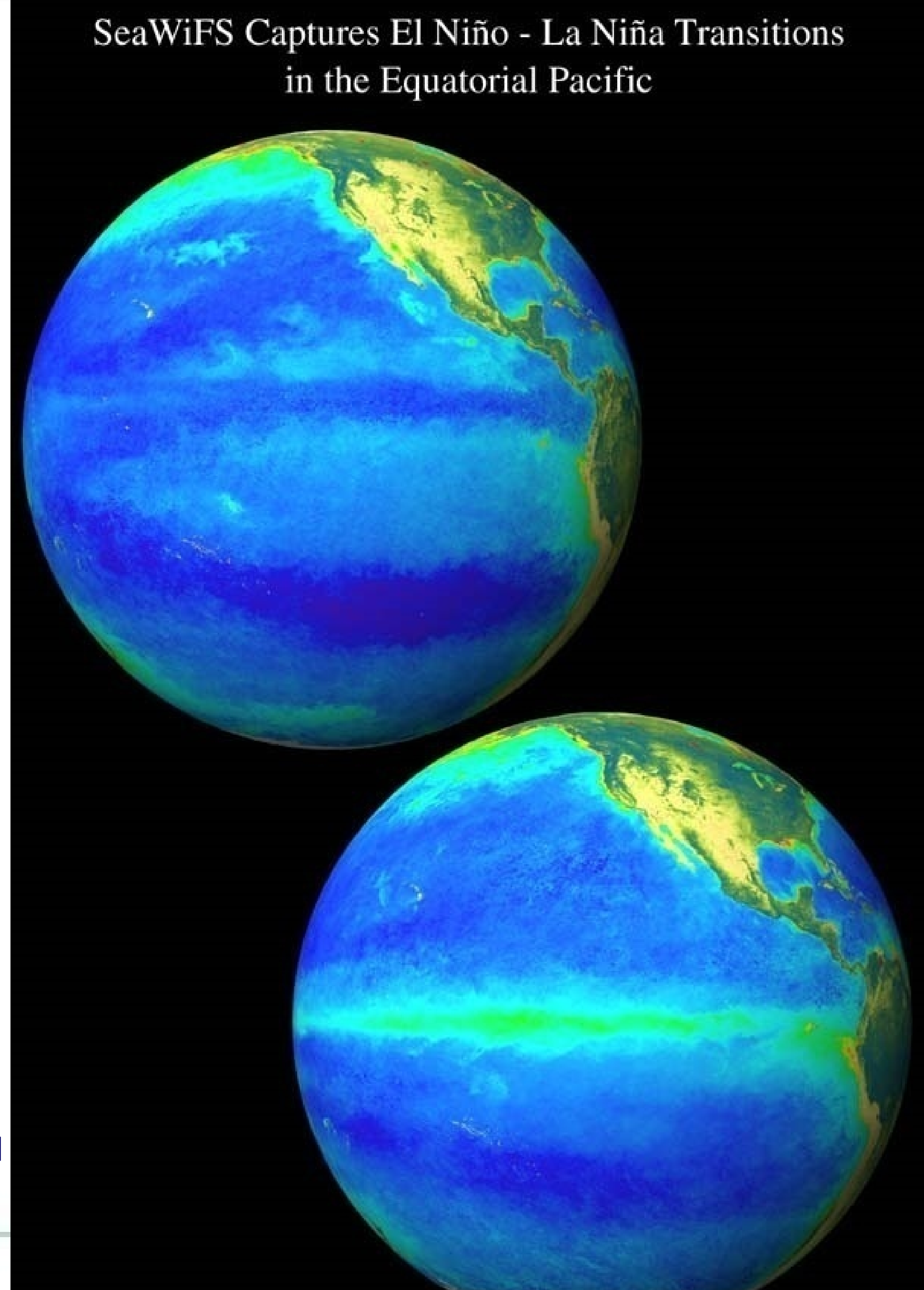


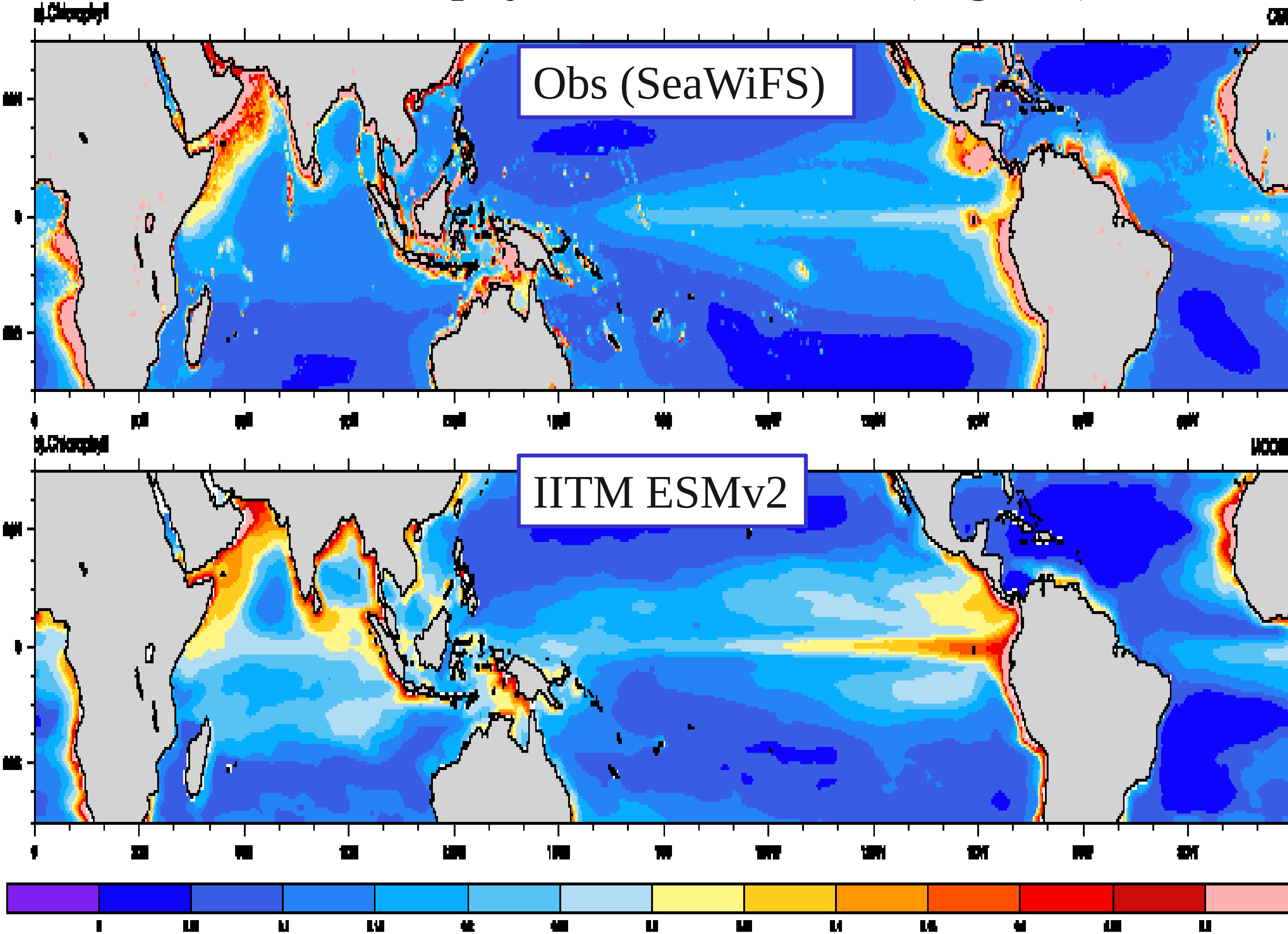
Image from SeaWIFS Project, NASA / GSFC

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)

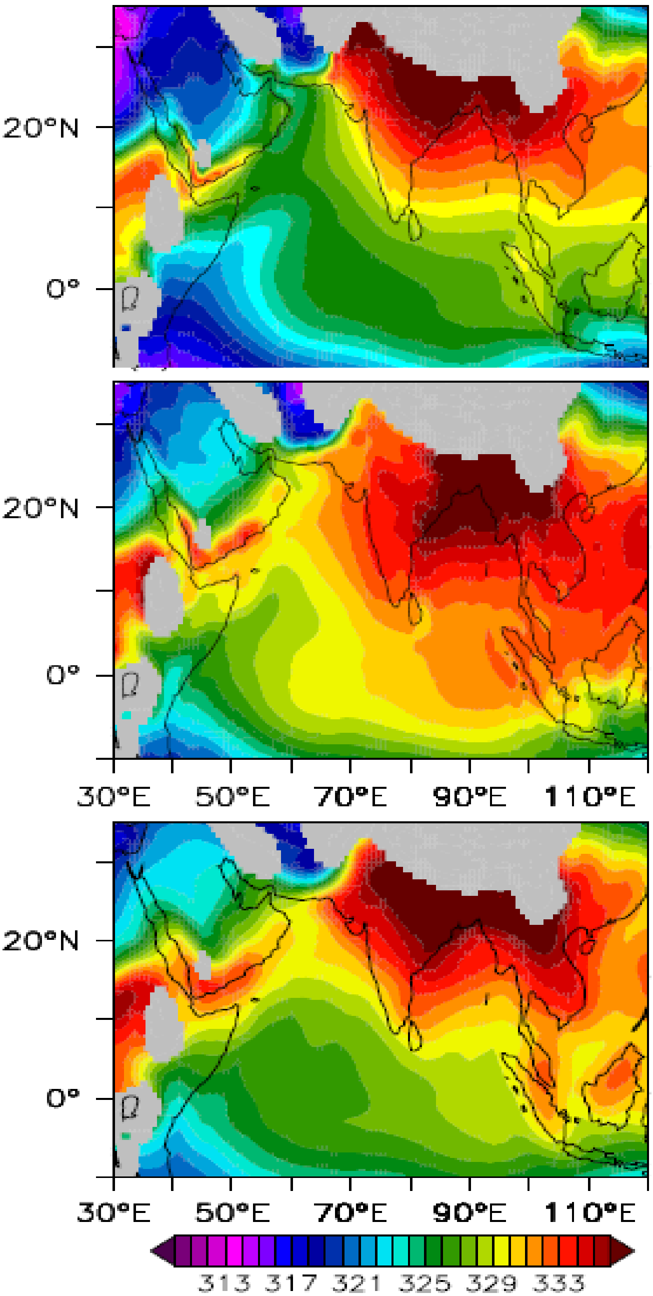
Chlorophyll Concentration (Mg m^{-3})



Courtesy: Sandeep, CCCR

Moist Static Energy

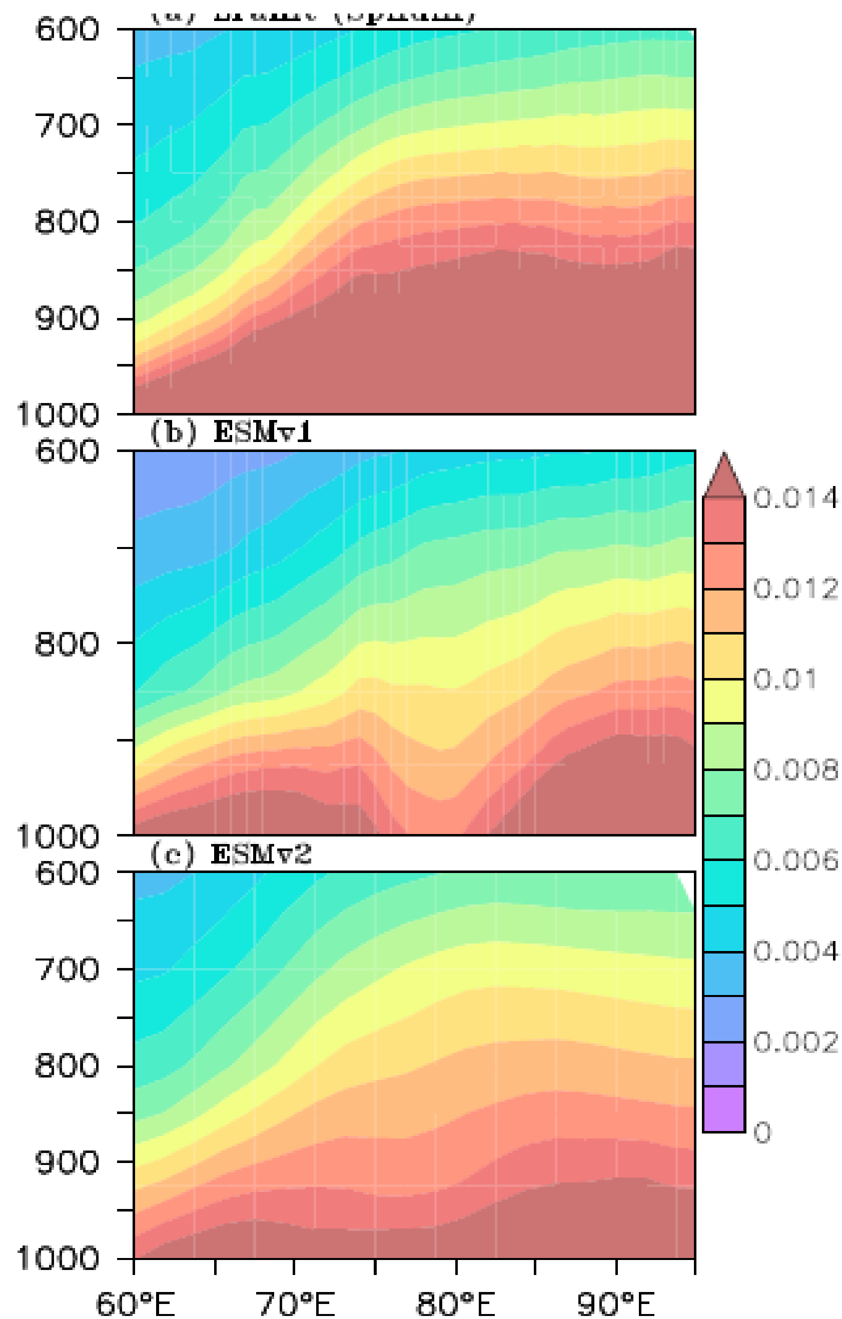
Specific Humidity



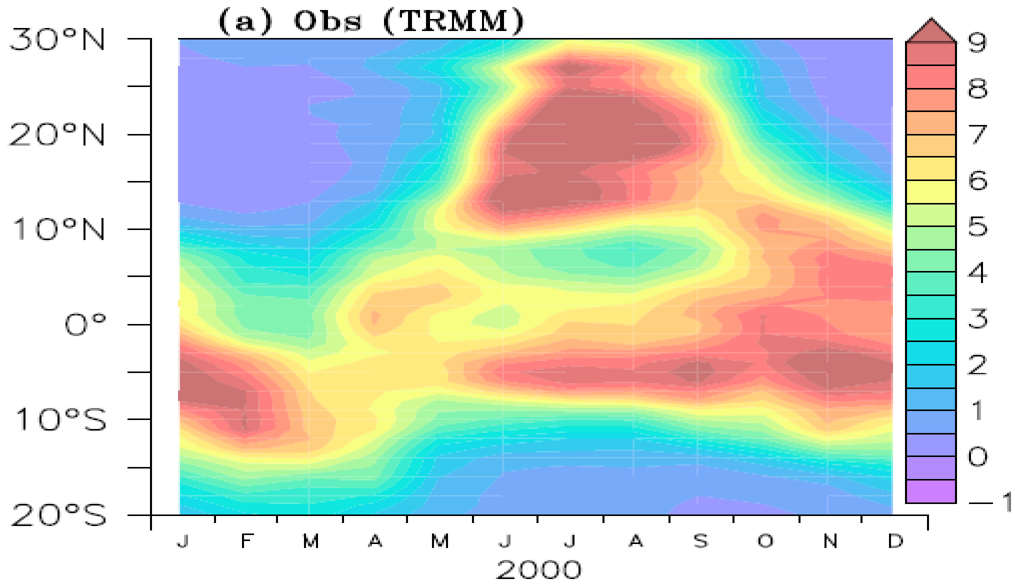
ERA
Interim

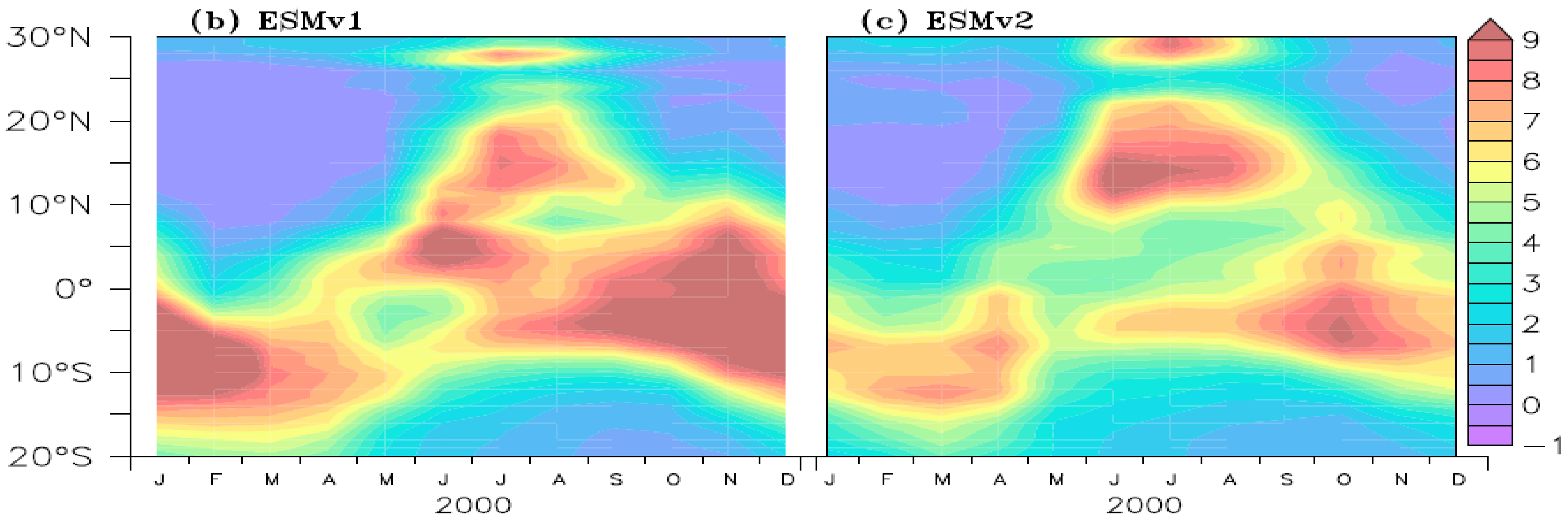
ESMv1

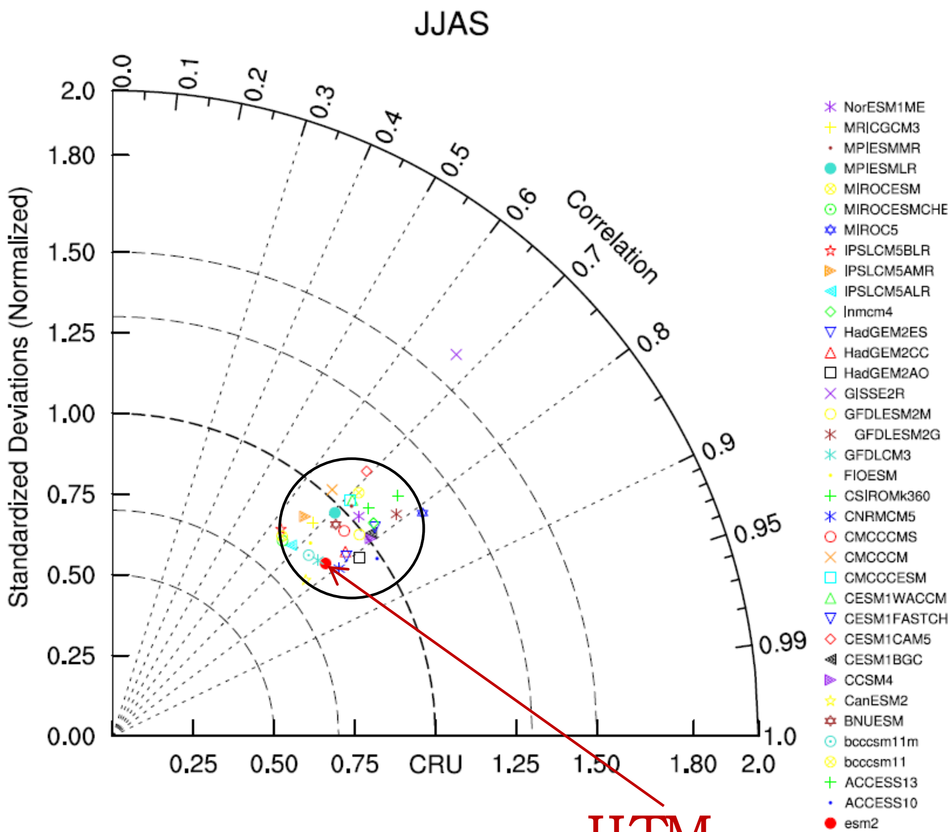
ESMv2



Precipitation Seasonal Cycle (70E-90E)



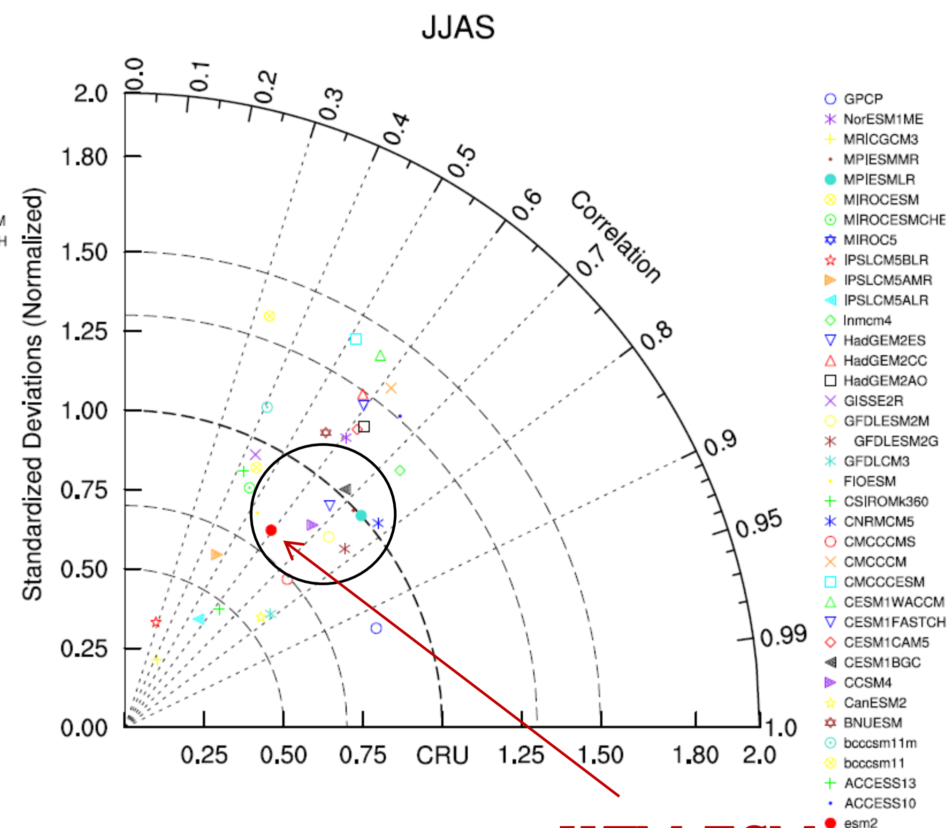




IITM-ESM

Asian region (JJAS precipitation)

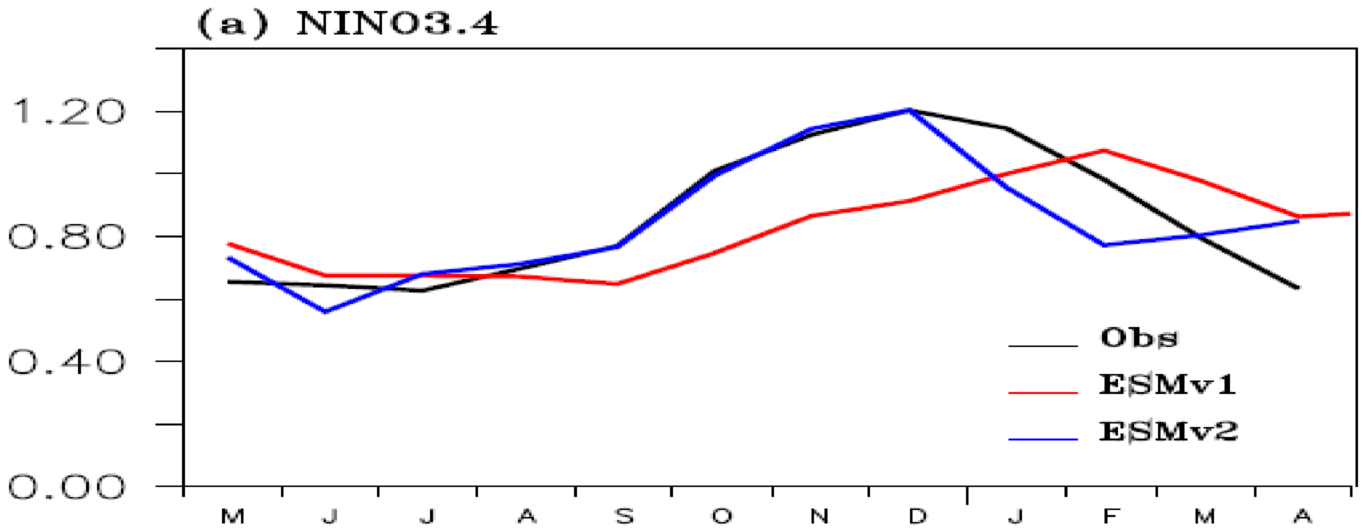
Indian region (JJAS precipitatio



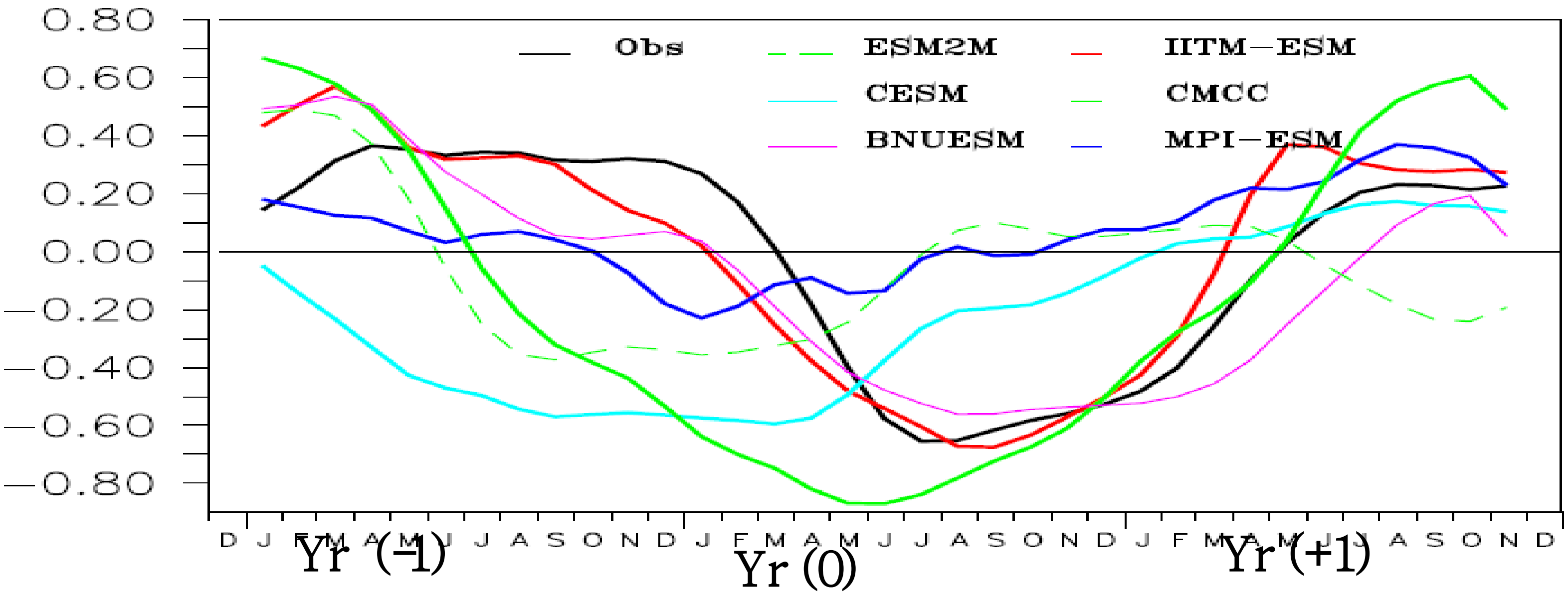
IITM-ESM

Courtesy: Swapna

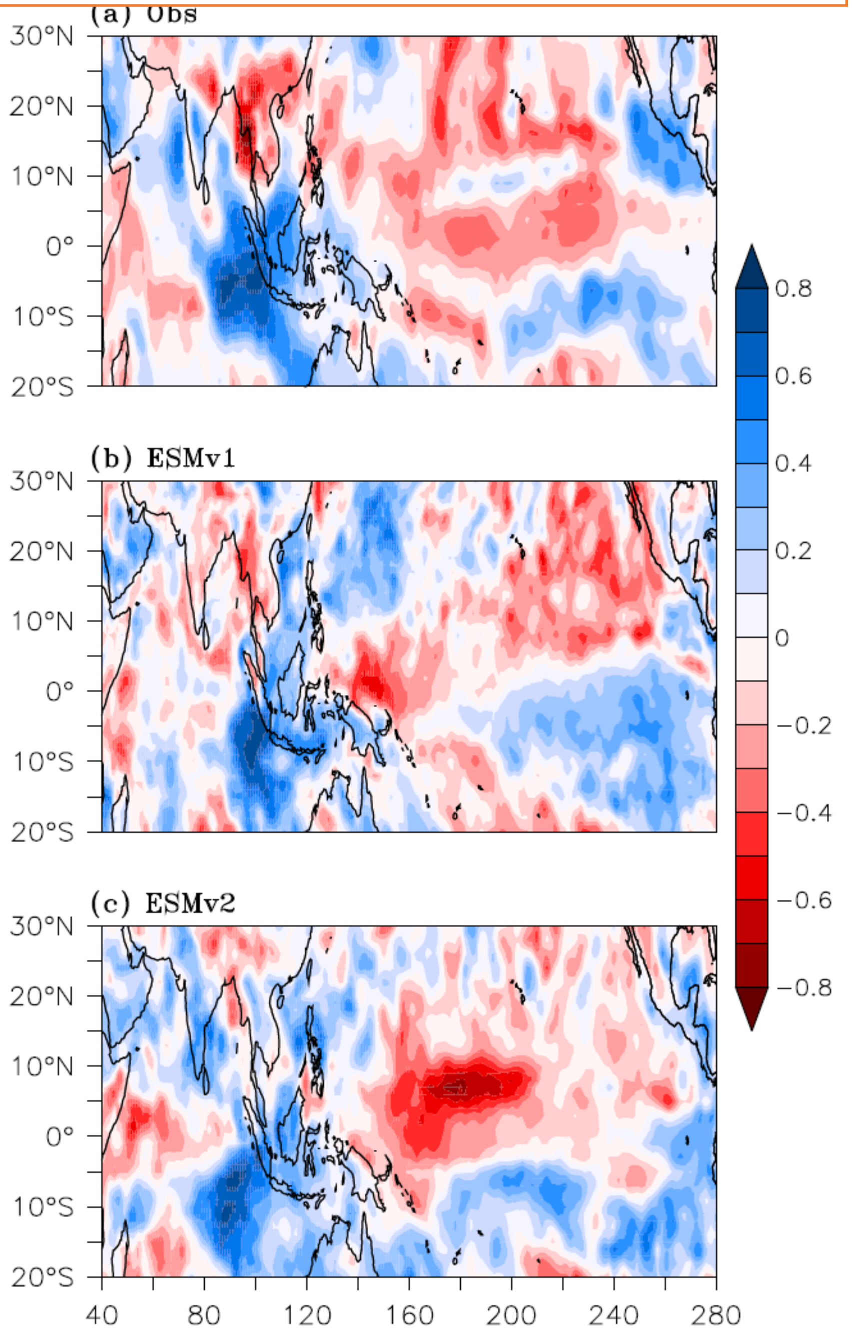
Seasonal variability of NINO3.4



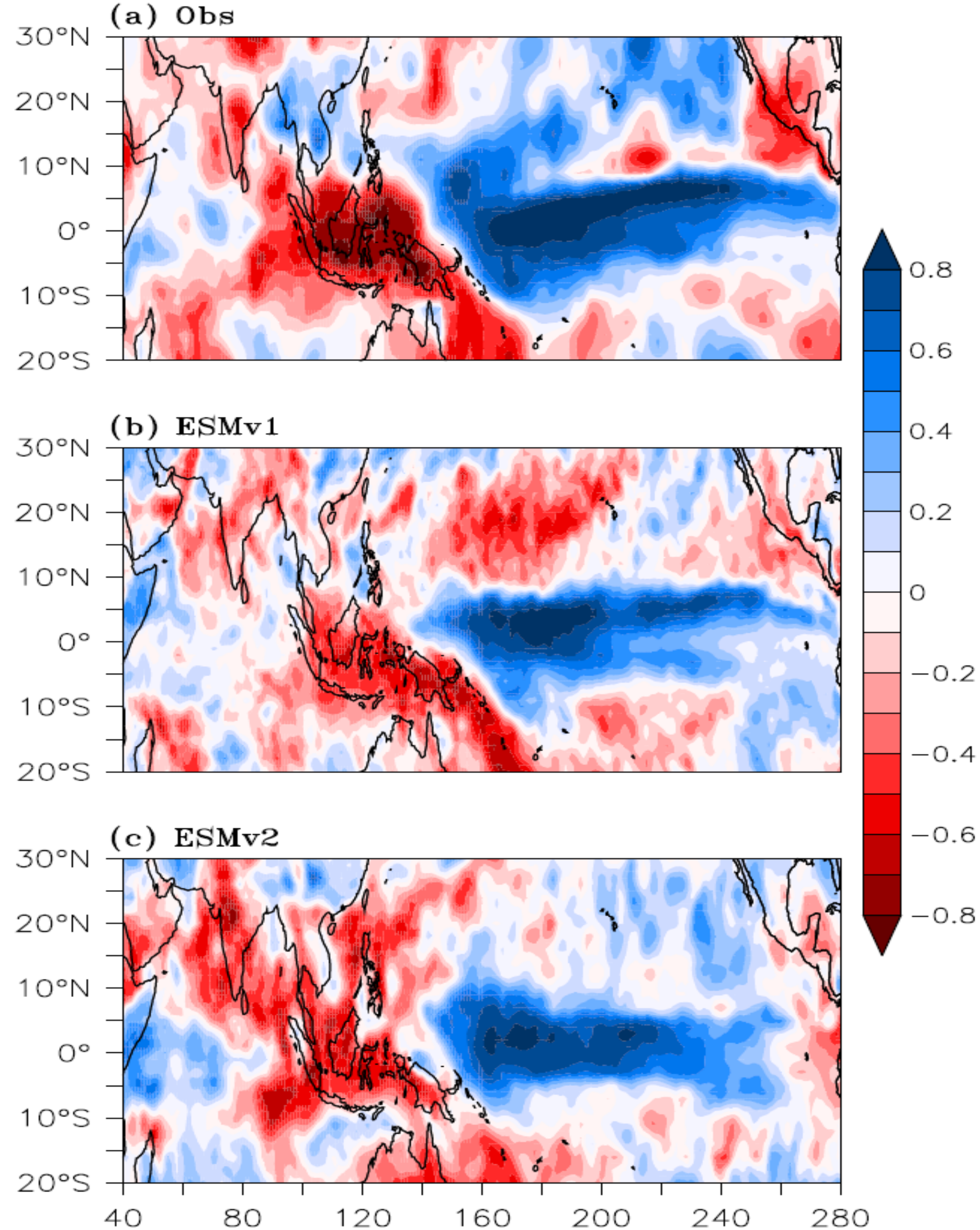
ENSO-Monsoon teleconnection



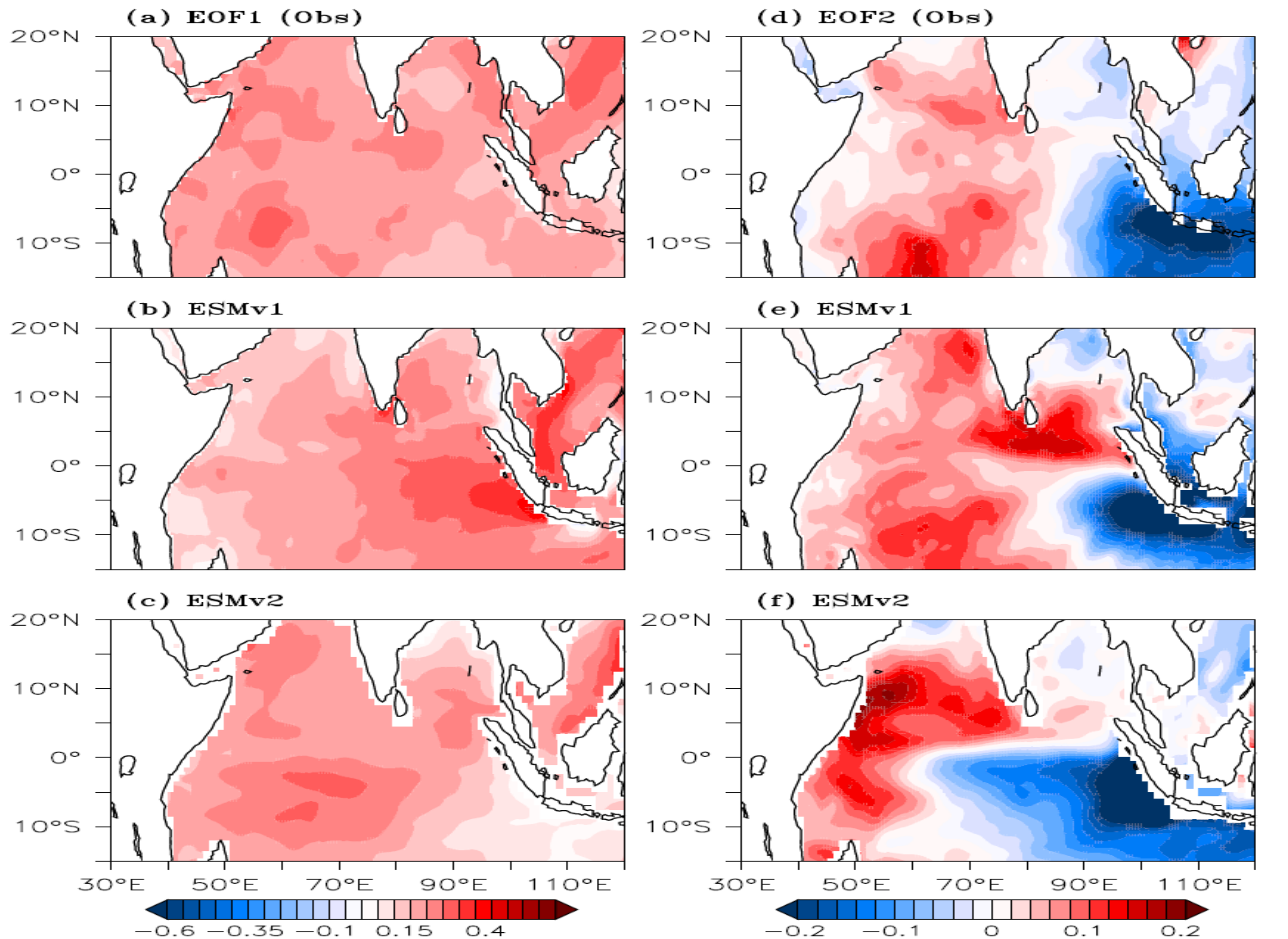
nsoon teleconnection (SST EIO vs JJAS pr



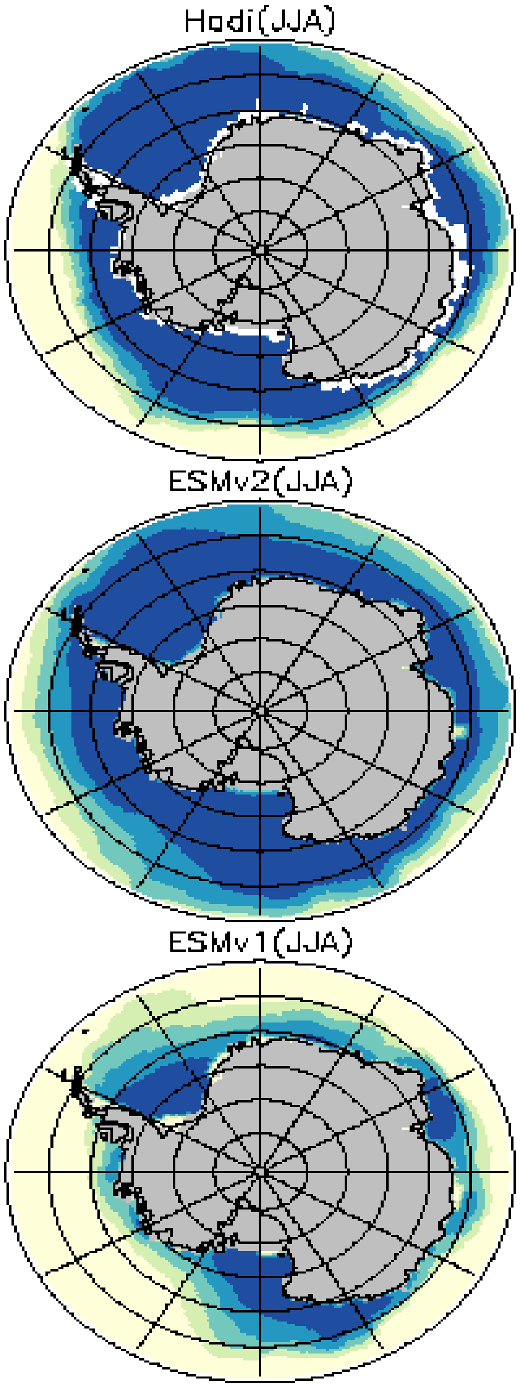
ENSO-Monsoon teleconnection (NINO3.4 vs JJAS



Tropical Indian Ocean Variability (IOBM & IOD)



Sea-Ice concentration

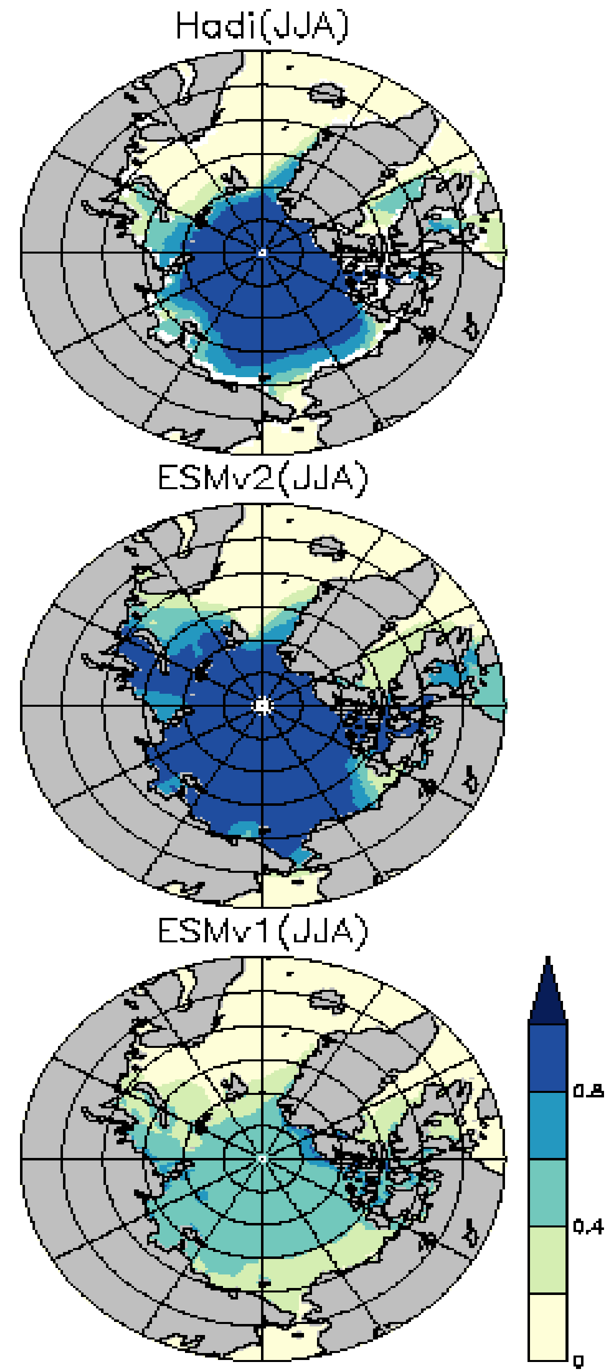


Obs

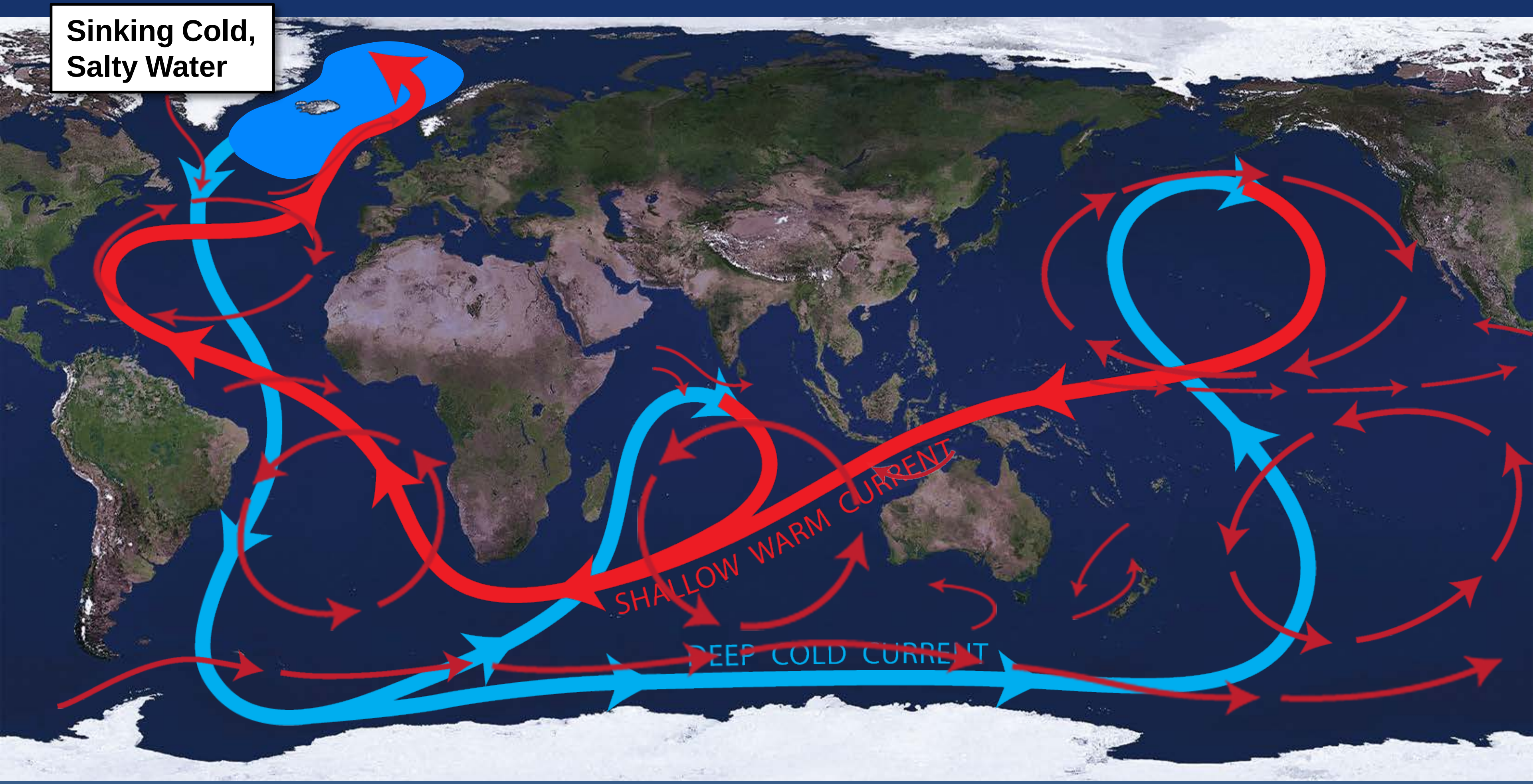
ESMv2

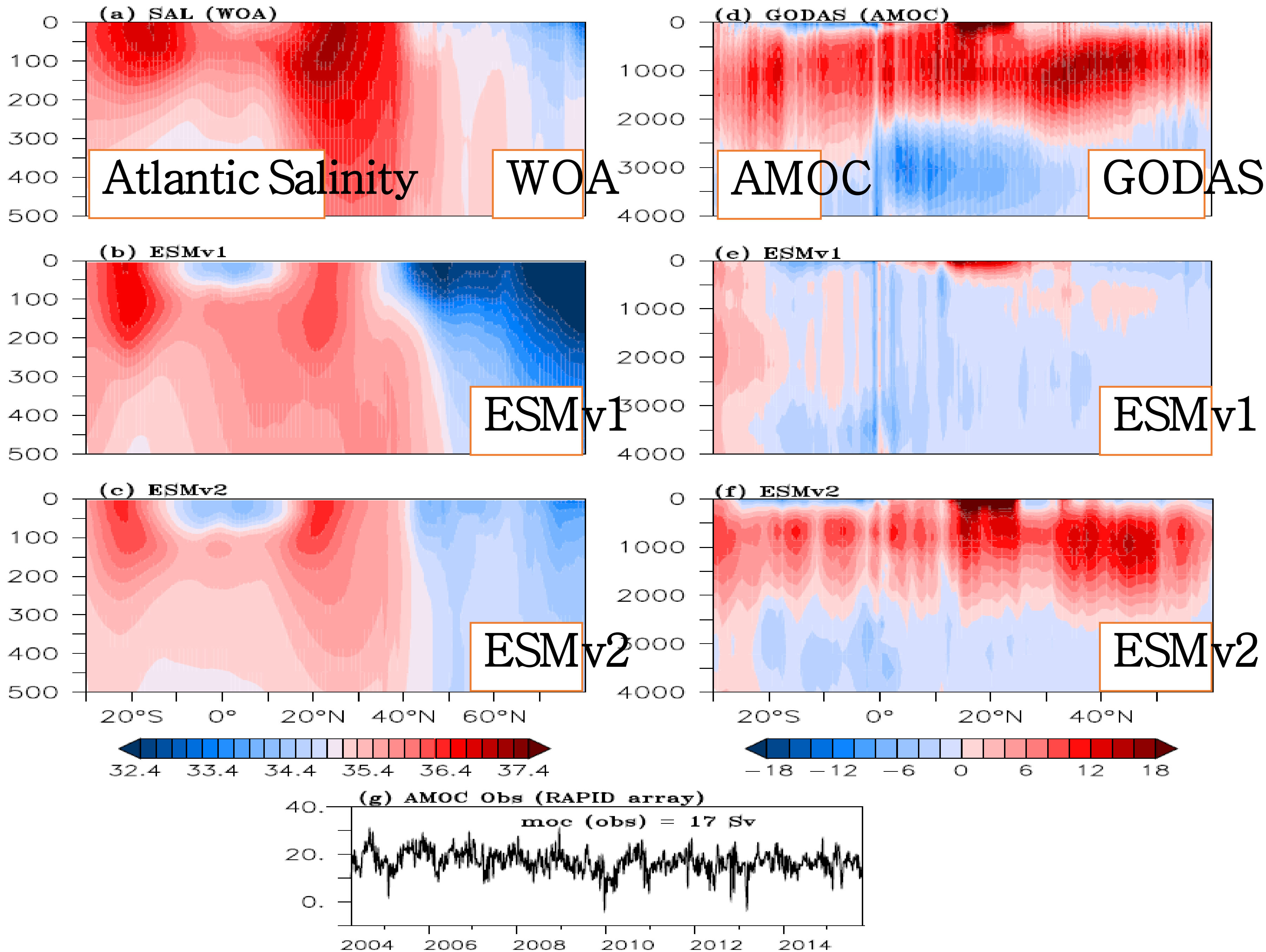
Improved simulation of NH sea-ice during JJA

ESMv1



Thermohaline Circulation (THC)
Global Conveyor Belt

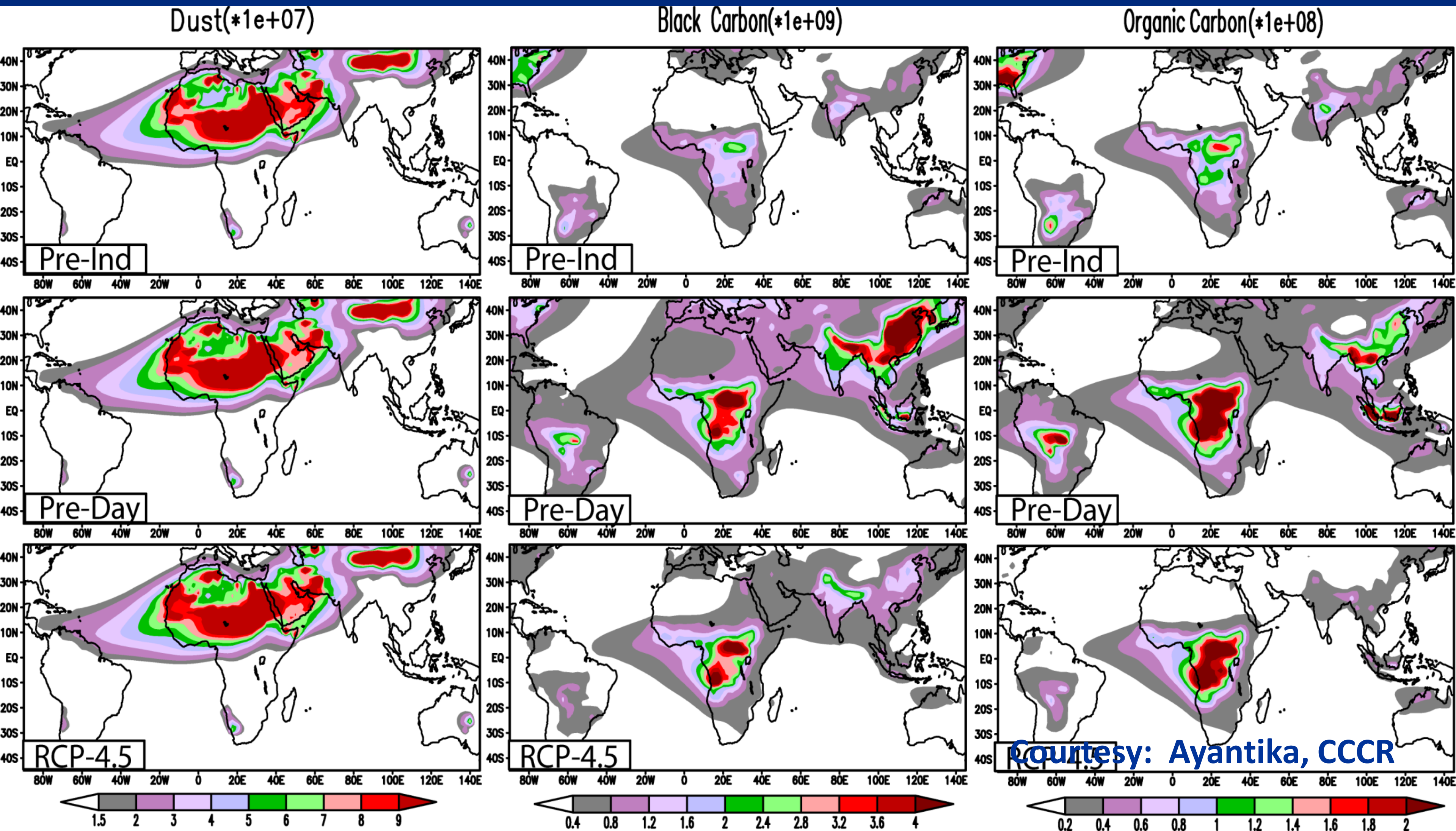




(a) SAL (WOA)
Atlantic Salinity
WOA
(b) ESMv1
ESMv1
(c) ESMv2
ESMv2
(d) GODAS (AMOC)
AMOC
GODAS
(e) ESMv1
ESMv1
(f) ESMv2
ESMv2
0 100 200 300 400 500
0 1000 2000 3000 4000
20°S 0° 20°N 40°N 60°N
20°S 0° 20°N 40°N
32.4 33.4 34.4 35.4 36.4 37.4
−18 −12 −6 0 6 12 18
(g) AMOC Obs (RAPID array)
moc (obs)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

Prescribed time-varying aerosol distributions in IITM-ESM from CMIP

Total column aerosol content provided by CMIP5 for Pre-industrial period (1850 -1879), Present day (1980 – 2009) and RCP4.5 (2089 – 2109). The units of the aerosol fields (Dust, BC and OC) are kg/kg. Information about other aerosol fields (eg. Sulphate, Sea Salt and Secondary Organic Carbon is also available from CMIP)



Courtesy: Ayantika, CCCR

CMIP Aerosols

•Aerosol concentration for the following species: SO4, black carbon, organic carbon, secondary organic aerosols, dust and sea-salt

•Wavelength resolved complex refractive indices and estimates of the aerosol size distributions (geometric mean, geometric std.dev) for different relative humidity are supplied to a Mie code [Mischenko et al., 1999, 2002] for optical property calculations

•Mie parameters averaged over size distributions are pre-tabulated as a function of RH, and then used to calculate aerosol optical properties e.g. AOD for a given time and grid cell

$$AOD = \sum_{i=1}^{N} \frac{3}{4} \frac{\overline{Q}_{ext,i}(RH)}{\rho_i \, r_{eff,i}(RH)} M_i$$

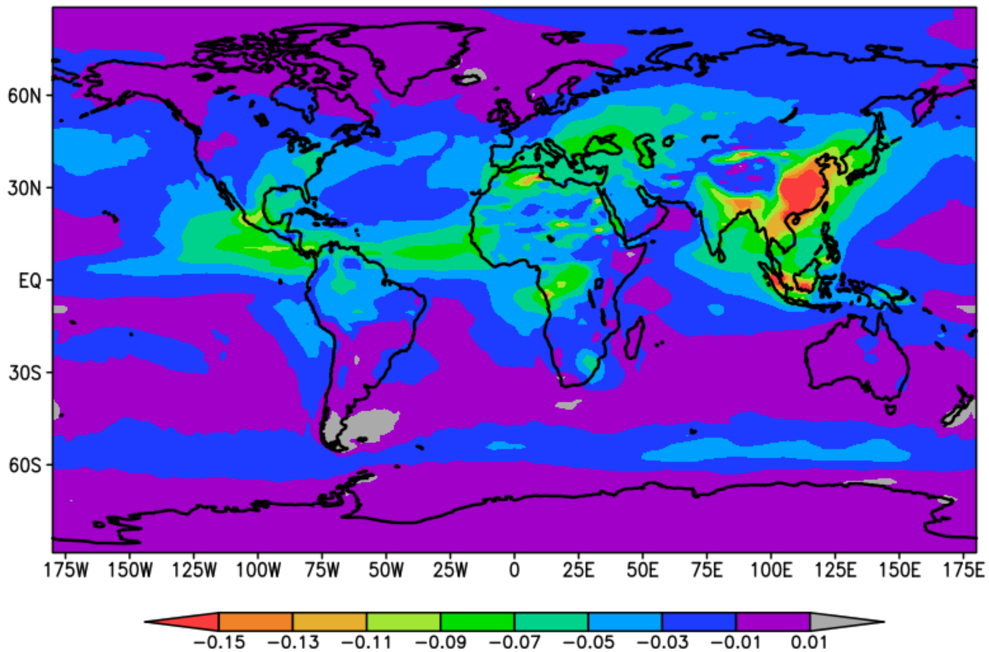
(Curci et al 2012)

•Aerosol Optical Depth, Single Scattering Albedo, Asymmetry Parameter calculated for ESM SW and LW bands

•The aerosol optical properties are used as input in ESM RRT radiation calculation

Courtesy: Ayantika, CCCR

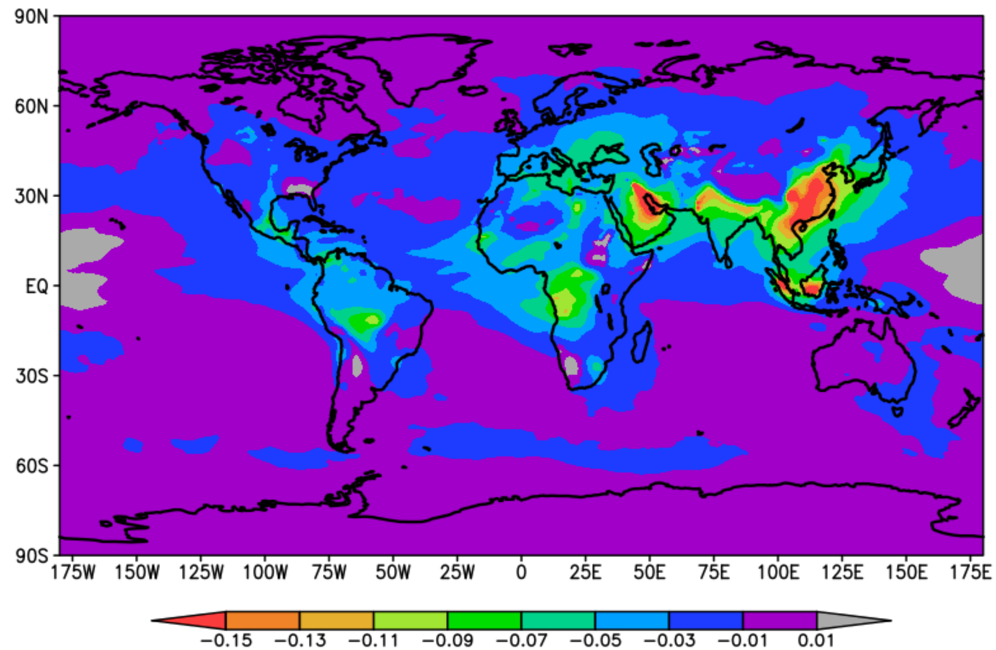
Calculated for IITM ESM



AOD difference map

Preindustrial (1870)- Present (2005)

CESM (CAM5)



Courtesy: Ayantika, CCCR

Time-varying aerosol distributions in IITM ESM from CMIP

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

To understand the impact of natural tropospheric aerosols on climate: as observed in IITM-ESM

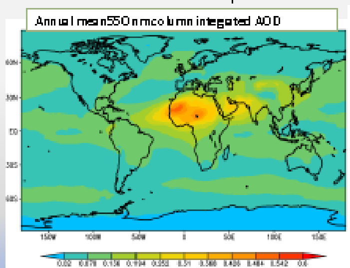
Sensitivity experiments : 50yrs model integration

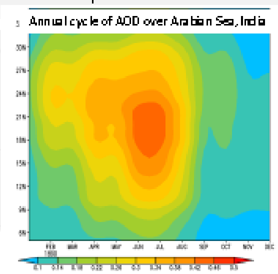
1) Pre-Industrial aerosols 2) No aerrosols (Clean Environment)

Pre-Industrial model setup

•PI Aerosols

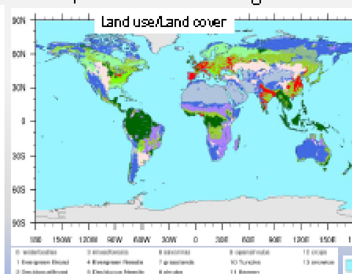
- MAC-V2 aerosol data (1°x1° AOD, SSA,ASY and 20layer EXT) (Max Planck Institute Aerosol Climatology V2, update of MAC-v1, Kinne et al 2013)
- The 3D (T62L64) AOD, SSA, ASY for IITM ESM-V2 is constructed by weighting the aerosol properties with the vertical profile of aerosol extiction data.
- Natural aerosols for 1850 are representative of Pre-Industrial era and implemented on monthly timescales

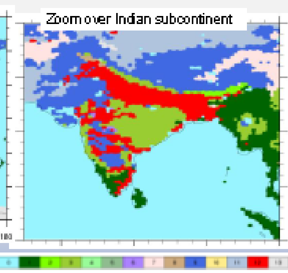




•PI Land use/ Land cover

- UNH transient historical crop and pasture dataset (.25 x .25)(Hurtt et al. (2015) for the period1870-2015)
- Crop area in IITMESM-v2 set to UNH data. Reduction of anthropogenic area implies proportional increase in all natural vegetation types for the cell. The most abundant vegetation type is set as dominant for that cell
- This method is used to derive the Pre-Industrial land use/land cover at T62 grid





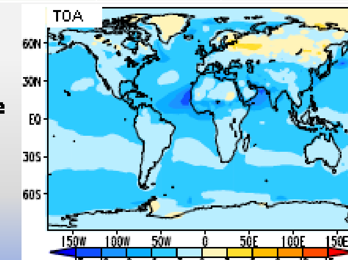
Aerosol Direct Radiative Forcing

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)

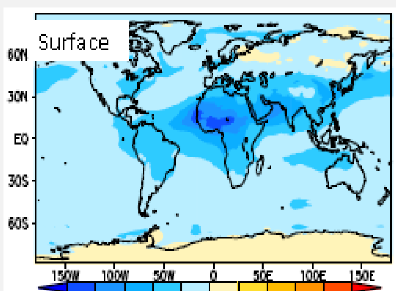
ARF		Clear Sky (W/m²)	Total Sky (W/m²)
TOA	Net Total Radiation (SW+LW)	-2.63	-0.45
	Net Solar Radiation (SW)	-3.49	-0.89
ATM	Net Total Radiation (SW+LW)	2.47	2.39
	Net Solar Radiation(SW)	1.65	1.52
SFC	Net Total Radiation (SW+LW)	-5.11	-2.84
	Net Solar Radiation (SW)	-5.15	-2.39

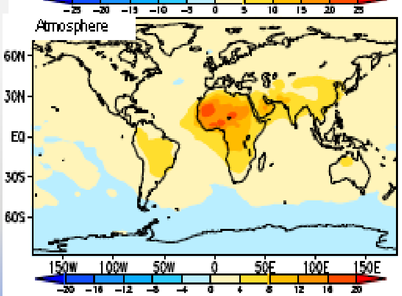
Solar Radiative forcing for clear sky



Aerosol Direct Radiative Forcing

Solar Radiative forcing for clear sky





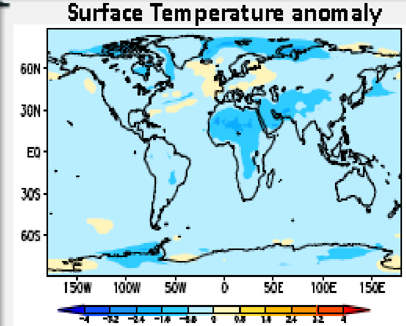
✓TOA direct solar radiative flux for clear sky conditions indicate negative forcing over tropics

✓The Surface radiative forcing show considerable decrease over regions with high natural aerosol loading

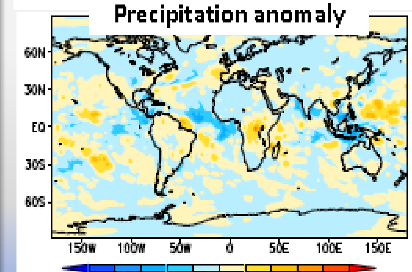
✓The atmospheric radiative forcing show an increase in absorption of solar energy over high aerosol regions

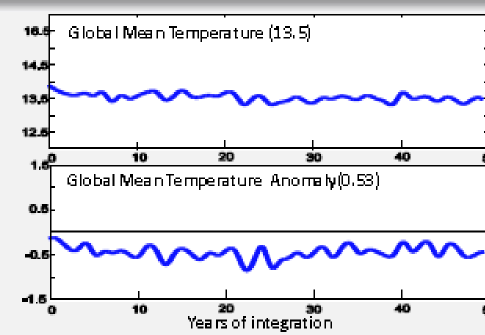
Surface Temperature & Precipitation Change

Surface Temperature anomaly



Precipitation anomaly

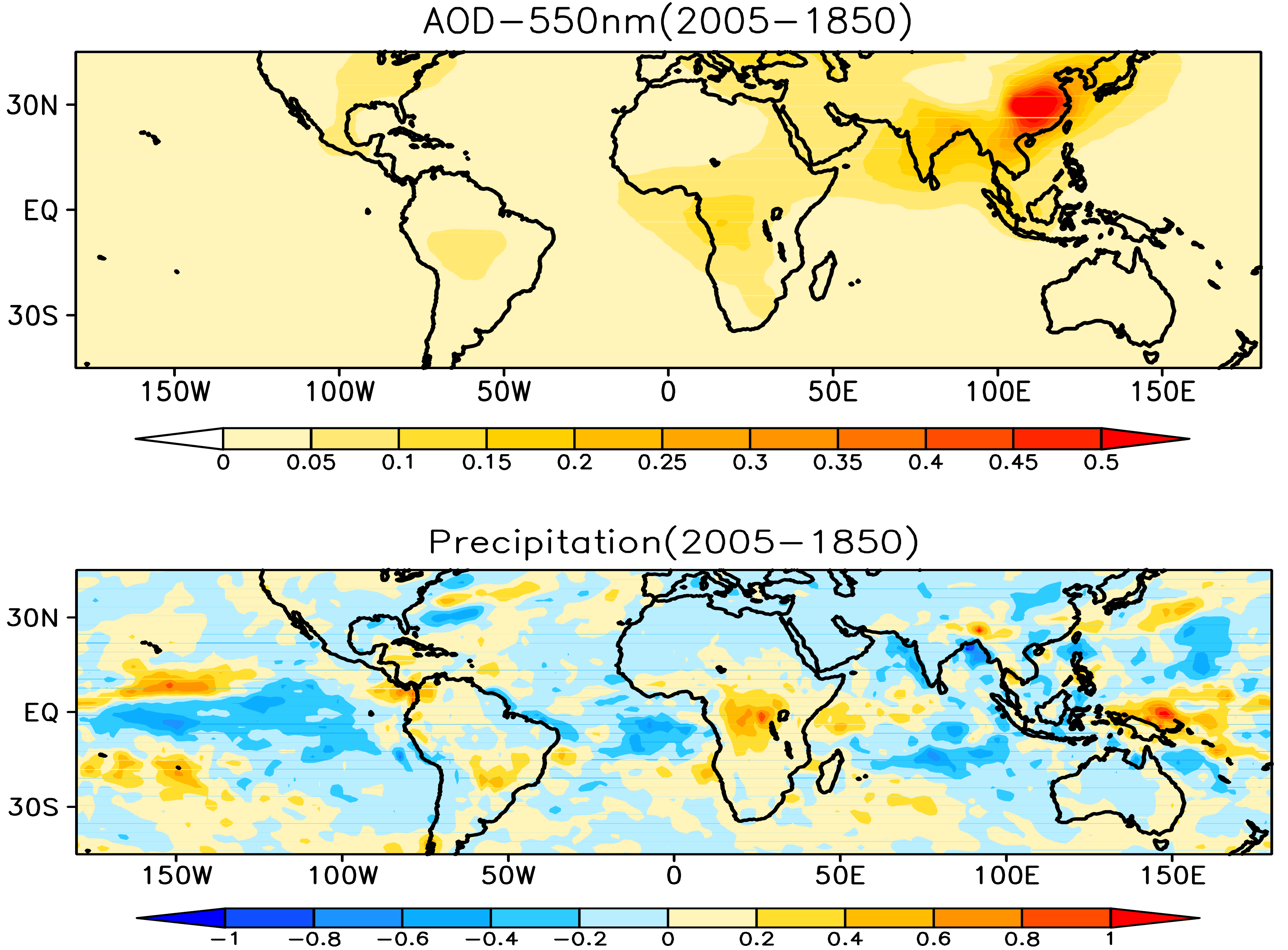




Global Tropics	
Temperature Change ~-0.48° C	Precipitation Change 0.06 mm/day

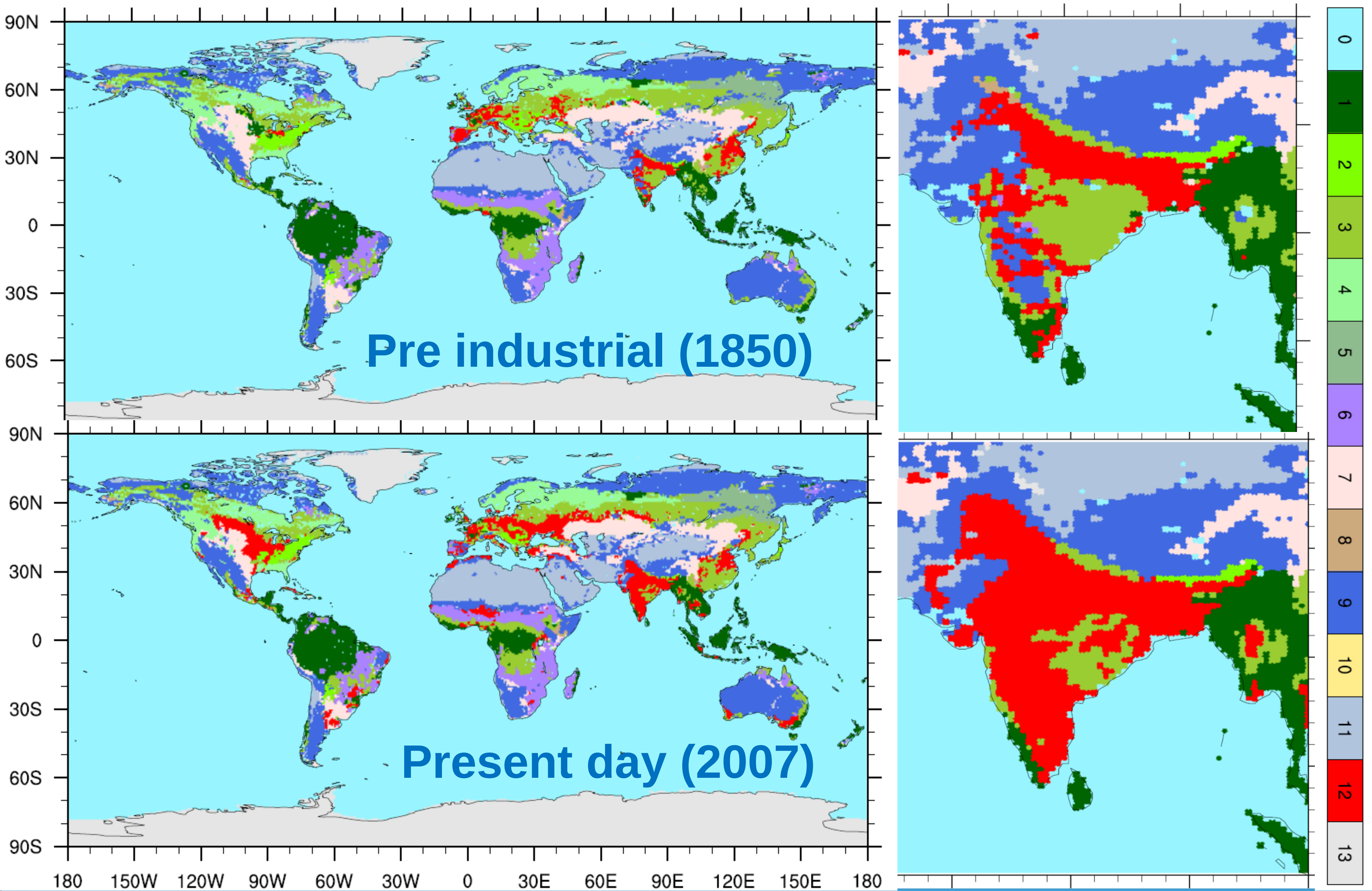
✓Surface temperature response indicates cooling over almost entire globe , specially over northern hemispheric continents

✓Precipitation anomaly shows a reduction over various tropical region s like South Asia and equatorial Atlantic



AOD−550nm(2005−1850)
30N
EQ
30S
150W
100W
50W
0
50E
100E
150E
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Precipitation(2005−1850)
30N
EQ
30S
150W
100W
50W
0
50E
100E
150E
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1

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 Barren	

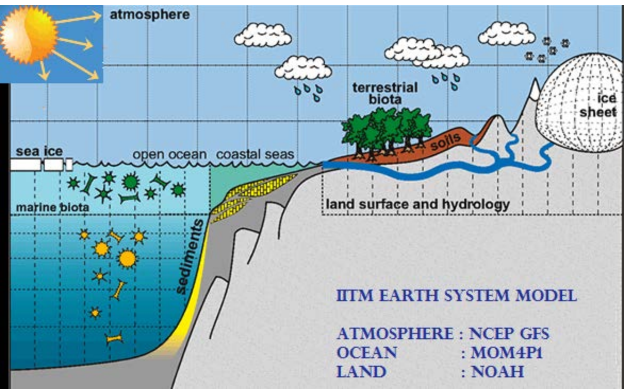
THE IITM EARTH SYSTEM MODEL

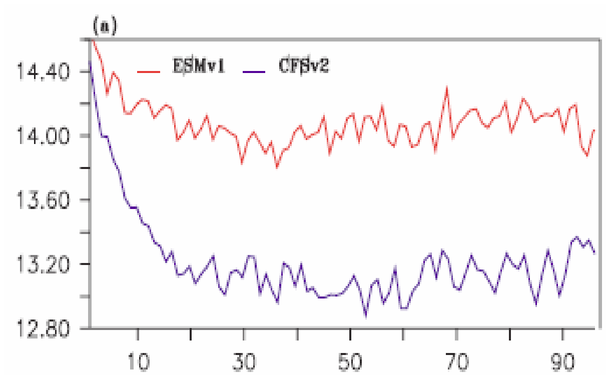
Transformation of a Seasonal Prediction Model to a Long-Term Climate Model

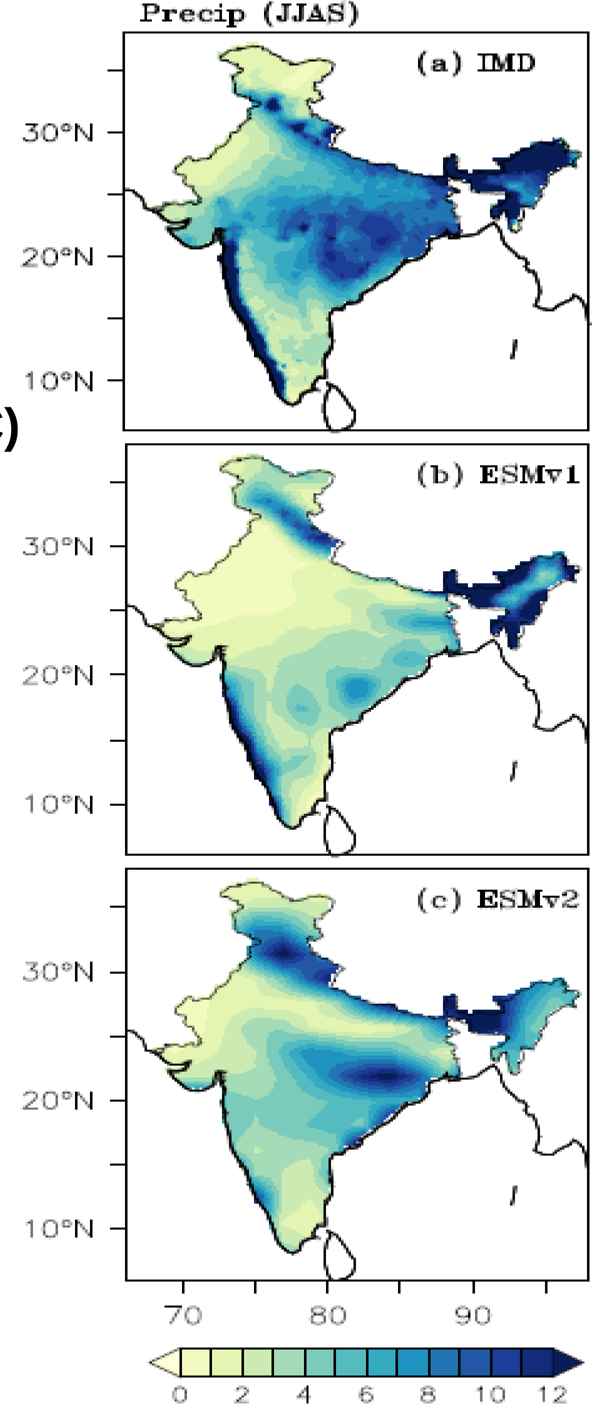
BY P. SWAPNA, M. K. ROXY, K. APARNA, K. KULKARNI, A. G. PRAJEESH, K. ASHOK, R. KRISHNAN, S. MOORTHI, A. KUMAR, AND B. N. GOSWAMI

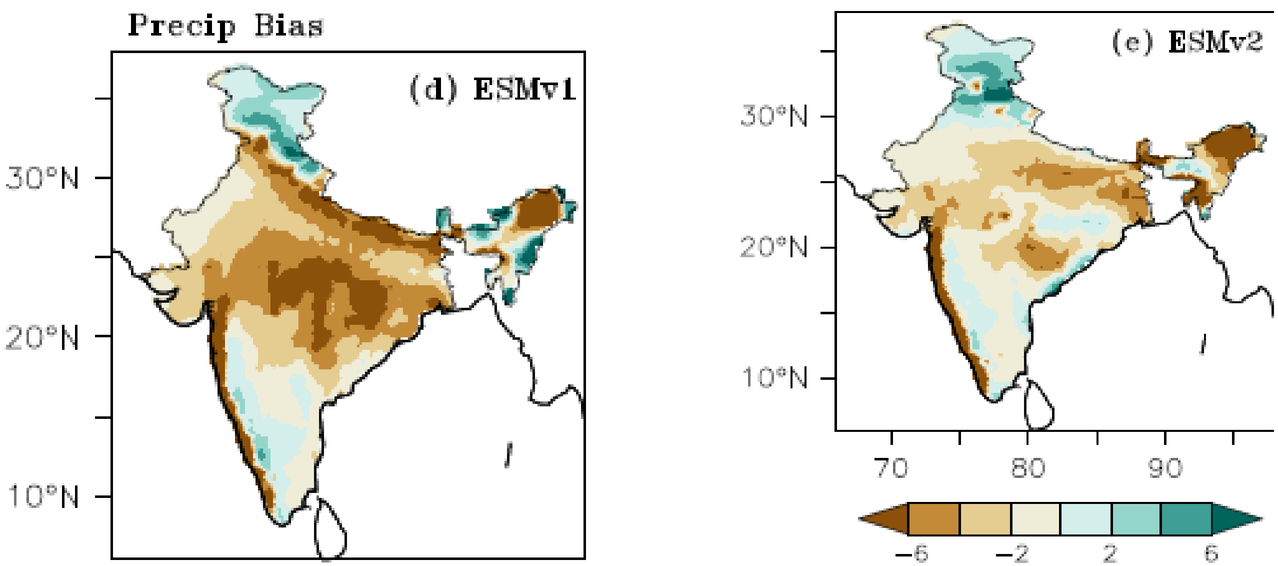
Centre for Climate Change Research, IITM, Pune

The first climate model from India to contribute to the next Intergovernmental Panel on Climate Change (IPCC)



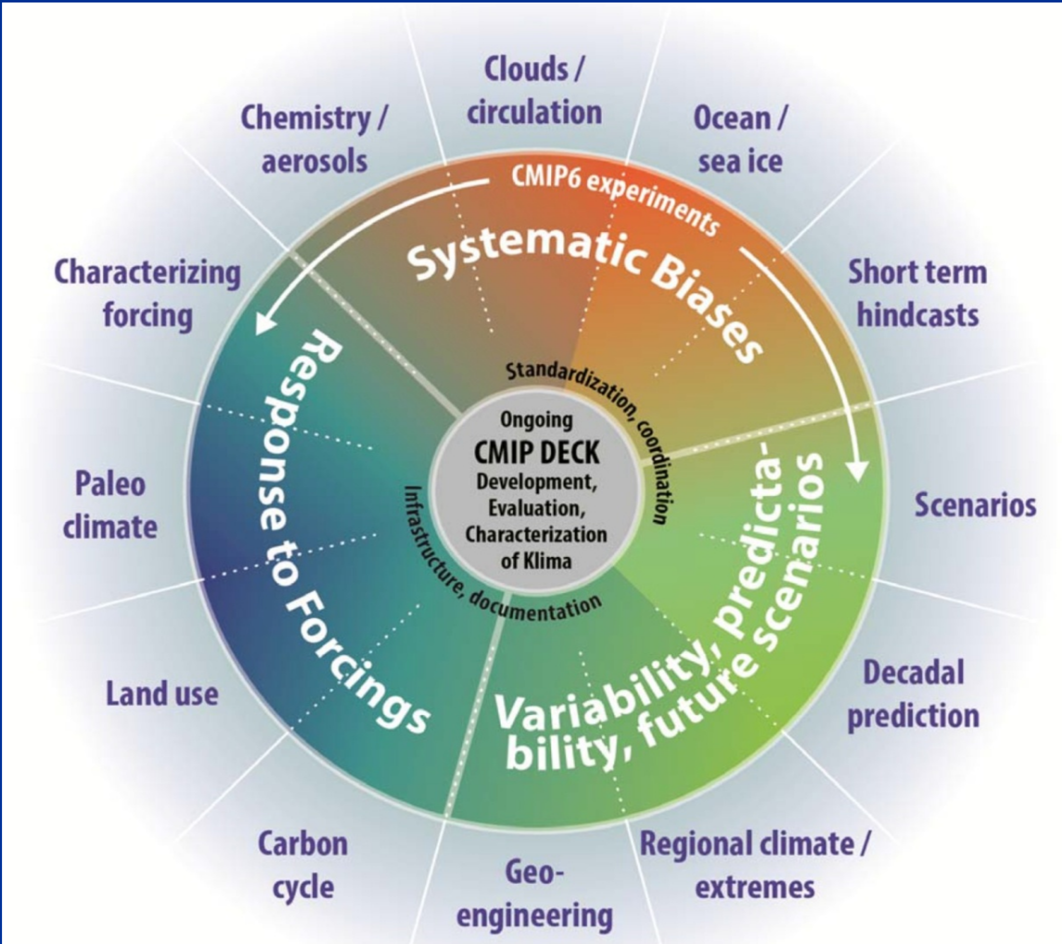






CMIP6 Schematic: Participation in the 6th Intergovernmental Panel for Climate Change (IPCC)

Initial proposal for the CMIP6 experimental design has been released



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

The DECK experiments

The DECK experiments:

- provide continuity across past and future phases of CMIP
- evolve only slowly with time
- are already common practice in many modelling centres
- are to be done by all participating coupled models

Specifically**:**

1. an AMIP simulation (~1979-2010);
2. a multi-hundred year pre-industrial control simulation;
3. a 1%/yr CO2 increase simulation to quadrupling to derive the transient climate response;
4. an instantaneous 4xCO2 run to derive the equilibrium climate sensitivity;
5. a simulation starting in the 19th century and running through the 21st century using an existing scenario (RCP8.5).

Summary

- **IIITM ESMv1:** 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°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)*
- **IITM ESMv2:** 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

Future Roadmap

•Basic research: Scientific questions on detection, attribution and future projections of global and regional climate change, including the South Asian monsoon, in addition to contribution to CMIP6 and IPCC AR6

•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. Timeline: 2018-2021

•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. Timeline: 2020-2025+

•Development of next-generation IITM-ESM coupled model, to include new components (eg., interactive aerosols, chemistry, carbon cycle). Timeline: 2020-2025+

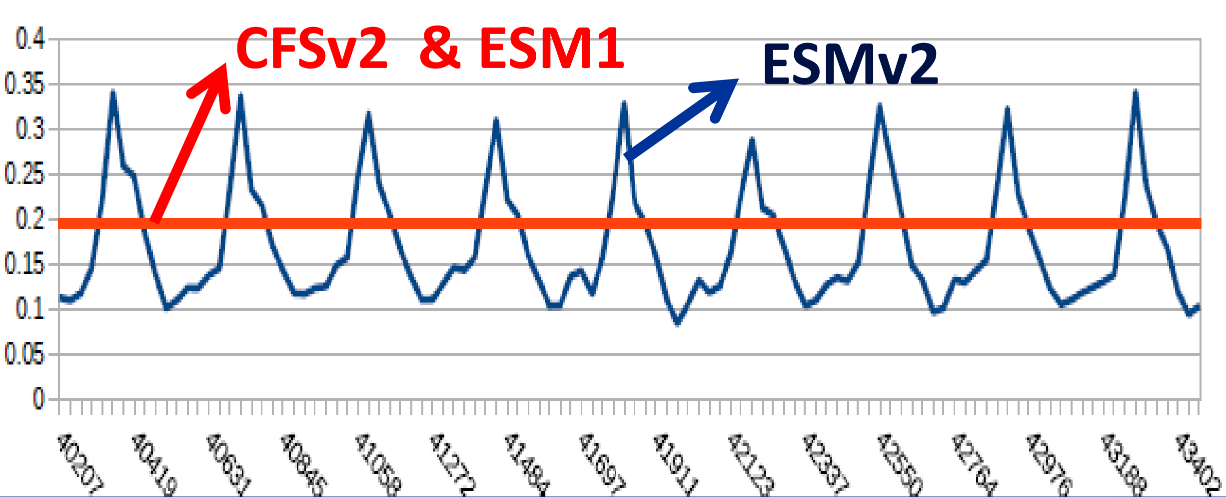
Thank you

Water balance in ESMv2

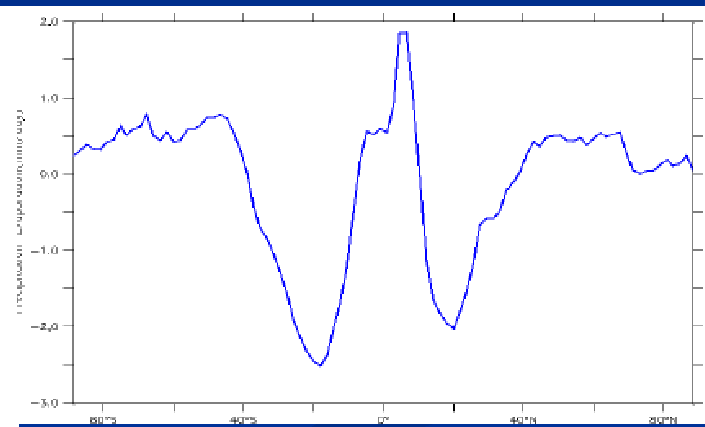
CFSv2 and ESMv1: Constant value of runoff was used in the Ice Model

ESMv2: Runoff calculated from Land Model & discharged into the nearest ocean point

Runoff (kg m^{-2} s^{-1})

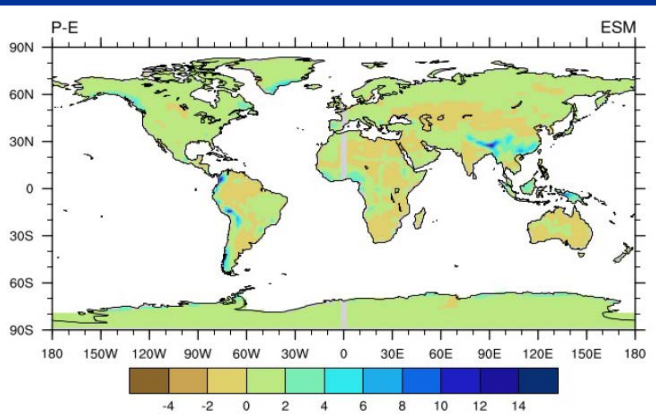


Zonal mean (P-E) in mm day^{-1}

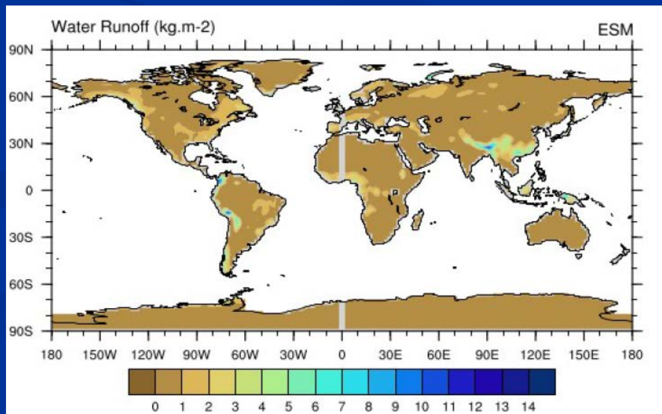


Latitude

Precipitation minus Evaporation



Runoff from Land Model



Hydrology statistics

Total Runoff from Land = 1.06×10^9 kg s^{-1}

Total Water Discharge into Ocean = 1.06×10^9 kg s^{-1}