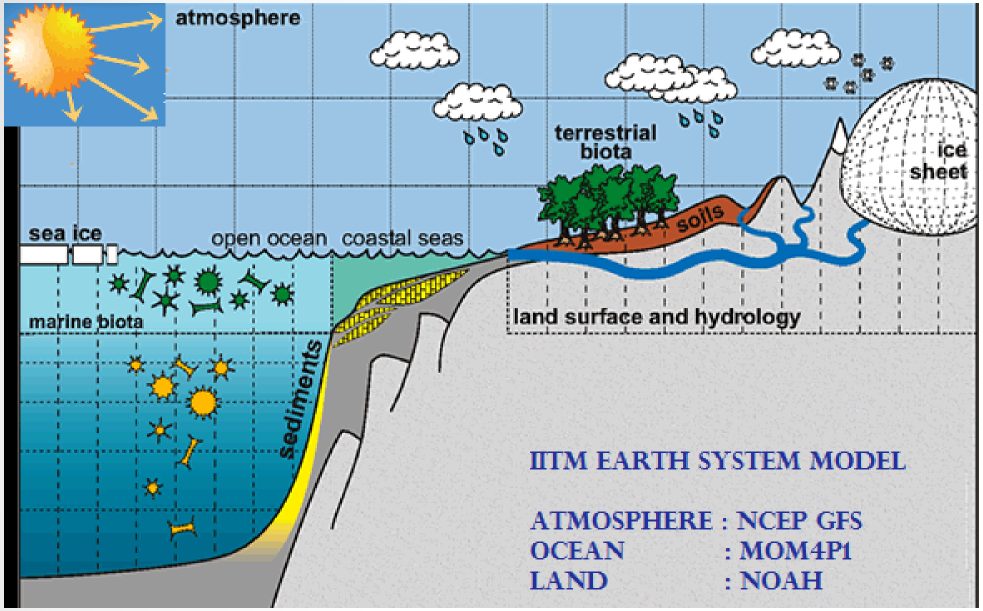
Earth System Model for Future Projections of Sea level



http://cccr.tropmet.res.in/home/esgf_node.jsp

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

Outline

- Overview of IITM-ESM development
- Future projections of sea level
- Roadmap towards next generation IITM-ESM

Phases of IITM-ESM Development and CMIP6 Simulations

ESMv1 : Incorporation of new ocean model with interactive ocean BGC (MOM4p1). 6 Wm^{-2} energy imbalance

ESMv2 : Radiatevely balanced framework with improved coupling between component models. Partial grid implementation and incorporation of sea ice model (SIS)

IITM-ESM CMIP6 : Long control runs to reach quasi-equilibrium. Incorporated 3-D varying aerosol conc., GHG, ozone, LULC changes

2018	2019	2020
Incorporated CMIP6 forcings	Completed DECK Simulations	Scenario runs, Publications & Data Publishing

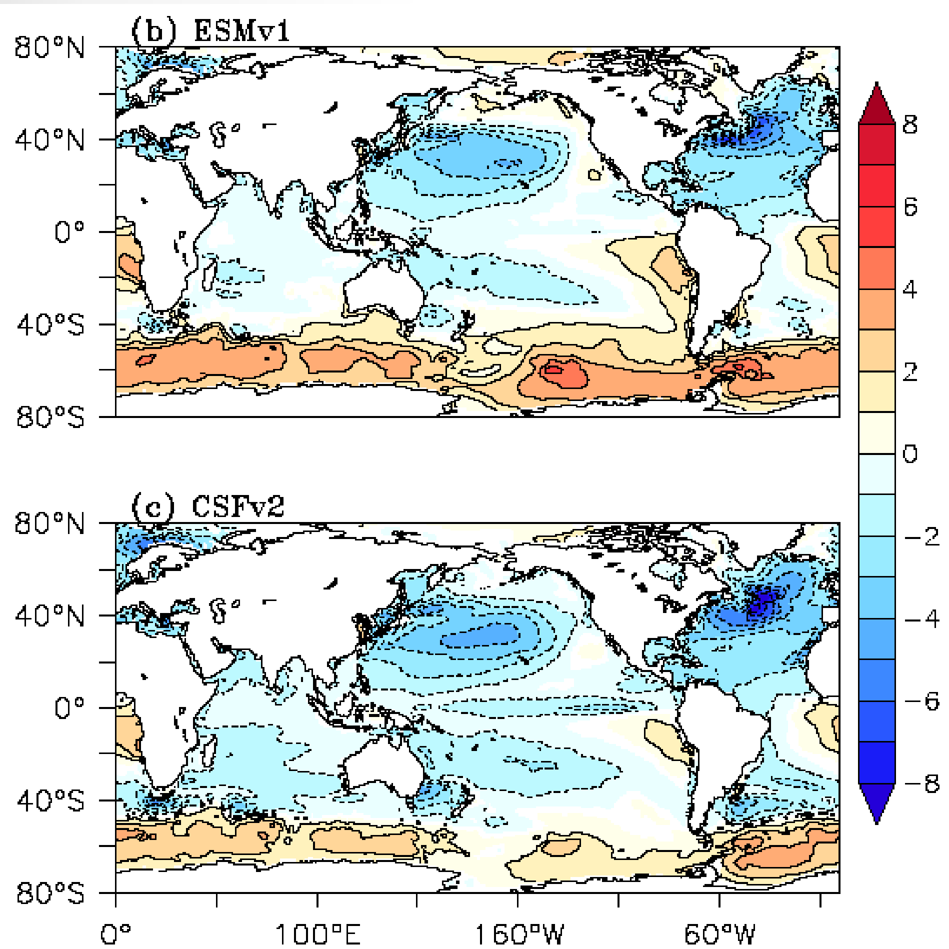
Bulletin of the American Meteorological Society

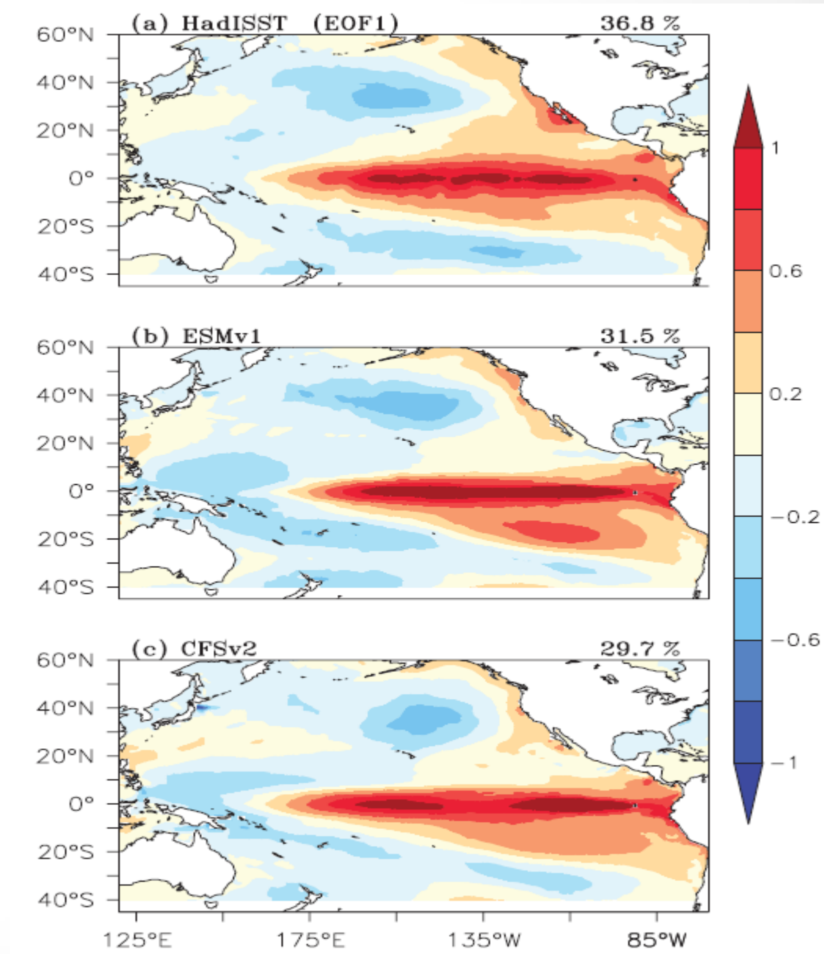
Volume 96: Issue 8

Editorial Type: Article

The IITM Earth System Model: Transformation of a Seasonal Prediction Model to a Long-Term Climate Model

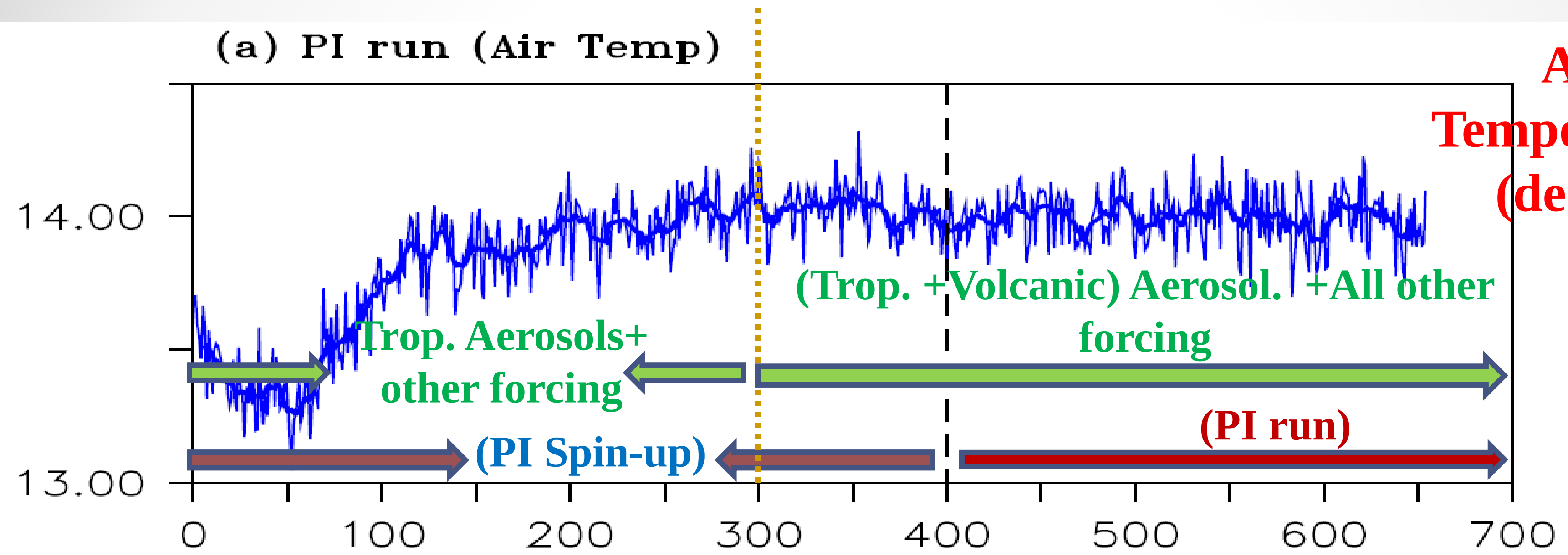
P. Swapna[1], M. K. Roxy[1], K. Aparna[1], K. Kulkarni[2], A. G. ... View More +



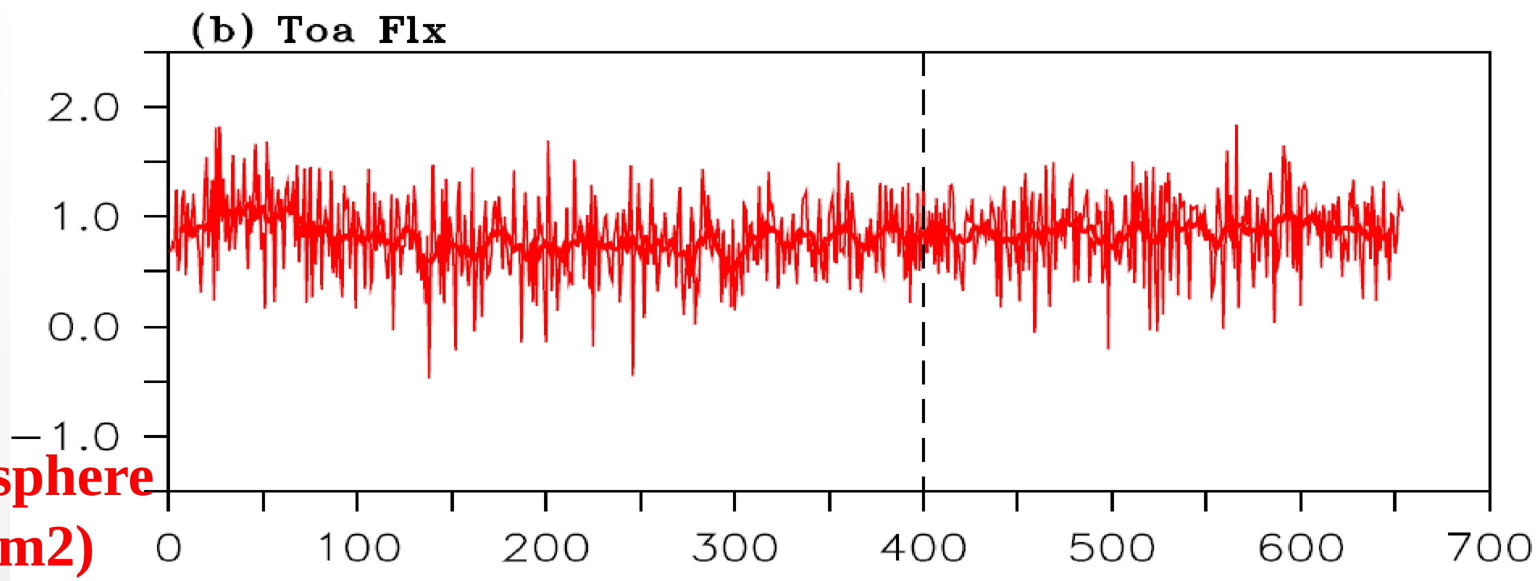


Swapna et al., 2015

Pre-industrial Control Simulation



Air Temperature (deg C)



Top-of-Atmosphere Fluxes (W/m2)

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Journal of Advances in Modeling Earth Systems

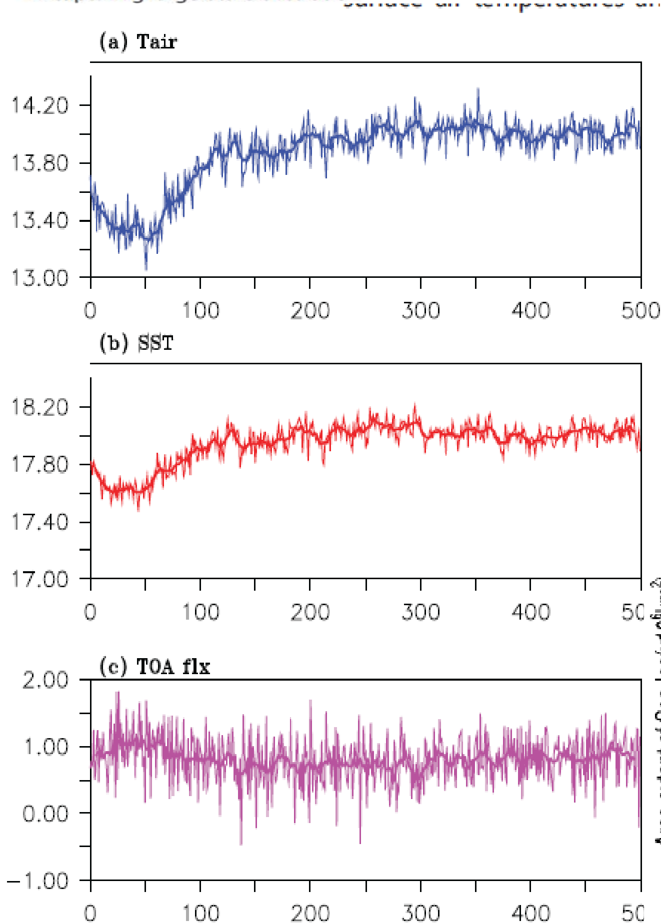
RESEARCH ARTICLE

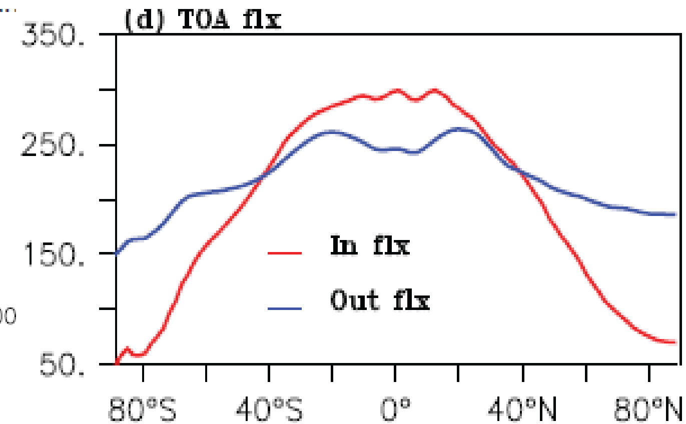
10.1029/2017MS001262

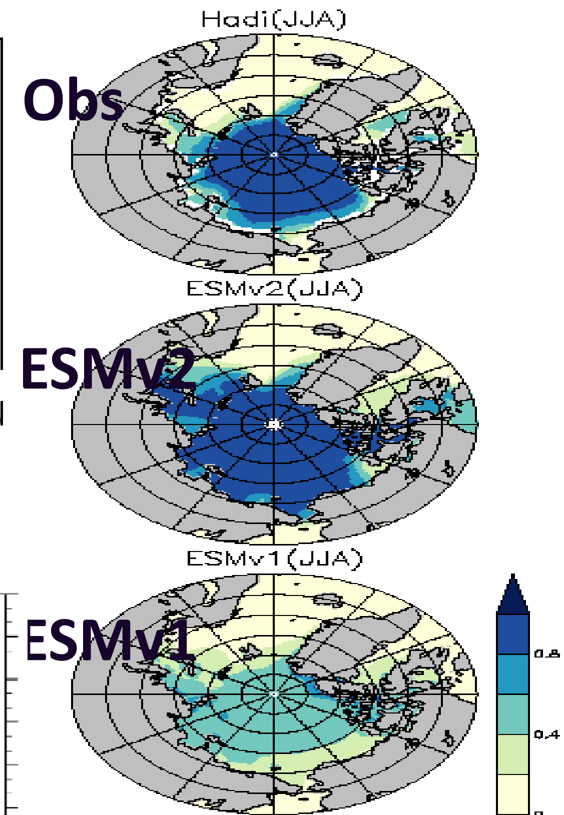
Long-Term Climate Simulations Using the IITM Earth System Model (IITM-ESMv2) with Focus on the South Asian Monsoon

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

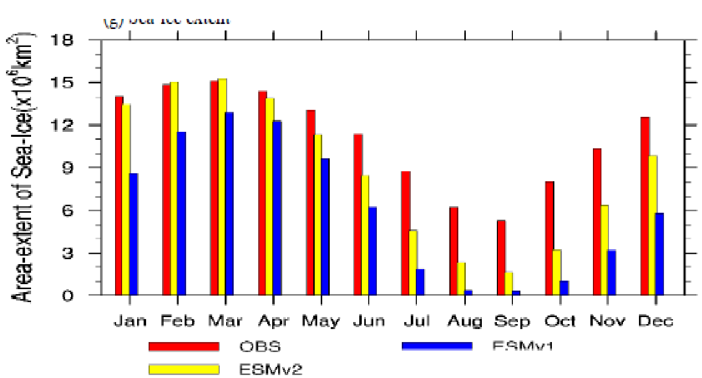
Key Points:
- IITM-ESMv2 simulations show fidelity in capturing large-scale circulation





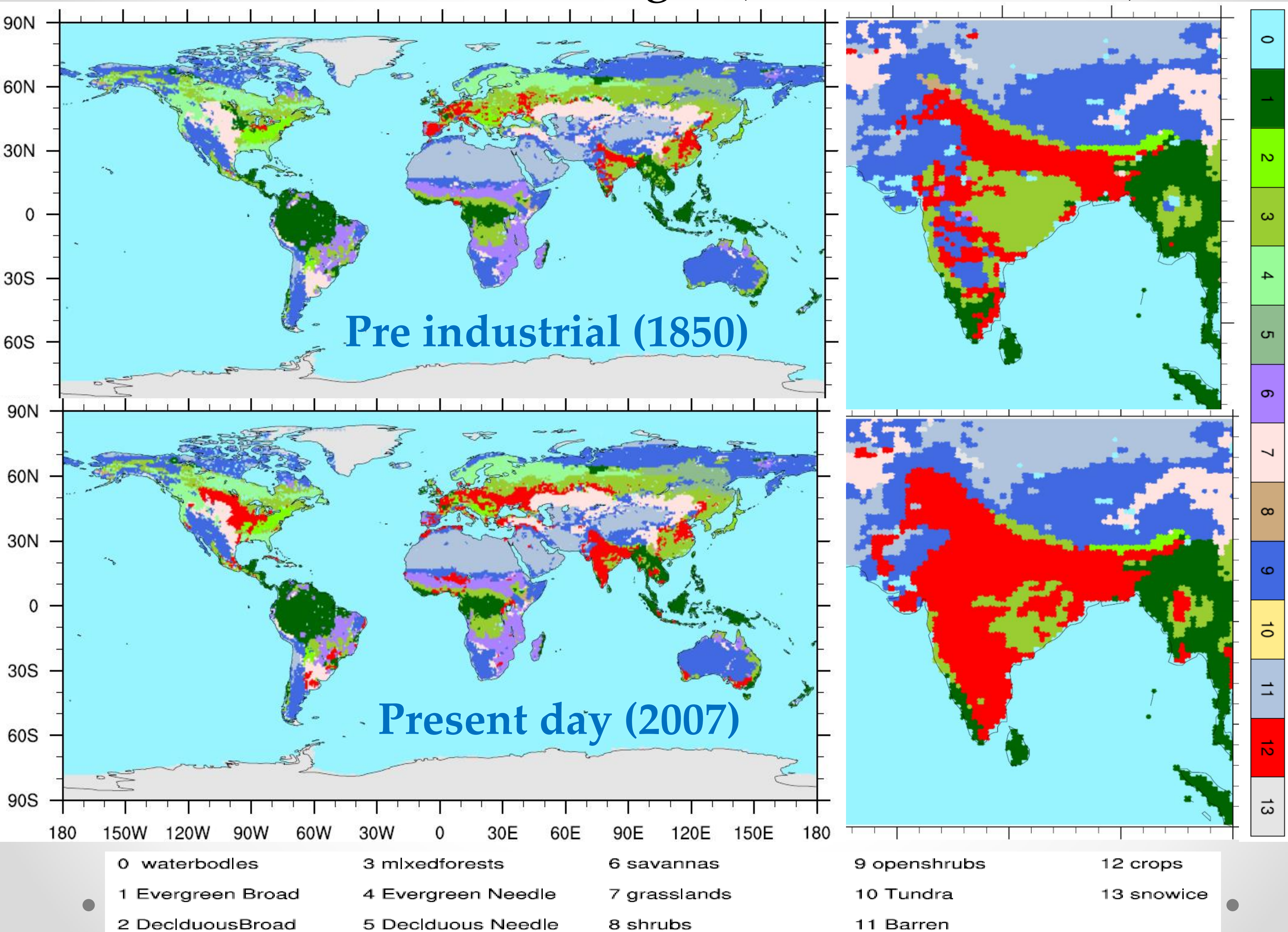


Improved simulation of NH sea-ice during JJA



Swapna et al., 2018

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



IITM-ESM CMIP6 Simulations

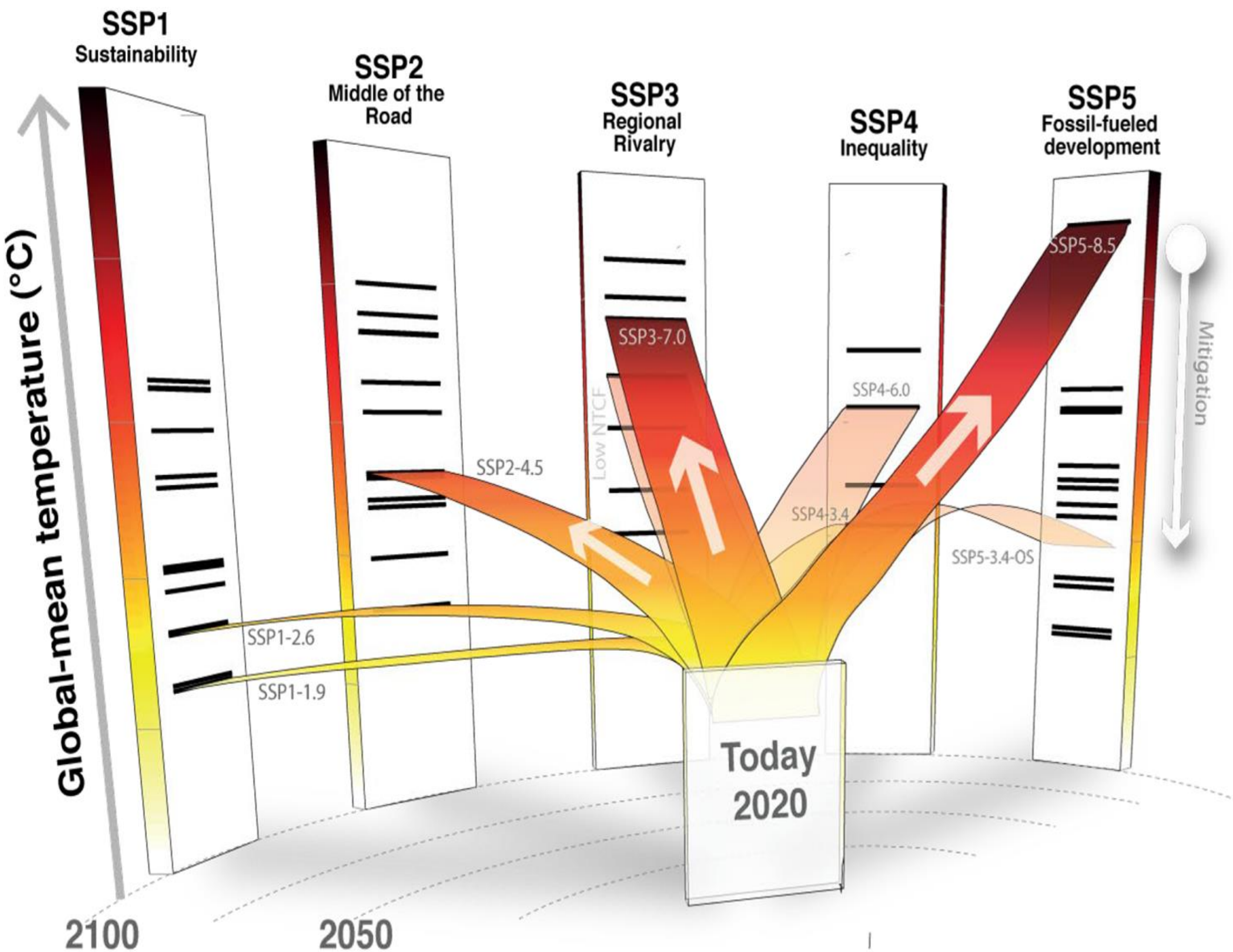
Experiments	Details of Simulation	No. of years of integration
PI-Control	Pre-industrial control simulation	**800 yrs**
Transient CO2 runs	1% /Yr increase in CO2 to quadrupling	**140 yrs**
	Abruptly Quadruple CO2 and fix	**140 yrs**
CMIP6	Historical	**165 yrs** Emission-or concentration-driven simulation of recent past
Global Monsoon MIP & AMIP Simulations	AMIP Simulation	` **~150 yrs**
Future Projections	Future projections based on scenarios	**400 yrs**

Scenarios

The philosophy Behind SSPs..

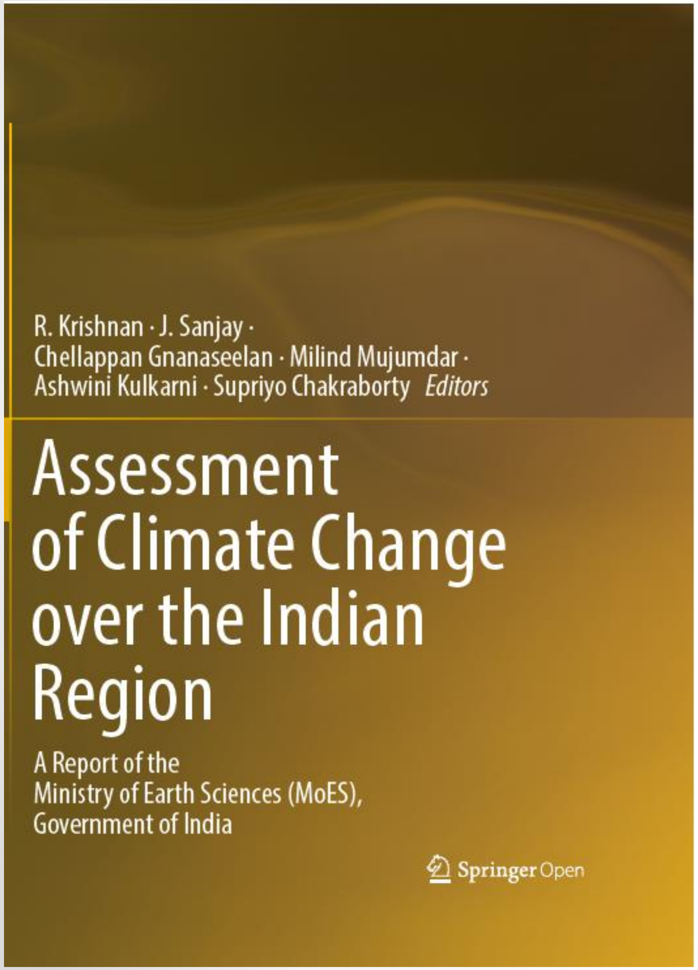
- AR5 used the RCPs
- AR6 has the SSF

*SSPs stands for two things: either just the socio-economic narrative, or a particular SSPX-Y scenarios, uch as SSP1-1.9.



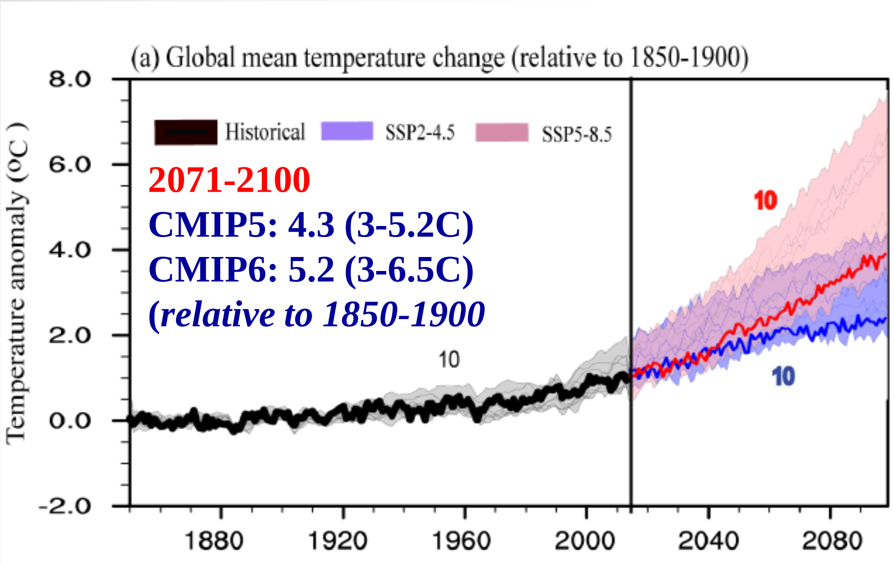
Assessment of Climate Change over the Indian Region

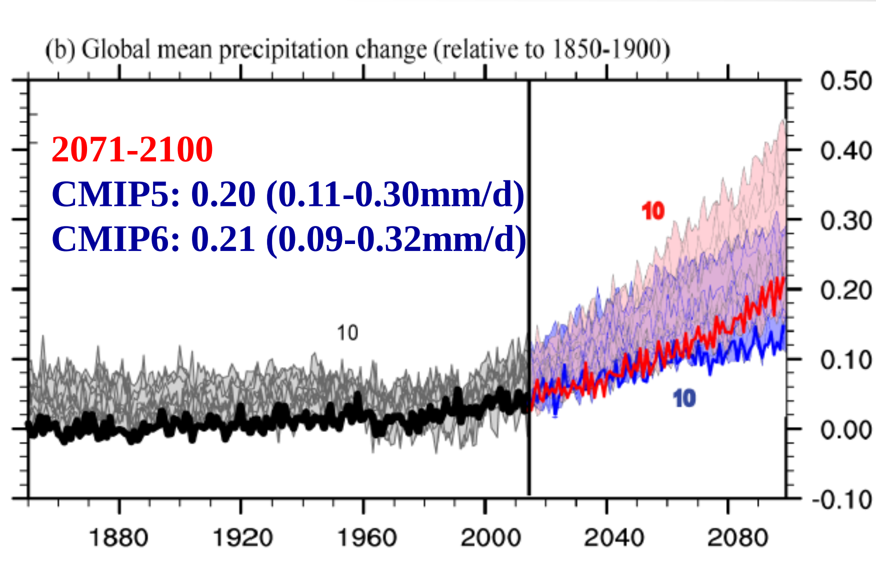
A Report of the Ministry of Earth Sciences (MoES)
Government of India



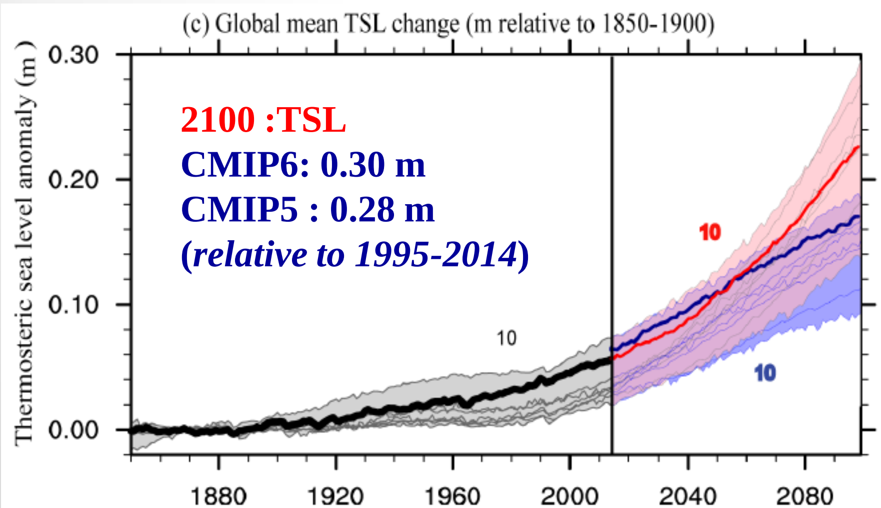
- Discusses the influence of human-induced global climate change over the Indian subcontinent
- Presents a synthesis of historical and future projected changes in the global and regional climate over the India subcontinent - based on scientific literature, observations, climate model projections and published IPCC reports
- Serves as a reference resource for researchers, practitioners in academia and industry, and policymakers

IITM-ESM CMIP6 projections of key climate variables

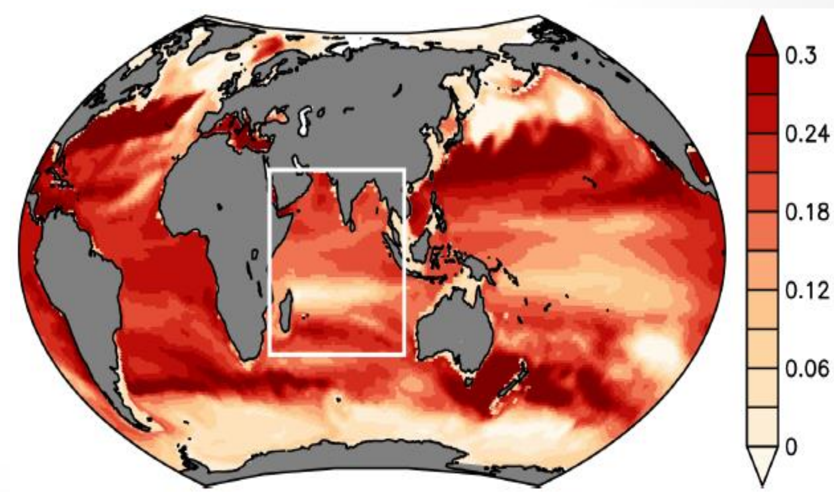




CMIP6 projected warming > CMIP5 more than 20%



TSL (IITM-ESM)

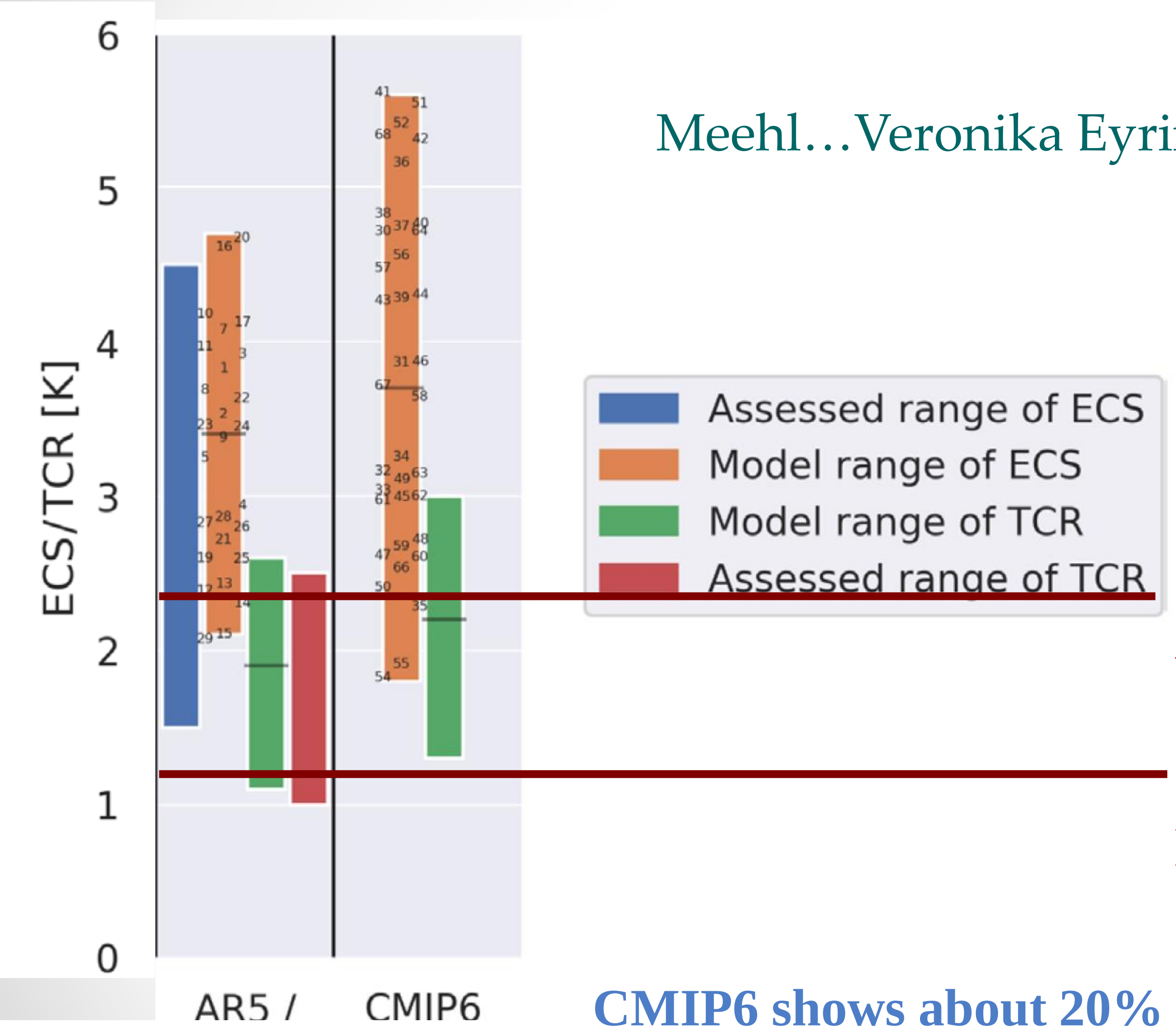


Krishnan et al. 2020

CMIP6 models,

sensitivity and transient climate response

Meehl…Veronika Eyring, et al., *Sci. Adv.* 2020



Ch07 IPCC TCR *very likely*, upper

Ch07 IPCC TCR *very likely*, lower

CMIP6 shows about 20% larger range of projected global surface warming by late 21st century than CMIP5

[redacted]

sensitivity and transient climate response

ECS and TCR from CMIP5 & CMIP6 models,

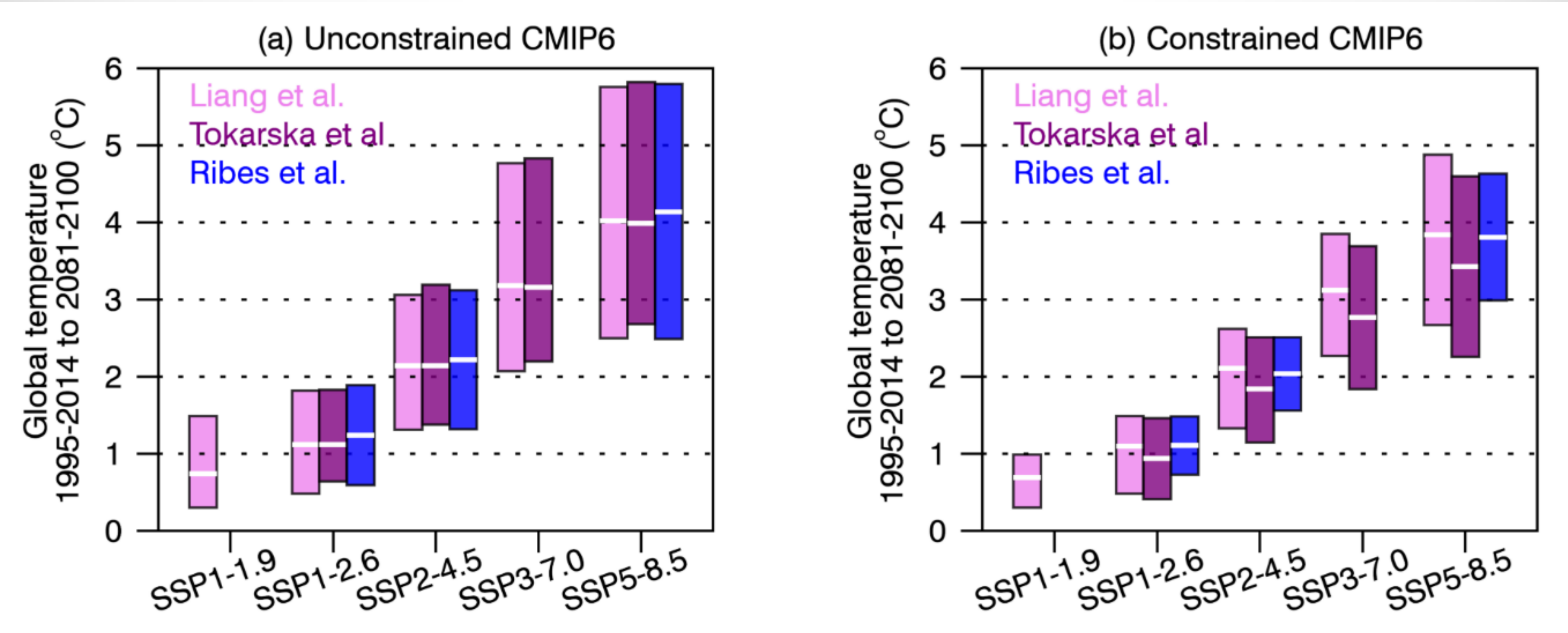
$$\mathbf{N = F + \lambda\Delta T}$$

where for the net top of atmosphere energy balance, *N*, and a given radiative forcing, *F*, there is a global surface temperature response, Δ*T*, multiplied by a feedback factor, λ.

The era of the IPCC assessments, starting in the 1990s, each assessment largely maintained the same assessed range for ECS (1.5° to 4.5°C),

[redacted]

limit, of GSAT change, 2081–2100 relative to 1995–2014



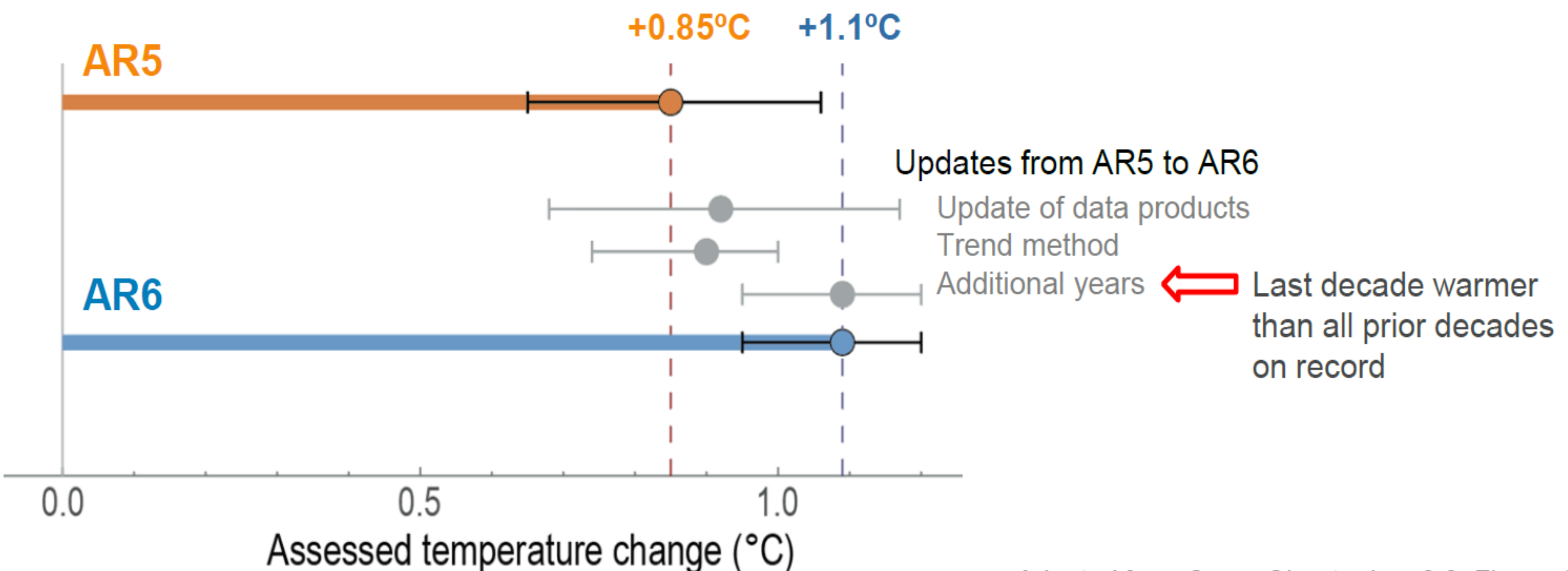
SOD

Climate feedback parameter α and ocean heat uptake coefficient $\kappa\varepsilon$, using the eqns. $\alpha = -\Delta F2 \cdot_{CO2} ECS^{-1}$ and $\kappa\varepsilon = \Delta F2 \cdot_{CO2} TCR^{-1} - \Delta F2 \cdot_{CO2} ECS^{-1}$ (e.g., Jiménez-de-la-49 Cuesta and Mauritsen, 2019);

[redacted]

Updated global temperature estimates since AR5

Change in assessed historical global surface temperature estimates since AR5



Adapted from Cross-Chapter box 2.3, Figure 1

Human activities affect all the major climate system components, with some responding over decades and others over centuries

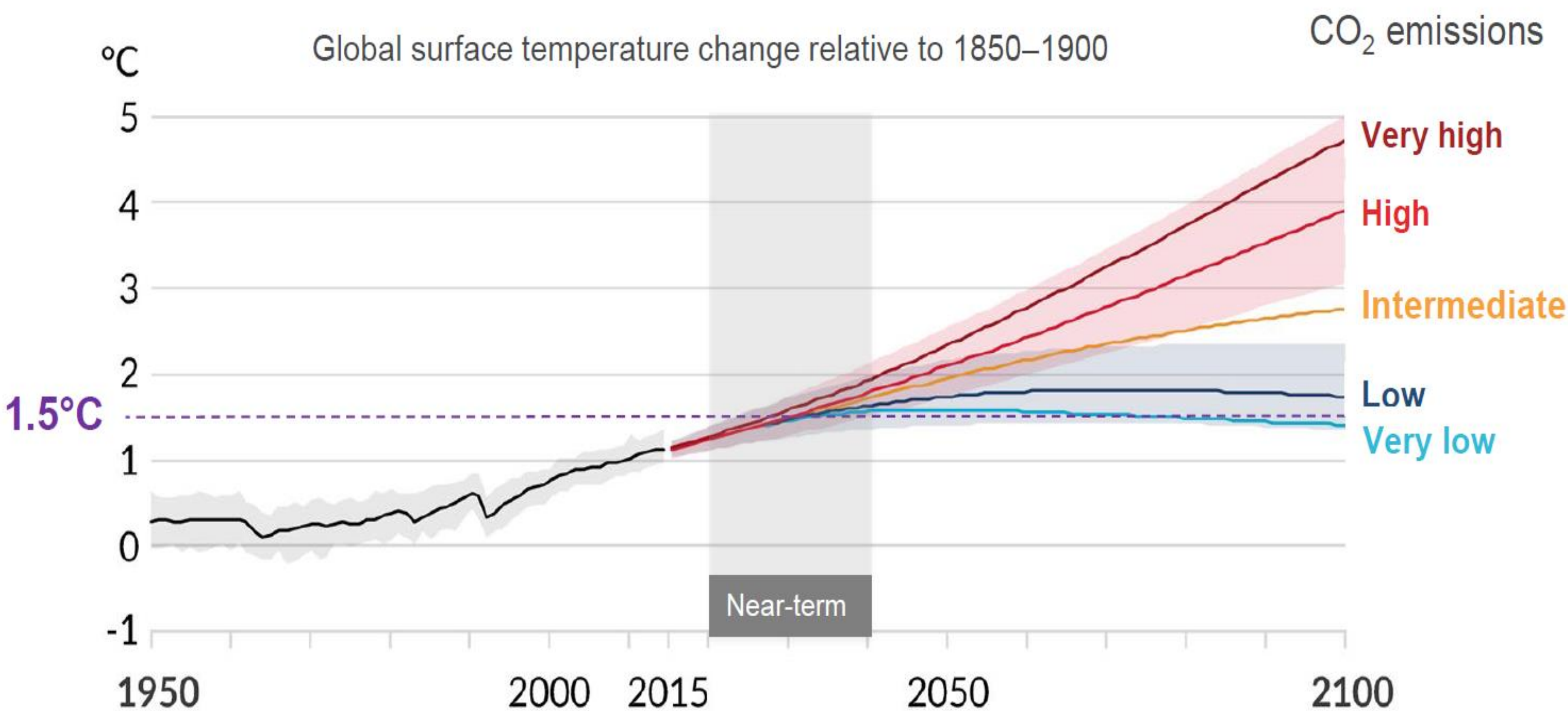


Figure SPM.8

Global warming of 1.5°C and 2°C will be exceeded unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades

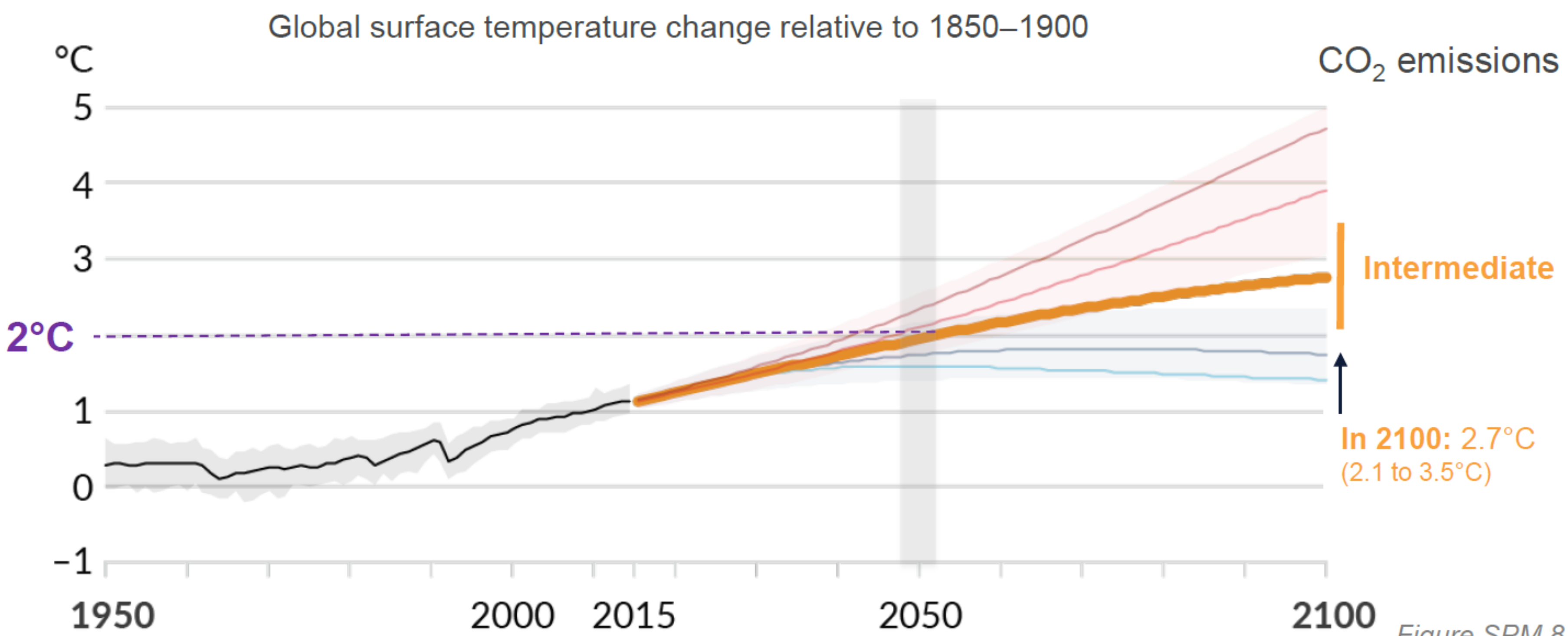
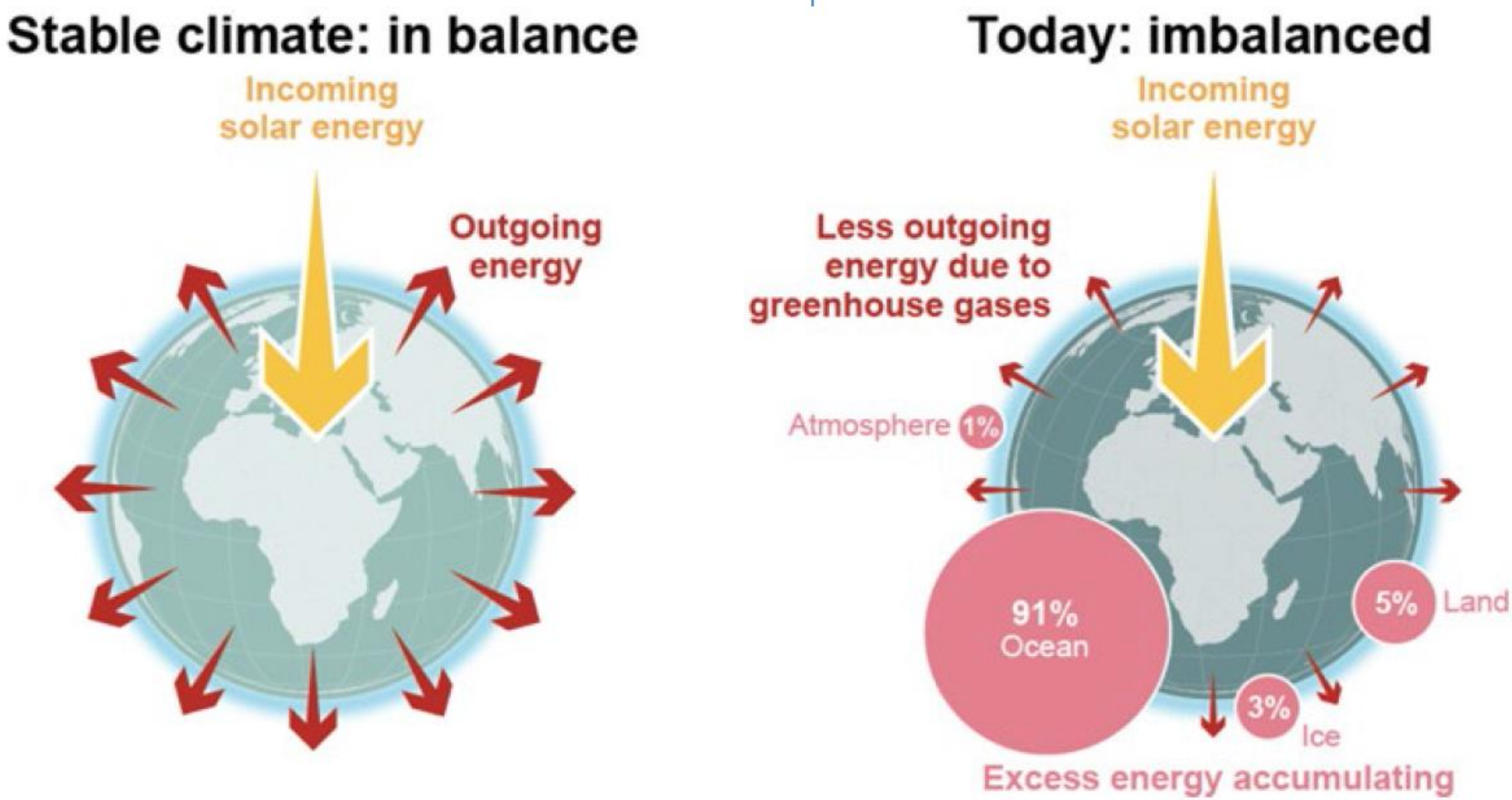


Figure SPM.8

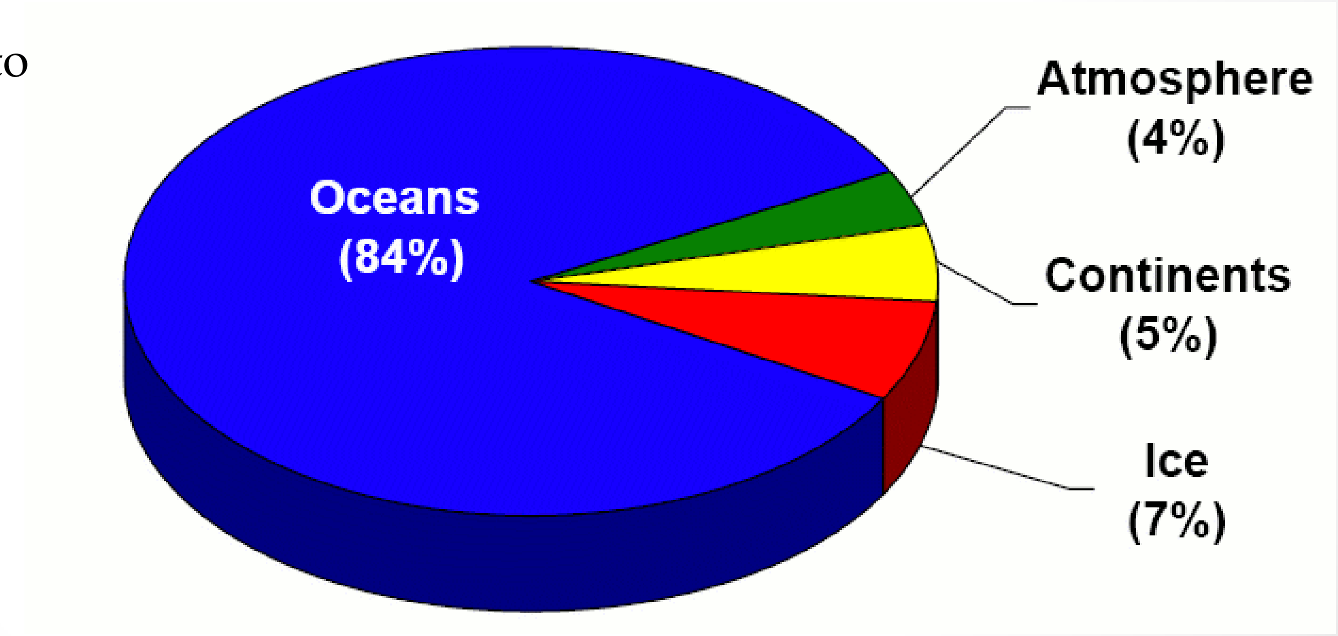
Human influence causes heating of the climate system



Oceans the largest absorber of heat

Amount of Heat Absorbed by Parts of Earth Climate System Over Past 40 Years

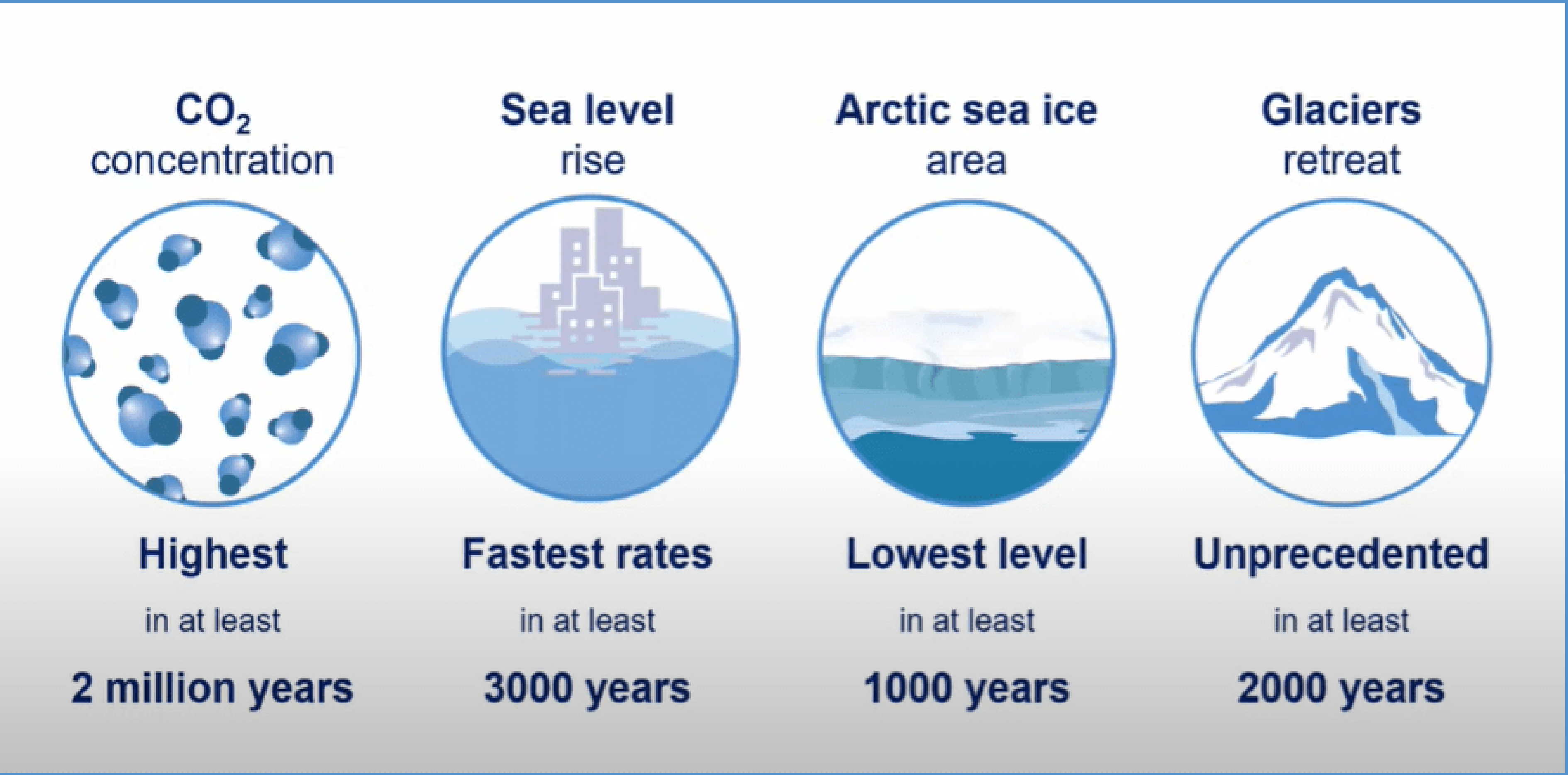
Net Heat Input to Earth System



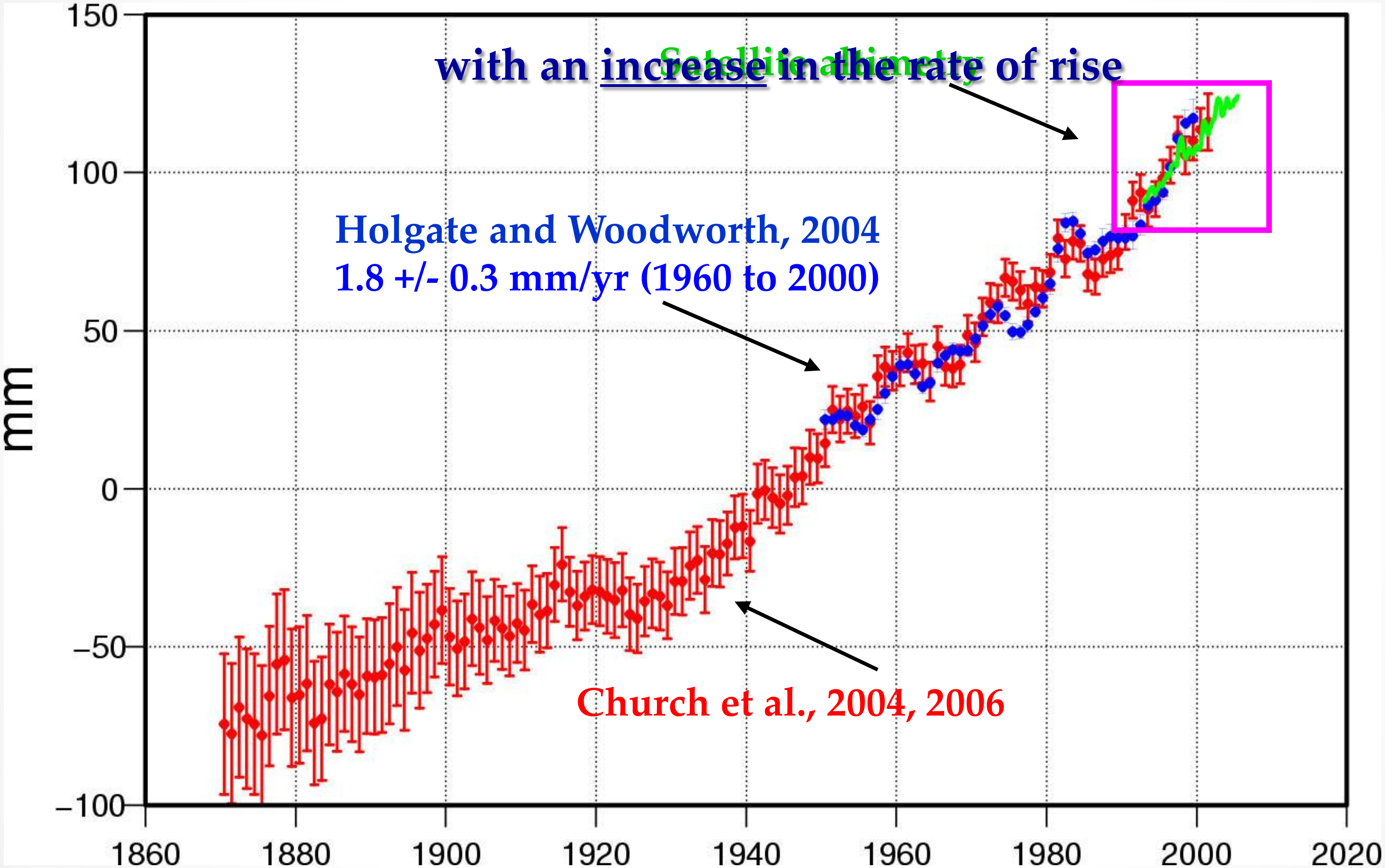
> 90% -- Saved By The Oceans!

(Church et al. 2013)

Key Indicators : IPCC Sixth Assessment Report



What is the most obvious consequence of ocean warming?



Mean Sea Level Rise : 1870-2000: ~1.7 mm/yr

1993-2017 : ~3.3 mm/yr

Global mean sea level will continue to rise over thousands of years with a rate and magnitude depending on global greenhouse gas emissions

Sea level rise greater than 15 m cannot be ruled out with high emissions due to deep uncertainty on Antarctic ice sheet dynamics

Figure SPM.8

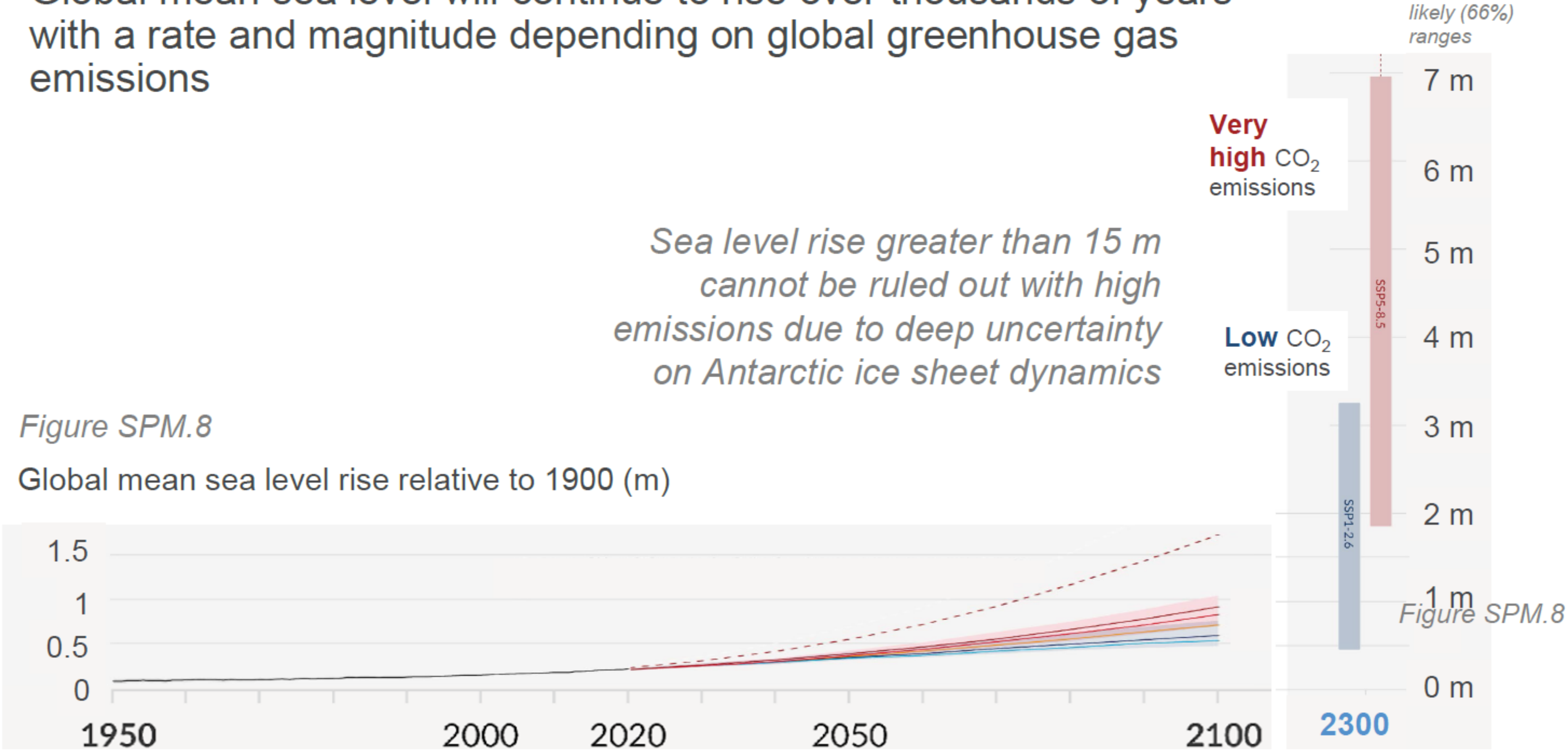
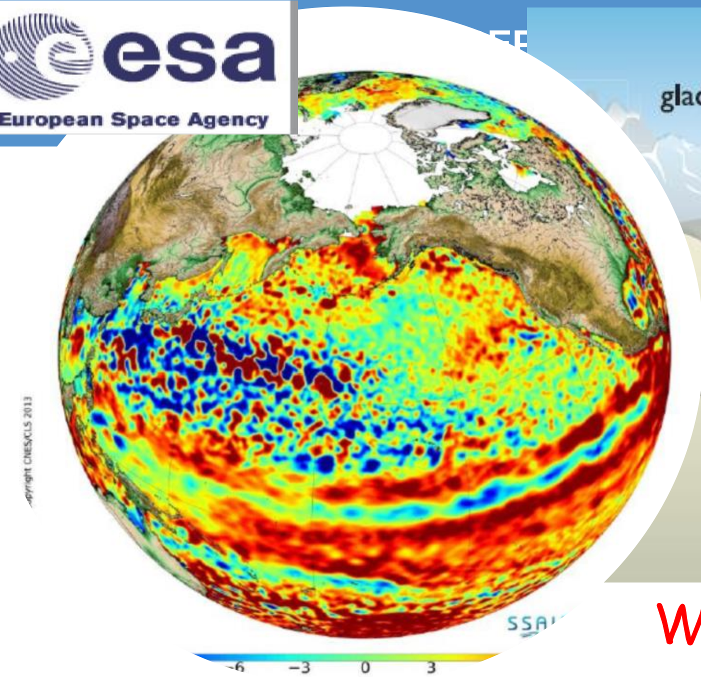
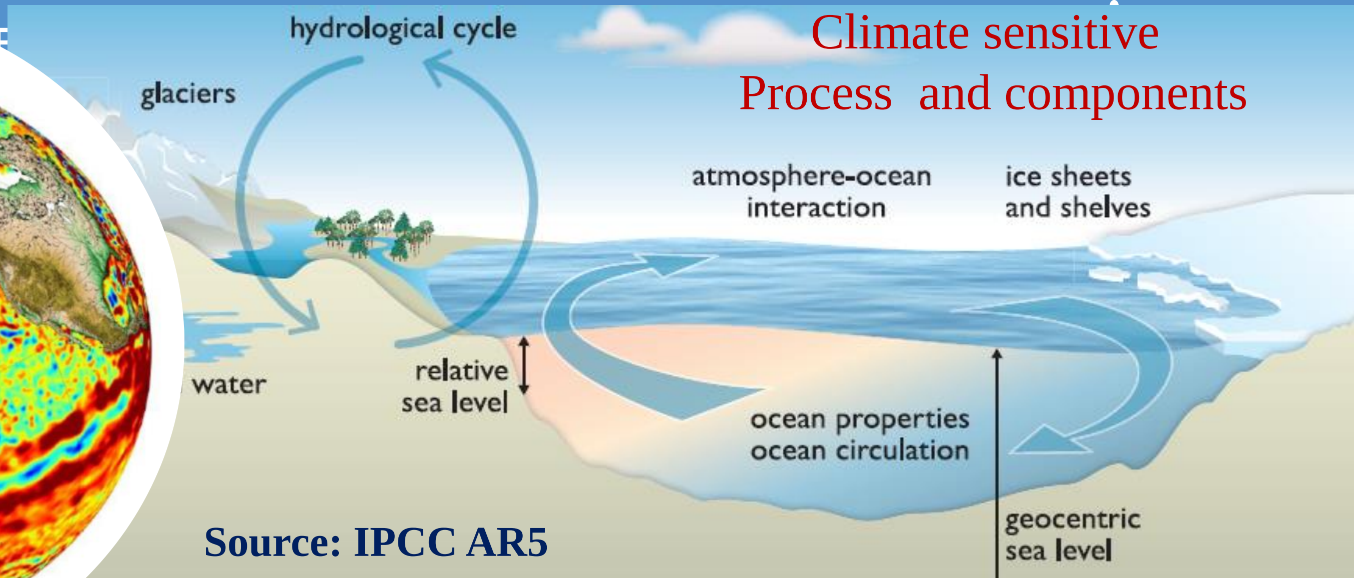


Figure SPM.8

Climate sensitive Process and components





Source: IPCC AR5

What causes the changes in Sea Level ?

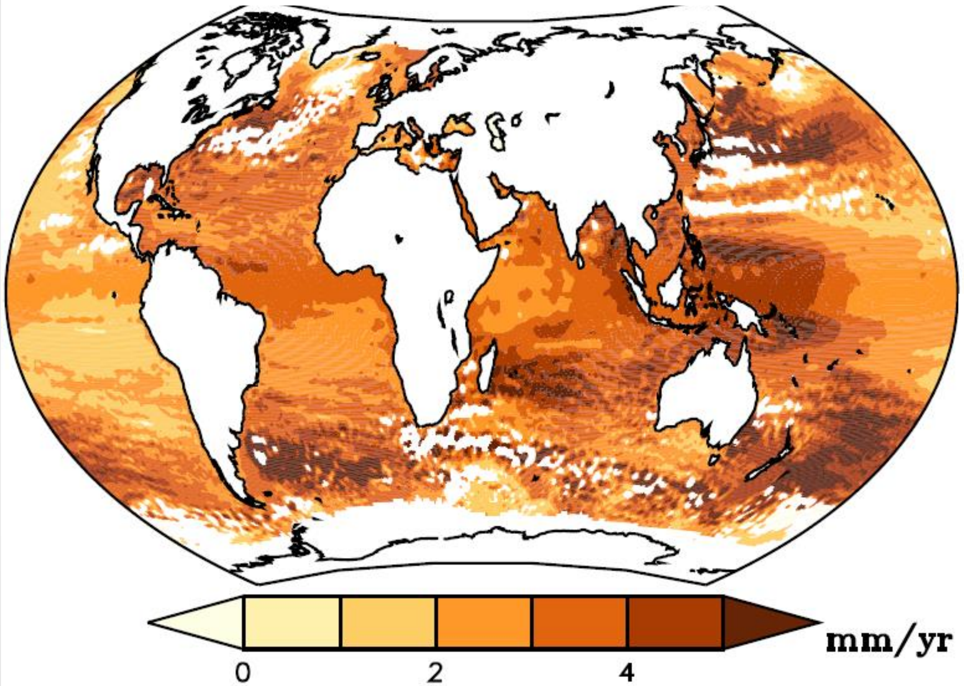
- **Changes in Volume**
  - **Sea water density (Steric)**
    - **Temperature (Thermosteric)**
    - **Salinity (Halosteric)**
- **Shape of the Ocean Basin**
  - **Vertical displacement of land**

Relative sea level

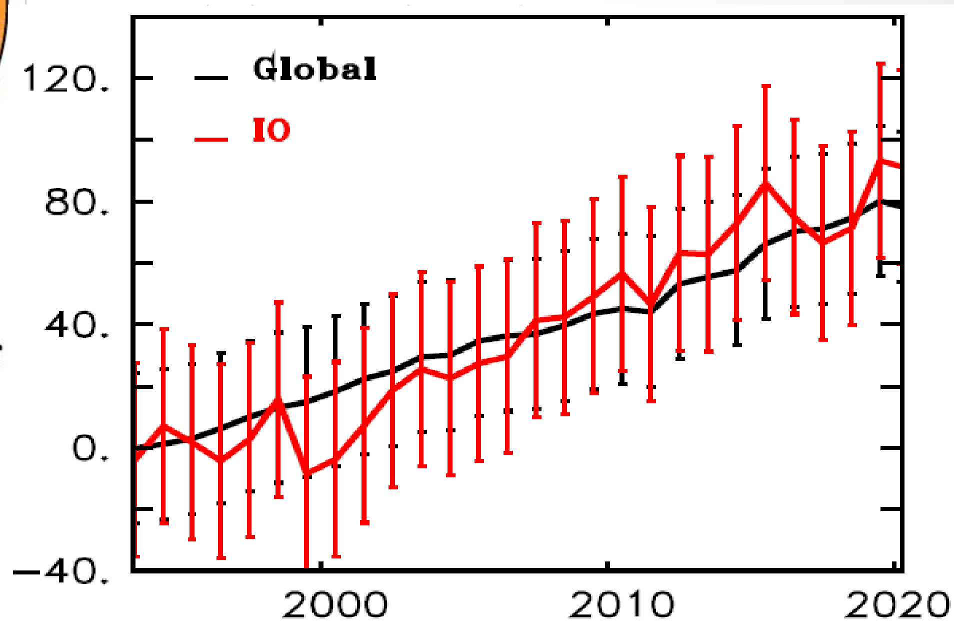
Contribute significantly to regional sea level change

Mean Sea Level (MSL) Rise in the Indian Ocean

MSL Trend (mm/yr)
Satellite (1993-2020)

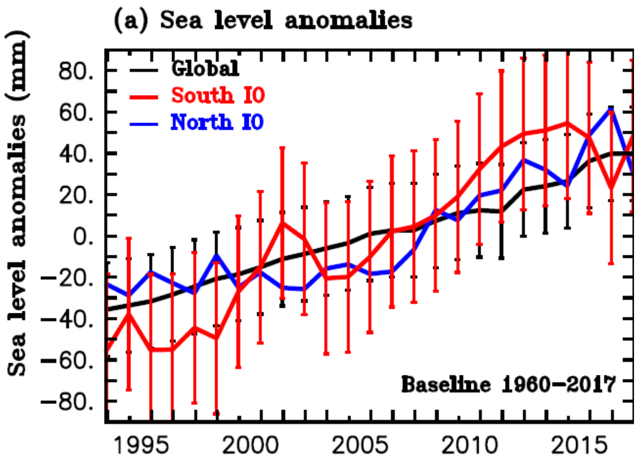


MSL Trend (1993-2020)
(without GIA correction)
IO : 3.51 mm/yr
Global: 2.93 mm/yr

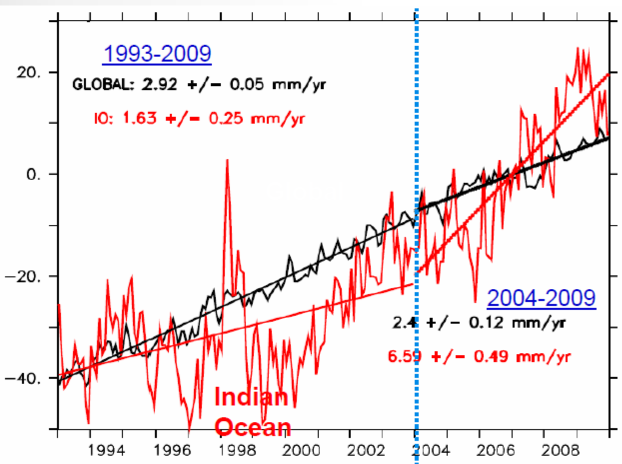


Indian Ocean Warming and Sea Level Rise

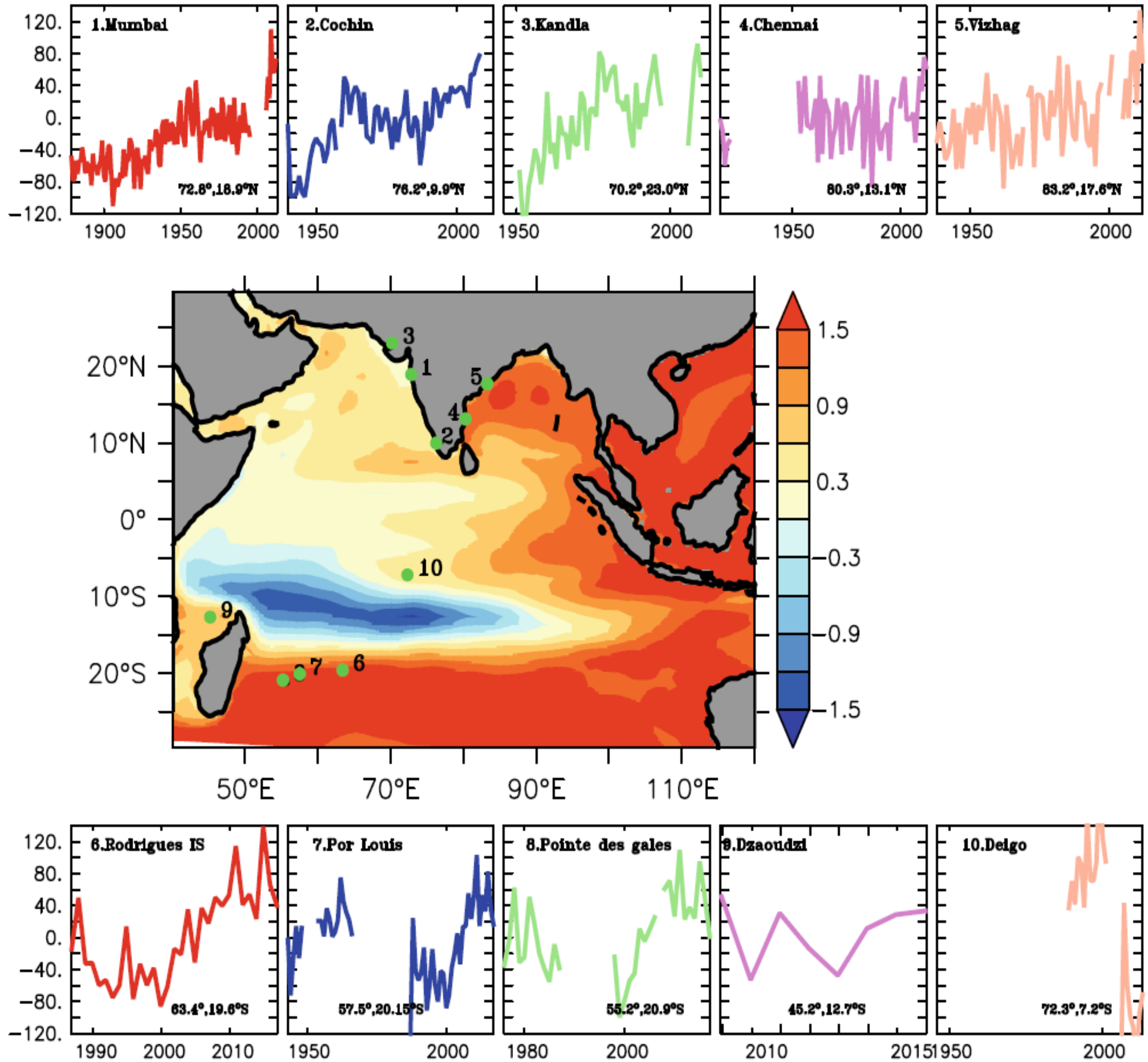
Sea level rise in NIO



Swapna et al., 2017

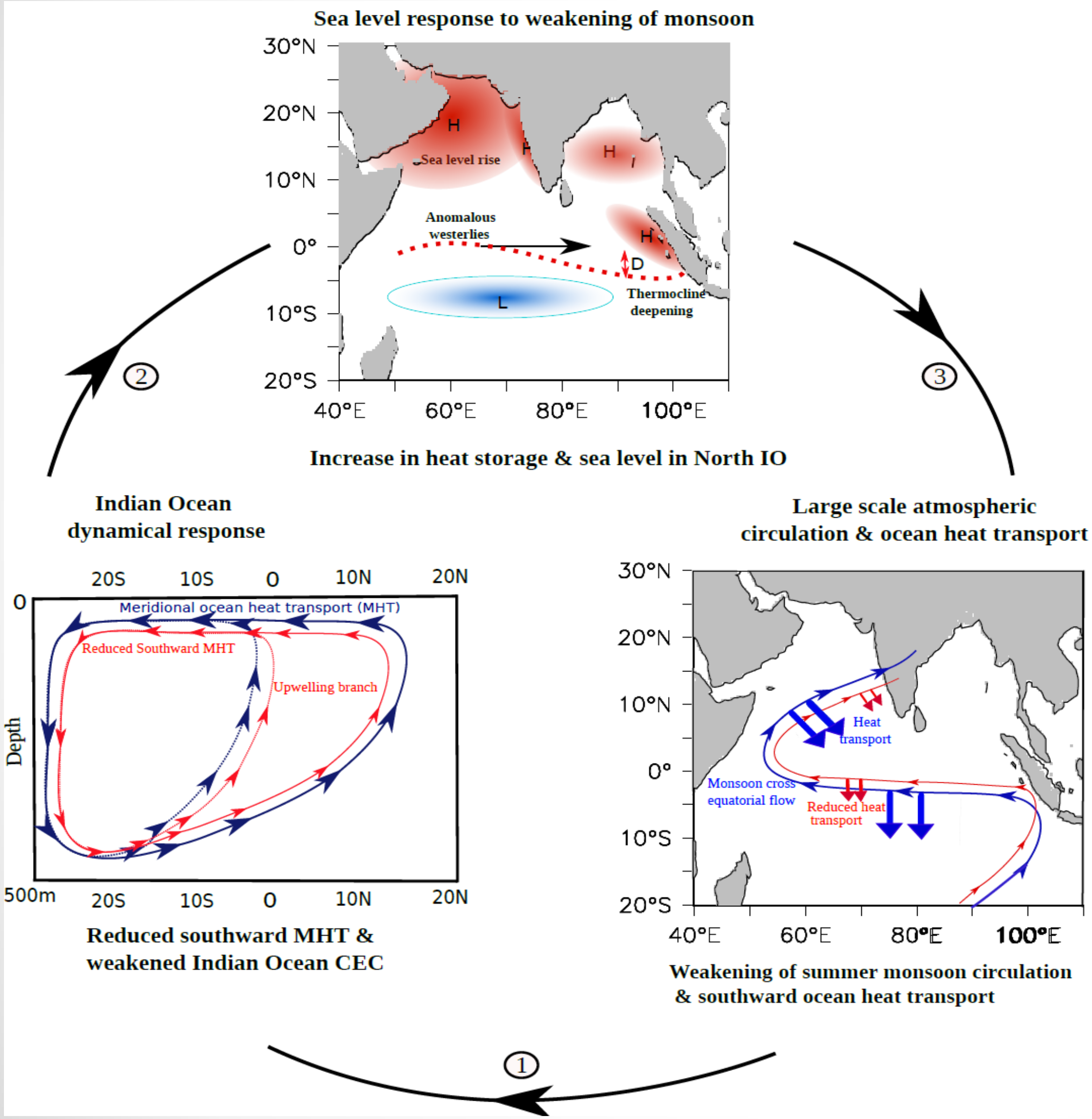


Sreenivasu et al., 2017



Swapna et al., 2020

Dynamics of multi-decadal sea level rise in the NIO



Swapna et al., Geophysical Res. Lett., 2017

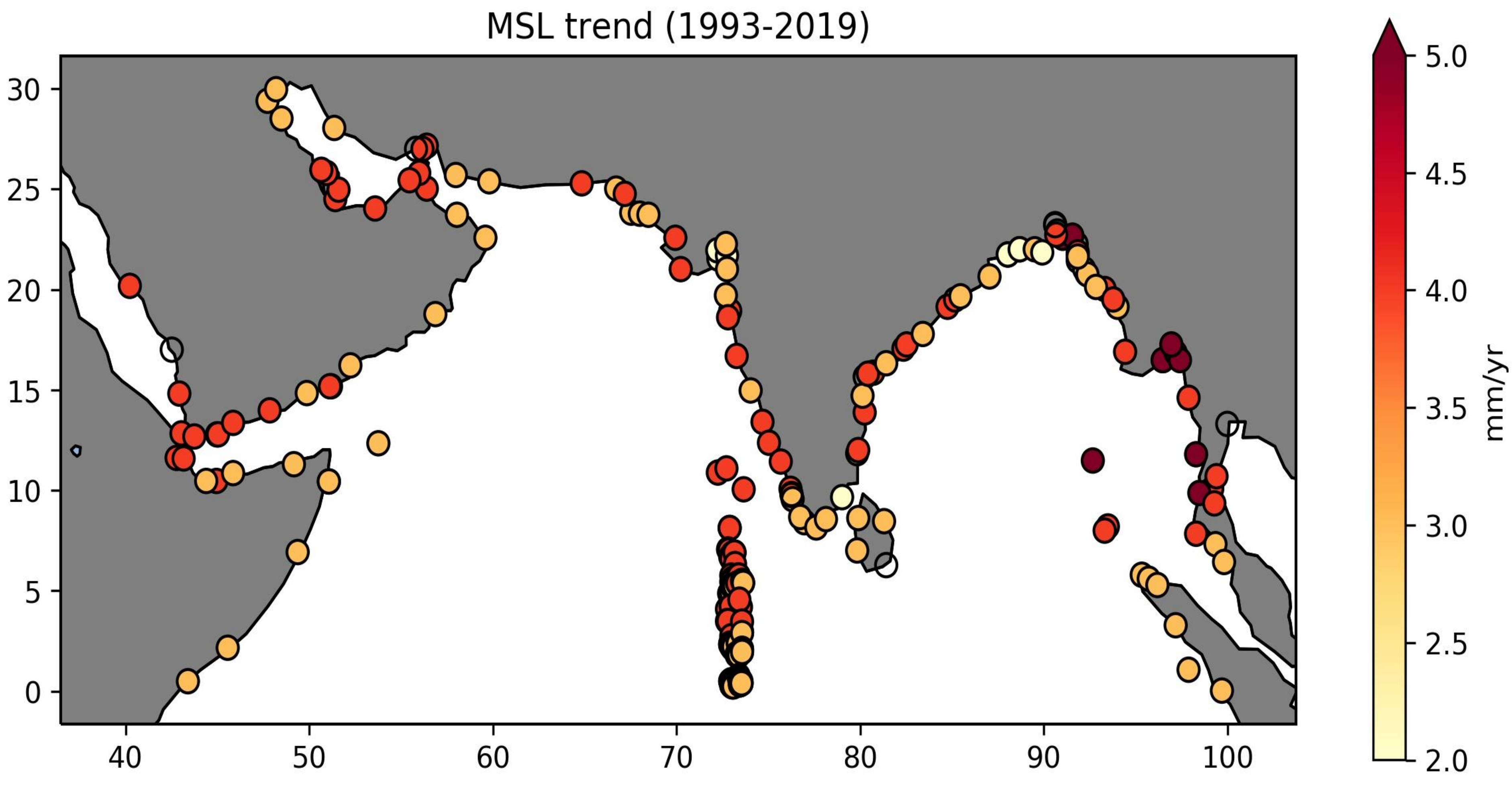
I. Weakening of summer monsoon circulation and associated reduction in southward ocean heat transport (red arrows).

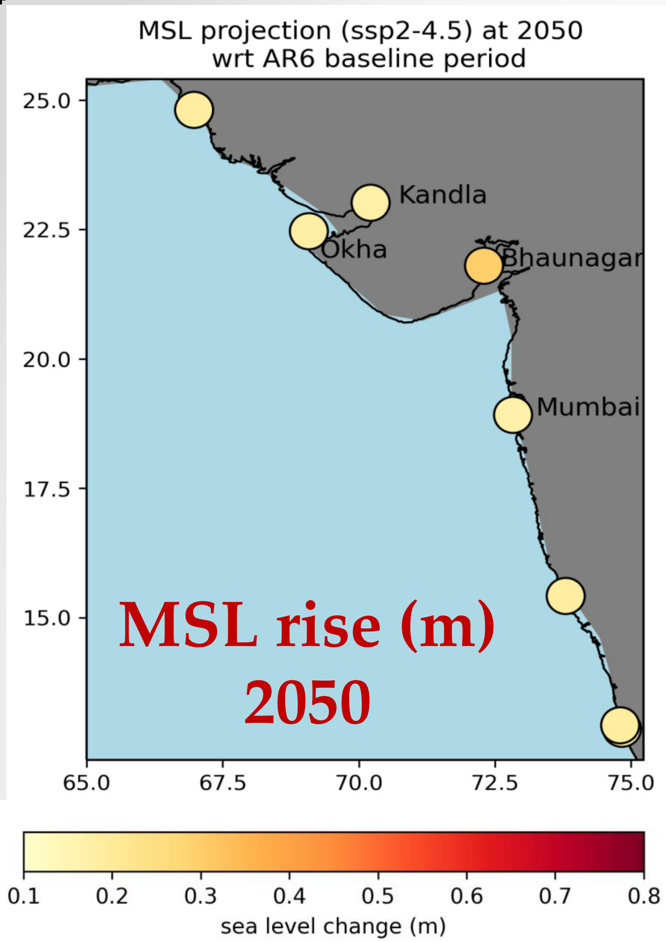
II. Decreased southward meridional heat transport weakens the Indian Ocean cross-equatorial cell.

III. Weakened cross-equatorial cell with reduced southward meridional heat transport increases heat storage and sea level rise in the NIO.

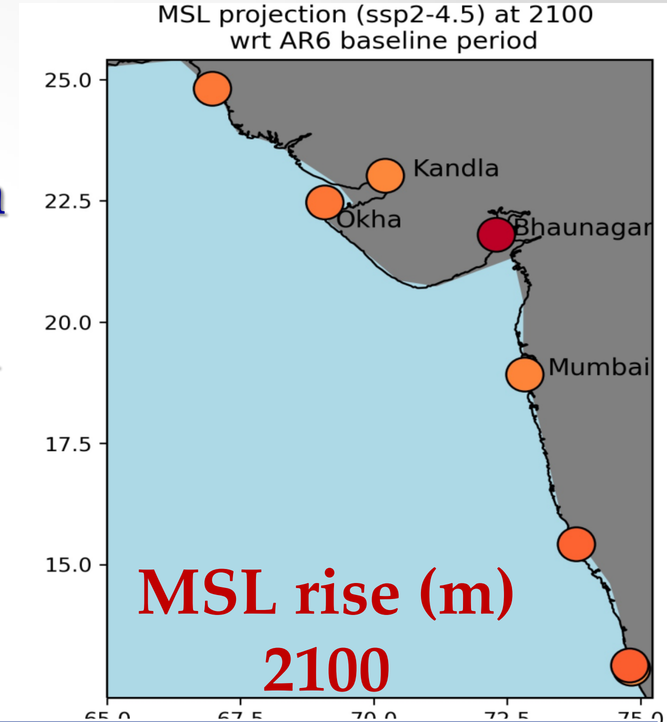
Mean Sea Rise along Indian Ocean coastline

MSL Trend (mm/yr) from Satellite



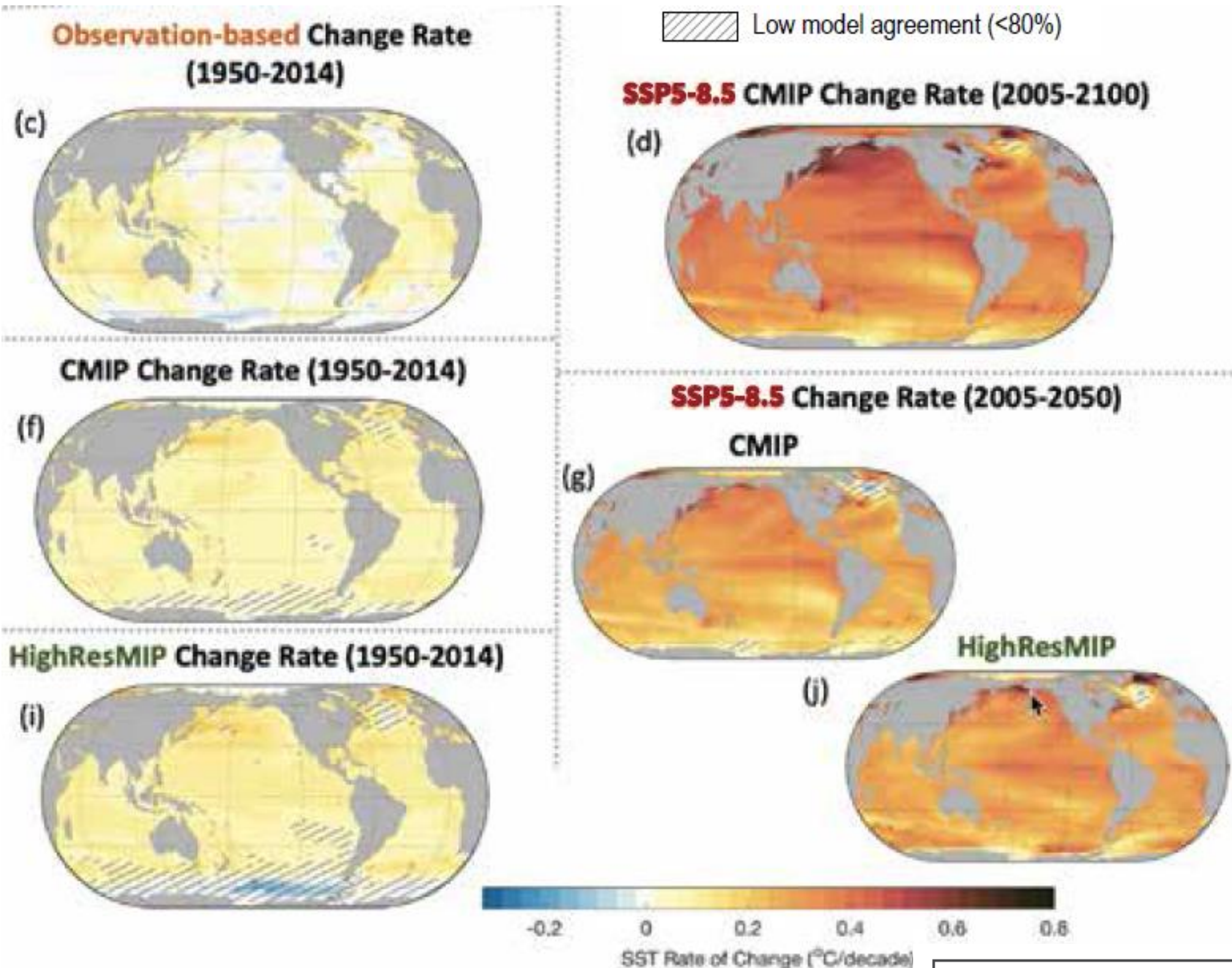


Projected Mean Sea Level Rise along West Coast of India (SSP2-4.5 Scenario)



Station	Median projections of MSL rise (m) relative to 1995-2014 baseline period (IPCC AR6 projection based on SSP2-4.5 Scenario)	
	2050	2100
Mumbai	0.17	0.46
Adani Port	0.18	0.52
Bhaunagar-I	0.3	0.71
Veraval	0.19	0.52
Okha	0.18	0.48

Rate of change in Sea Surface Temperature (ºC/decade)



- **Positive SST trend since 1950 globally**
- **Faster warming rate in observed in the Indian Ocean, western EQ Pacific & western boundary currents (*high confidence*)**

Indian Ocean (ARS, BOB, EIO, SIO)

- The surface Indian Ocean has warmed faster than the global average (*very high confidence*)

Fox-Kemper et al (2021) : IPCC AR6

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL094650

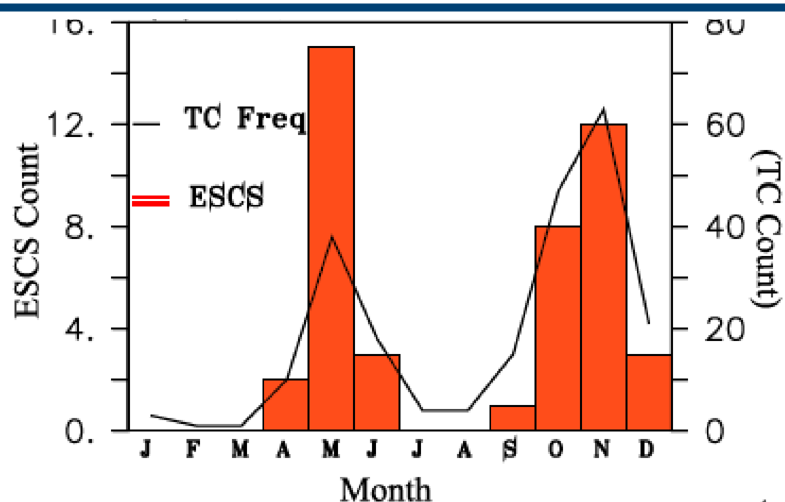
Key Points:

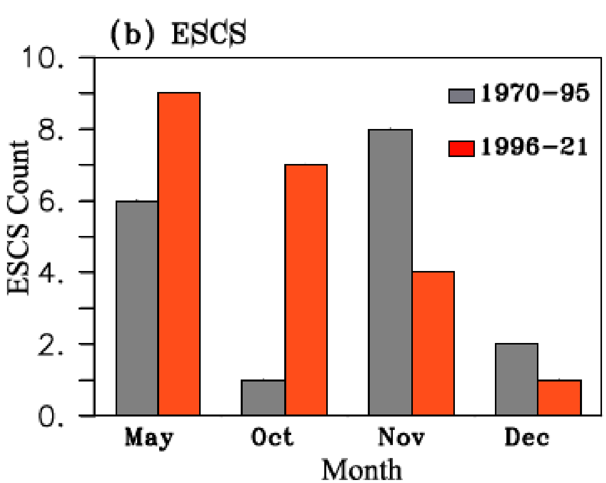
- North Indian Ocean has shown an increase in the frequency of extremely severe and higher-category cyclonic storms, especially during May
- Increase in Potential intensity with higher increase during May and weakening summer monsoon circulation has led to increasing

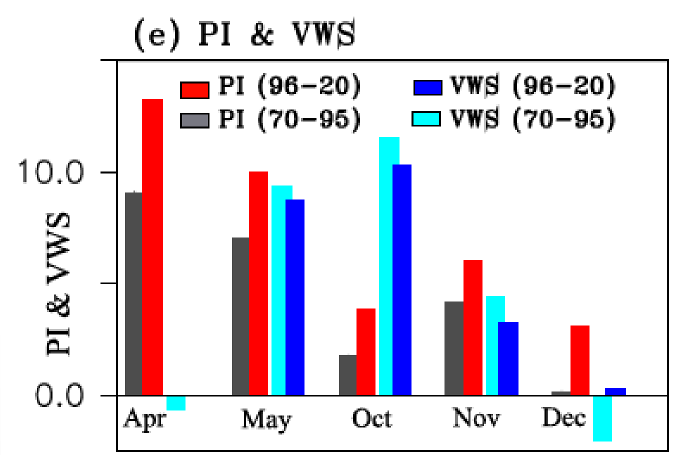
Increasing Frequency of Extremely Severe Cyclonic Storms in the North Indian Ocean by Anthropogenic Warming and Southwest Monsoon Weakening

Panickal Swapna[1,2], P. Sreeraj[1,2], N. Sandeep[1,2], J. Jyoti[1], R. Krishnan[1,2], A. G. Prajeesh[1,2], D. C. Ayantika[1], and S. Manmeet[1]

[1]Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, India, [2]Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, India

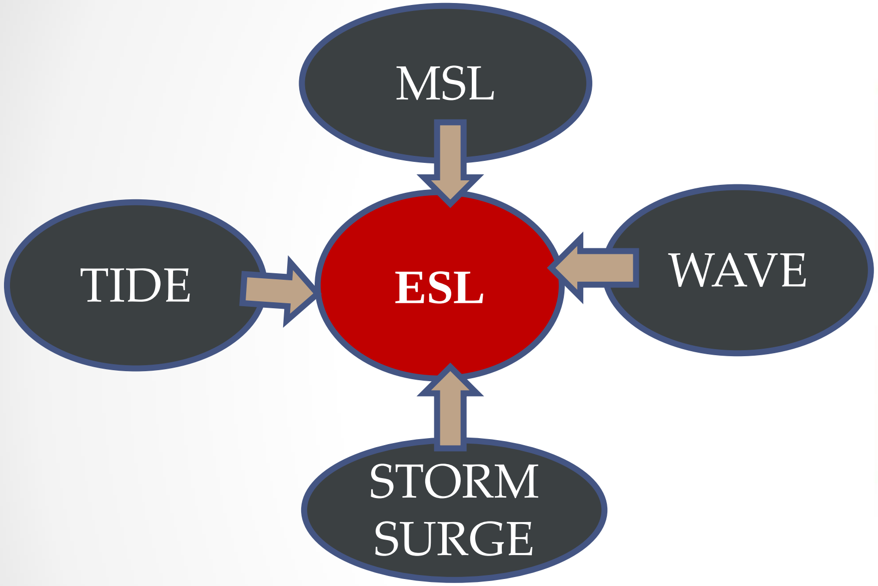


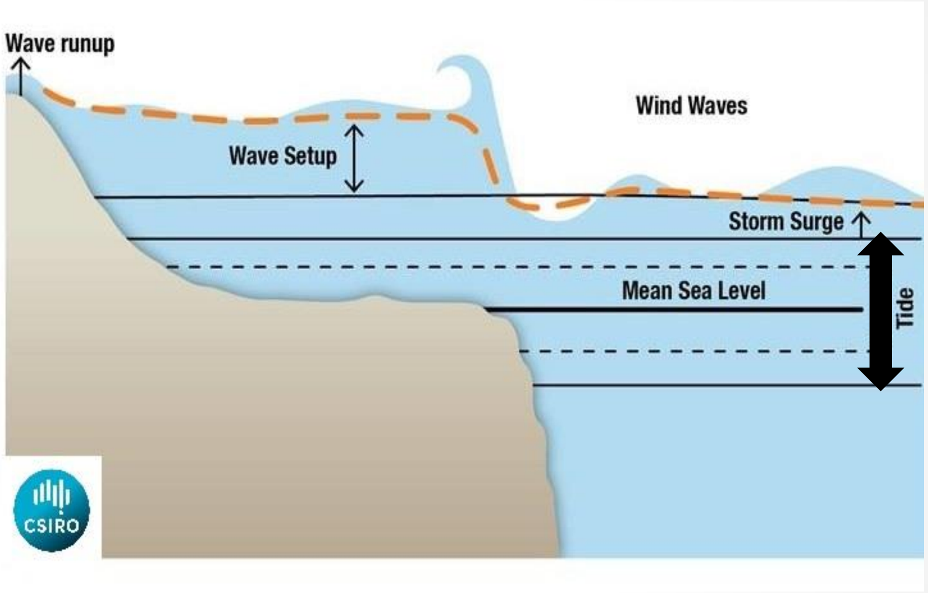




Extreme sea level (ESL)

Extreme sea levels (ESLs) are short span (hours to days) coastal flooding events caused by the combination of mean sea level, tides, surges and waves.

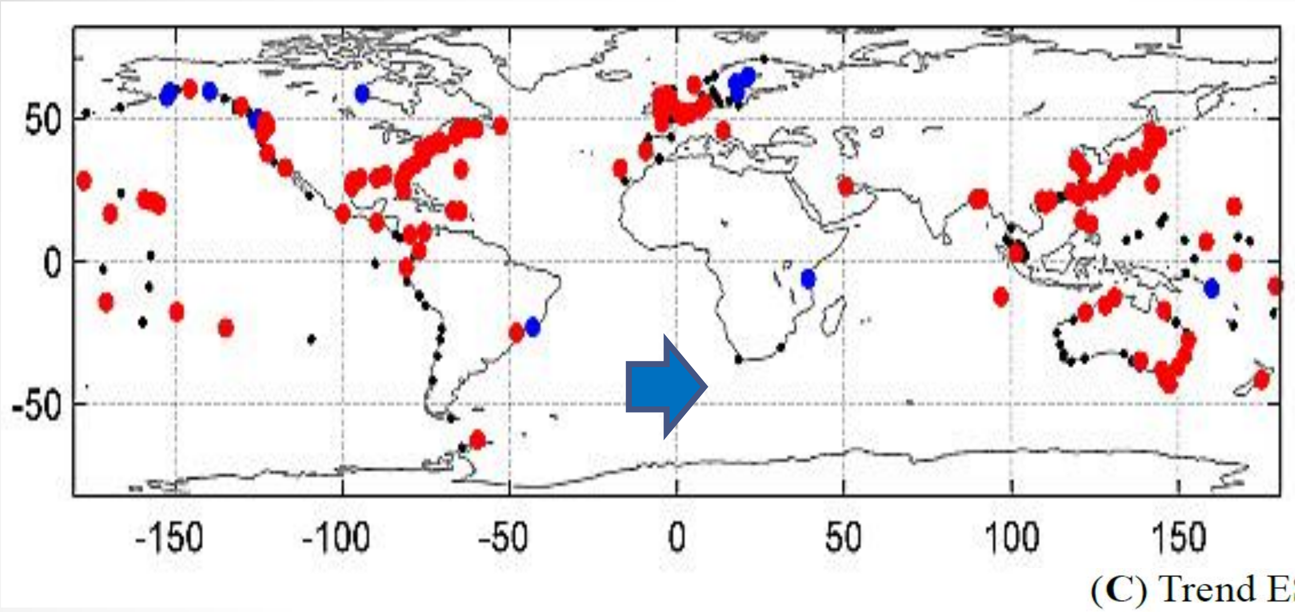


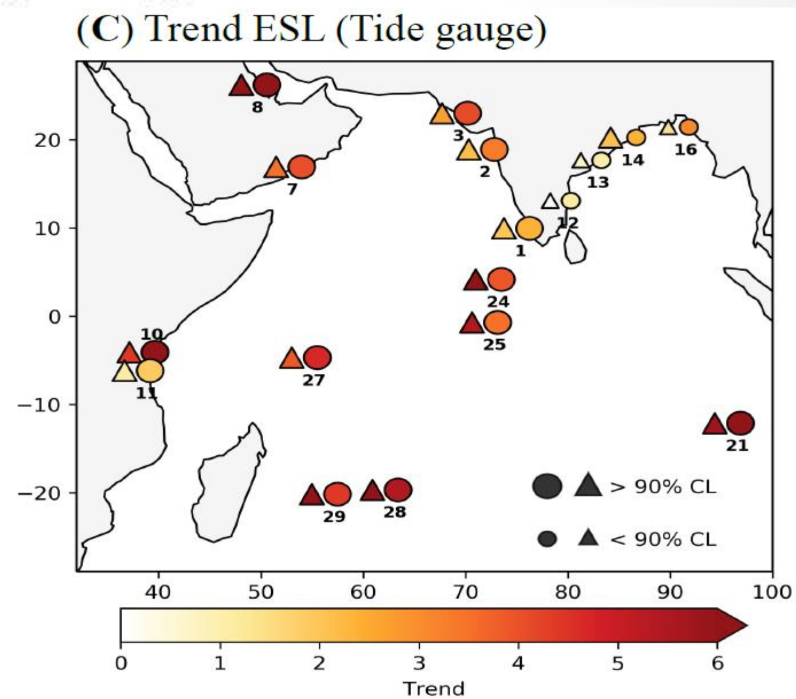


- ❑ Relationship between water level and flooding at each location depends on the coastal shape, bathymetry, and storminess etc.

Pugh, 1987

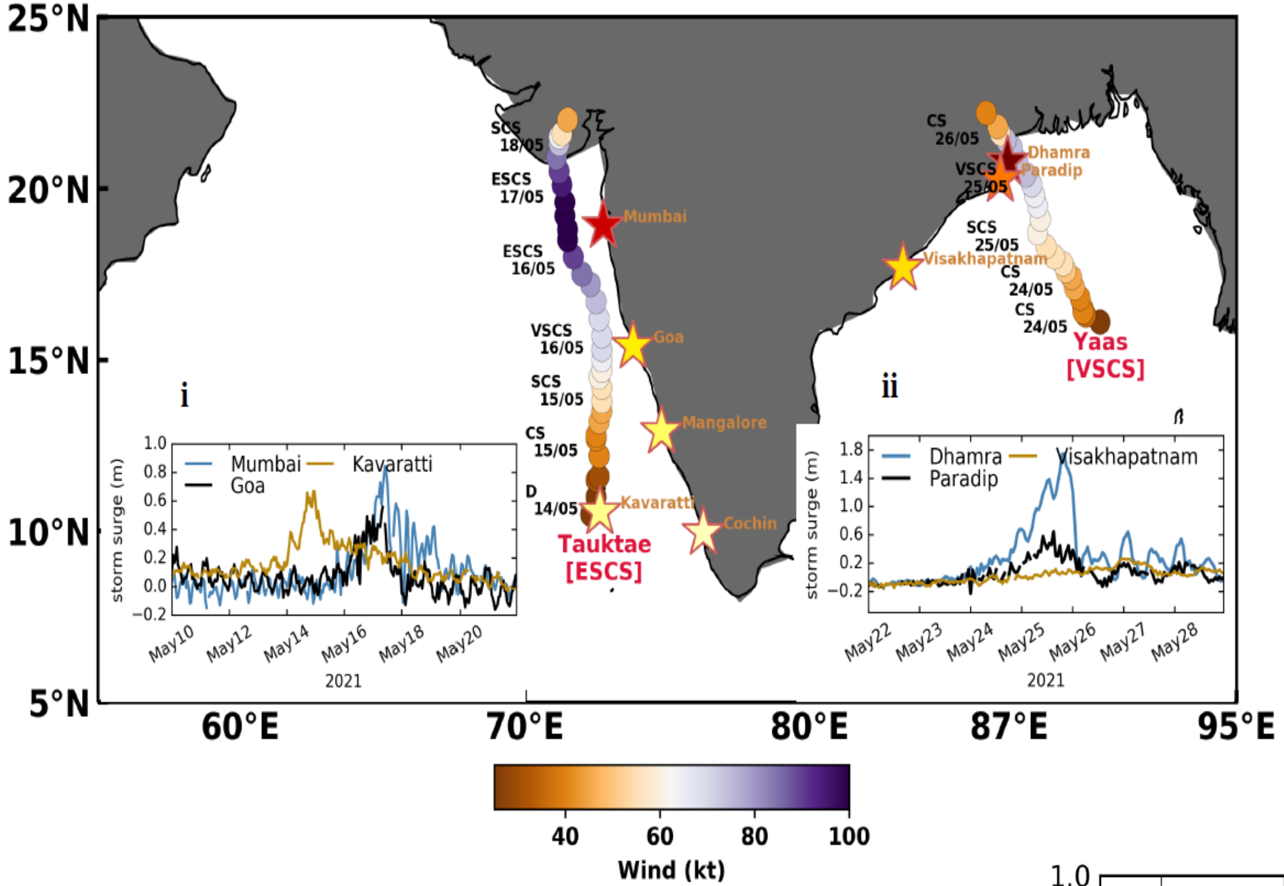
Rise in Extreme Sea Level

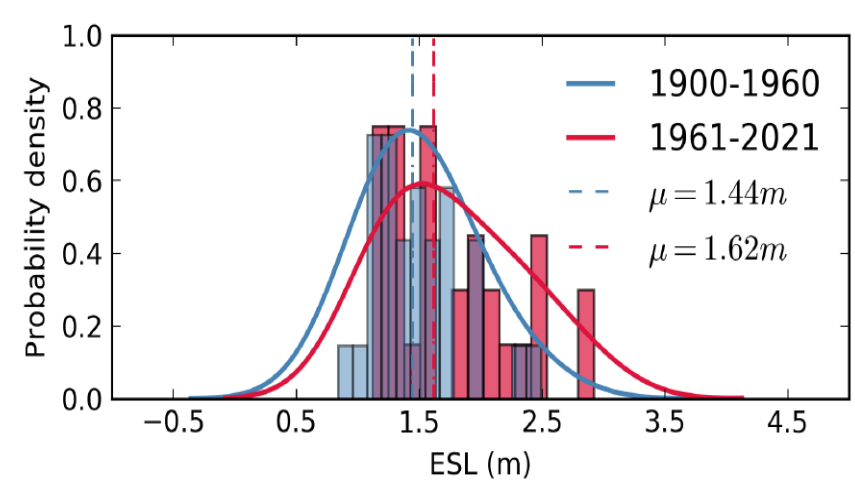




ESL events are increasing
In the Indian Ocean

ESL and storm surge





Sea Level Budget changes with time : *Current rate largely due to mass changes*

Observed contribution to GMSL rise (2006 – 2018)

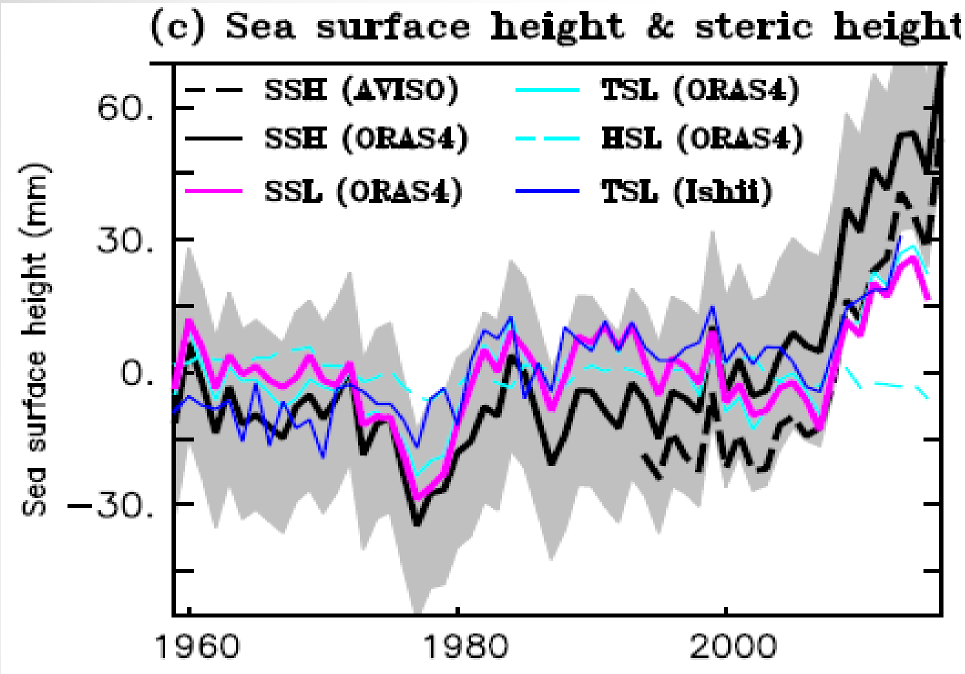
Source	Sea Level Rise ($mm\ yr^{-1}$) 2006–2018
Thermal Expansion	1.39
Glaciers	0.62
Greenland Ice Sheet	0.63
Antarctic Ice Sheet	0.37
Land-water storage	0.60
Sum	3.61
Observed	3.69

IPCC AR6

- Thermal expansion (~38.6%)
- Ocean mass (~ 44.8%)
- Land water storage (~16.6%)

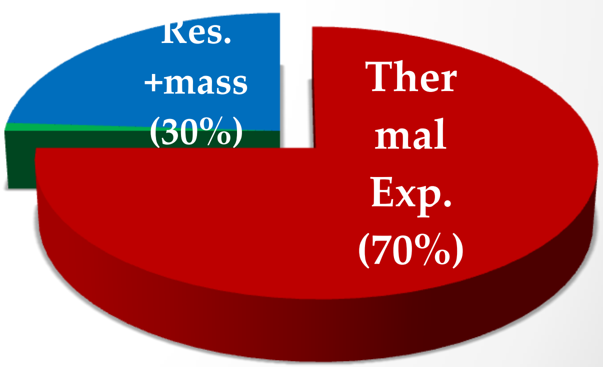
Because of the increased ice-sheet mass loss, the loss of land ice (glaciers and ice-sheet) was the largest contributor to GMSL

Regional Sea Level Budget : Indian Ocean



Indian Ocean

Thermal expansion (~70%)
Ocean mass + residual (~30%)

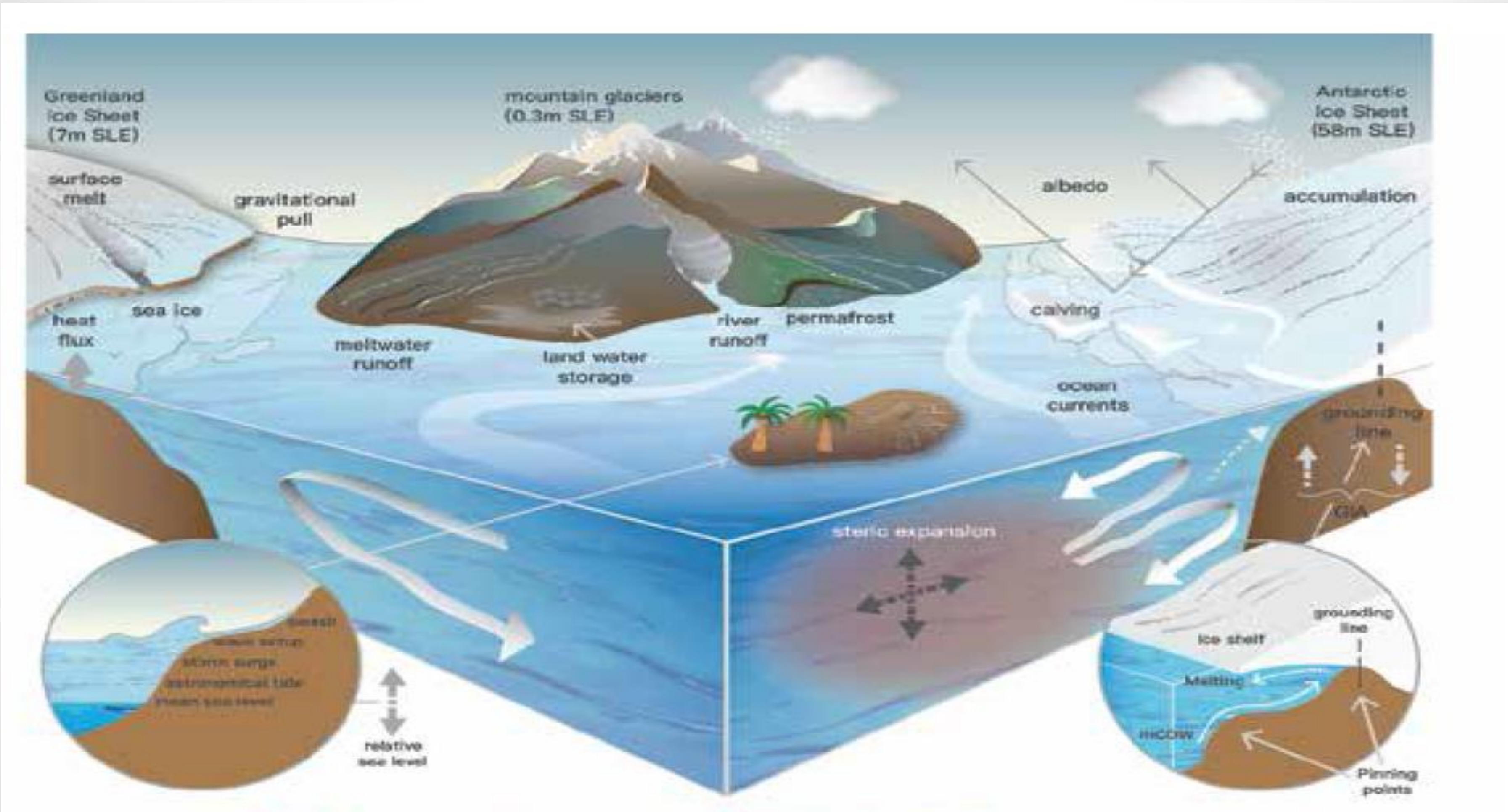


Indian Ocean sea level rise is dominated by the steric height with further dominance by the thermosteric component.

Table 9.9 | Global mean sea level projections for five Shared Socio-economic Pathway (SSP) scenarios, relative to a baseline of 1995–2014, in metres. Individual contributions are shown for the year 2100. Median values (*likely* ranges) are shown. Average rates for total sea level change are shown in mm yr^{-1}. Unshaded cells represent processes in whose projections there is *medium confidence*. Shaded cells incorporate a representation of processes in which there is *low confidence*; in particular, the SSP5-8.5 *low confidence* column shows the 17th–83rd percentile range from a p-box including SEJ- and MICI-based projections rather than an assessed *likely* range. Methods are described in 9.6.3.2.

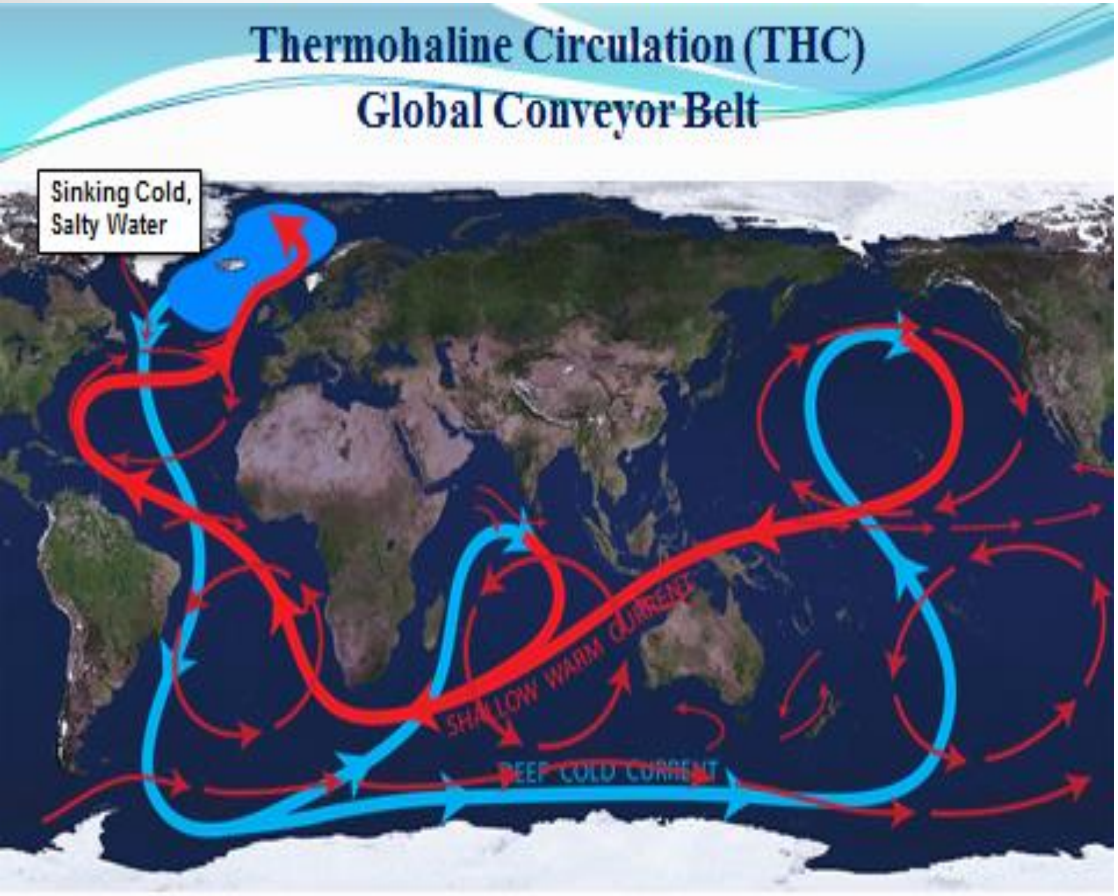
	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP5-8.5 *Low Confidence*
Thermal expansion	0.12 (0.09–0.15)	0.14 (0.11–0.18)	0.20 (0.16–0.24)	0.25 (0.21–0.30)	0.30 (0.24–0.36)	0.30 (0.24–0.36)
Greenland	0.05 (0.00–0.09)	0.06 (0.01–0.10)	0.08 (0.04–0.13)	0.11 (0.07–0.16)	0.13 (0.09–0.18)	0.18 (0.09–0.59)
Antarctica	0.10 (0.03–0.25)	0.11 (0.03–0.27)	0.11 (0.03–0.29)	0.11 (0.03–0.31)	0.12 (0.03–0.34)	0.19 (0.02–0.56)
Glaciers	0.08 (0.06–0.10)	0.09 (0.07–0.11)	0.12 (0.10–0.15)	0.16 (0.13–0.18)	0.18 (0.15–0.21)	0.17 (0.11–0.21)
Land-water Storage	0.03 (0.01–0.04)	0.03 (0.01–0.04)	0.03 (0.01–0.04)	0.03 (0.02–0.04)	0.03 (0.01–0.04)	0.03 (0.01–0.04)
Total (2030)	0.09 (0.08–0.12)	0.09 (0.08–0.12)	0.09 (0.08–0.12)	0.10 (0.08–0.12)	0.10 (0.09–0.12)	0.10 (0.09–0.15)
Total (2050)	0.18 (0.15–0.23)	0.19 (0.16–0.25)	0.20 (0.17–0.26)	0.22 (0.18–0.27)	0.23 (0.20–0.29)	0.24 (0.20–0.40)
Total (2090)	0.35 (0.26–0.49)	0.39 (0.30–0.54)	0.48 (0.38–0.65)	0.56 (0.46–0.74)	0.63 (0.52–0.83)	0.71 (0.52–1.30)
Total (2100)	0.38 (0.28–0.55)	0.44 (0.32–0.62)	0.56 (0.44–0.76)	0.68 (0.55–0.90)	0.77 (0.63–1.01)	0.88 (0.63–1.60)
Total (2150)	0.57 (0.37–0.86)	0.68 (0.46–0.99)	0.92 (0.66–1.33)	1.19 (0.89–1.65)	1.32 (0.98–1.88)	1.98 (0.98–4.82)
Rate (2040–2060)	4.1 (2.8–6.0)	4.8 (3.5–6.8)	5.8 (4.4–8.0)	6.4 (5.0–8.7)	7.2 (5.6–9.7)	7.9 (5.6–16.1)
Rate (2080–2100)	4.2 (2.4–6.6)	5.2 (3.2–8.0)	7.7 (5.2–11.6)	10.4 (7.4–14.8)	12.1 (8.6–17.6)	15.8 (8.6–30.1)

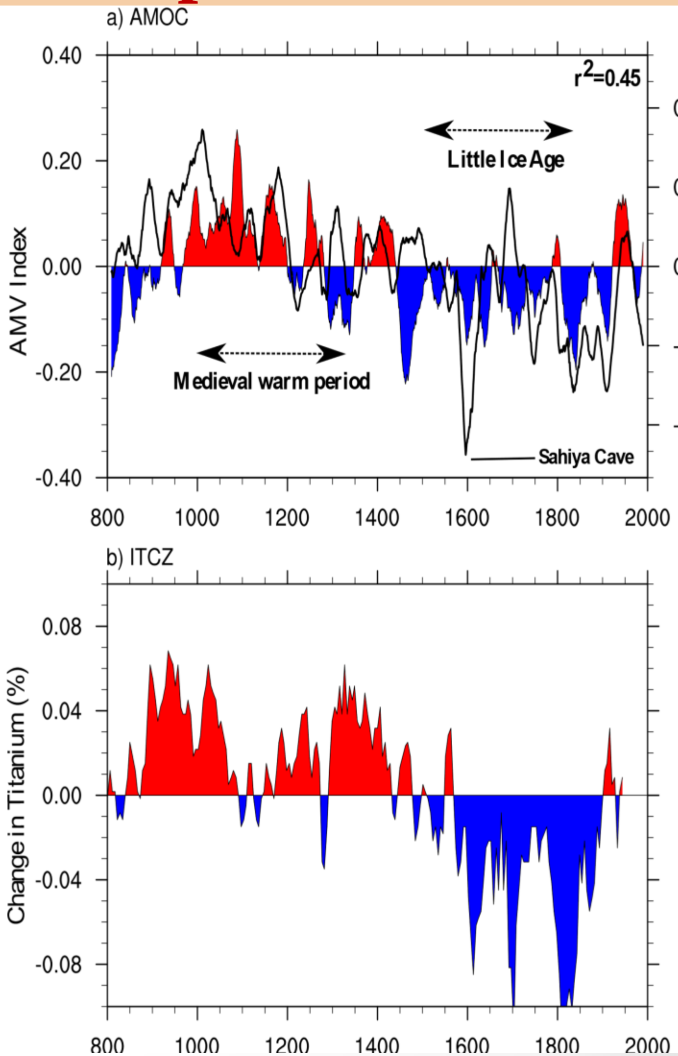
Climate-sensitive processes and components that can influence sea level rise



Source : IPCC AR6

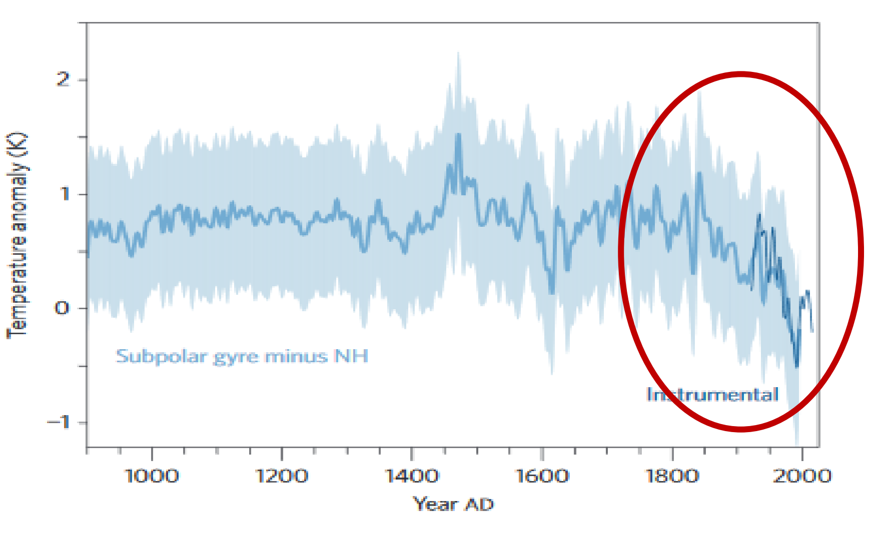
Atlantic meridional overturning circulation (AMOC) and its possible global climate impacts

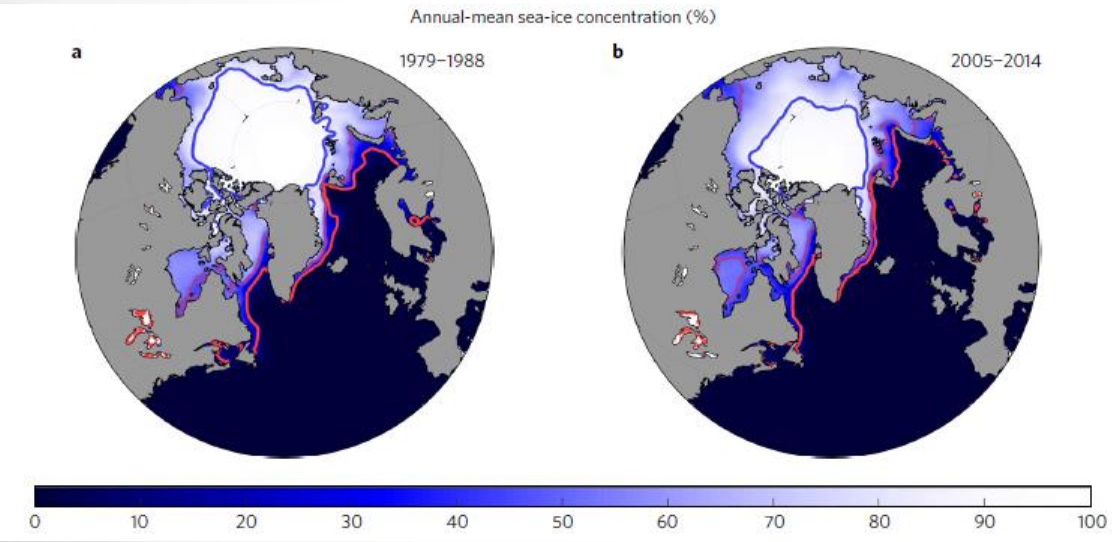




Decreasing strength of AMOC and its possible global climate impacts

- Slow-down of AMOC to the ongoing decline of Arctic sea ice, which exposes the ocean to anomalous surface heat and freshwater fluxes, resulting in positive buoyancy anomalies that can affect ocean circulation.



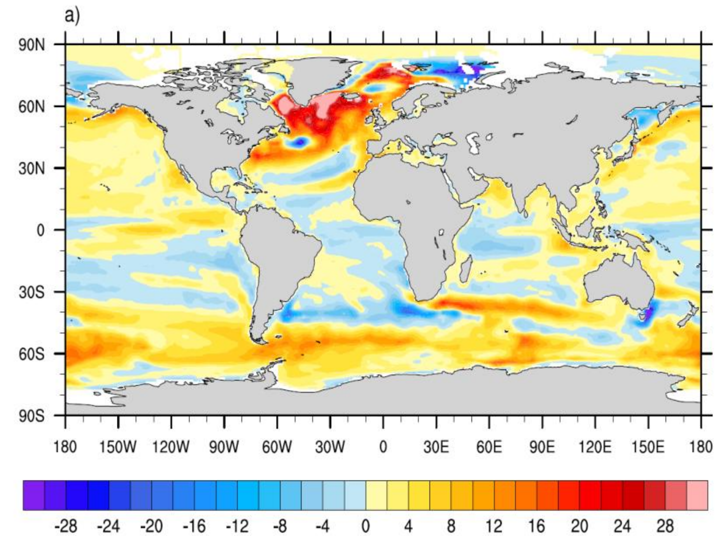


Proxy reconstructed data shows a sharp decline
in the strength of AMOC in 21st century alone

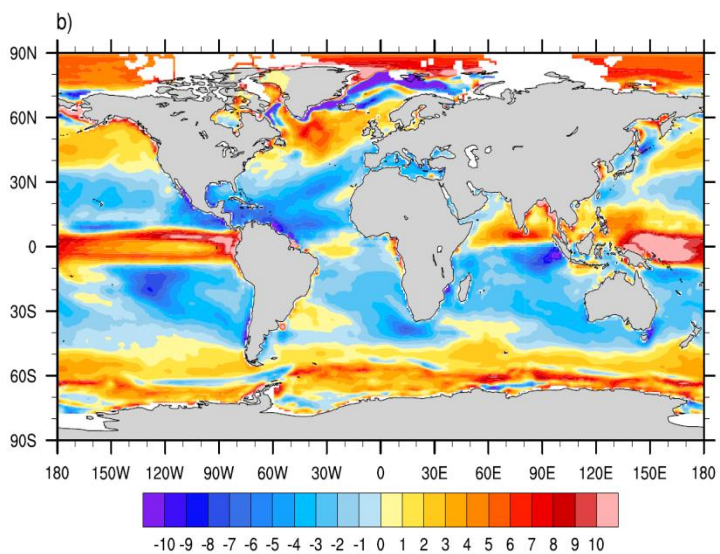
-

Sevellec et al., (2(

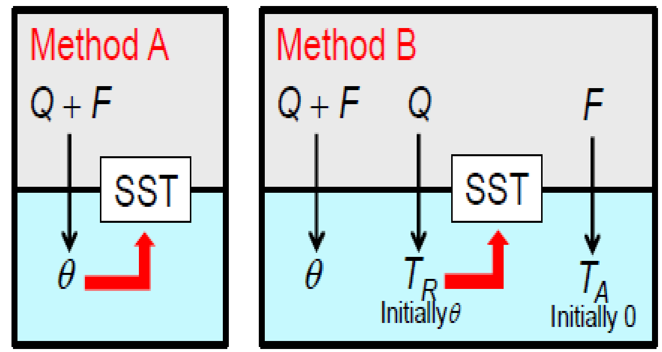
Flux anomaly forcing model Intercomparison project (FAFMIP)



•Net Surface heat flux (W/m^2) anomaly used as forcing



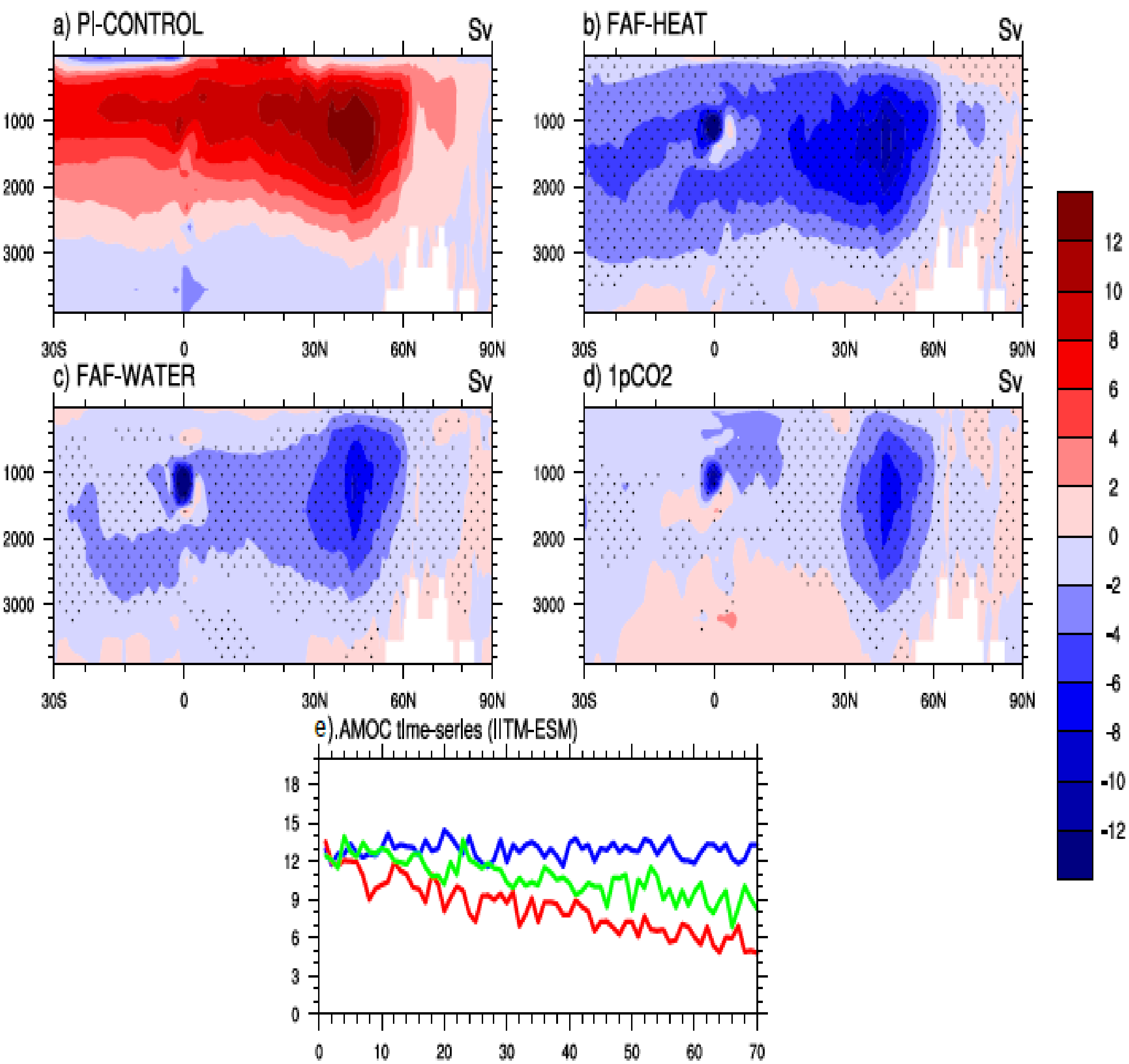
•Net Precipitation – evaporation (kg/m^2.s^{-1})

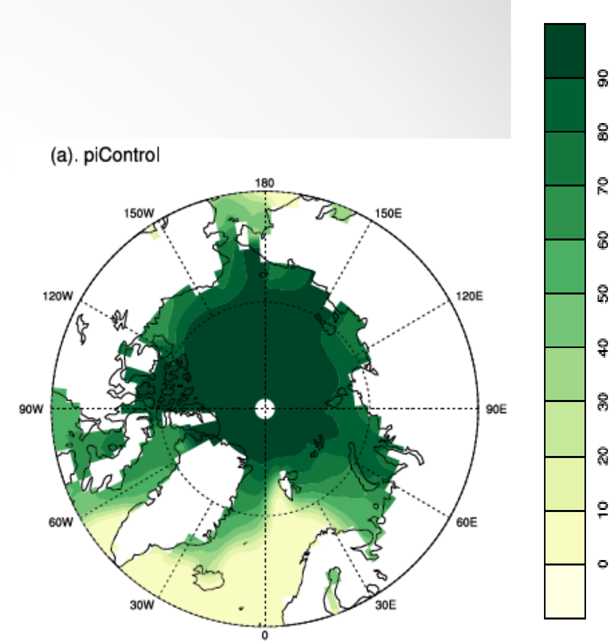


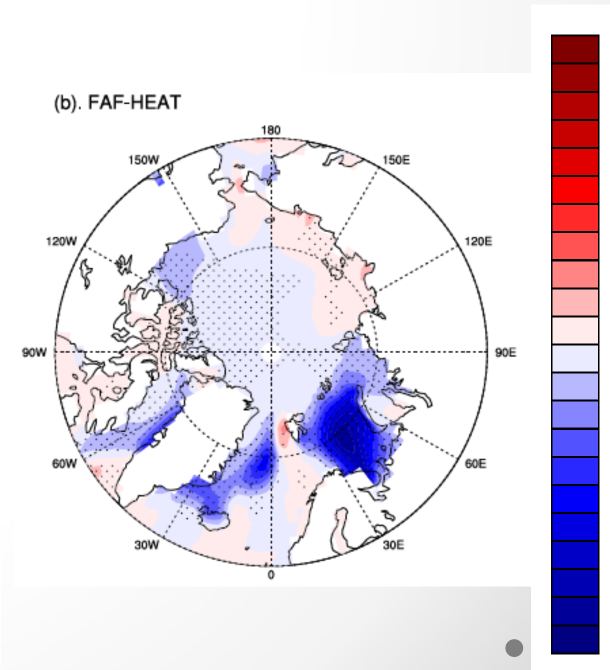
$$\frac{\partial \theta_p}{\partial t} = \frac{\partial T_R}{\partial t} + \frac{\partial T_A}{\partial t}$$

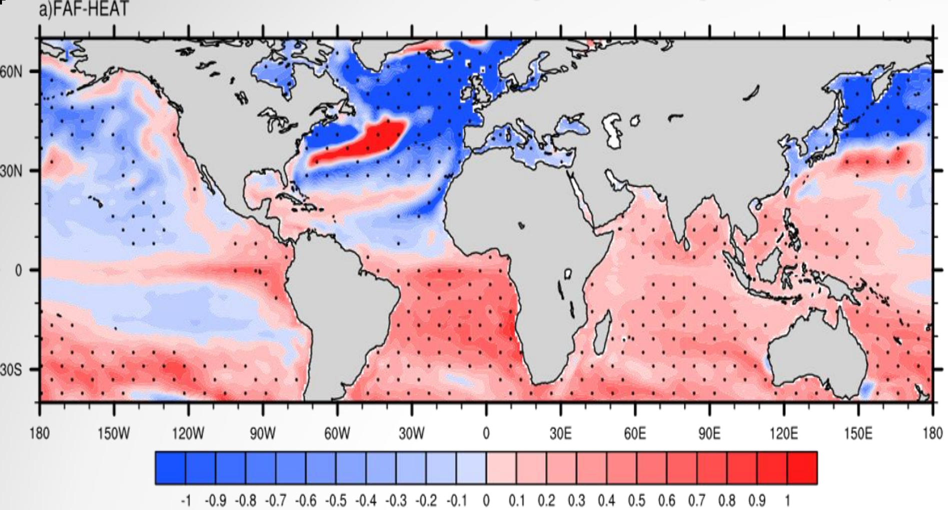
- Partitioning of the temperature change between effects of local addition of heat and changing heat transports using 3dimensional ocean tracers; Added heat (T_A)and Redistributed heat (T_R)
- T_R is a passive tracer (it doesn't affect density)
- We initialize T_R to potential temp (theta) at the start of the experiment.
- T_R gets transported similar to theta; except it doesn't feel the perturbation (F)
- SST is computed from T_R and therefore not directly affected by F.
- T_A is the added heat tracer which can only feel the perturbation.

Response of AMOC to FAFMIP

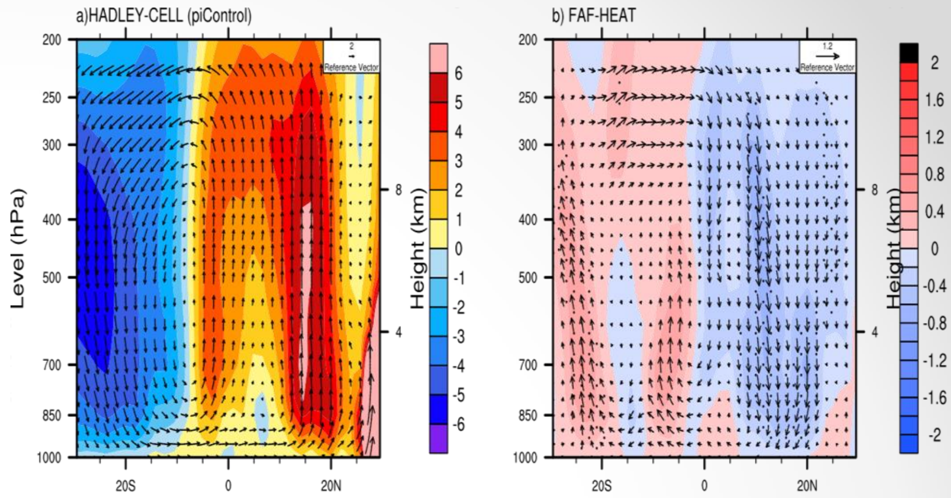




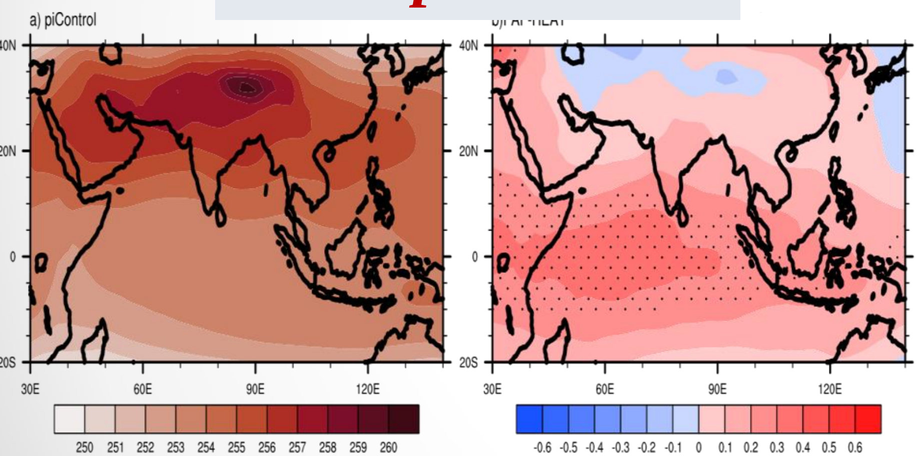


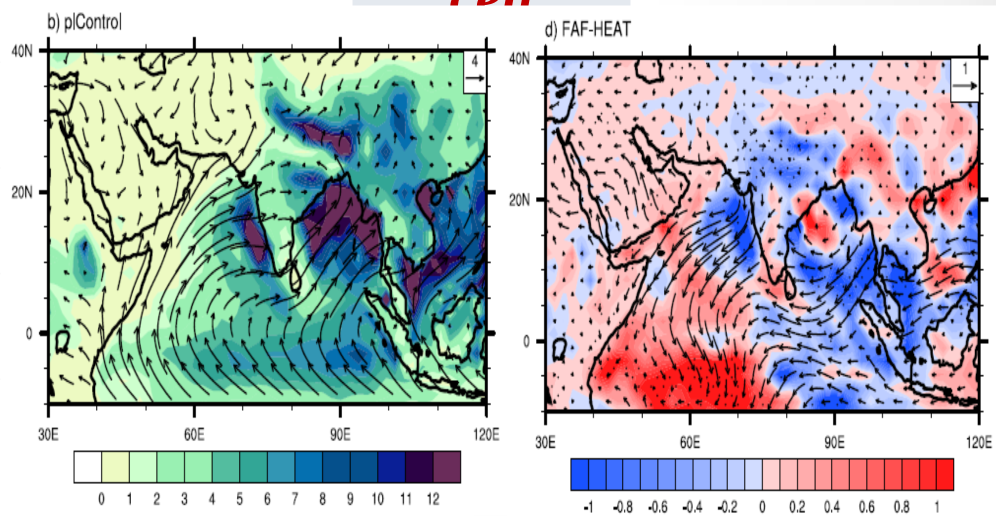


Sea Surface temperature



Hadley cell





850hPa-200hPa temperature

Precipitation and 850hPa winds

Sandeep et al. 2020, Clim. Dyn,

IITM-ESM

Future Plans

New Dynamical Core

CISM -Ice Model

High Resolution Modeling

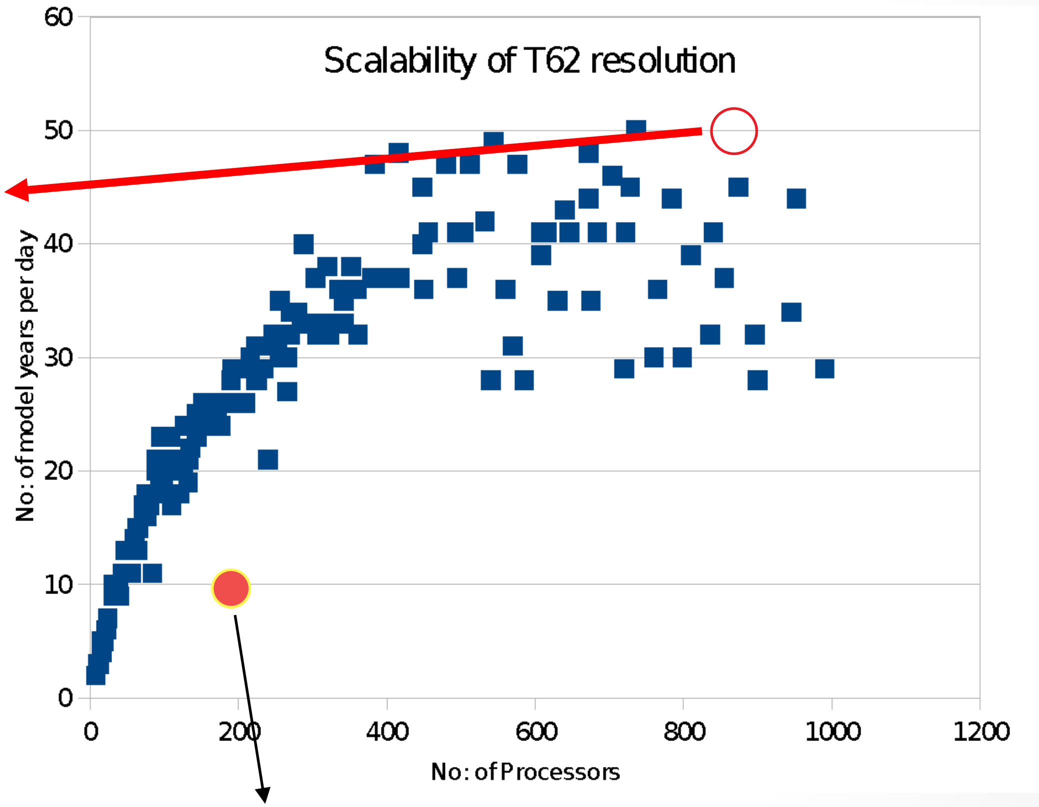
2020 - 2023 | **2024**

New Dyn. Core → **IITM-ESM - GLIMMER coupling** → **Testing IITM-ESMv3 & High Res. Modeling**

Implementation of New Dynamical Core in IITM-ESM

- **A highly scalable spectral Dynamical core for IITM-ESM atmospheric model**

T62 resolution with new dynamical core gives a maximum throughput of 50 model years per day



T62 resolution of current model gives a maximum throughput of 8 model years per day

Courtesy : Prajeesh

Implementation of New Dynamical Core in IITM-ESM

- Uses exactly the same formulations as the current dynamical core
- Uses a octahedral reduced gaussian grid (adopted from ECMWF) in place of the traditional reduced gaussian grid.
- Highly scalable compared to the current dynamical core, for e.g. T62 version can be run on more than 1000 processors, the current dynamical core can only be scaled upto 62 processors

Higher scalability and better performance

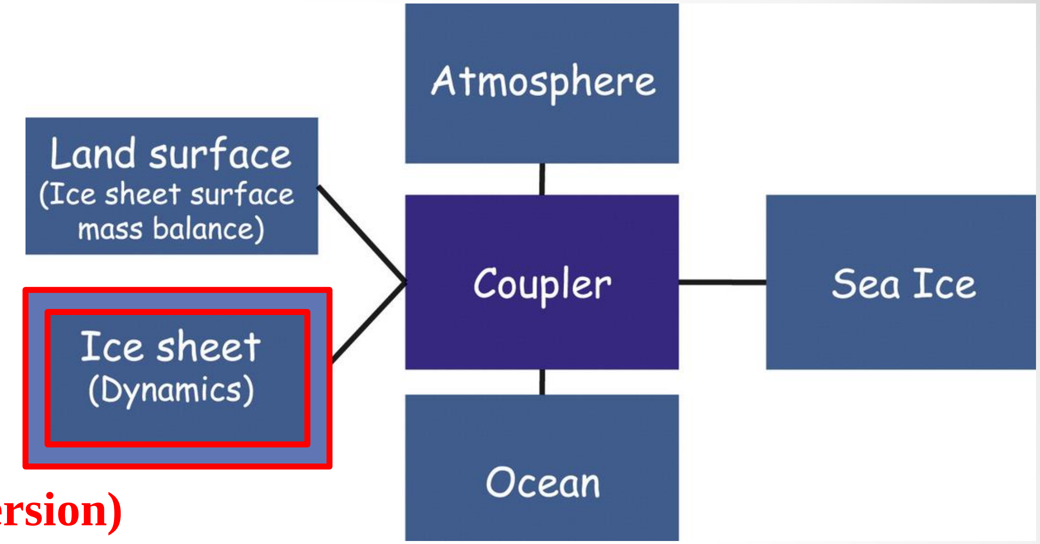
Easy coupling with other components

High Resolution Modeling
Very long palio-climatic runs.

Implementation of Land-Ice model in IITM-ESM

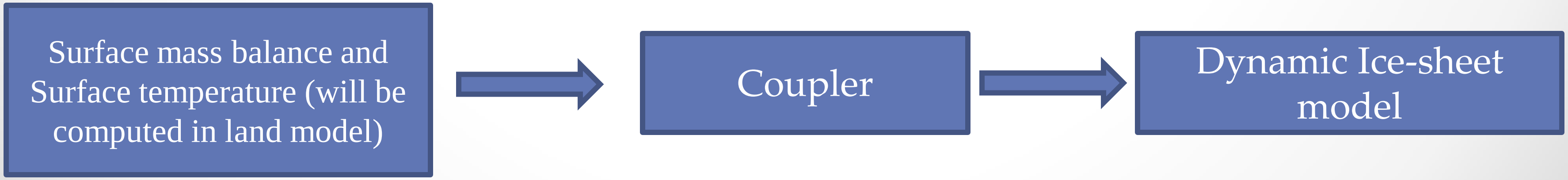
Components of IITM-ESM include :

- **Atmosphere**
- **Ocean**
- **Land surface**
- **Sea ice**
- **Ice sheet (to be included in the new-version)**



GLIMMER Ice-sheet model

- Community Ice Sheet model : Glimmer is a Dynamic ice sheet model, which computes ice velocities and the resulting evolution of ice sheet geometry and temperature.
- A surface mass balance scheme in the Land Model (Noah LSM), which computes accumulation and ablation at the upper surface of ice sheets.

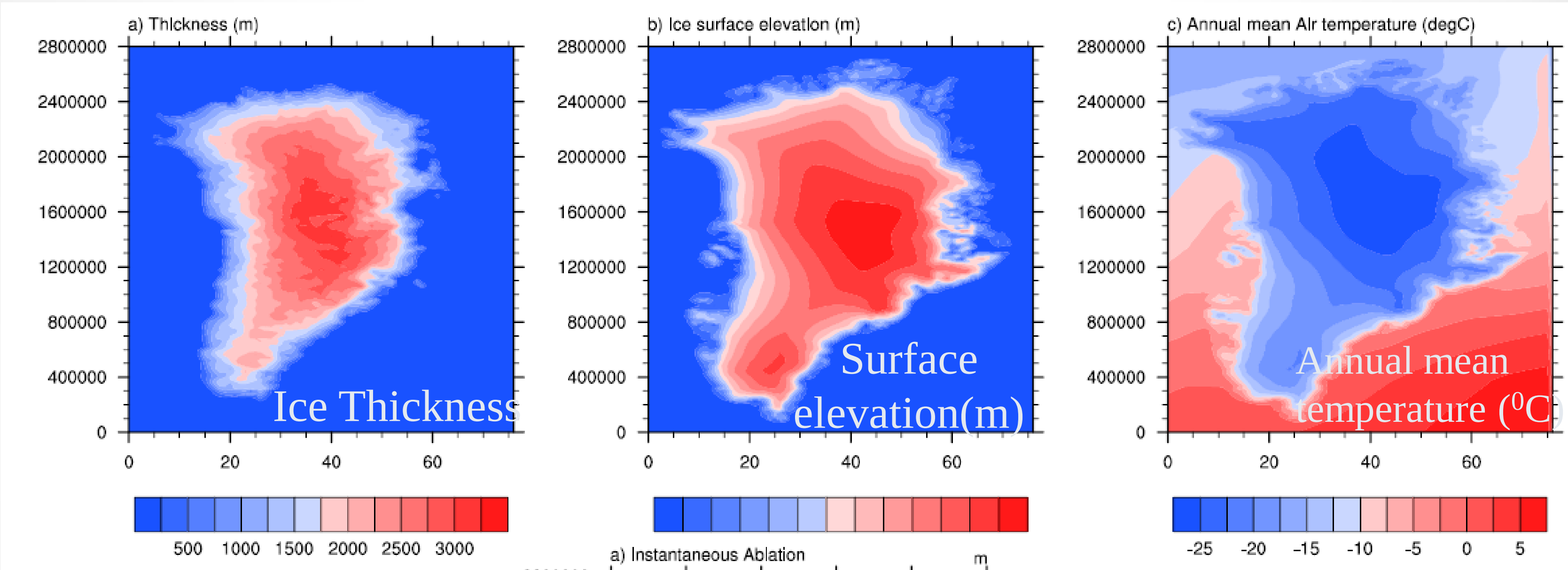


- The atmosphere and land models exchange fields hourly, and the land model passes fields to the ice sheet model daily.

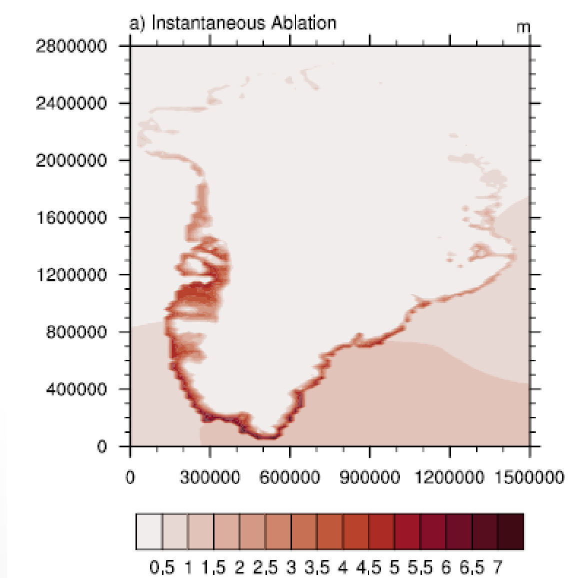
Courtesy : Sandeep

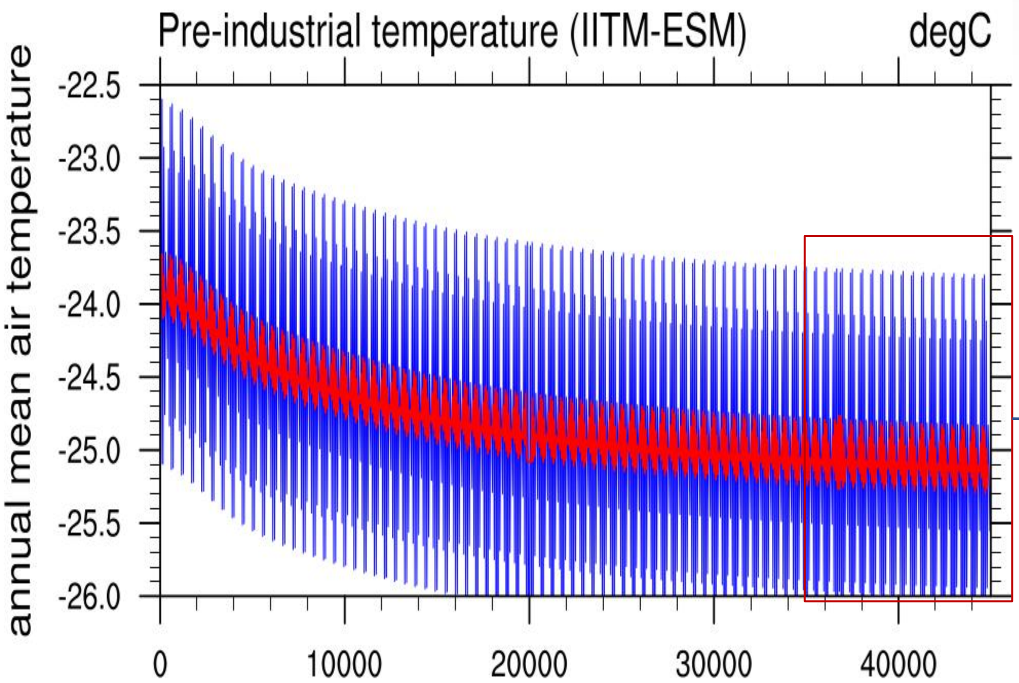
Implementation of Land-Ice model in IITM-ESM

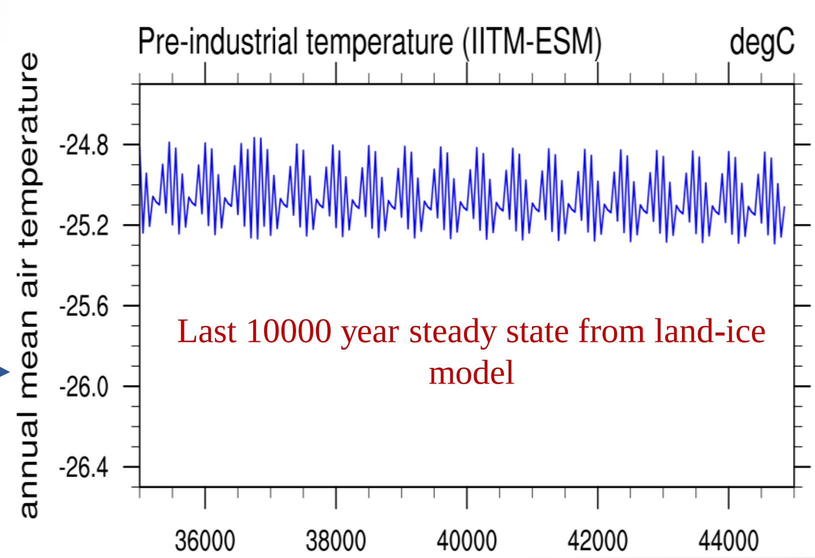
- Preliminary results:
- Stand-alone version of GLIMMER forced with NCEP surface fluxes.

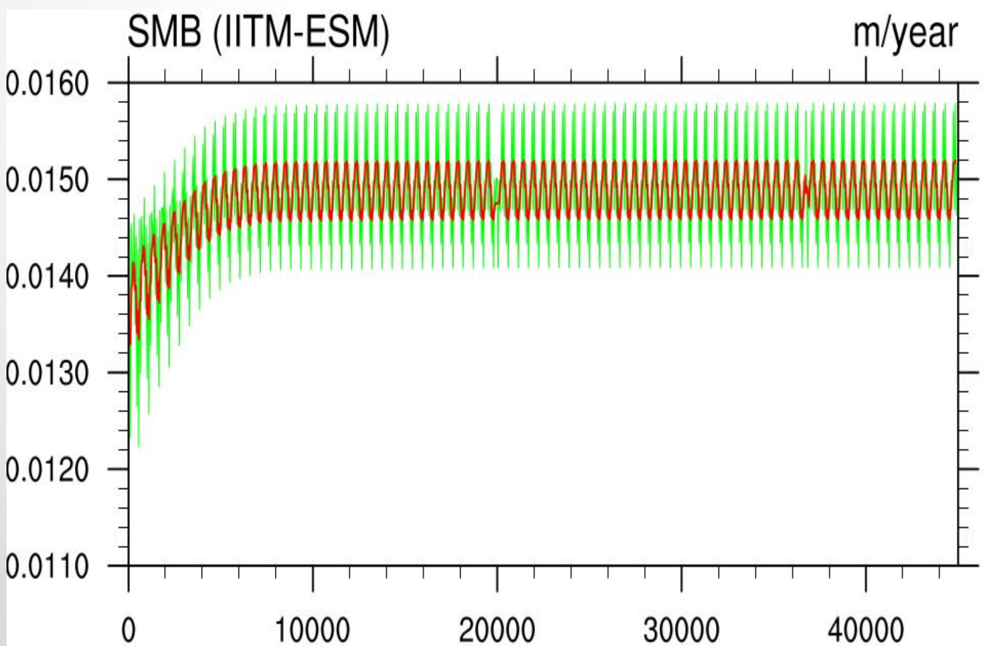


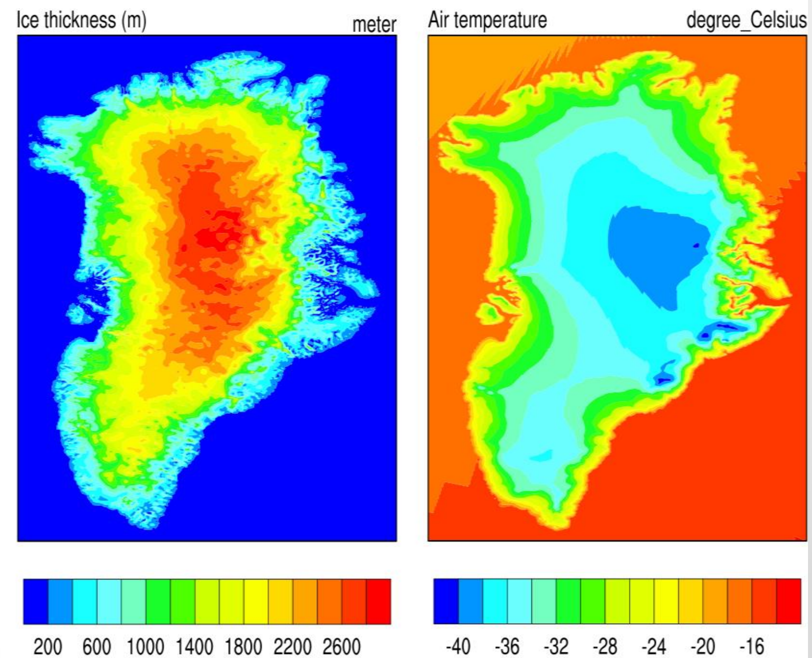
- Instantaneous Ablation (m) :



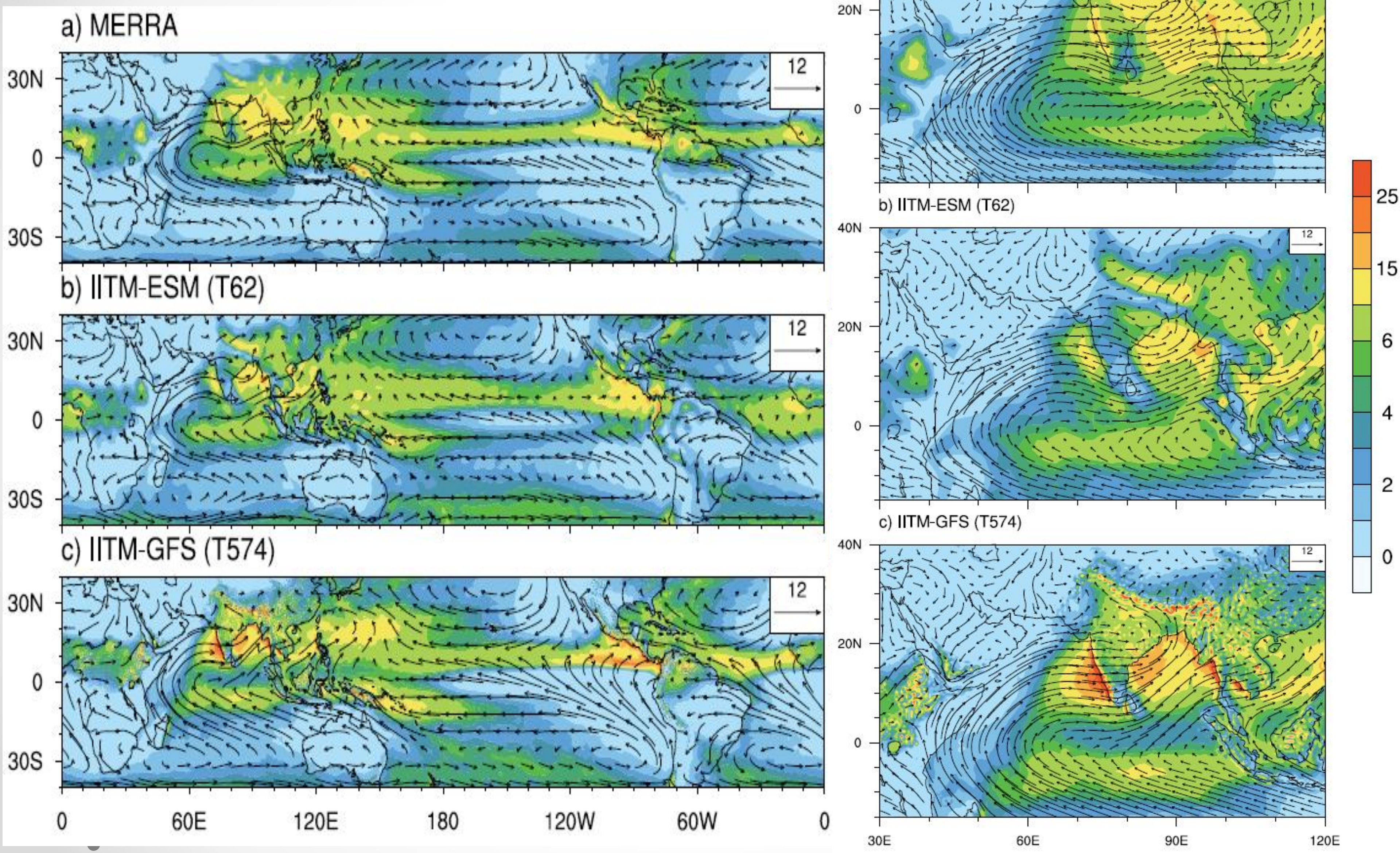

Pre-industrial temperature (IITM-ESM)
degC
annual mean air temperature
-22.5
-23.0
-23.5
-24.0
-24.5
-25.0
-25.5
-26.0
0
10000
20000
30000
40000


Pre-industrial temperature (IITM-ESM)
degC
annual mean air temperature
-24.8
-25.2
-25.6
-26.0
-26.4
36000
38000
40000
42000
44000
Last 10000 year steady state from land-ice model


SMB (IITM-ESM)
m/year
0.0160
0.0150
0.0140
0.0130
0.0120
0.0110
0
10000
20000
30000
40000


Ice thickness (m)
meter
Air temperature
degree_Celsius
200 600 1000 1400 1800 2200 2600
-40 -36 -32 -28 -24 -20 -16

IITM-ESM : High resolution modeling (T574)



Courtesy : Sabin

Way forward

- New Spectral Dynamical Core
- High Resolution ESM
- Interactive Land-Ice model
- Improved mean state


THANK
YOU!