

# Climate Change and the Oceans

## Climate Change Adaptation and Mitigation

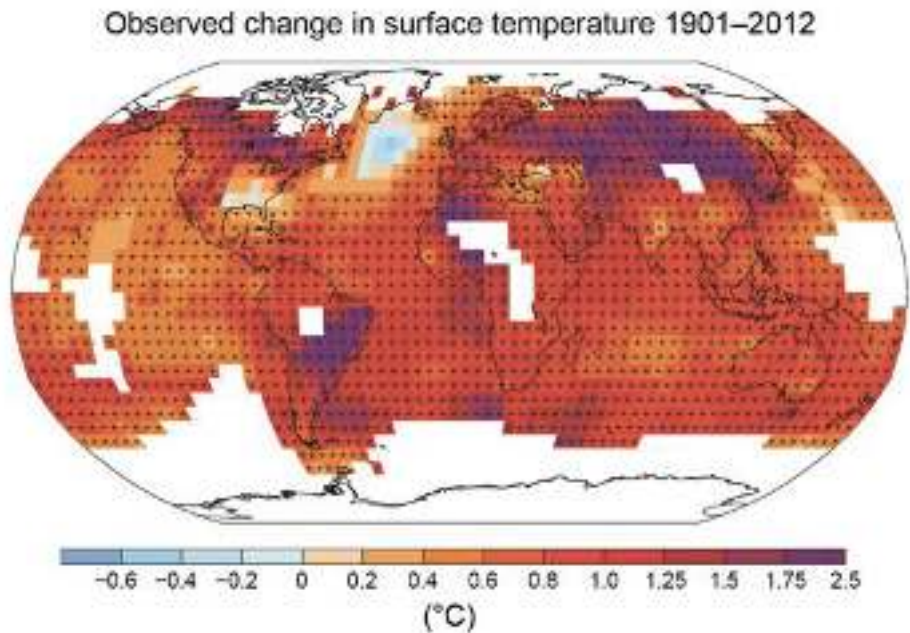
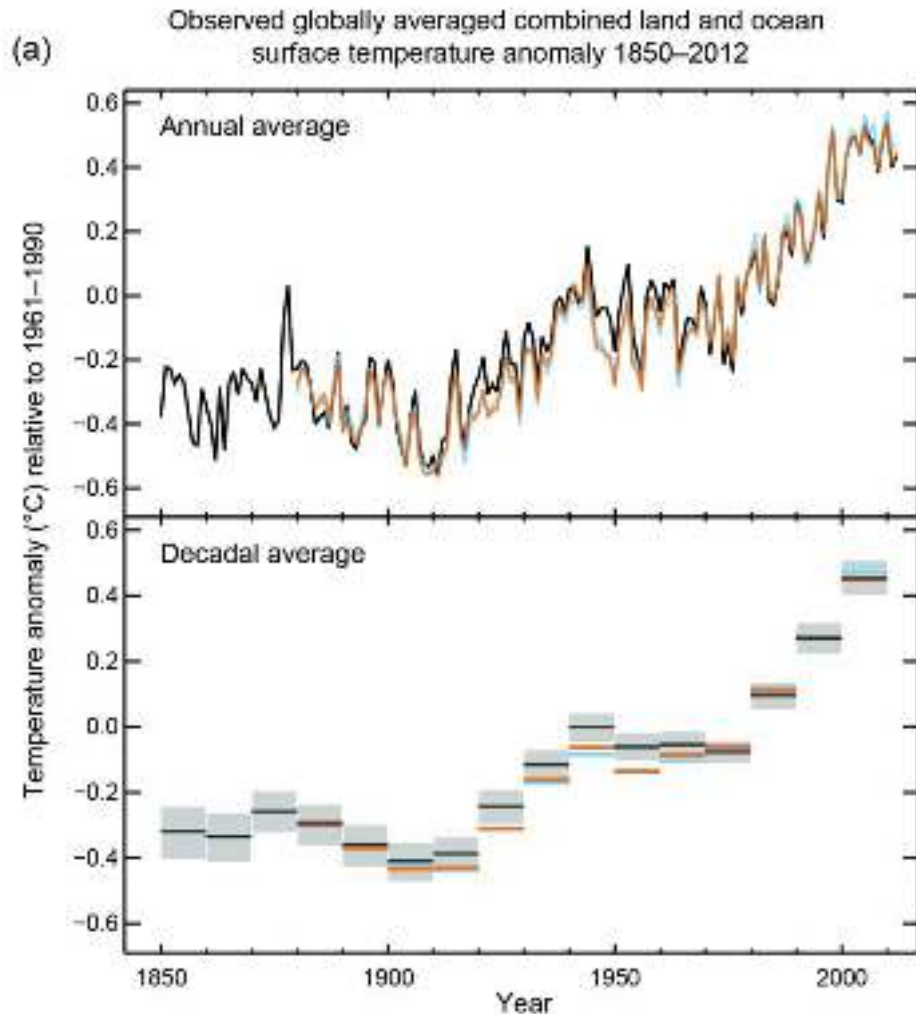
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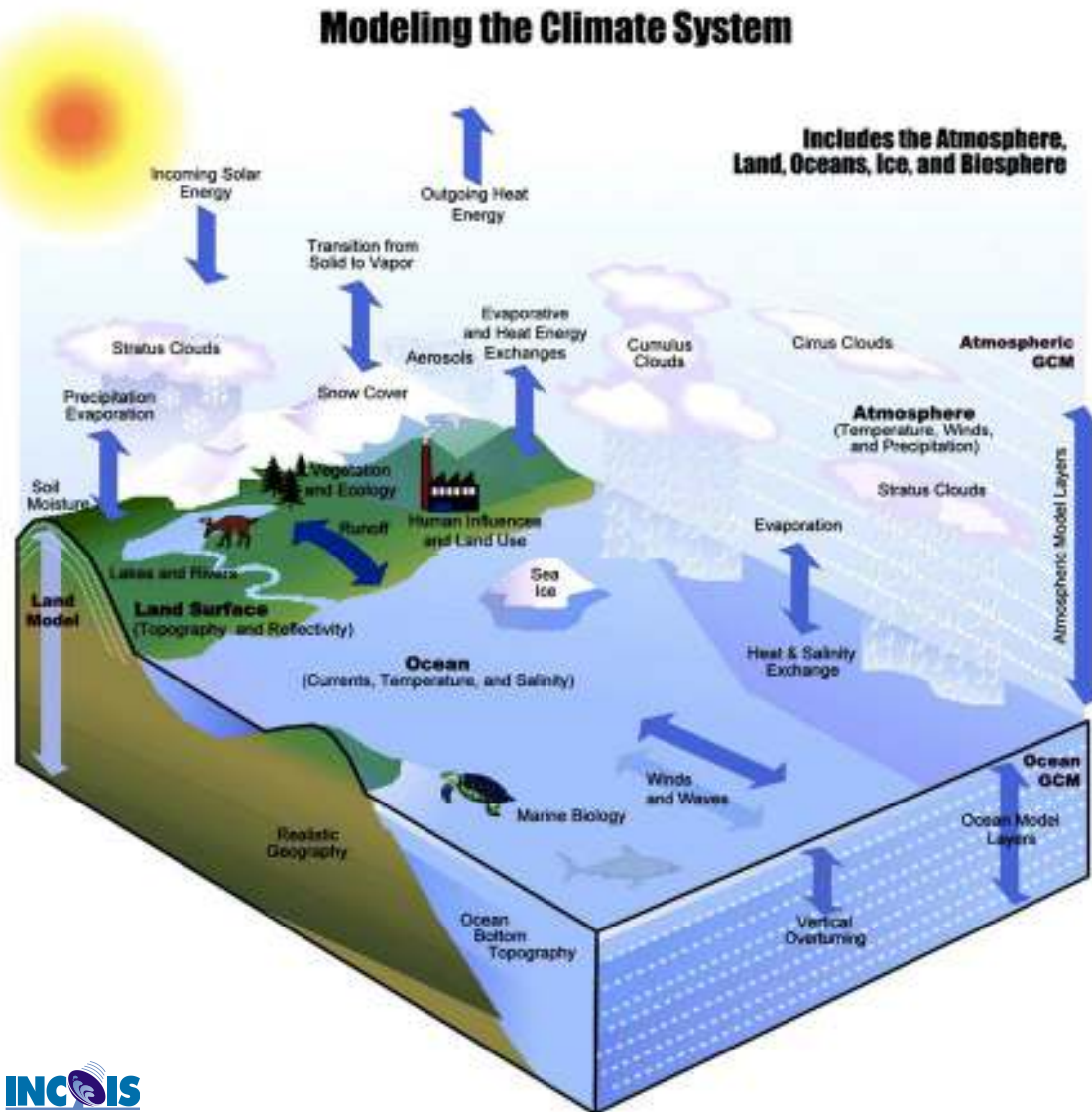
Email [shenoi@incois.gov.in](mailto:shenoi@incois.gov.in)

# Warming of the climate system is unequivocal



IPCC, AR5, 2013

# Where all that Heat is getting Accumulated?



- **1% atmosphere**
- **3% soils**
- **3% glacier melt**
- **93% oceans**

# **Our oceans .....**

**Contains 96% of the living space on Earth**

**Has 80% Earth's living organisms**

**Covers 71% of the Earth**

**Almost half of the oxygen we breath is produced  
by ocean plants**

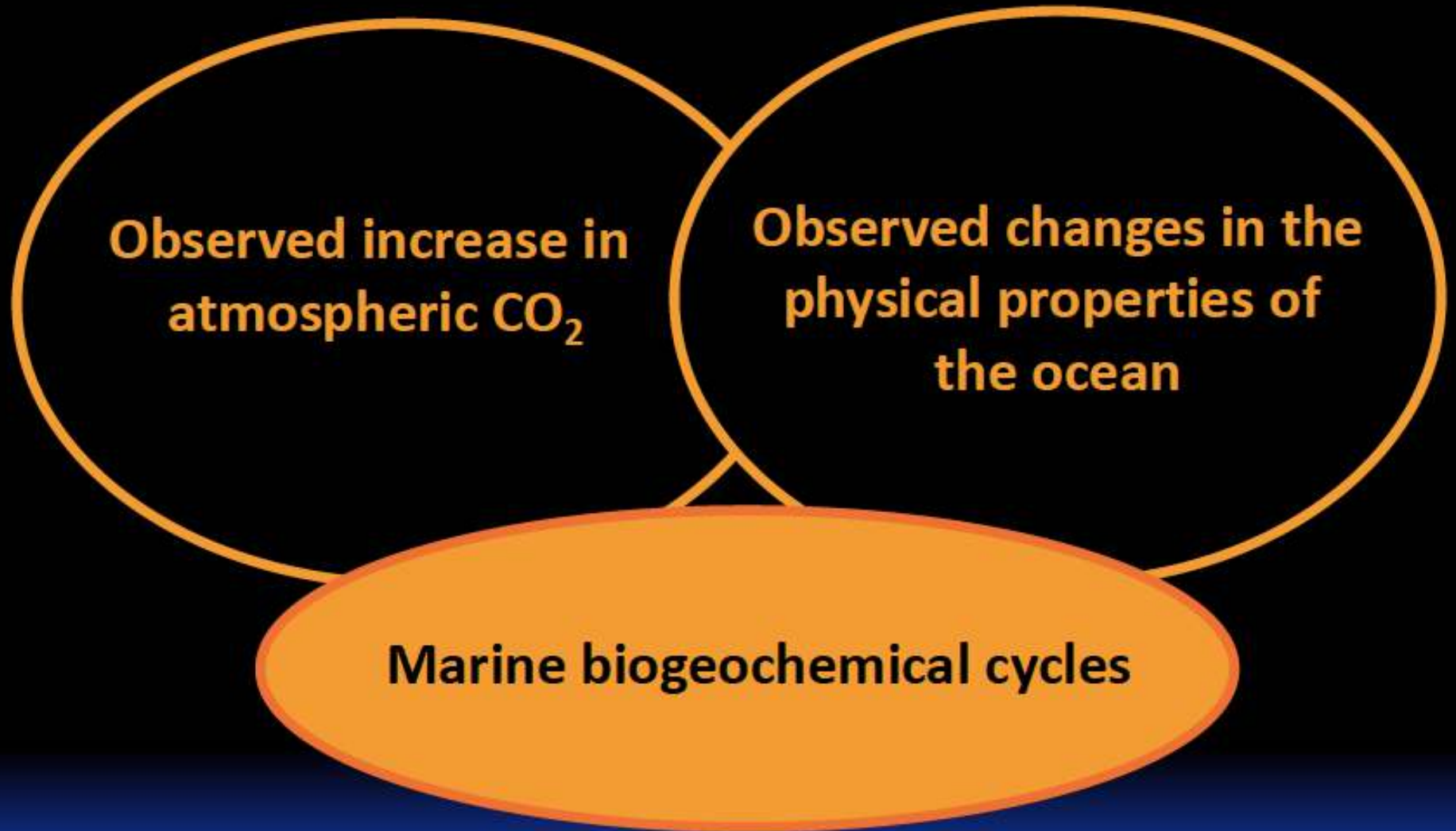
**Fish provide 4.2 billion people with at least 15% of  
their animal protein**


**90% of the world trade is carried across the ocean**

**Holds an estimated 80% of Earth's mineral  
resources**




# in a warmer world.....






**Increase in atmospheric CO<sub>2</sub> :**  
**Additional CO<sub>2</sub> dissolves in the ocean**



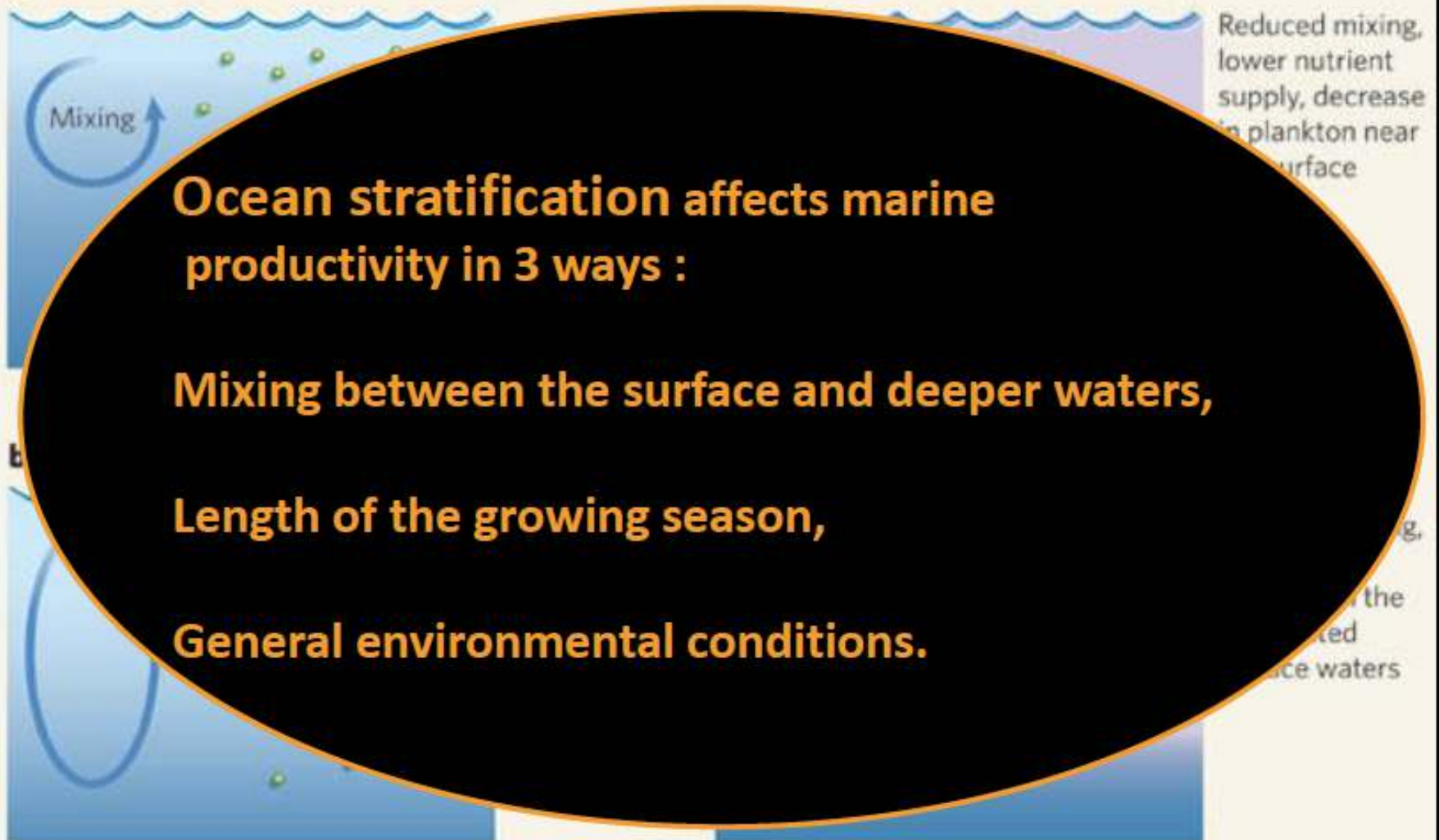
**Changes in temperature and salinity :**  
**Solubility and chemical equilibration of gases**



**Changes in circulation :**  
**Supply of carbon and nutrients from below,**  
**Ventilation of oxygen-depleted waters,**  
**Downward penetration of**  
**anthropogenic carbon**

Tropics and mid-latitudes (nutrient-limited)

a



**Ocean stratification affects marine productivity in 3 ways :**

**Mixing between the surface and deeper waters,**

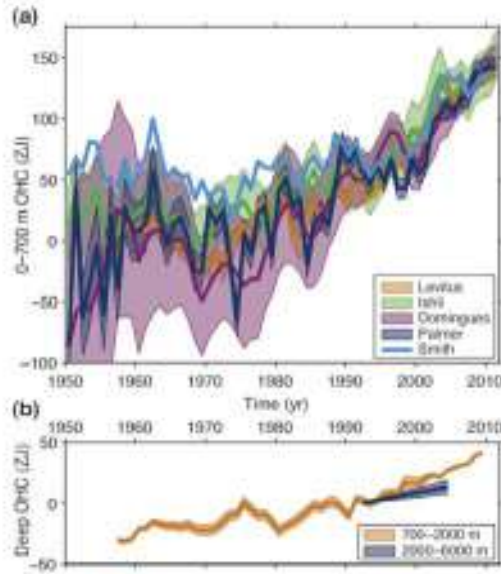
**Length of the growing season,**

**General environmental conditions.**



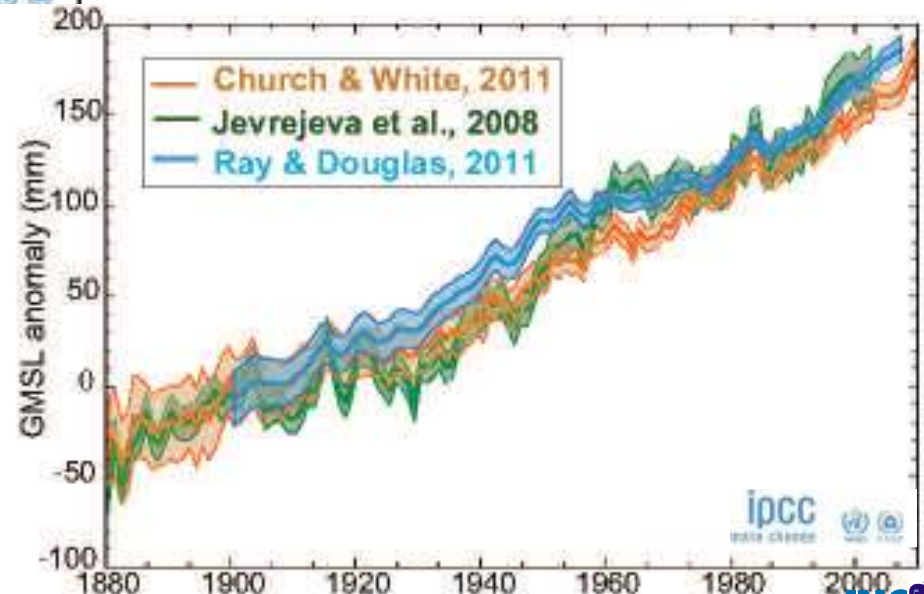
# Warming Oceans and raising sea levels

## Change in ocean heat content



“It is virtually certain that upper ocean (0 to 700 m) heat content increased during the relatively well-sampled 40-year period from 1971 to 2010” (IPCC AR 5).

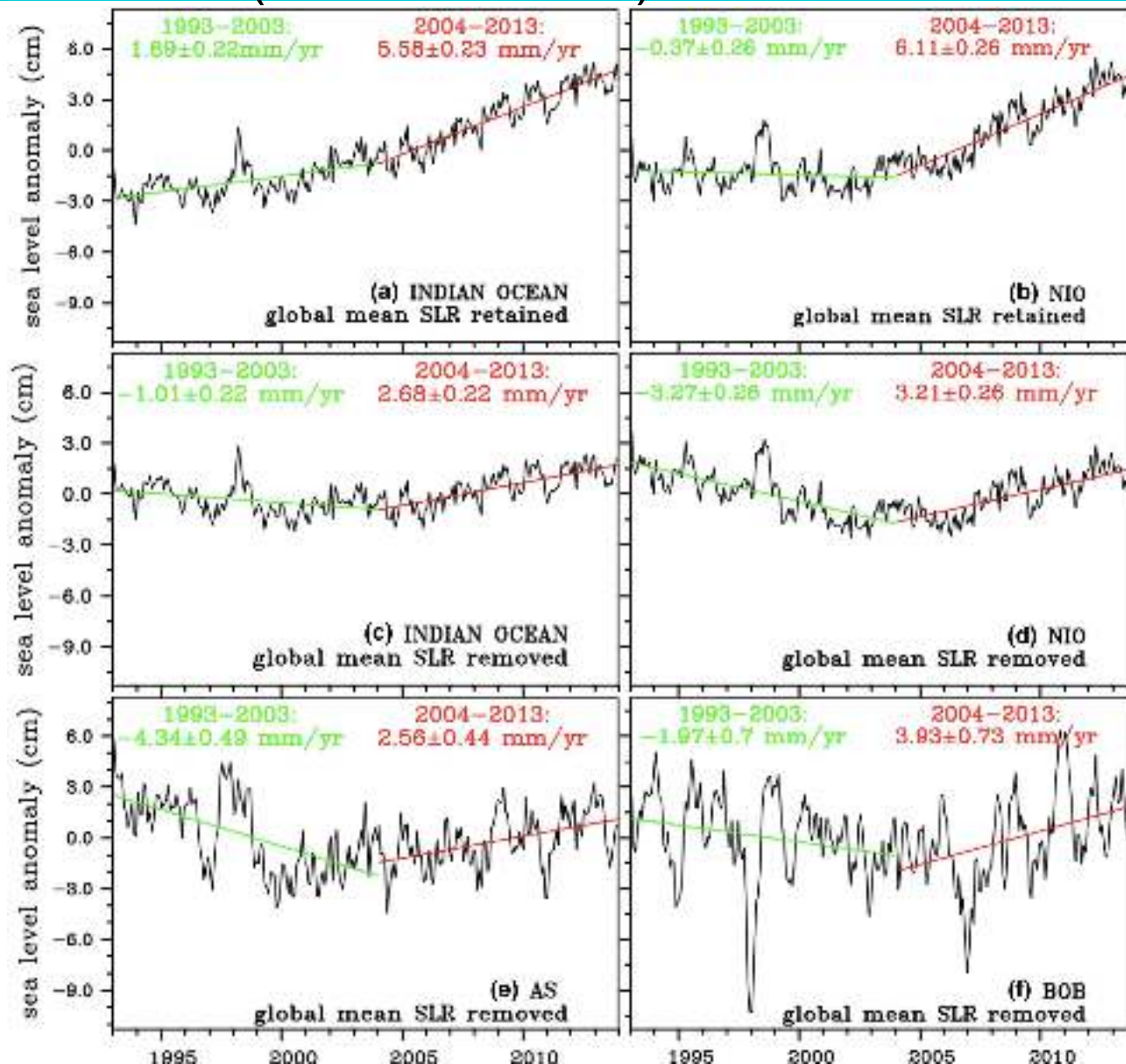
## Changes in sea level



“It is very likely that the mean rate was  $1.7 [1.5 \text{ to } 1.9] \text{ mm yr}^{-1}$  between 1901 and 2010 and increased to  $3.2 [2.8 \text{ to } 3.6] \text{ mm yr}^{-1}$  between 1993 and 2010” (IPCC AR 5)

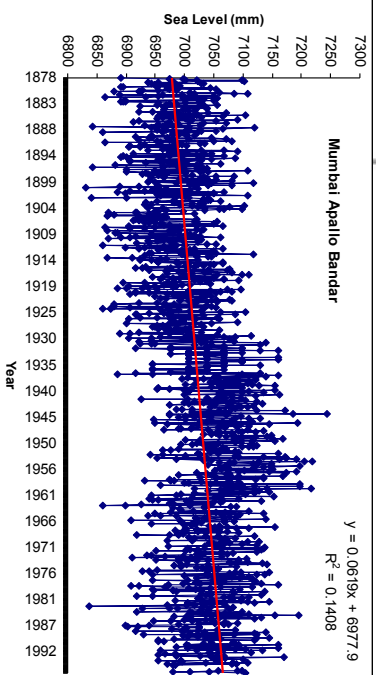
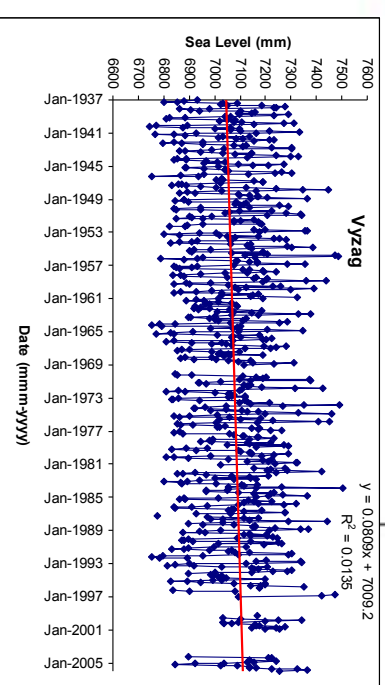
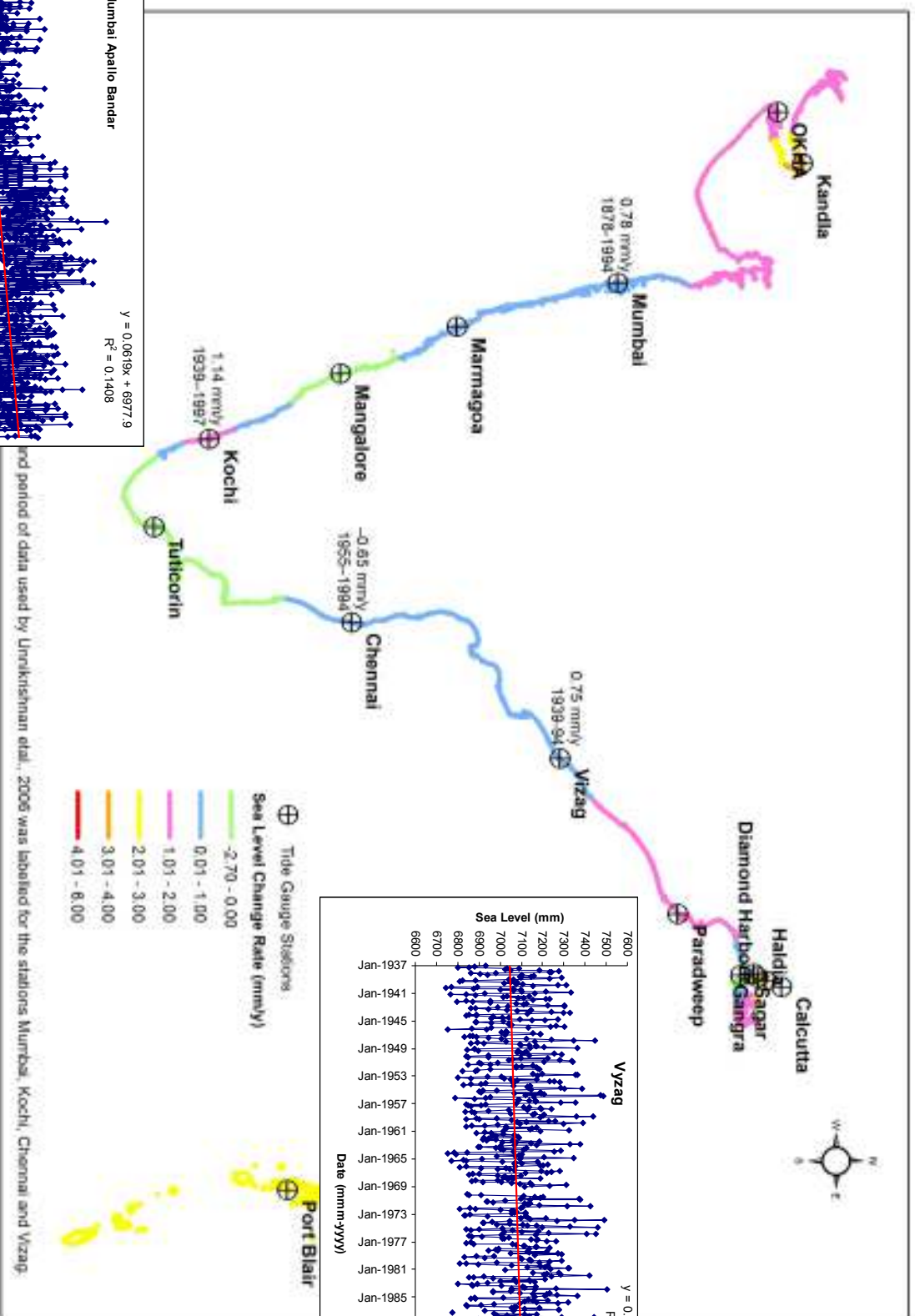


There seems to be a distinct change in the the sea level raise in the North Indian Ocean (NIO, north of 5°S) between 1993-2003 and 2004-2013 (decadal trend?)



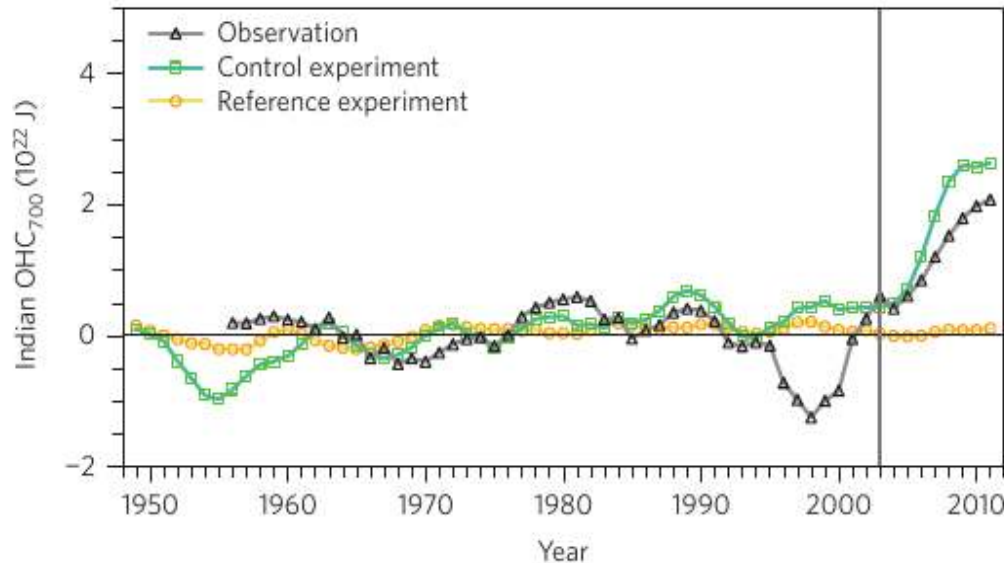
Srinivasu et al., 2017

# Historic Sea level data along the Indian coast



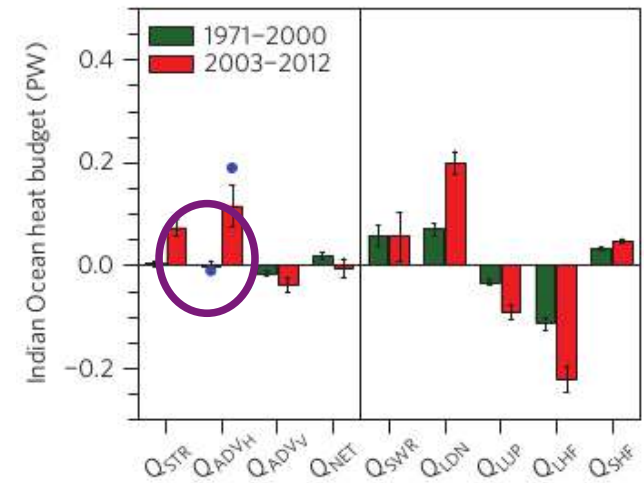
and period of data used by Lindekrishnan et al., 2006 was labelled for the stations Mumbai, Kochi, Chennai and Vizag.

# Indian Ocean is warming rapidly in the recent decade at a rate of $2.1 \times 10^{22}$ J per decade



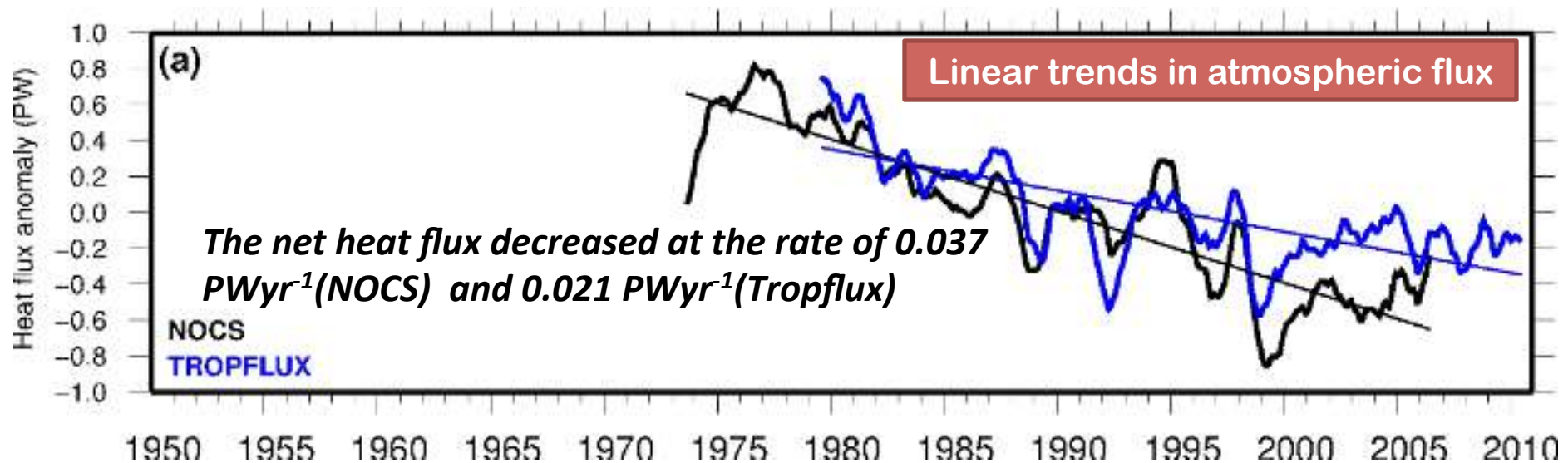
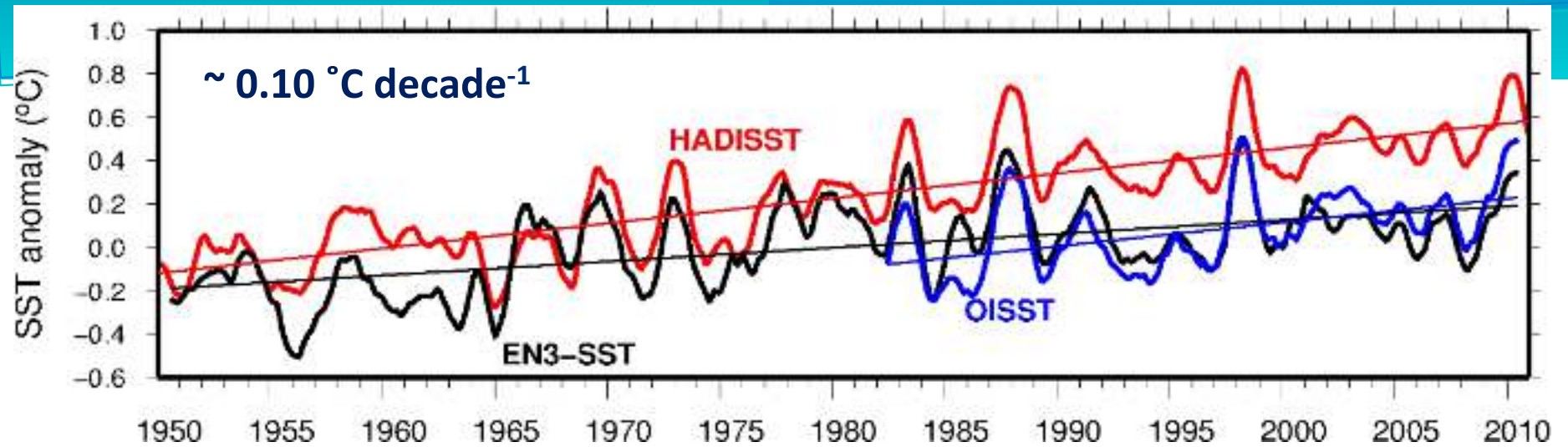
Net heat flux decreased during 2003-2012. Suggesting that net heat gain by the Indian Ocean must be transported from other basins.

Heat content in the top 700 m water column of Indian Ocean. **Green curve** shows the simulated heat content using NCAR Community Earth System Model forced by real-time surface flux fields and the **yellow curve** shows the solutions forced by the climatological flux.



Lee et al., Nature Geo., 2015

# Warming Indian Ocean

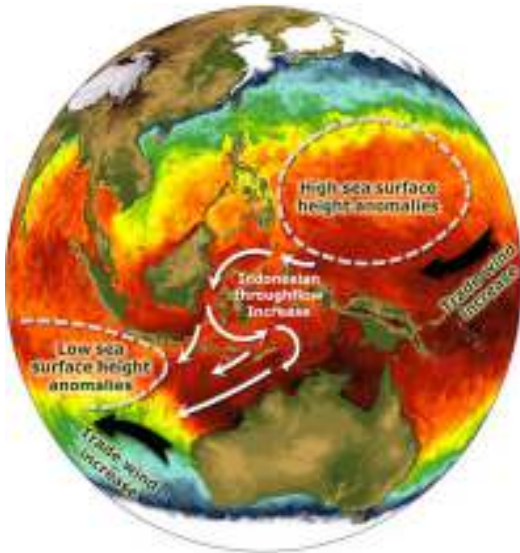
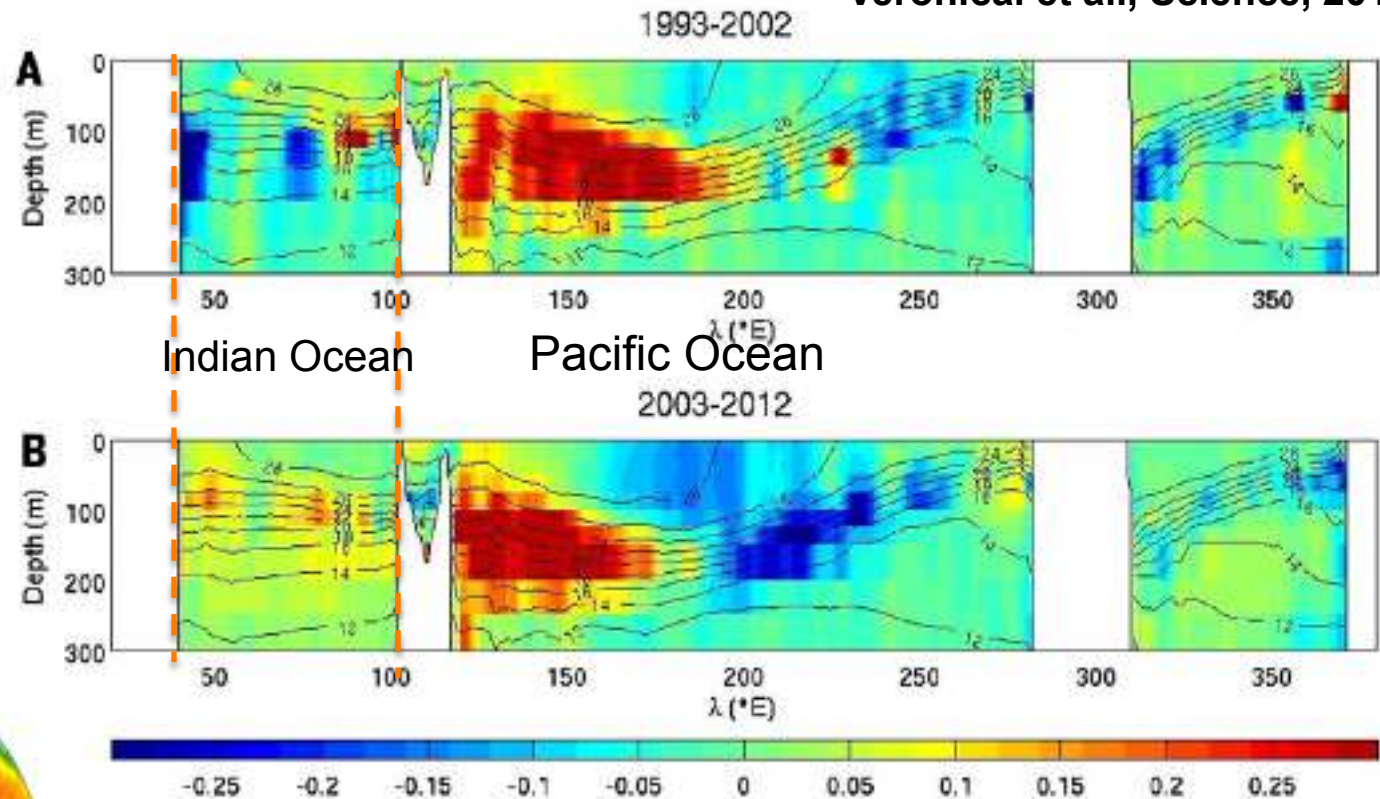


**If we assume that that heat will be used to warm/cool the mixed layer of the ocean, the 0.037 PW yr<sup>-1</sup> decrease should cool the mixed layer at the rate of 0.01 °Cyr<sup>-1</sup>.**



# Mechanisms of Indian Ocean warming

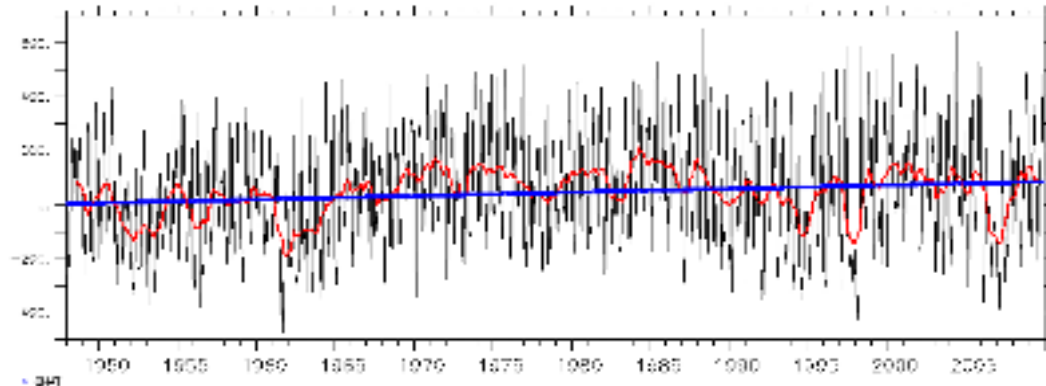
Veronica et al., Science, 2015



Lee et al. (2015) suggests that the surplus heat flux over the Pacific get transported into the southern Indian Ocean through Indian Ocean throughflow.

# Mechanisms of the Indian Ocean warming

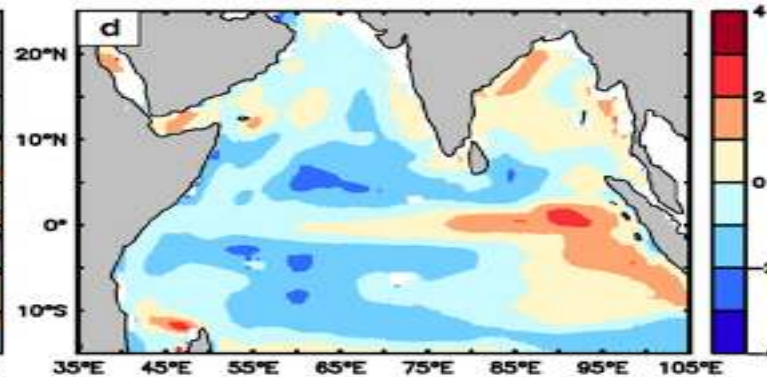
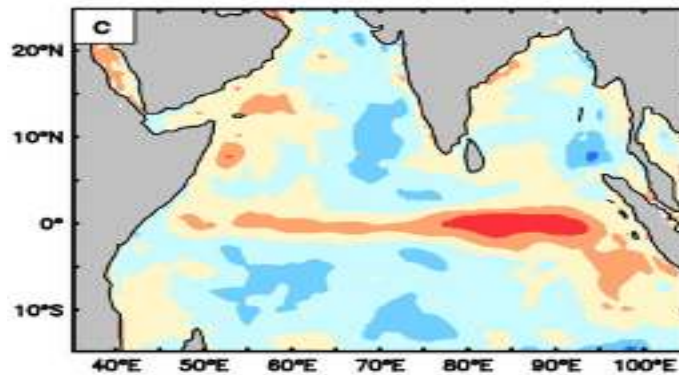
Westerly winds (averaged over 60-80E/2.5S-2.5N) enhanced by about  $1.0 \text{ m s}^{-1}$  during 1950-2008.



**MLD deepened by 1 m per decade in the Central and Eastern EIO**

SODA

ORAS4

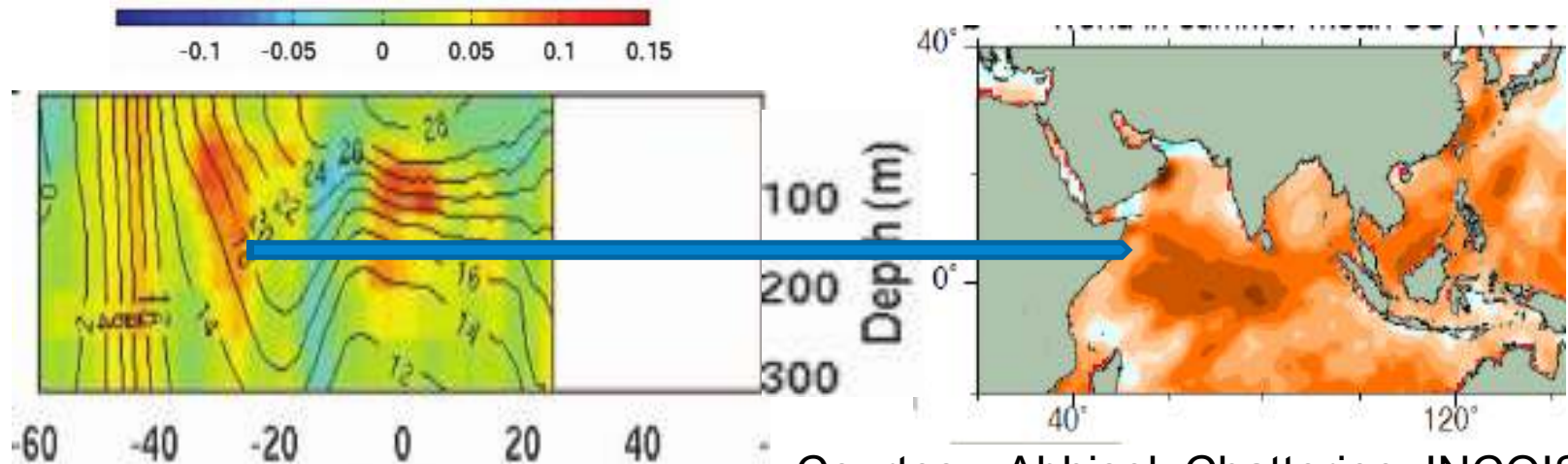
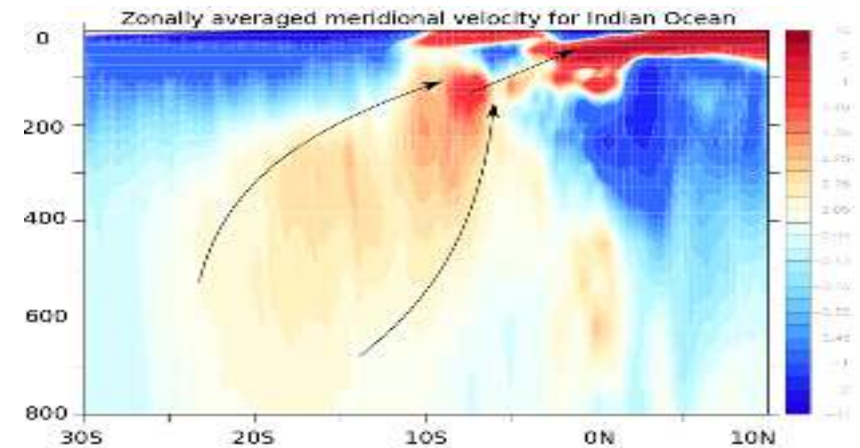


Warming trend in the central EIO is due to enhanced westerlies and thus deepening of the MLD in the equatorial Indian Ocean.

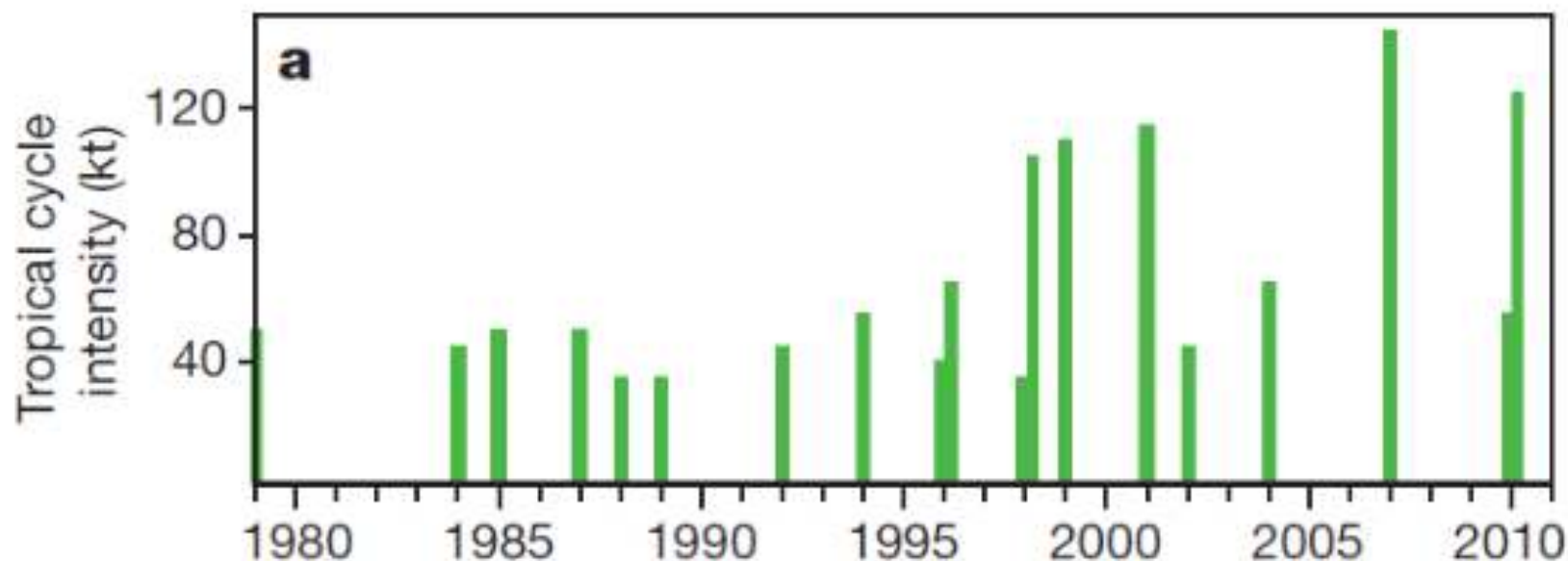
# Is there a roll for the Cross-Equatorial Cell in the perceived warming ?

Zonally averaged meridional velocity from CORE-II simulations shows cross equatorial cells (CECs)

CEC transports subsurface water from the south Indian Ocean (IO) to the surface of north-western IO



# Intensification of cyclones in the Arabian Sea

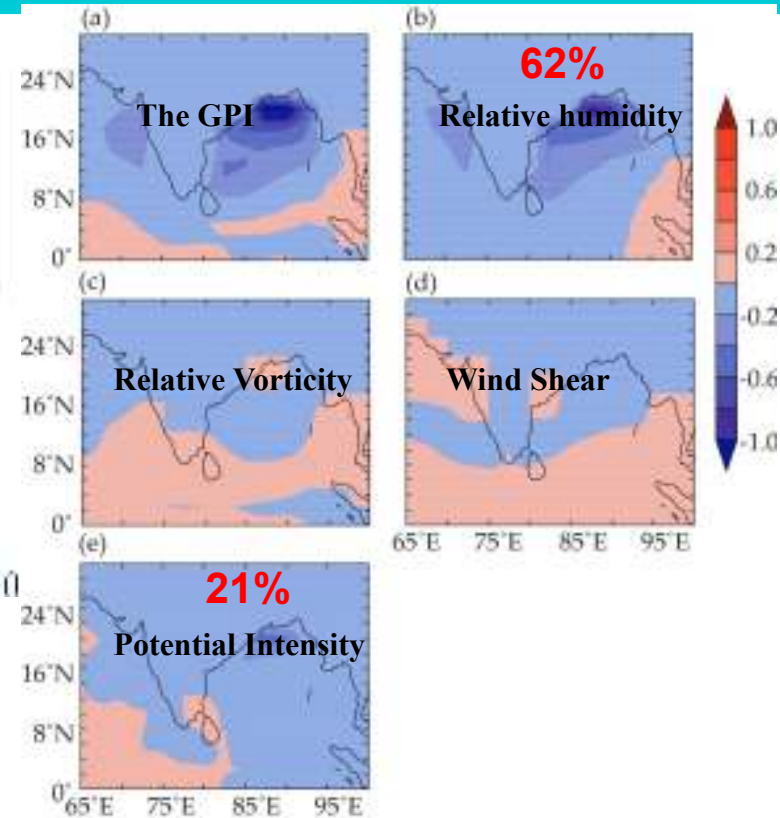
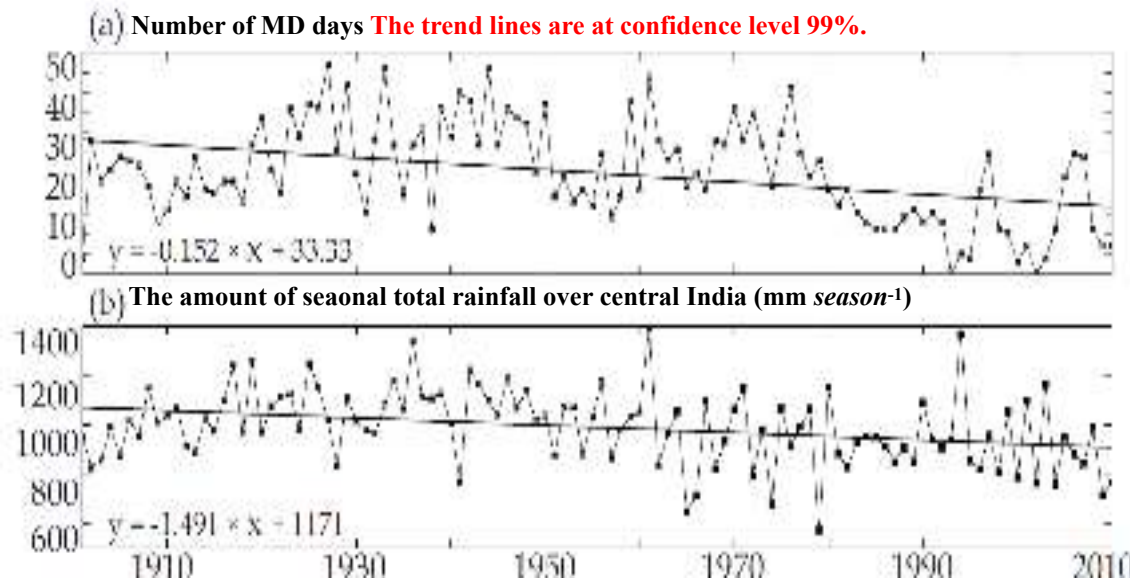


Intensification of the tropical cyclone shown by the maximum wind speed of each pre-monsoon Arabian Sea tropical cyclones.

Wang et al. (2012)

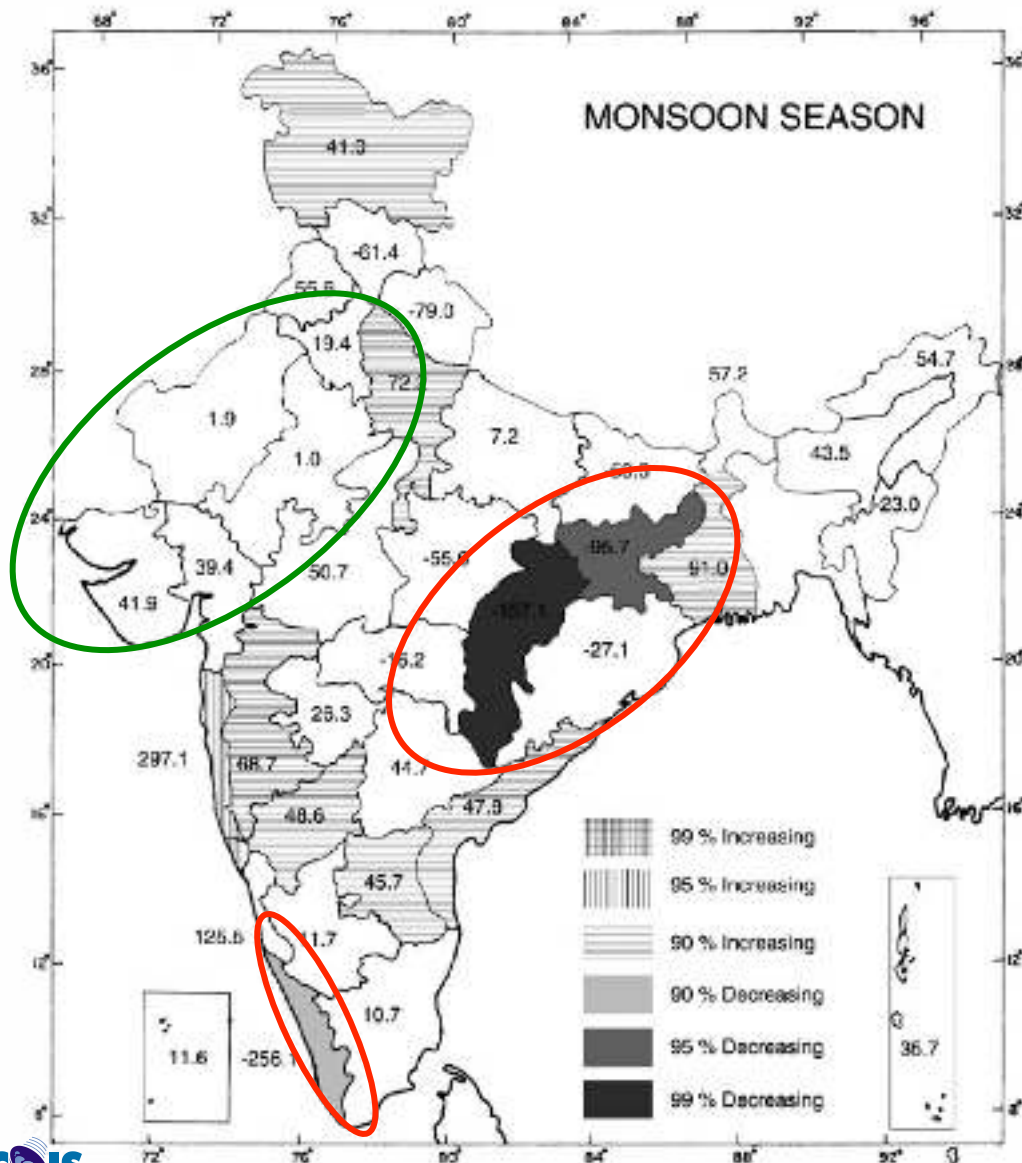


# Decreasing number of monsoon depressions over the Bay of Bengal



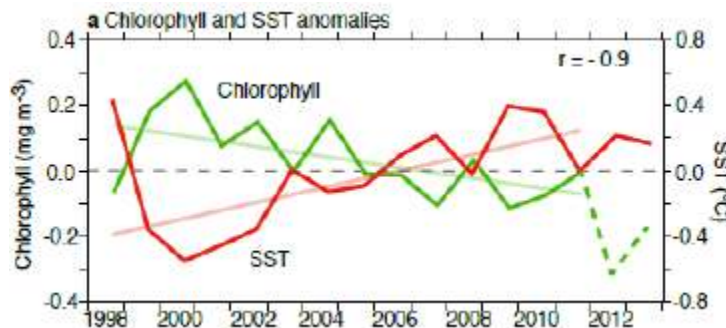
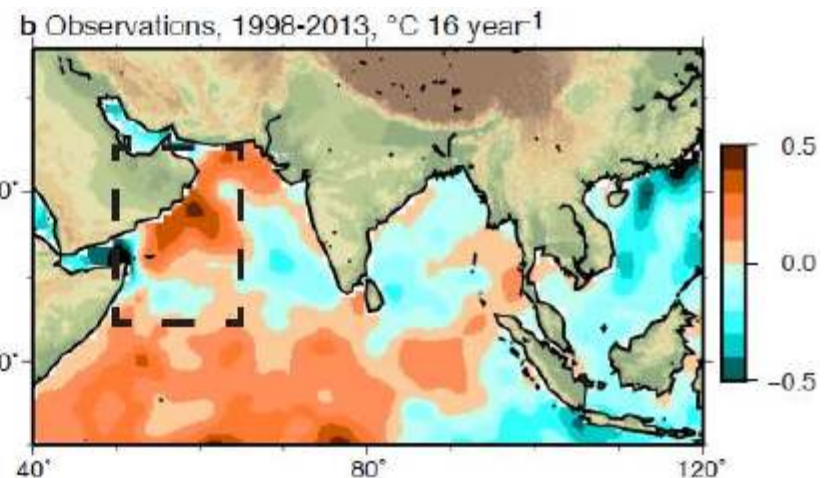
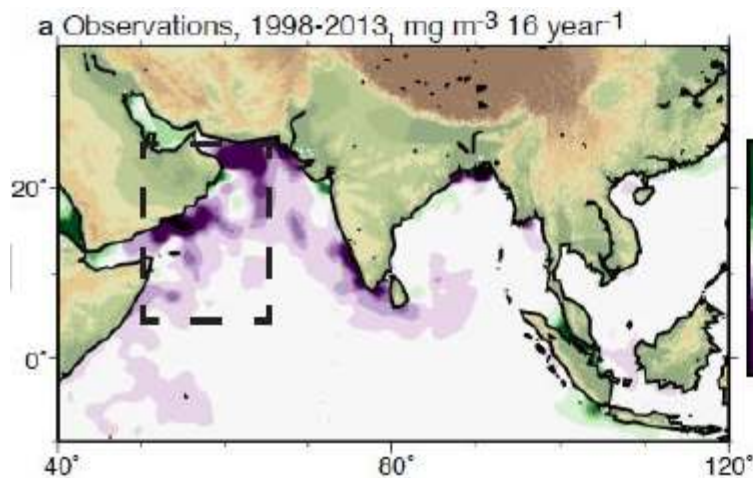
- A quantitative estimate of the relative contribution of each of the environmental variables responsible for the variation in the number of MD shows that decreasing trend in mid-tropospheric humidity (primary contribution, 62%) and Potential Intensity (PI) (secondary contribution, 21%) leads to the decreasing trend in MD.

# Climate change and changing monsoonal rainfall patterns



Guhathakurta and  
Rajeevan (2007)

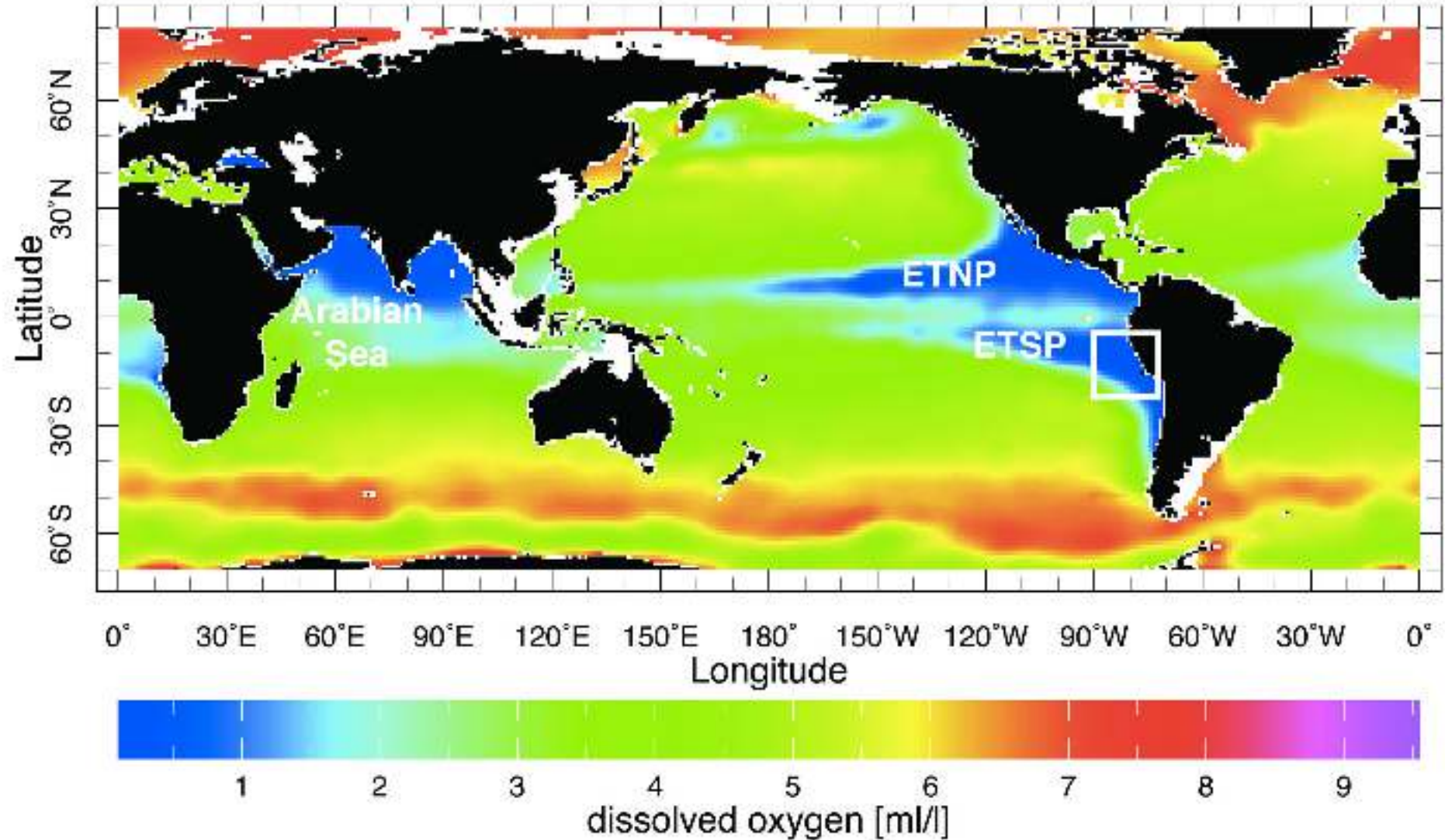
# Warming of the north Indian Ocean leads to decrease in productivity over the large part of the Arabian Sea



Recently, Roxy et al. (GRL, 2015) identified that the summer monsoon Chl productivity decreased by  $\sim 30\%$  in the last two decades. They attributed this decrease to the western IO warming, which in turn makes the ocean more stratified and reduces nutrient pumping to the surface layer.



# Are we running out of oxygen in our oceans?





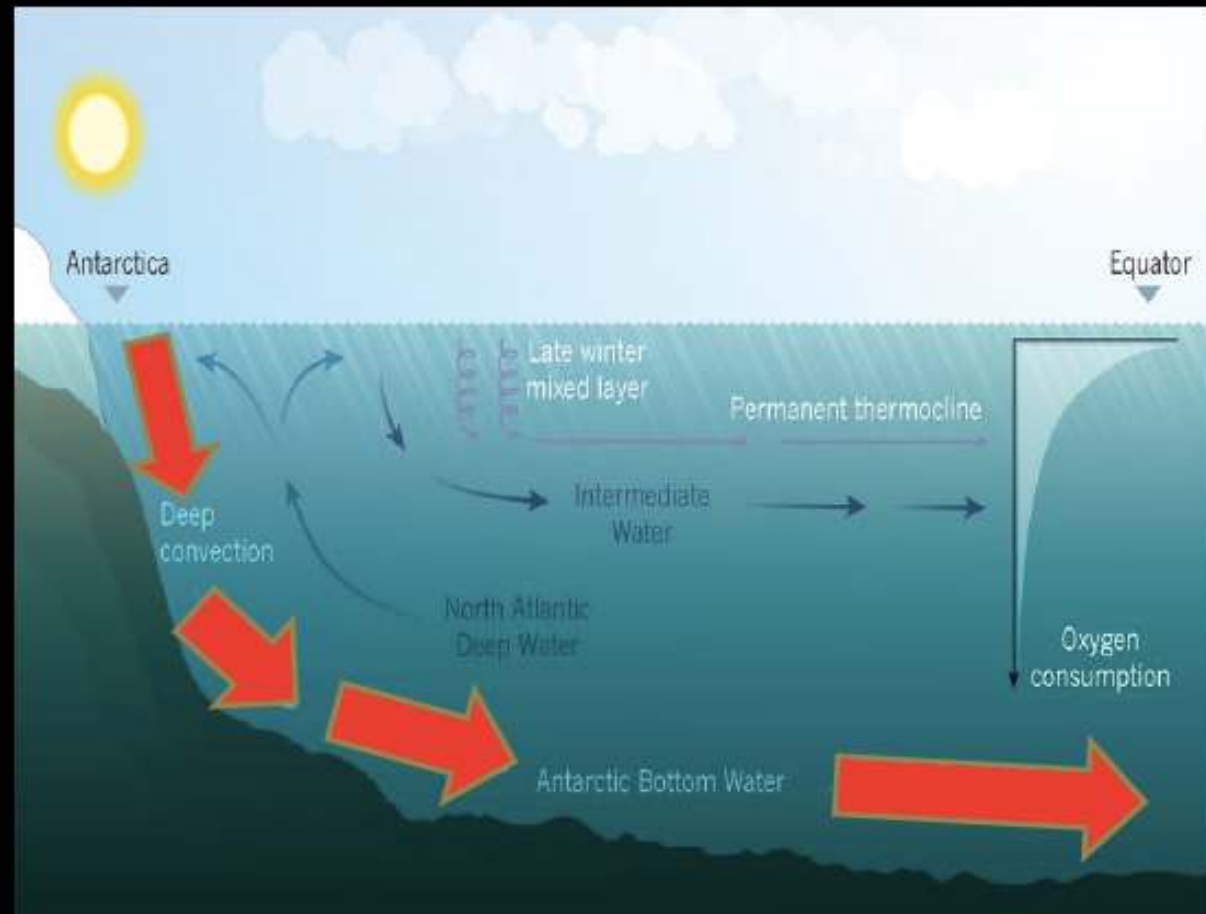
# Why is deoxygenation ongoing?

**Upper water column:**  
**Biological consumption**

**Deeper ocean:**  
**Oceanic overturning slowdown**

**Biological consumption**

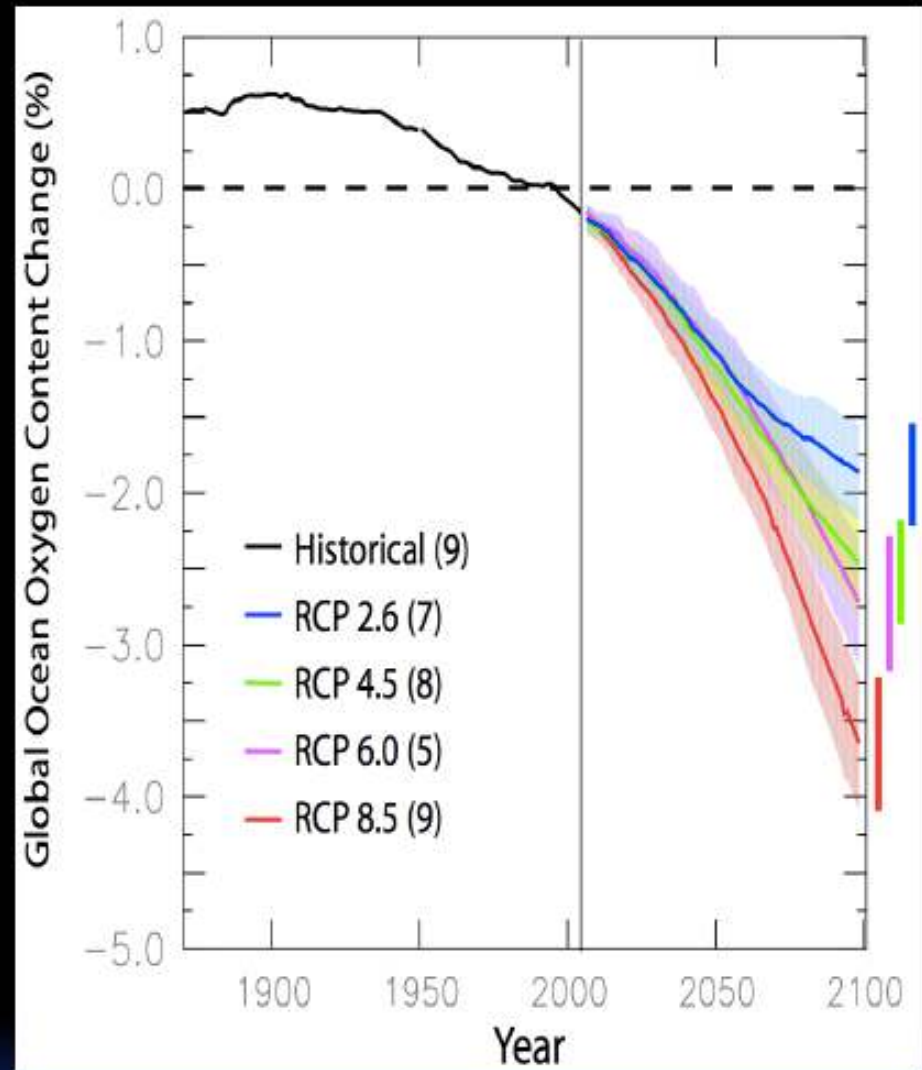
**Basin scale multi-decadal variability**



# Will deoxygenation continue?

Current IPCC models consistently predict that deoxygenation will continue

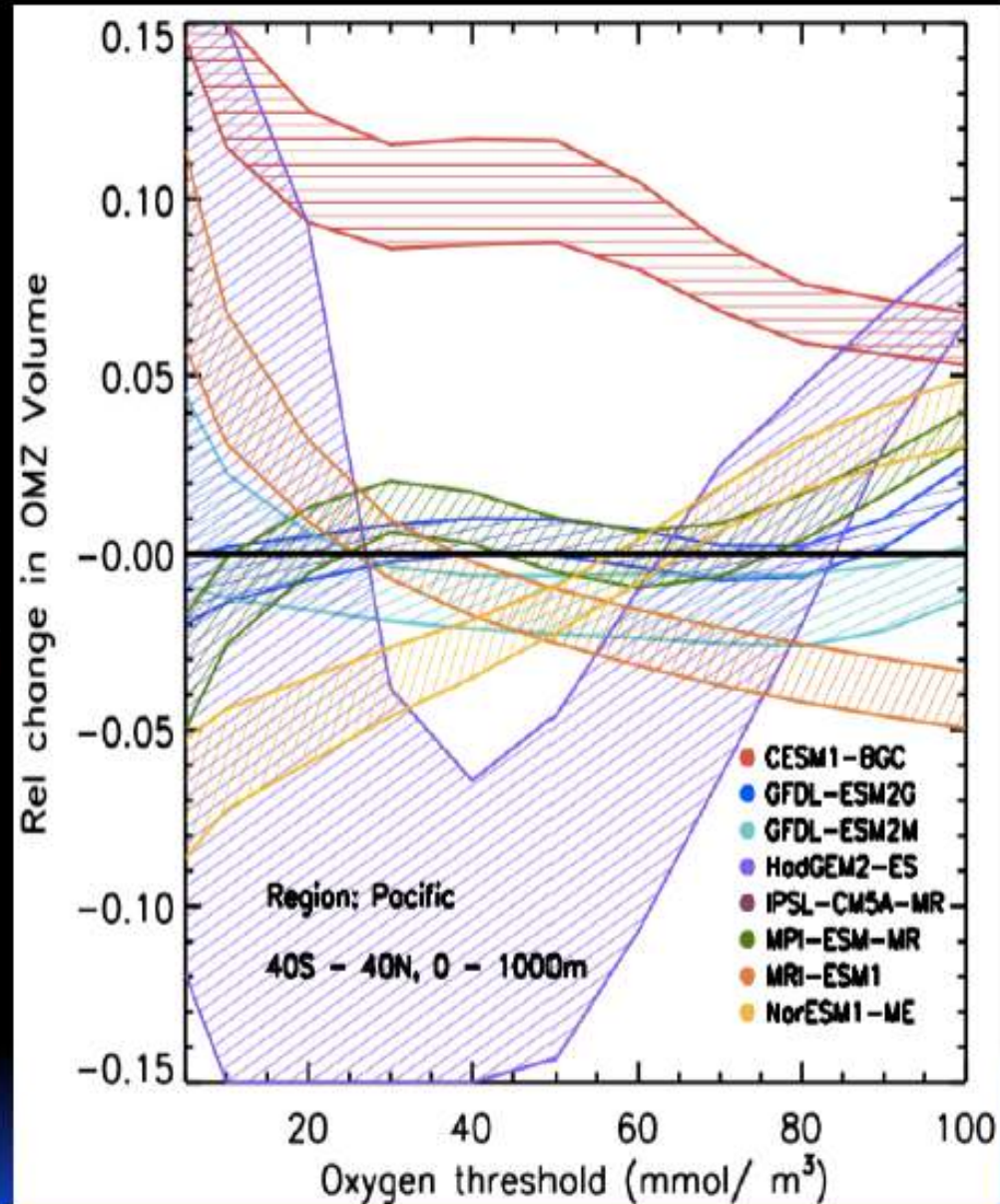
but



# OMZs are challenging to model

## Contrasting conclusions for OMZs ....

They disagree in their  
predictions of the volume of  
waters with oxygen values lower  
than  $50 \mu\text{mol/l}$  (they even  
disagree on the sign)





# Where are LOZs in the coastal ocean?

Most are related to increased N and P loads and subsequent eutrophication

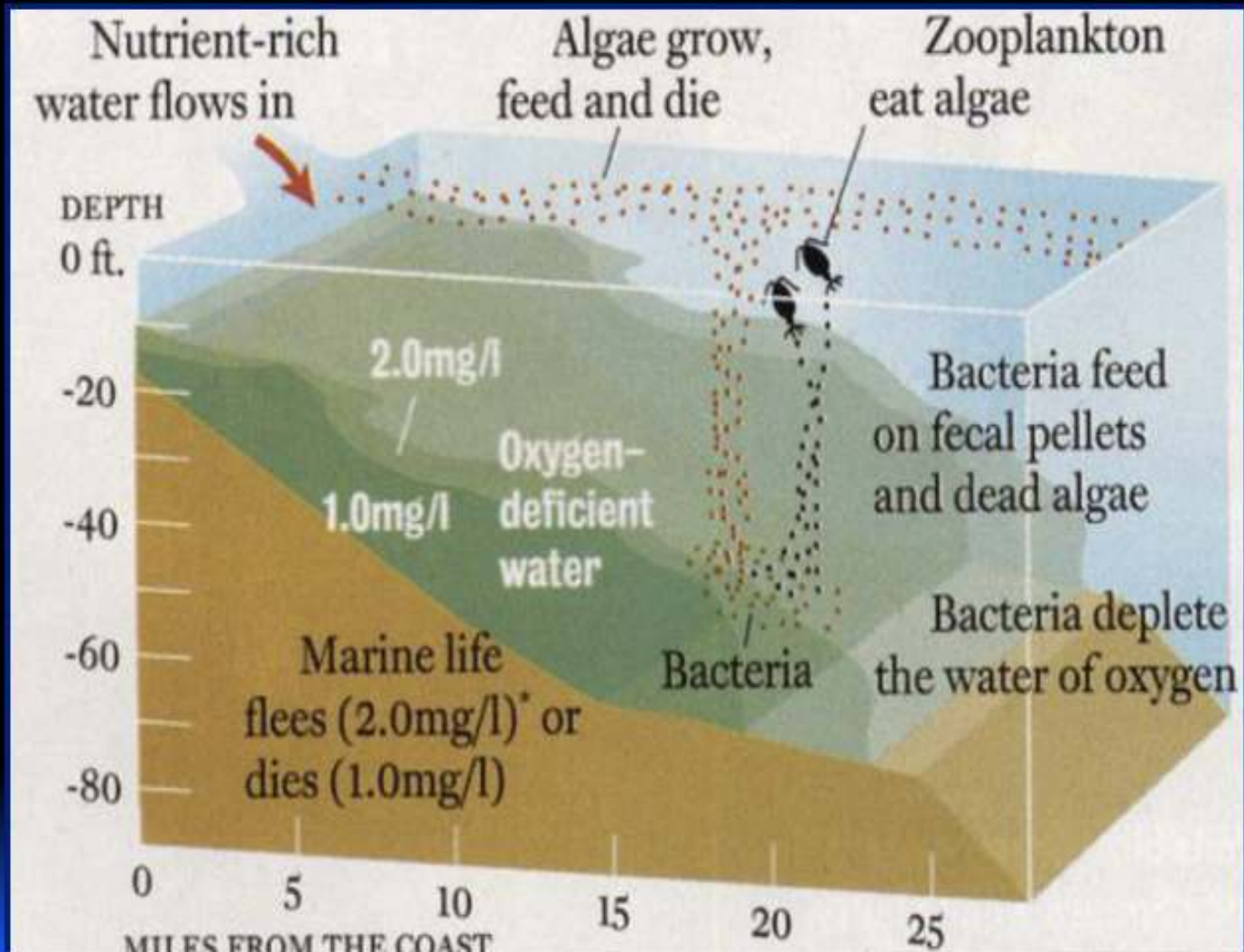




# What are the mechanisms in coastal waters?

Excess carbon reaching the seabed stimulates oxygen consumption by aerobic bacteria in a stratified water column.

Oxygen loss exceeds resupply.



# Integrated multi-scale approach

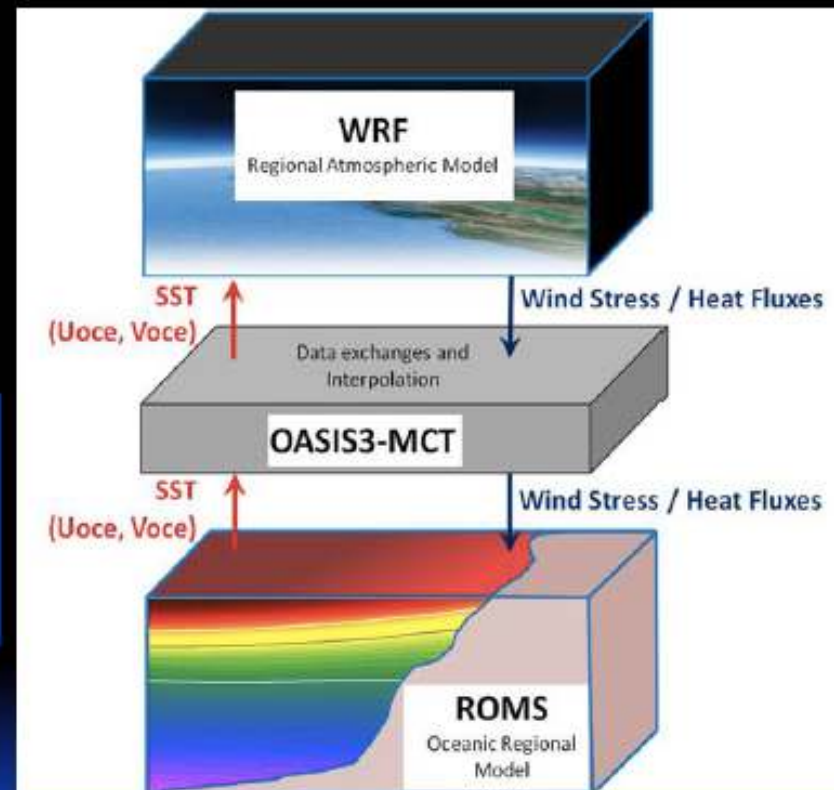
## EXPERIMENTATION

specific in situ data and experiments

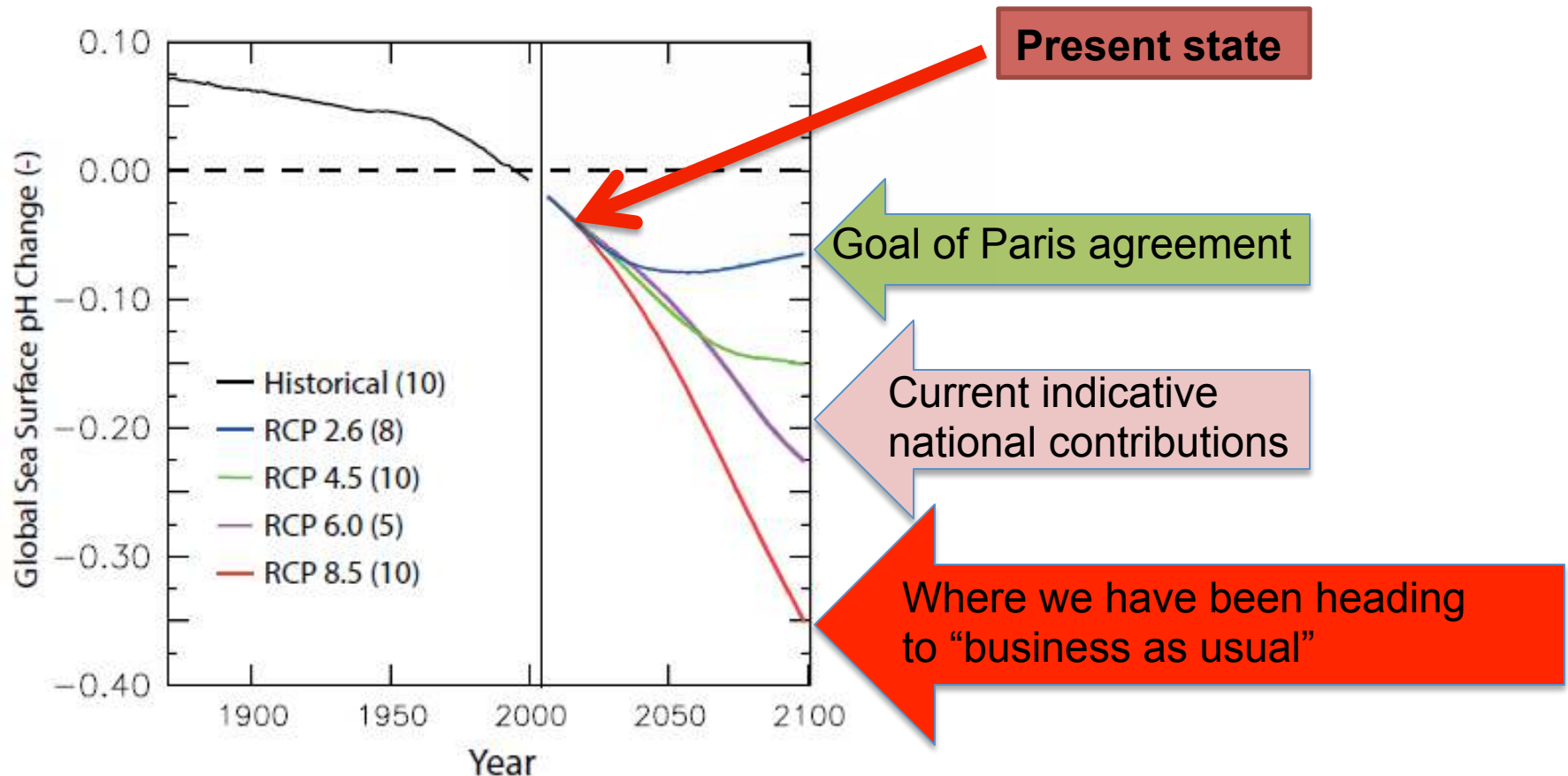
Continuous  
interaction

## MODELLING

Parameterizations from process  
to regional and global  
coupled platforms



# Warming oceans leads to acidification of waters



Model-based hindcasts and projections of global sea surface pH change over 1870-2100, with projections based on IPCC Representative Concentration Pathways (RCPs) and related to outcomes of the Paris Agreement. All changes are relative to 1990-1999 (Bopp et al., 2013).



# 17 SDGs to transform our world: Agenda 2030





# Building the future of Earth's climate towards sustainability, habitability and well-being



# Thank You