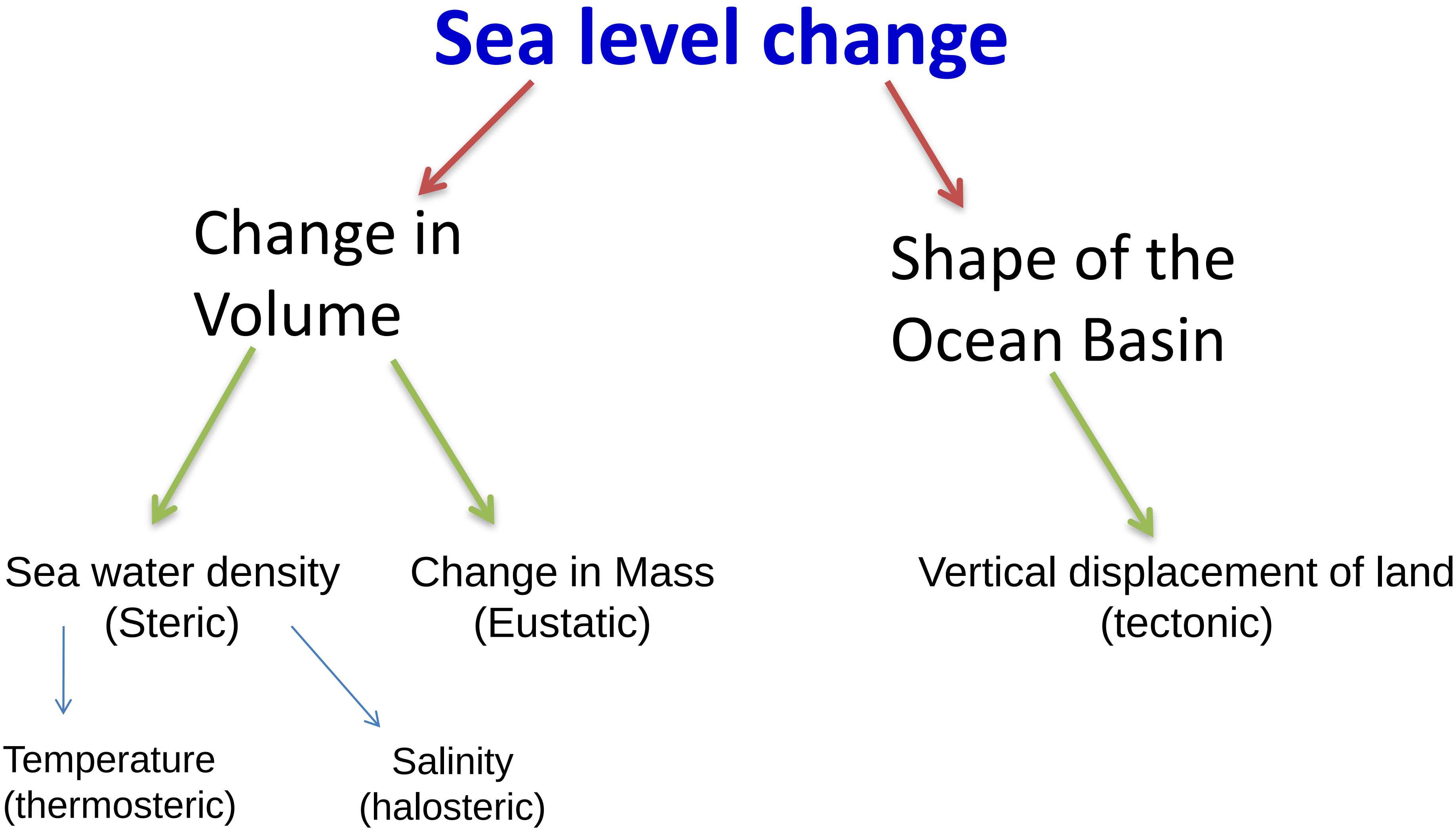
Sea level variability in the North Indian Ocean

M. Ravichandran
ESSO-National Centre for Antarctic and Ocean Research (NCAOR)
(Ministry of Earth Sciences, Govt. of India)
Goa
mravi@ncaor.gov.in

U.Srinivasu[1], M. Ravichandran[1*],Weiqing Han[2], S. Sivareddy[1], H. Rahman[1], Shailesh Nayak[3]
[1.]ESSO-Indian National Centre for Ocean Information Services, Hyderabad 500090, India
[2.]Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Colorado, USA.
[3]Earth System Science Organization (ESSO), New Delhi 110003, India.

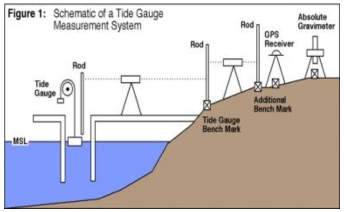
Outline

- What is the observed sea level change in the North Indian Ocean during the last two decades ?
- What are the Causative mechanisms?


Sea level change
Change in Volume
Shape of the Ocean Basin
Sea water density (Steric)
Change in Mass (Eustatic)
Vertical displacement of land (tectonic)
Temperature (thermosteric)
Salinity (halosteric)

Observations

Tide gauge



- Long sea level time series measurement along the coast

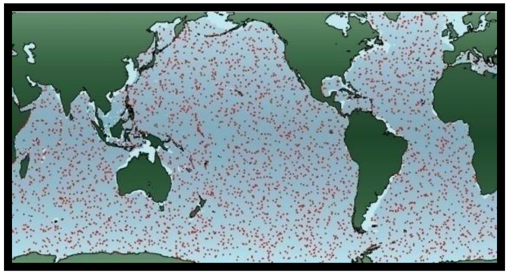
\> 100 yrs

ALTIMETRY

- Long sea level time series measurement in Open ocean

1993

ARGO



- Temperature + salinity

2002

GRACE

- Land waters
- Ice sheets mass balance
- Ocean mass change

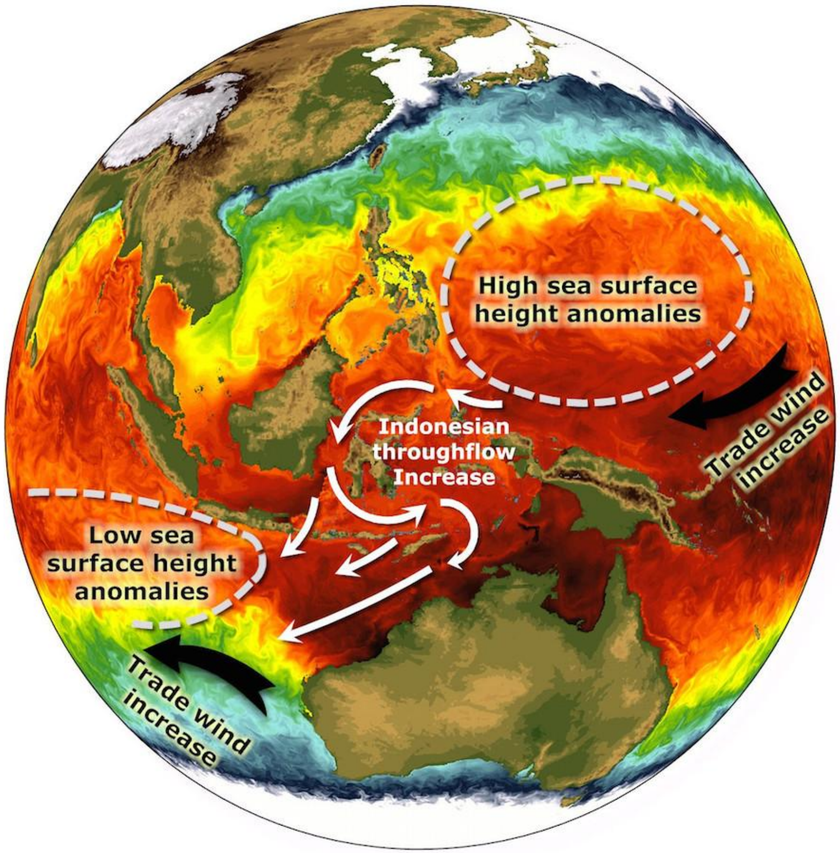
2002

Background

- The rate of global mean SLR during the last two decades is 3.2±0.4 mm/yr [*Nerem et al.*, 2010]
- The observed trends of sea level for the 1961-2008 period - surface winds associated with enhanced Hadley and Walker circulation, which is likely partly associated with the warming Indian Ocean [Han et al., 2010]
- Thermal variations dominate decadal sea level variability during the 1966-2007 period [Nidheesh et al. (2013)]
- Large halosteric contribution to the 2005-2013 sea level trends in the southeast tropical Indian Ocean [*Llovel and Lee* (2015)] and attributed it to the freshening of upper 300m ocean.

Indian Ocean is warming faster than other Oceans

Heat stored in the Pacific was transported by the Indonesian Throughflow, and ended up in the Indian Ocean. It means that the Indian Ocean is now home to 70 percent of all heat taken up by global oceans during the past decade.

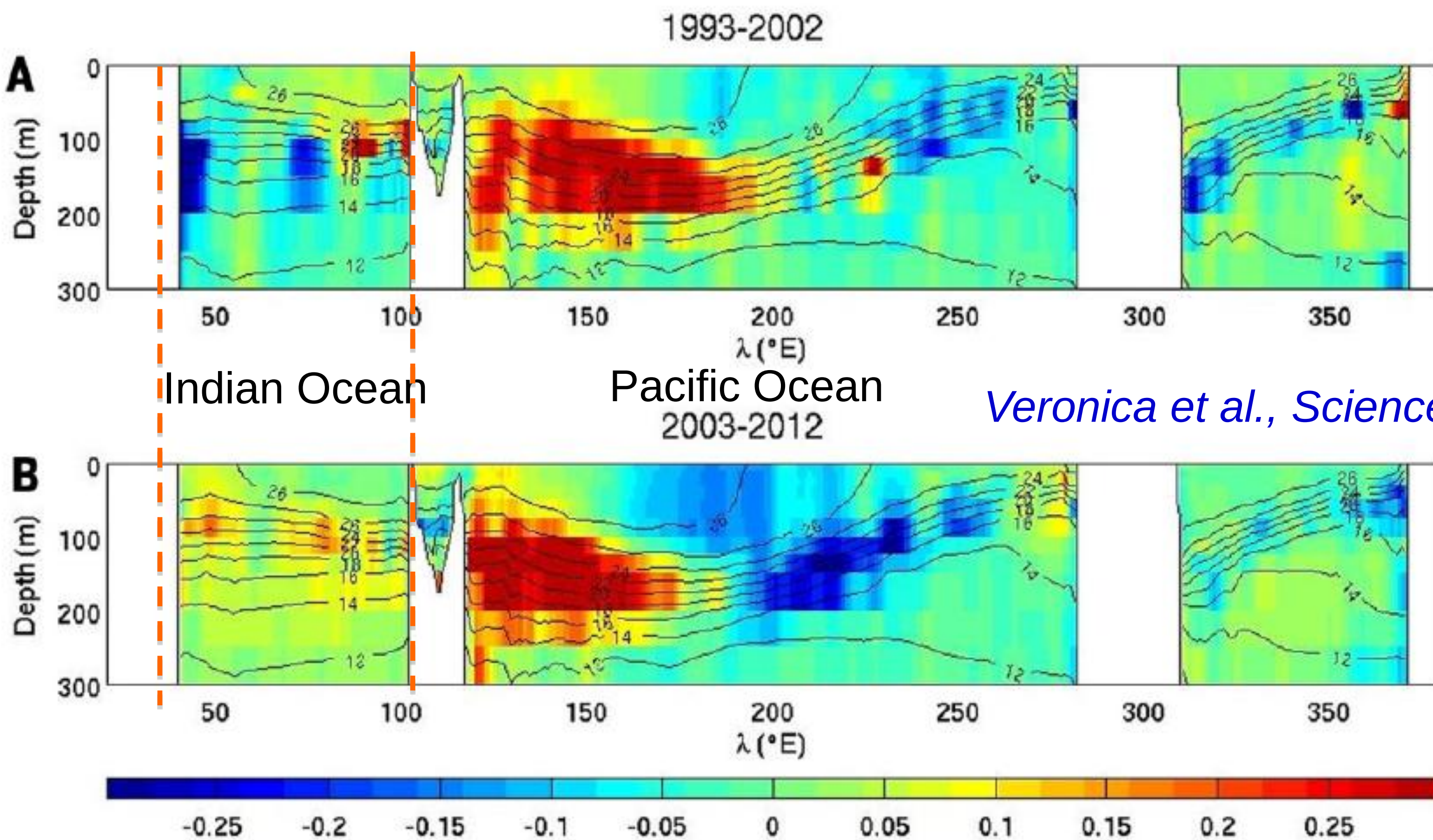


The Indian Ocean has become increasingly important in modulating global climate variability

Lee et al., Nature Geo., 2015

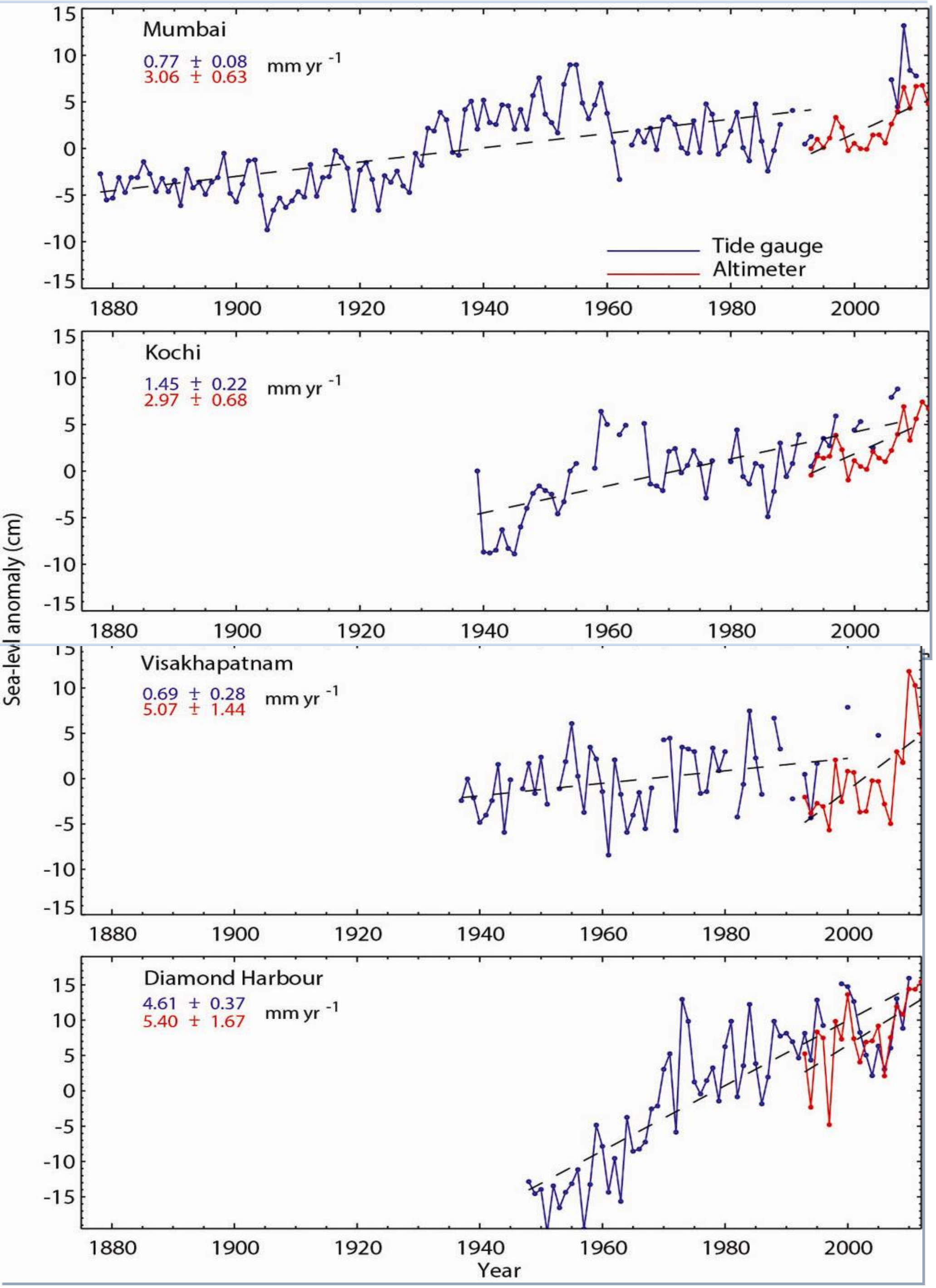
The recent Hiatus

The recent hiatus caused by the cooling in the top 100-meter layer of the Pacific Ocean was mainly compensated by warming in the 100- to 300-meter layer of the Indian and Pacific



Veronica et al., Science, 2015

WOA temperature trends along the equatorial band from 5°S to 5°N in the longitude-depth plane and upper 300 m. Isotherms correspond to the WOA 1955-2013 climatology.

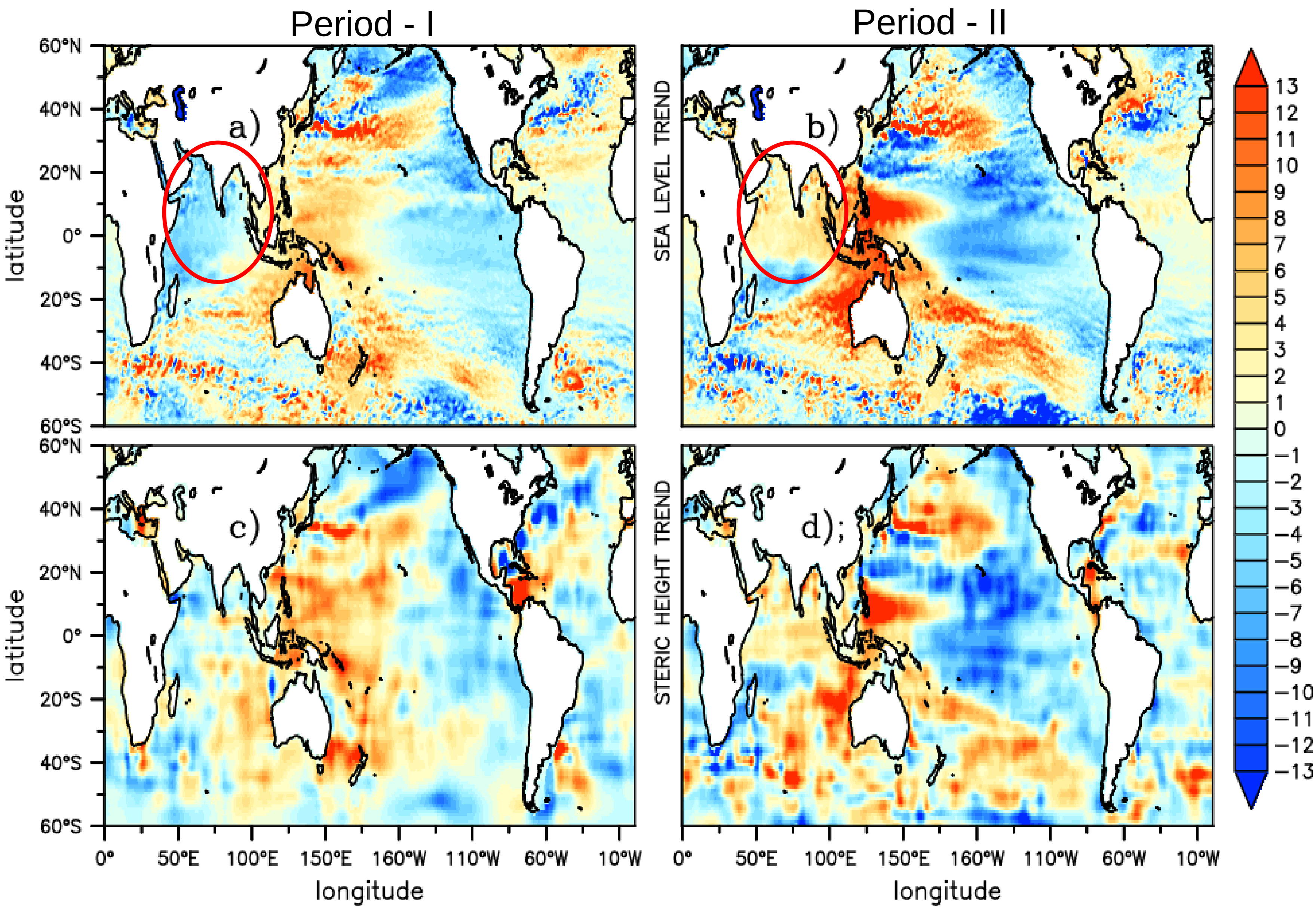


Sea level rise along the coast of India

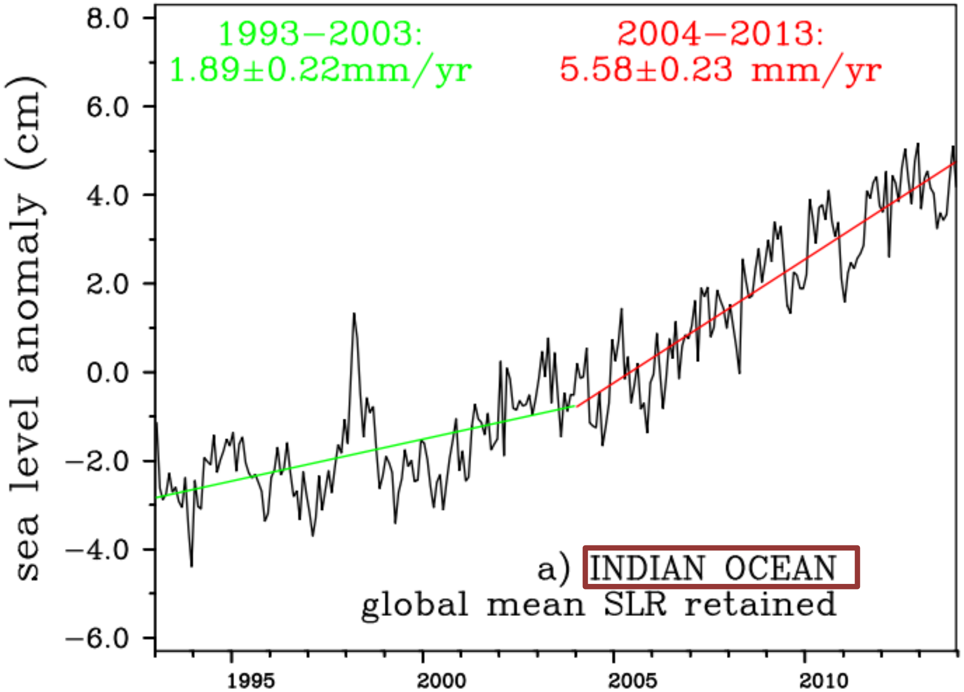
- **sea-level-rise in the north Indian Ocean does not experience any slowdown, but rather an acceleration over the past two decades.**
- **The northern and eastern coasts of the Bay of Bengal, which experience larger trends (5 mm /year and more).**

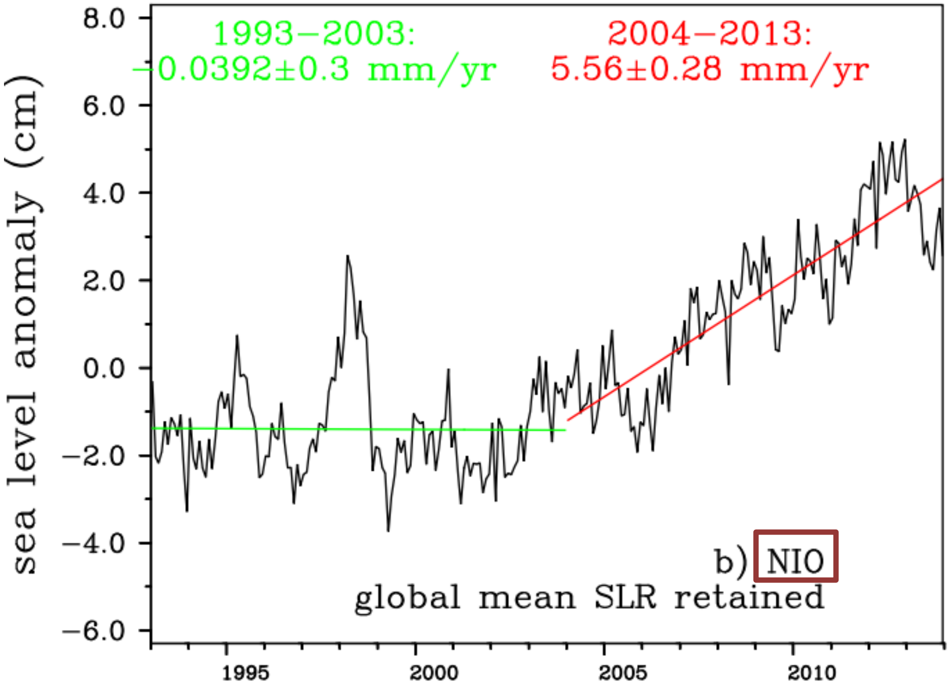
Unnikrishnan et al ., 2015, Cur. Sci

Mean Sea level (SL and Steric)

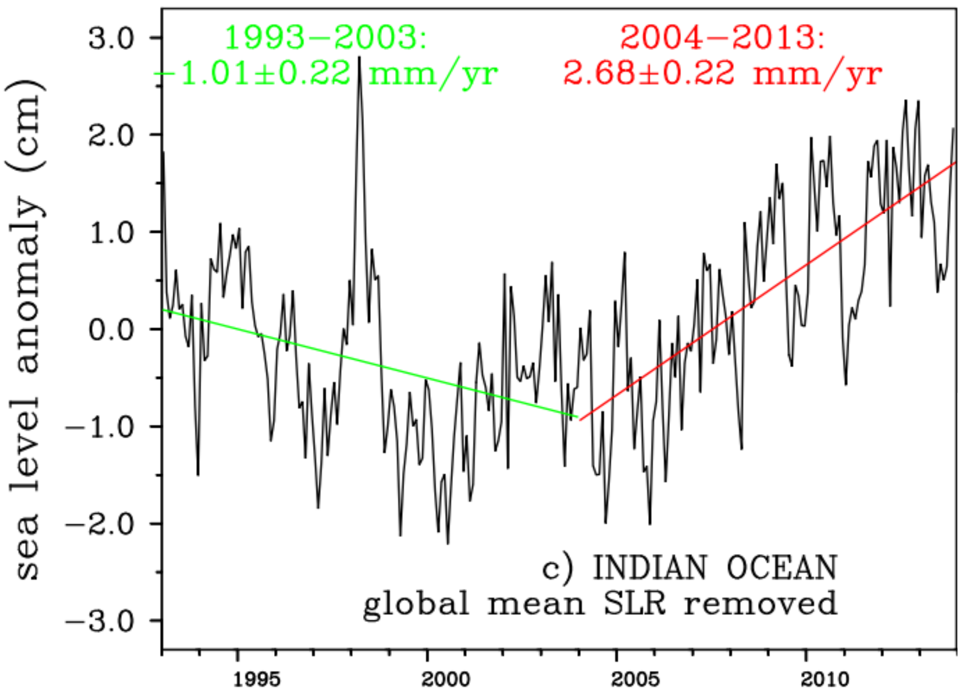


Sea level anomaly in the Indian Ocean





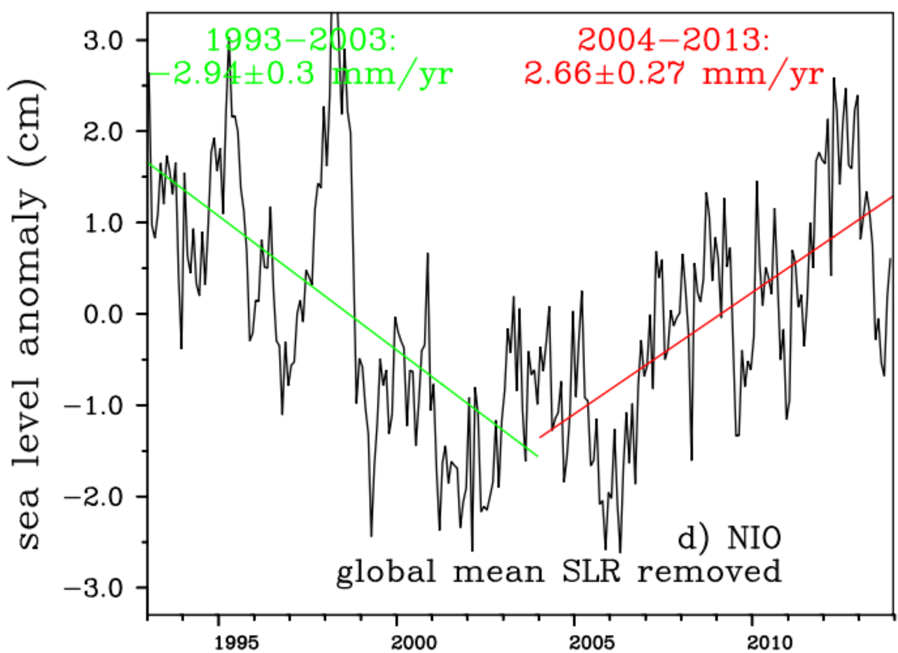
Sea Level anomaly
(Global SLR removed)



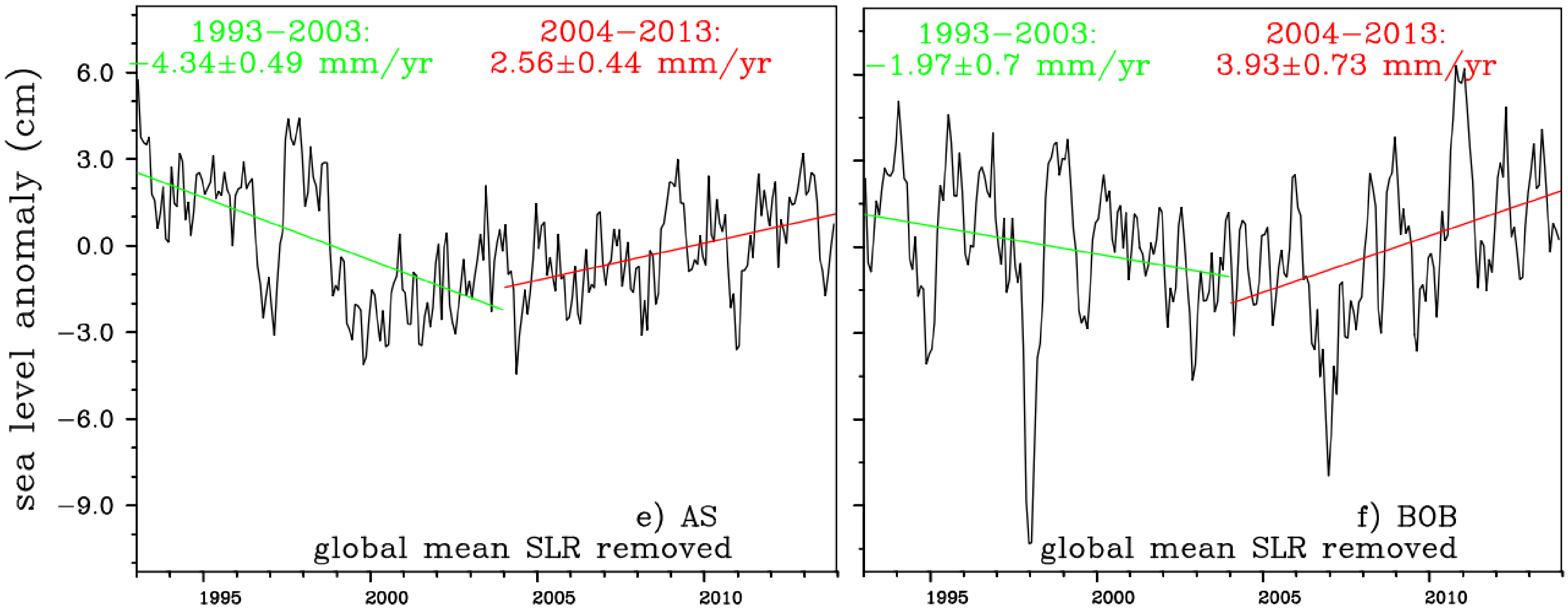
In the NIO, SL decreases at 2.94 ± 0.3 mm/yr during period I, which essentially balances the global mean SLR, but increases at 2.66 ± 0.27 mm/yr faster than the global SLR during period II.

Period I – 1993-2003

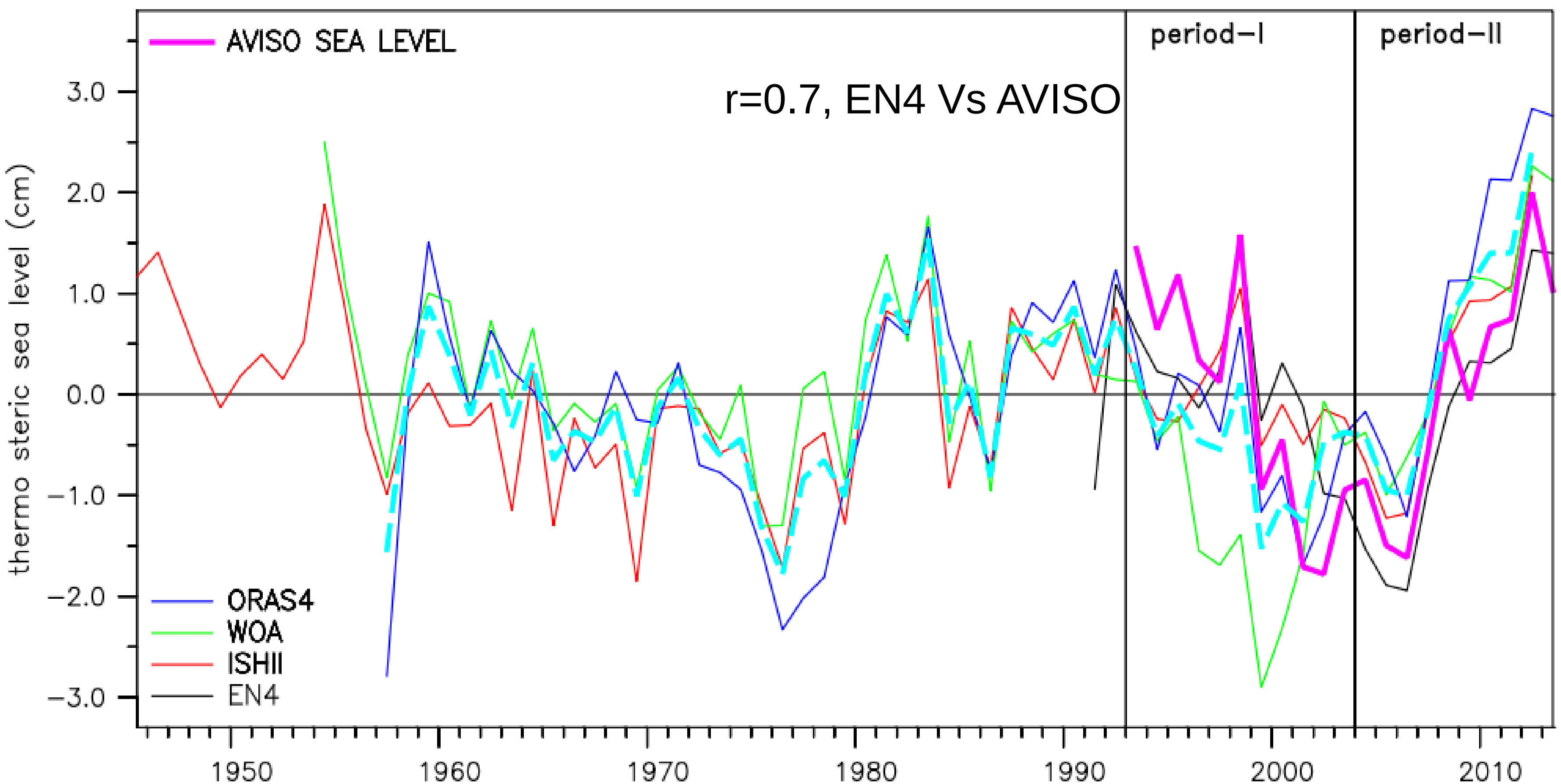
Period II – 2004-2013



Arabian Sea and BoB



Thermosteric sea level (0-700 m) averaged over the NIO



Observations

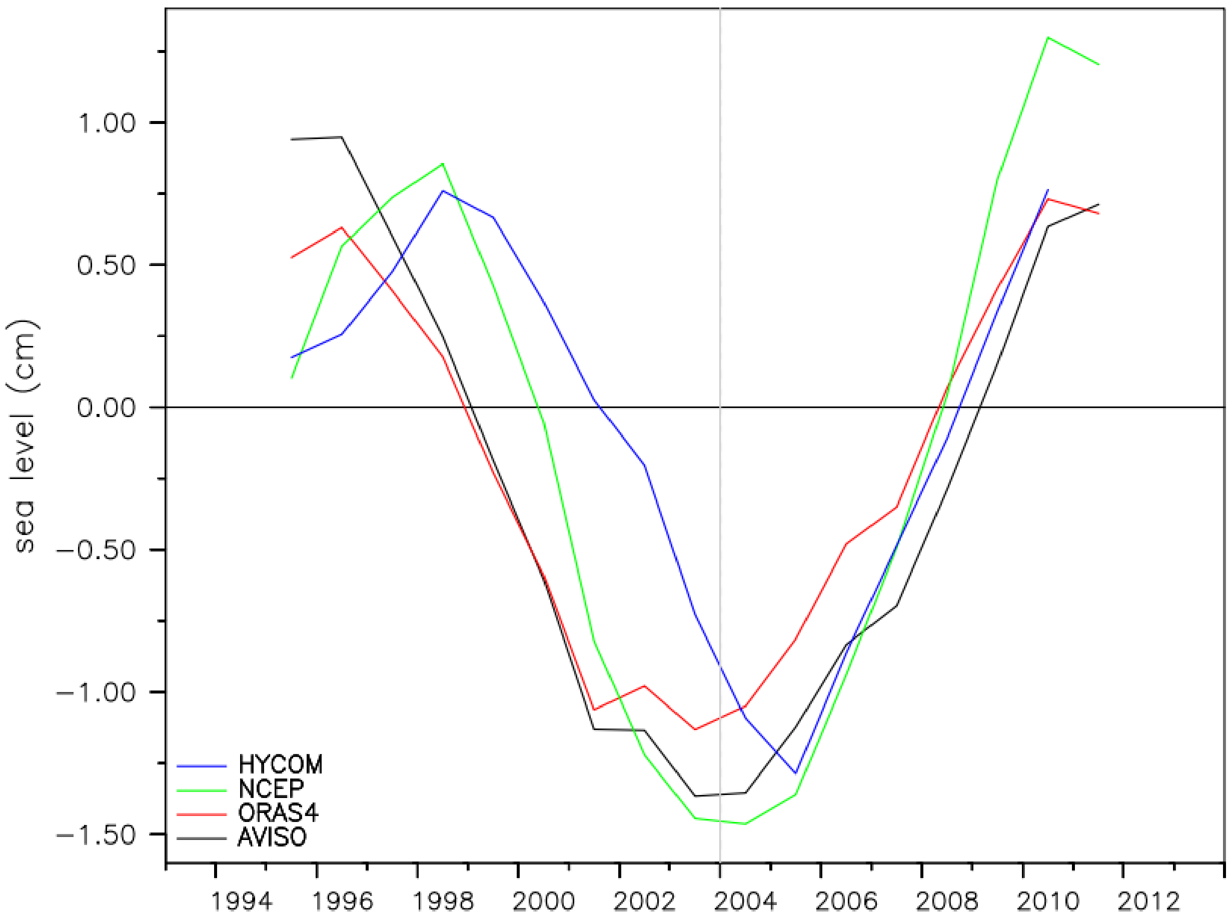
- During the last two decades
  - Indian Ocean SL rise is higher than Global
  - Decadal reversal around 2003 (NIO)
  - Thermosteric contributes most of the total SL (NIO)
- The decadal reversal is part of the decadal-scale variability over the longer period
- What are the causes of this decadal reversal?

Causative

- SL change over the NIO can be caused by
  - ocean mass and heat transport,
  - thermal expansion/contraction due to surface heating/cooling,
  - mass input from surface (Evaporation – Precipitation) and land (river runoff) and
  - Tectanic

$$\frac{\partial HC_t}{\partial t} = \int_S^N \int_W^E Qnet\, dxdy + \int_W^E Qtr\, dx + Rs$$

Sea Level change averaged over NIO



HYCOM Simulations **with ITF and without ITF**

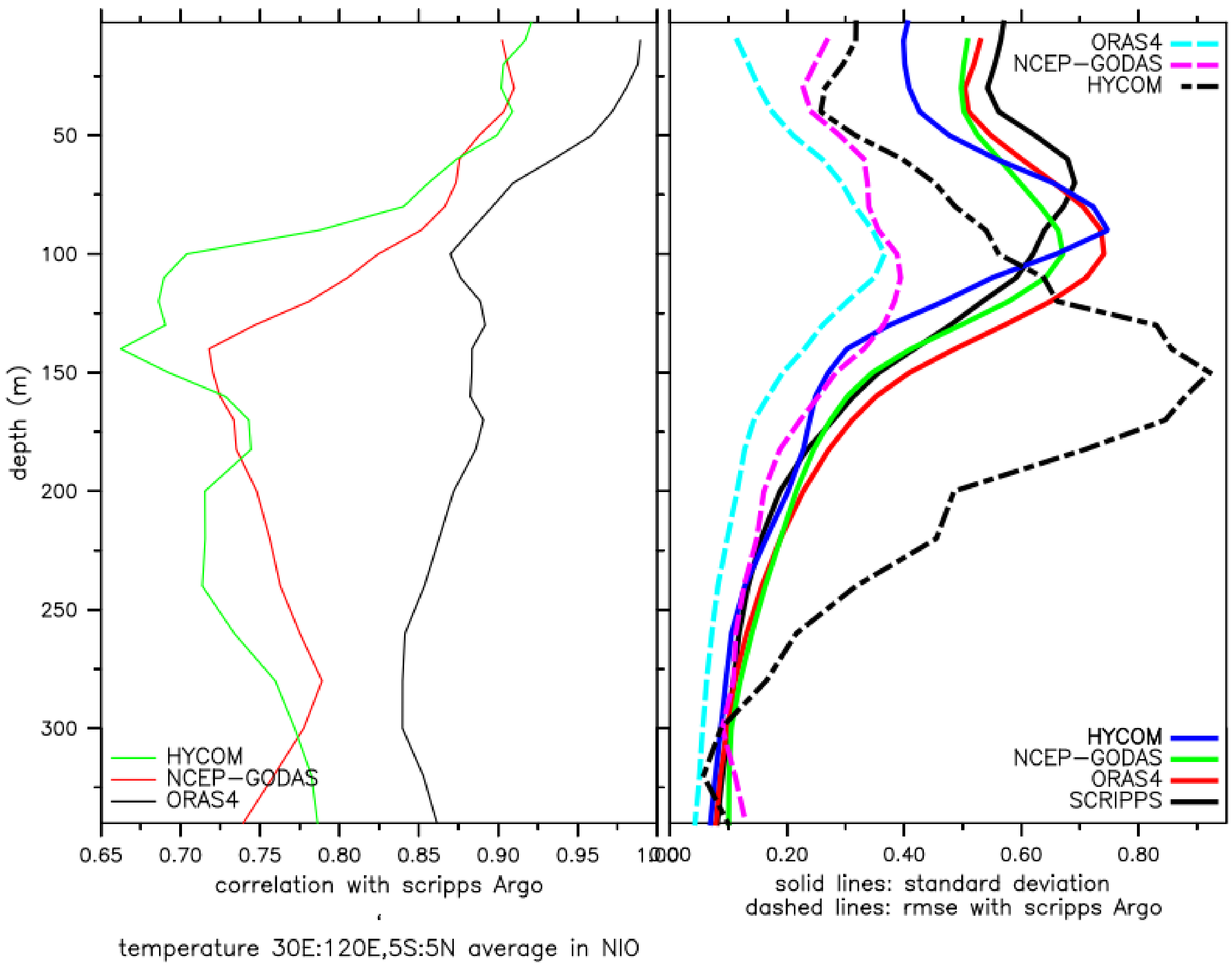
NCEP-GODAS

ORAS4

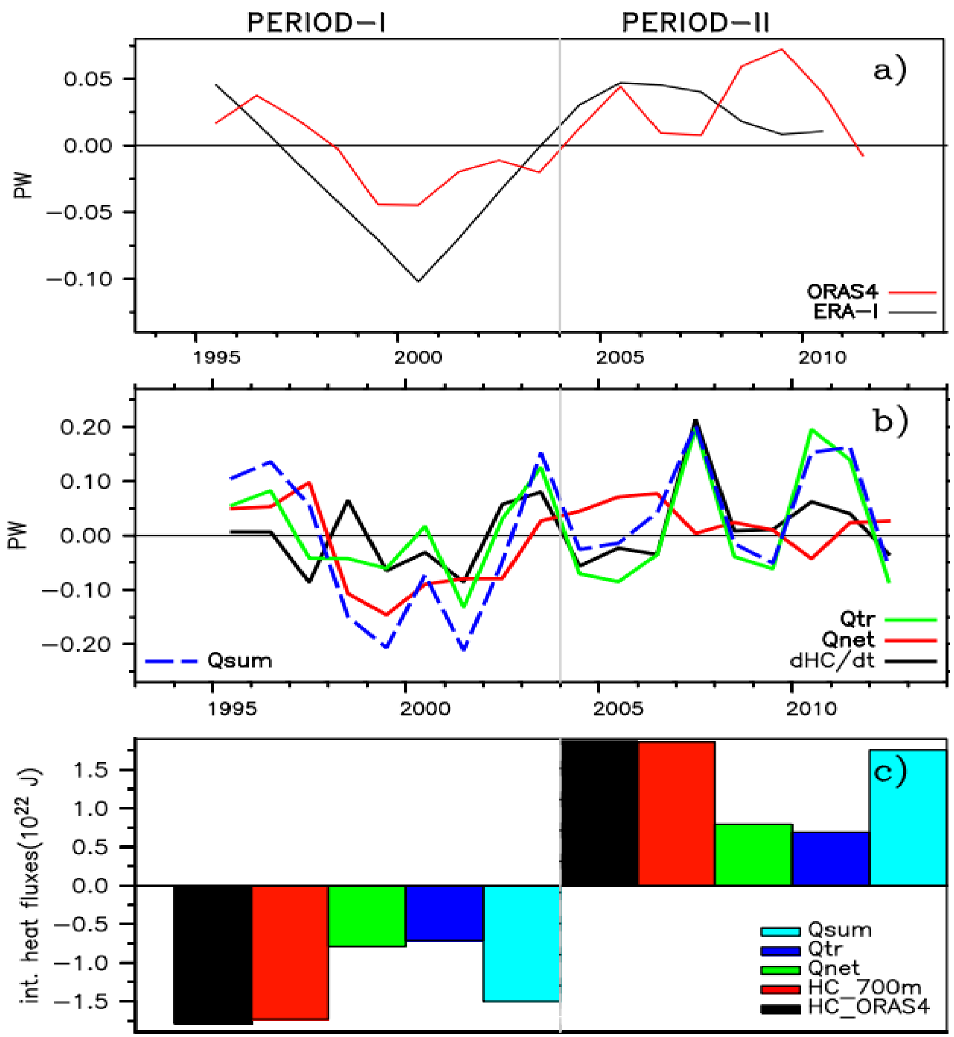
5 S – Southern Boundary

No influence on SL due to ITF

Evaluation of Subsurface currents



Heat transport and Net heat flux



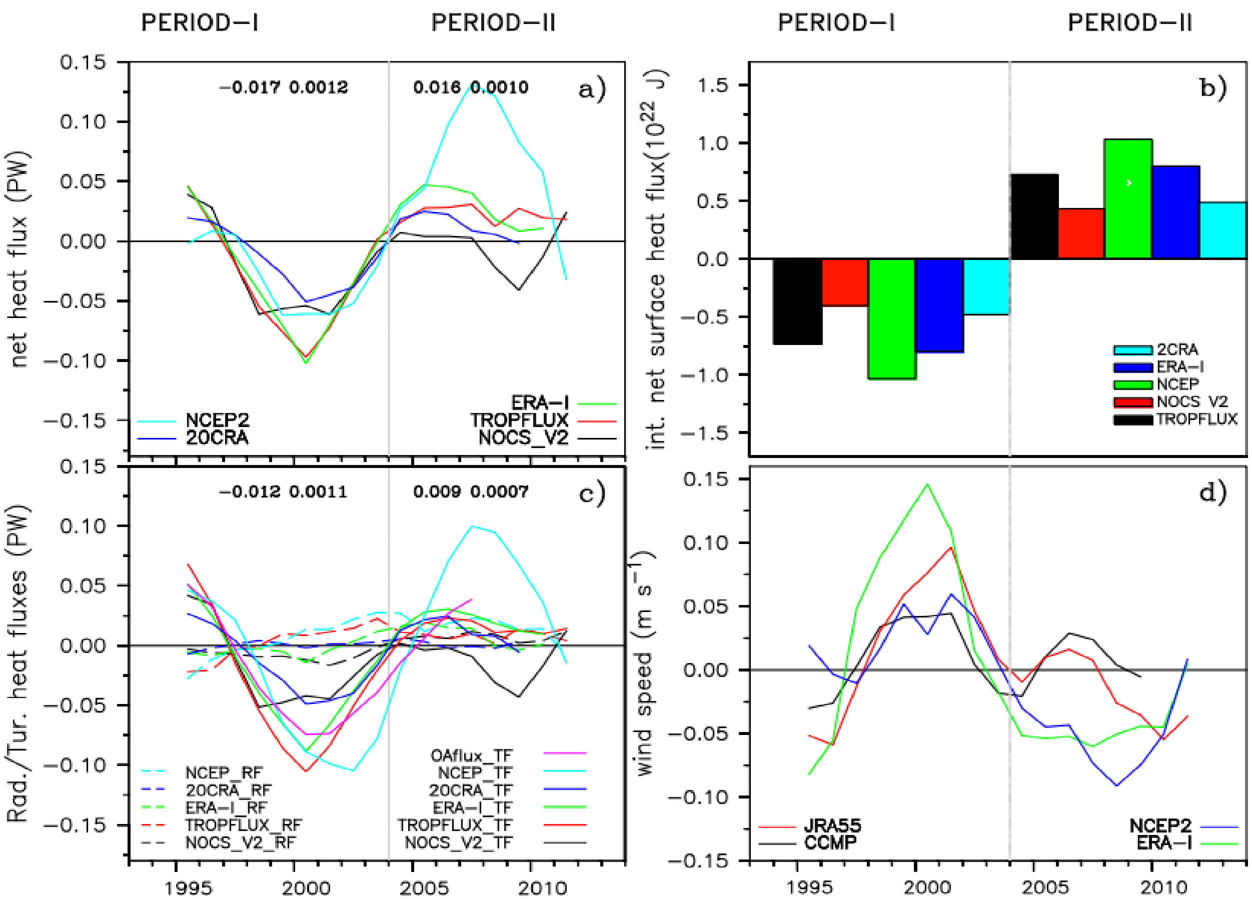
a. Five year running mean of **t**ime series of heat transport at 5ºS using ORAS4 and ERA-Interim surface net heat flux;

b. Heat content change or heat storage, dHC/dt term, Qnet term, Qtr term and Qnet+Qtr term;

c. Time integrated heat budget terms for Period I and Period II compared with the heat content differences (in 10^{22} J) for the beginning and end of each period and equivalent 700m heat content required to raise the thermosteric level to the observed values .

$$\frac{\partial HC_t}{\partial t} = \int_S^N \int_W^E Qnet\, dxdy + \int_W^E Qtr\, dx + Rs$$

Net Heat flux



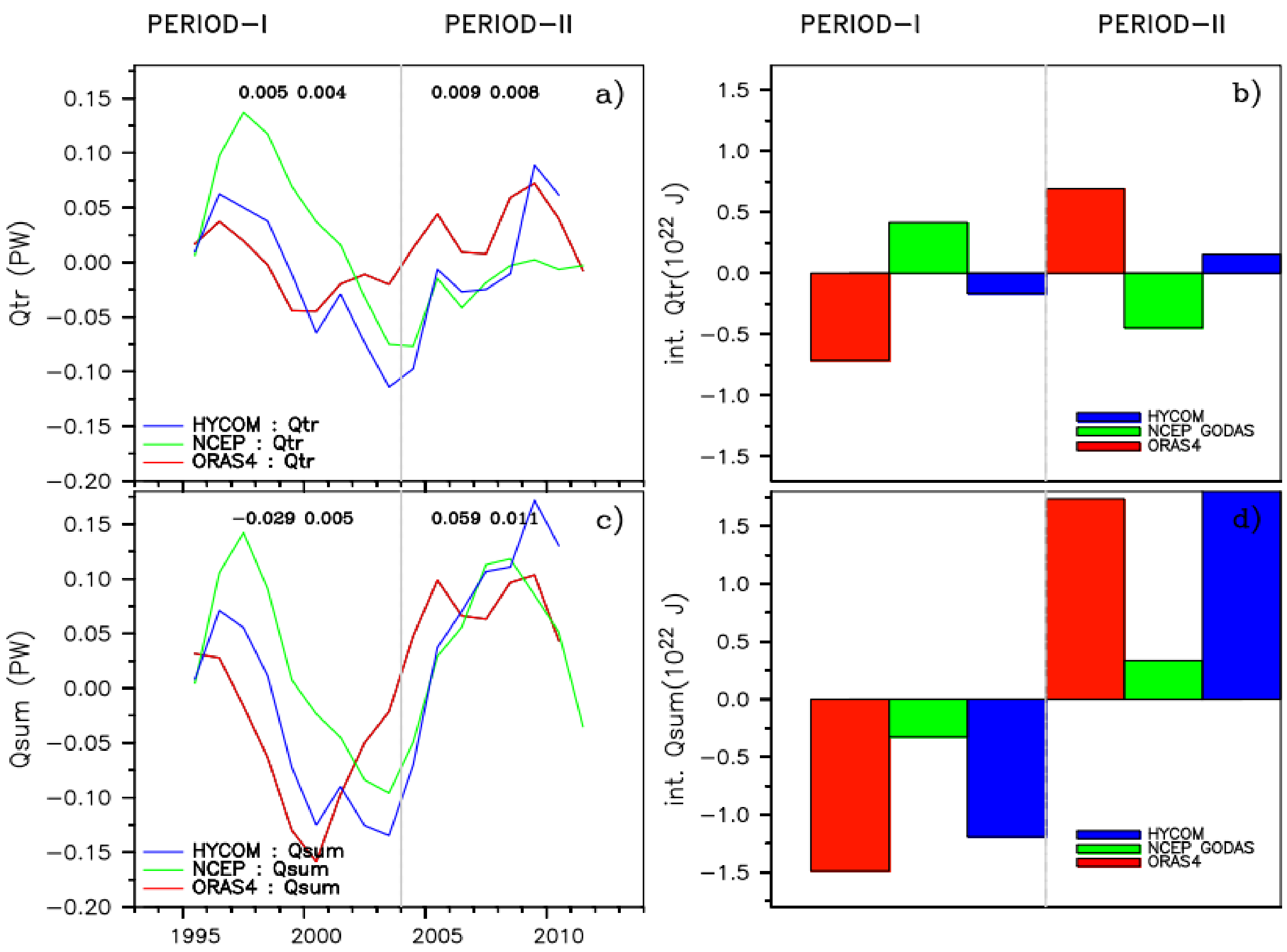
a. Time series of 5year running averages of net surface heat flux integrated over the NIO (north of 5°S) with linear trend of 1993-2013 removed

b. Time integrated surface net heat fluxes (in 10^{22} J) for Periods I and Period II,

c Time series of 5year running averages of net radiative flux (SW+LW; dashed) versus turbulent heat flux (Qsen+Qlat; solid) integrated over the NIO with linear trend for 1993-2013 removed.

d Time series of 5 year running mean surface wind speed averaged over the NIO with linear trend of 1993-2013 removed.

Heat transport across 5 S (700 m)



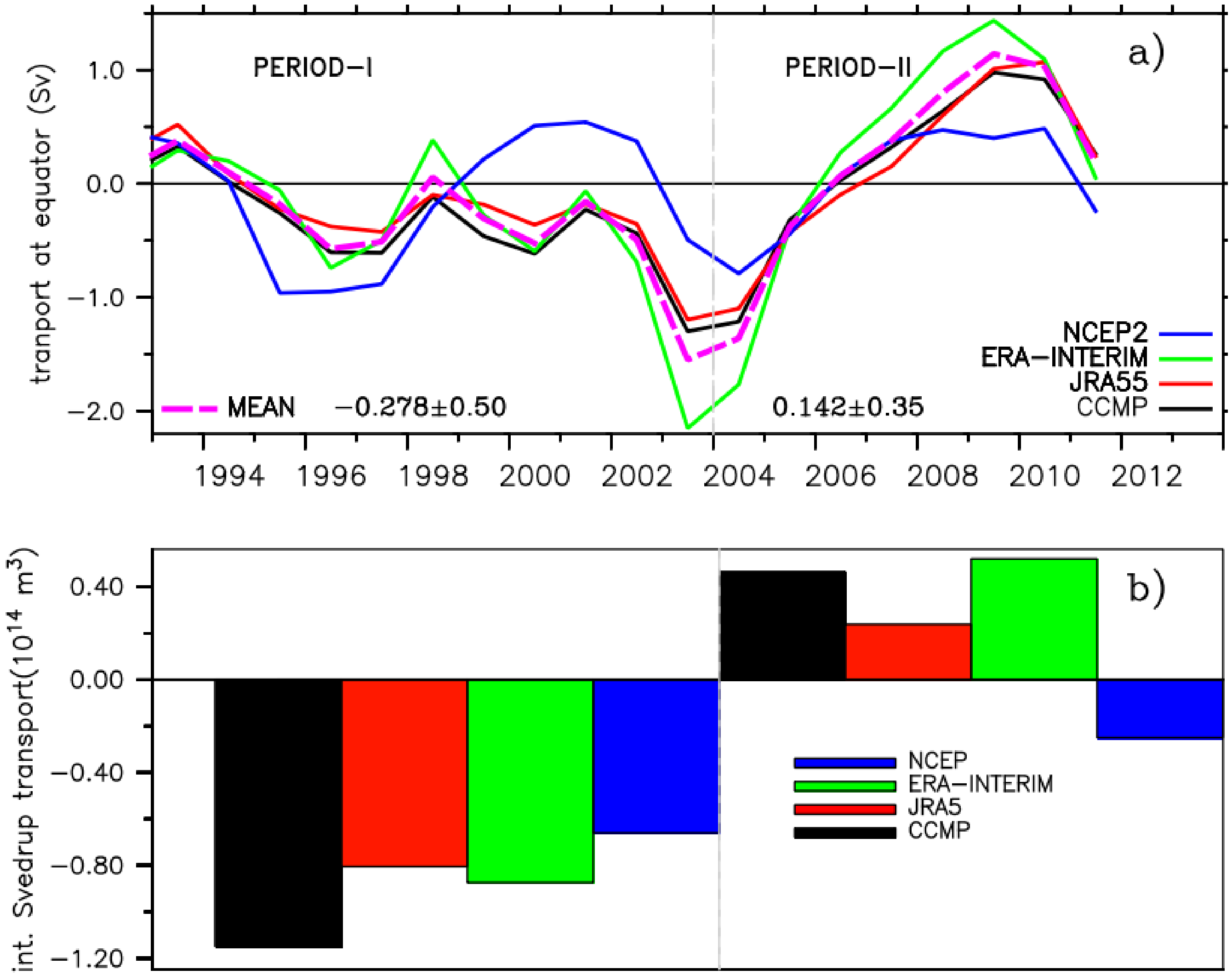
a Zonally integrated heat transport across 5°S in the upper 700m (ORAS4, NCEP-GODAS and HYCOM)

b time integrated heat transport (in 10^{22} J) time series of **a,**

c Qsum of ORAS4, NCEP-GODAS and HYCOM

d Time integrated heat transport time series of **c,** during Period I and Period II.

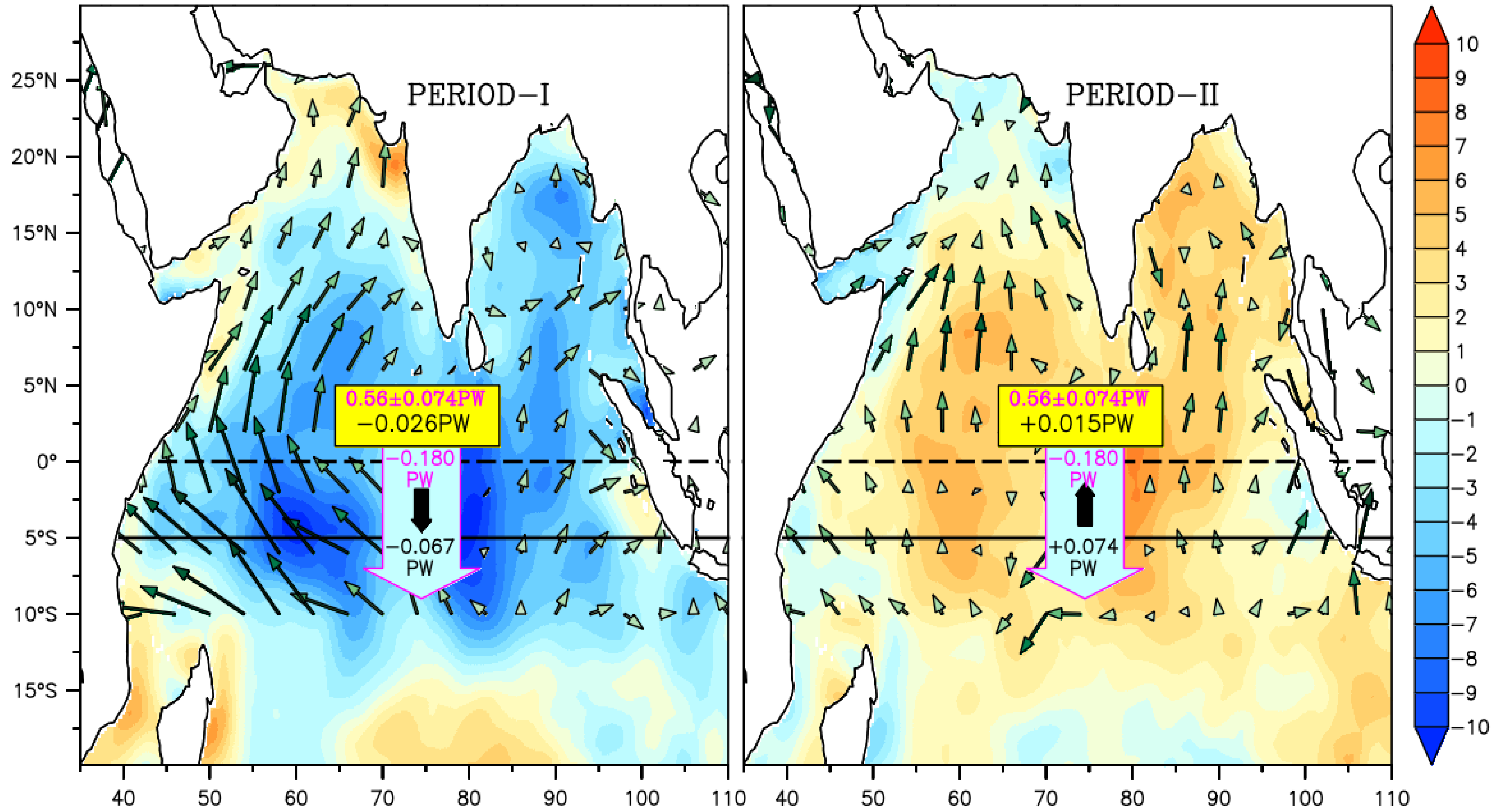
Cross Equatorial Cell strength



a. Time series of Sverdrup volume transport integrated (from 30°E to 120°E) across Equator from NCEP2 (blue), ERA-Interim (green) reanalysis, JRA55 (red) and CCMP wind (black)products for the 1993-2013 period, with linear trend of 1993-2013 removed.

b The time integrated volume transport (in 10^{14} m^3) time series of **a**, plotted as bars for different products during Period I and Period II

North Indian Ocean Sea Level



Summary

- Satellite and in situ observations, together with ocean reanalysis products, show a distinct decadal reversal of sea level change in the past two decades.
- Sea level falls from 1993-2003 (period-I) and rises sharply from 2004-2013 (period-II).
- It is shown that this decadal reversal is part of the long-term natural decadal climate variability.
- Steric height explains most of the spatial patterns of sea level change.
- The decadal change of surface turbulent heat flux acts in concert with the change of cross-equatorial heat transport, with both being associated with decadal change of surface wind, to cause sea level fall during period I and rise during period II.
- There is no influence in NIO sea level by Indoneisan Throughflow (ITF)

Thank You for your attention