Sea level variability in the North Indian Ocean

M. Ravichandran
ESSO-Indian National Centre for Ocean Information Services (INCOIS), Hyderabad

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 is the Causative mechanism?

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.

Sea Level change

Sea level change

Change in Volume

Shape of the Ocean Basin

Sea water density (Steric)

Change in Mass (Eustatic)

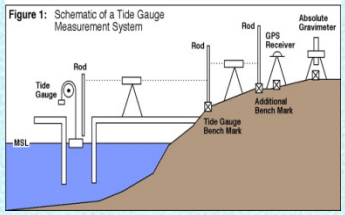
Vertical displacement of land (tectonic)

Temperature (thermosteric)

Salinity (halosteric)

Observations

Tide gauge



- **Long sea level time series measurement along the coast**

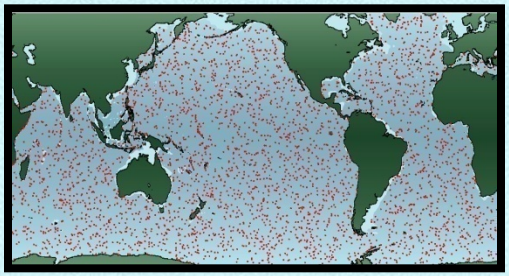
> 100 yrs

ALTIMETRY

- **Long sea level time series measurement in Open ocean**

1993

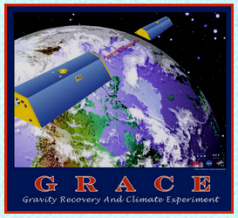
ARGO



- **Temperature + salinity**

2002

GRACE

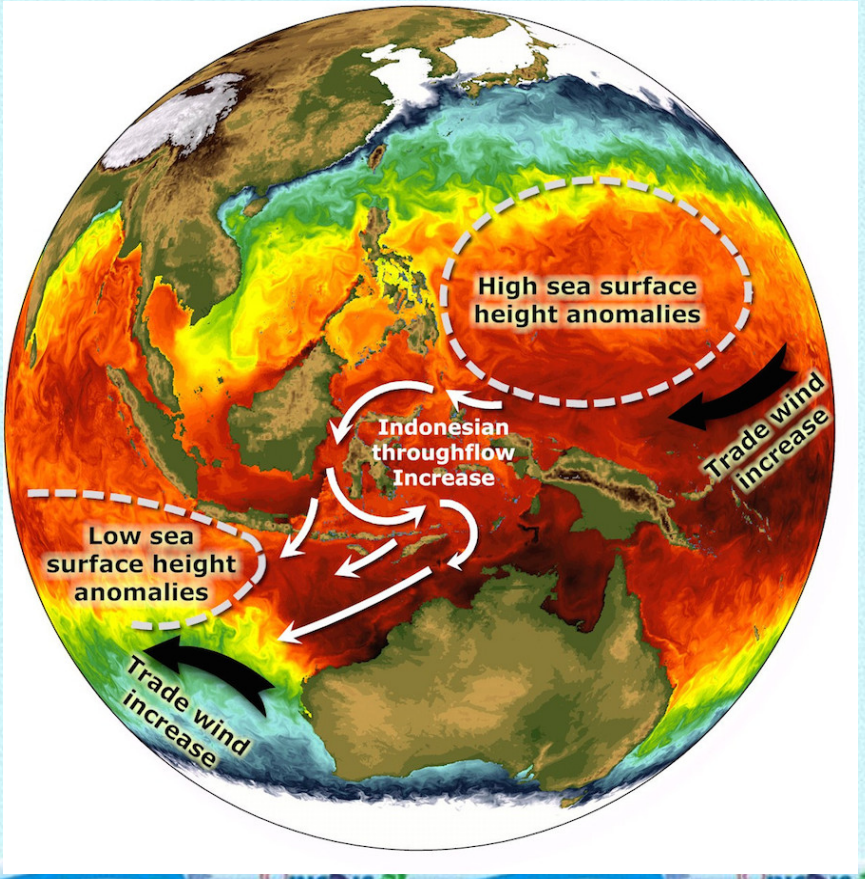


- **Land waters**
- **Ice sheets mass balance**
- **Ocean mass change**

2002

Indian Ocean is warming faster than other Oceans

Heat originally 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.

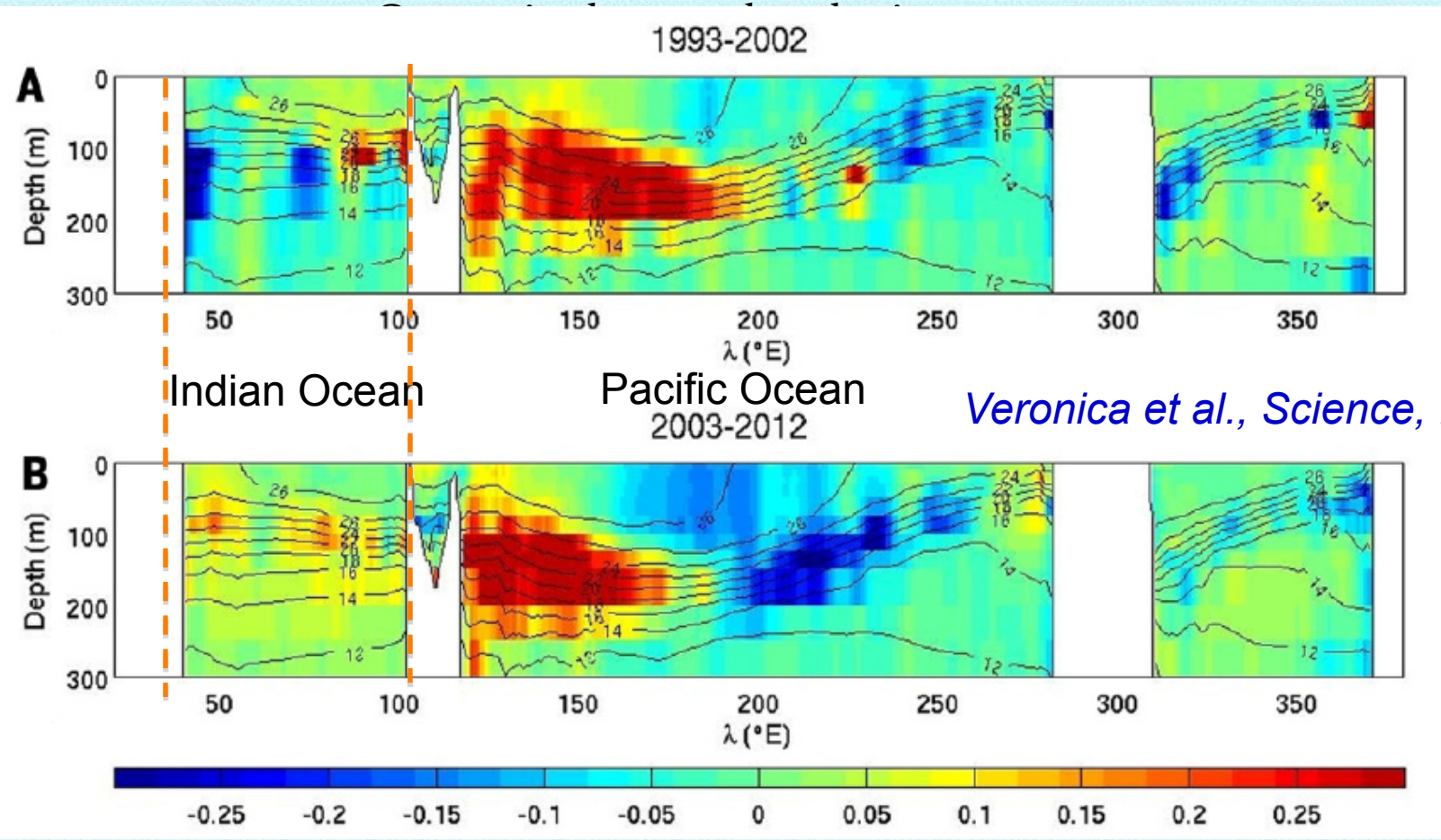


The Indian Ocean has become increasingly important in modulating global climate variability

Lee et al., Nature Geo., 2015

The recent Hiatus

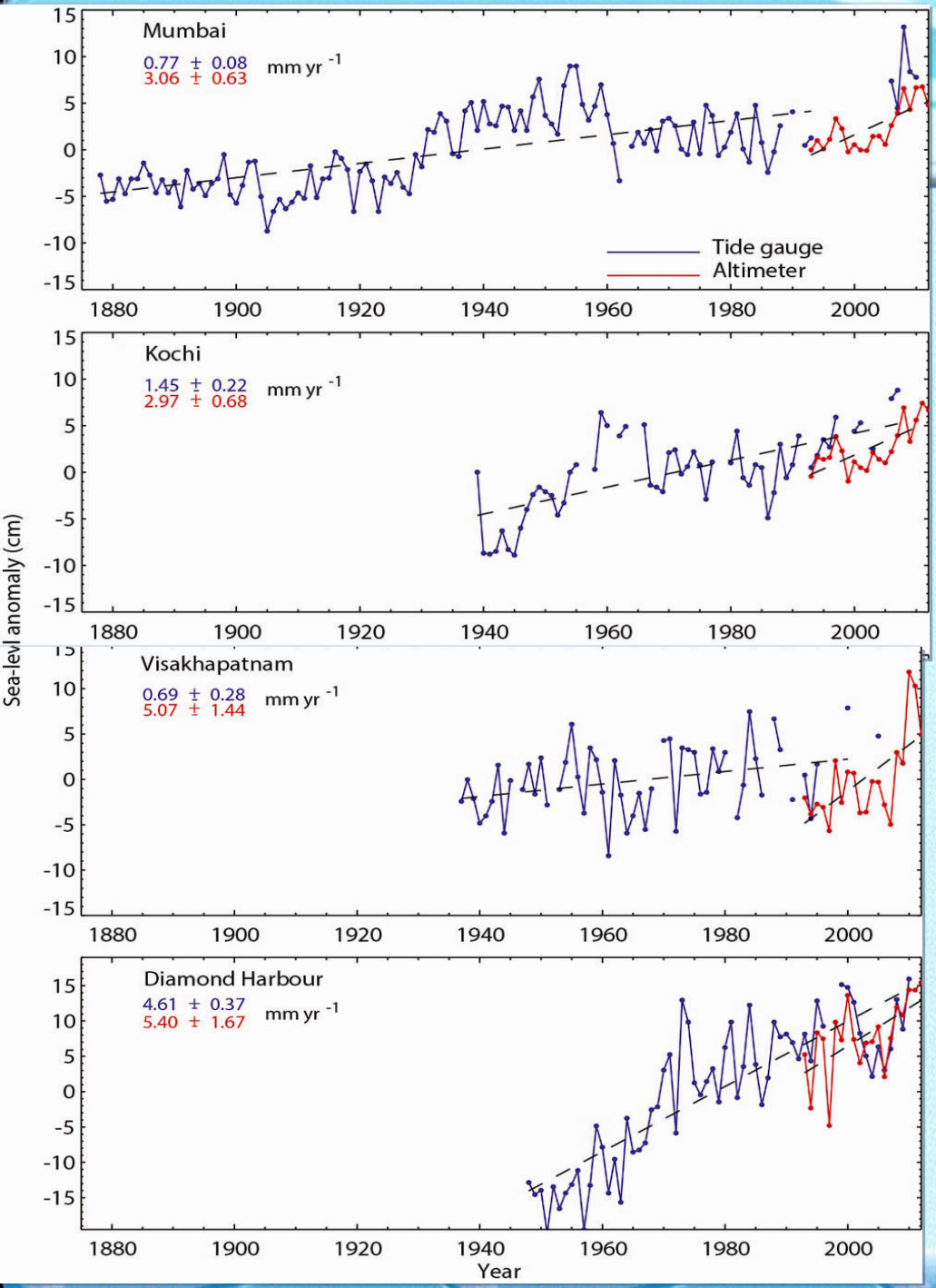
The recent hiatus caused by the cooling in the top 100-meter layer of the Pacific Ocean was mainly compensated by warming in the 100- to 300-meter layer of the Indian and Pacific



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.

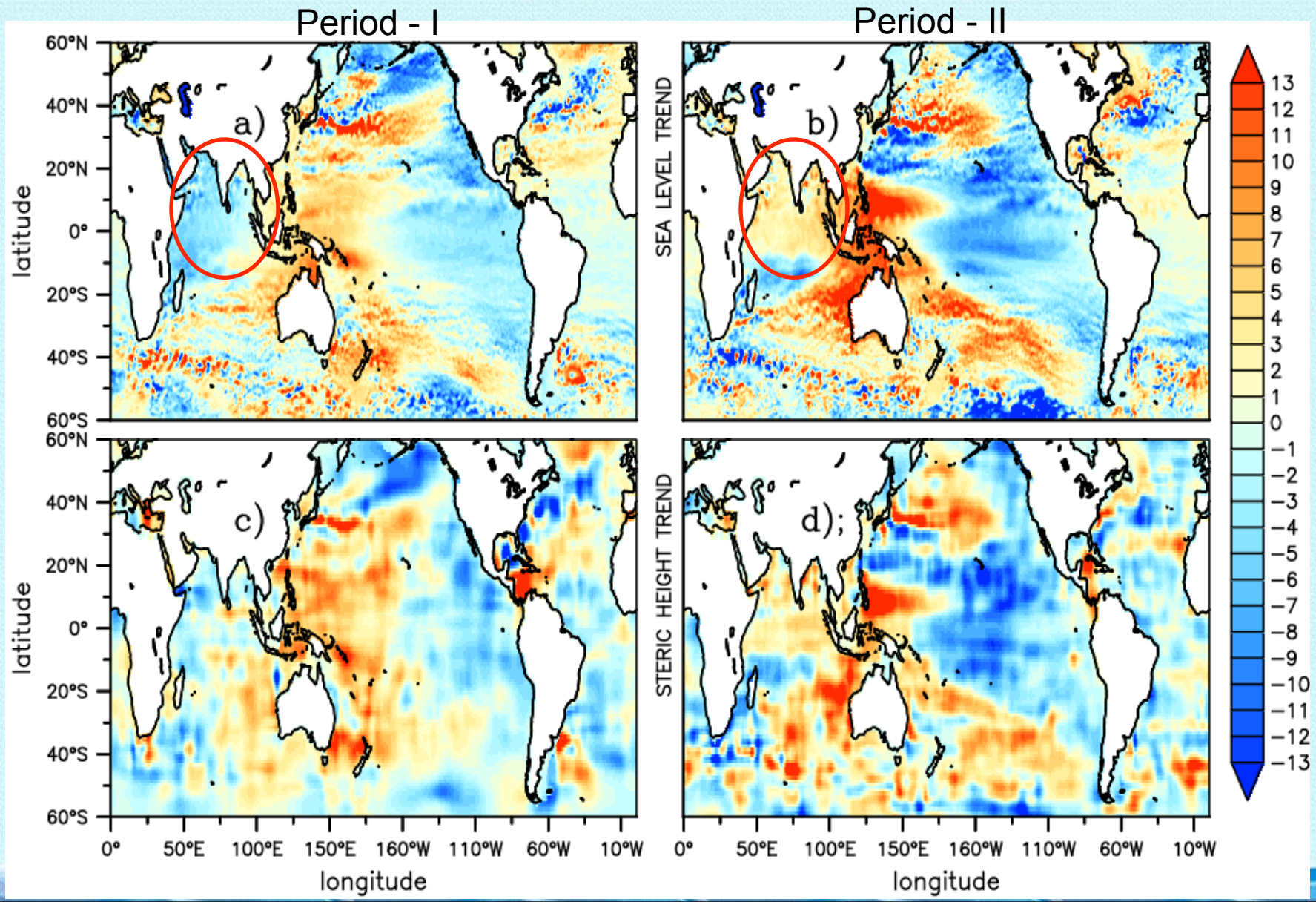
Sea level rise along the coast of India



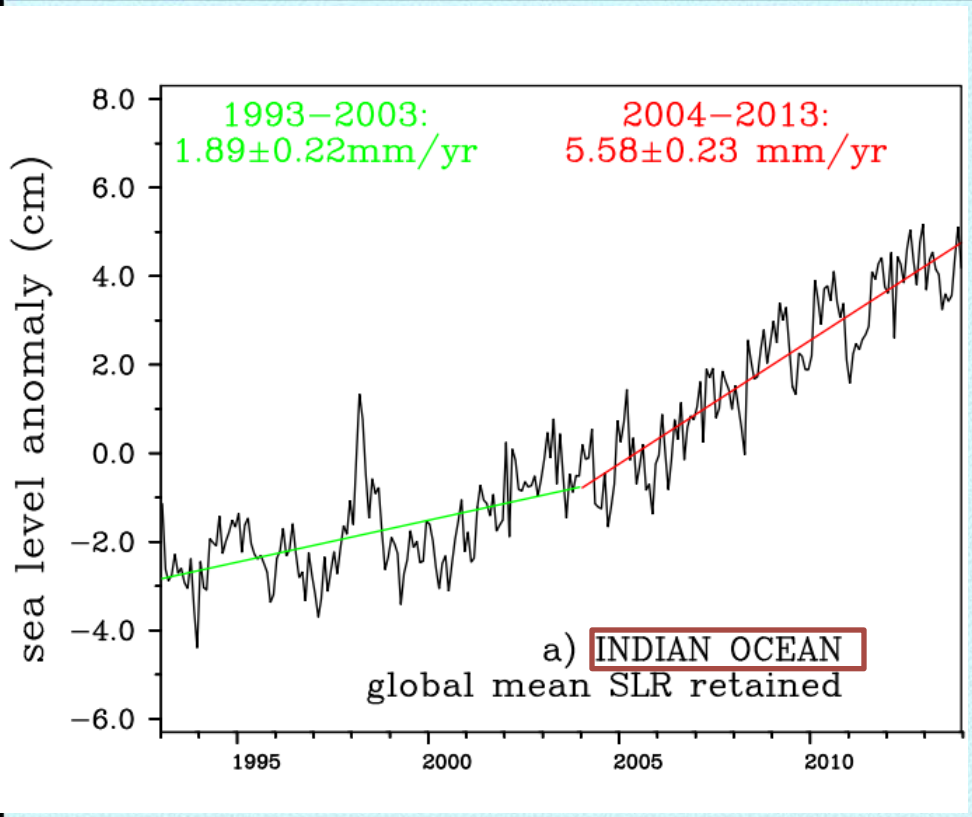
- **sea-level-rise in the north Indian Ocean does not experience any slowdown, but rather an acceleration over the past two decades.**
- **The northern and eastern coasts of the Bay of Bengal, which experience larger trends (5 mm /year and more).**

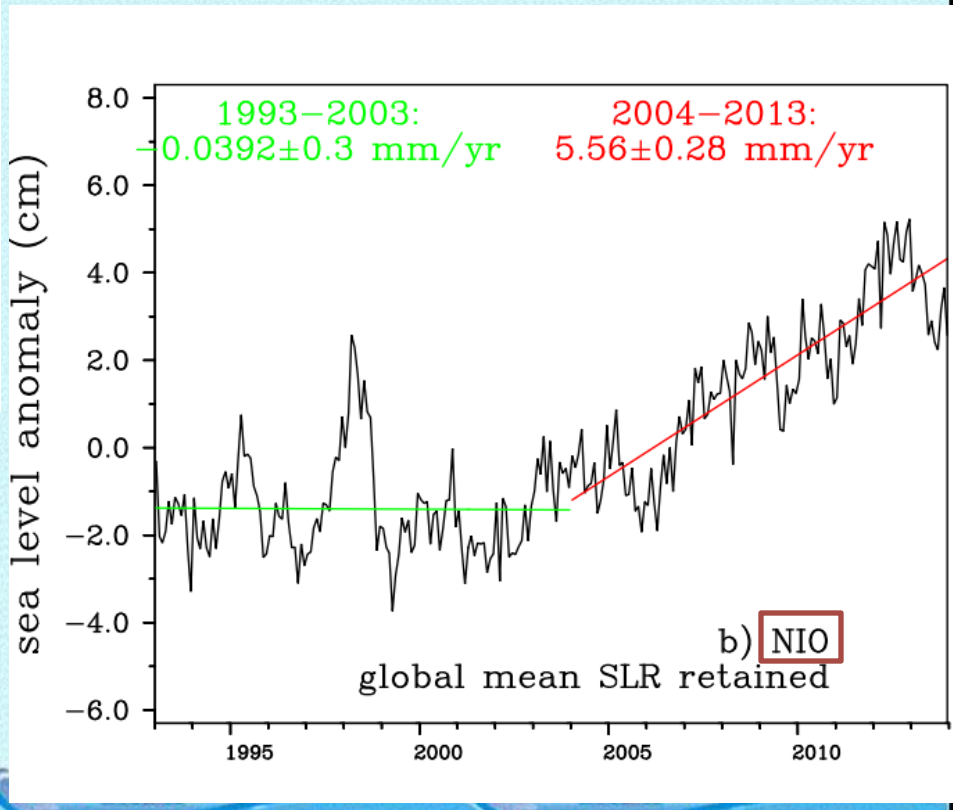
Unnikrishnan et al ., 2015, Cur. Sci

Mean Sea level – Spatial (SL and Steric)

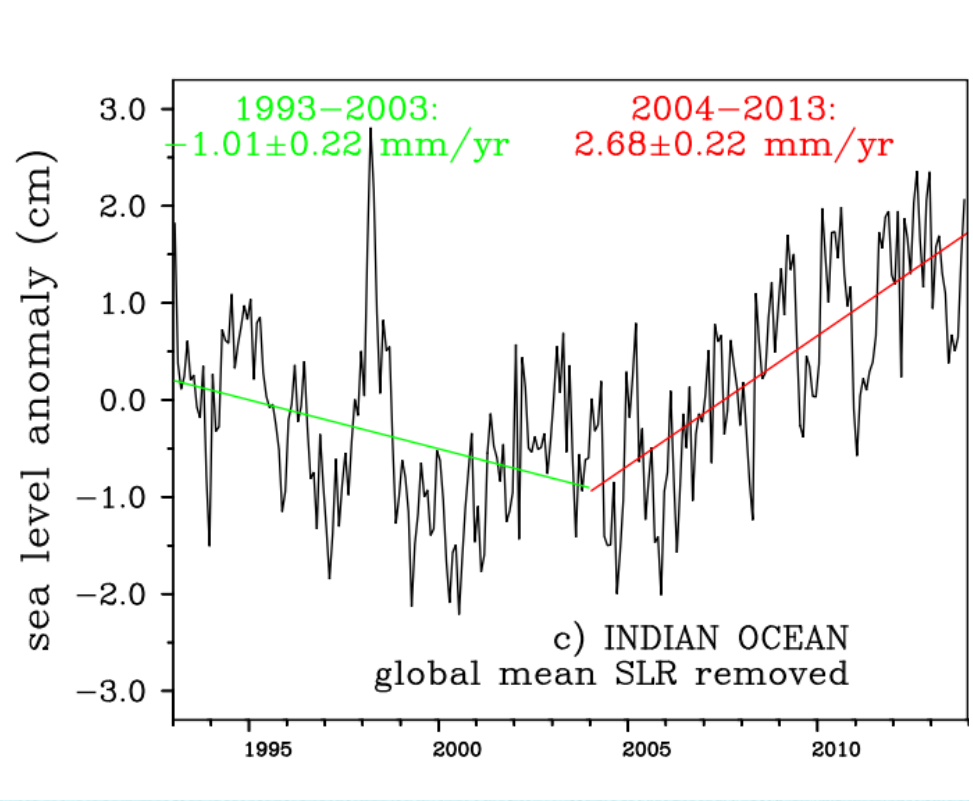


Sea level anomaly in the Indian Ocean





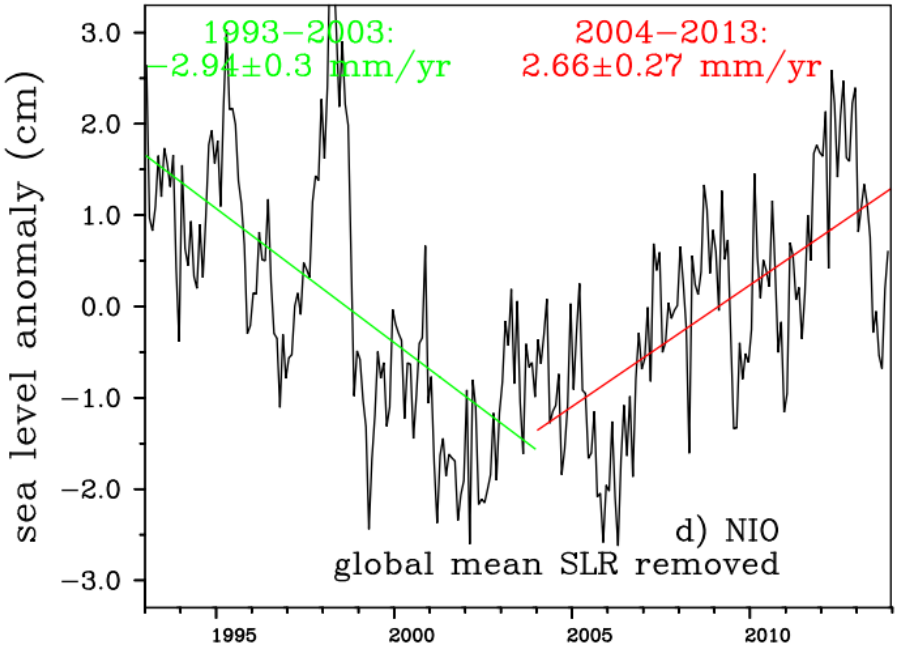
Sea Level anomaly (Global SLR removed)



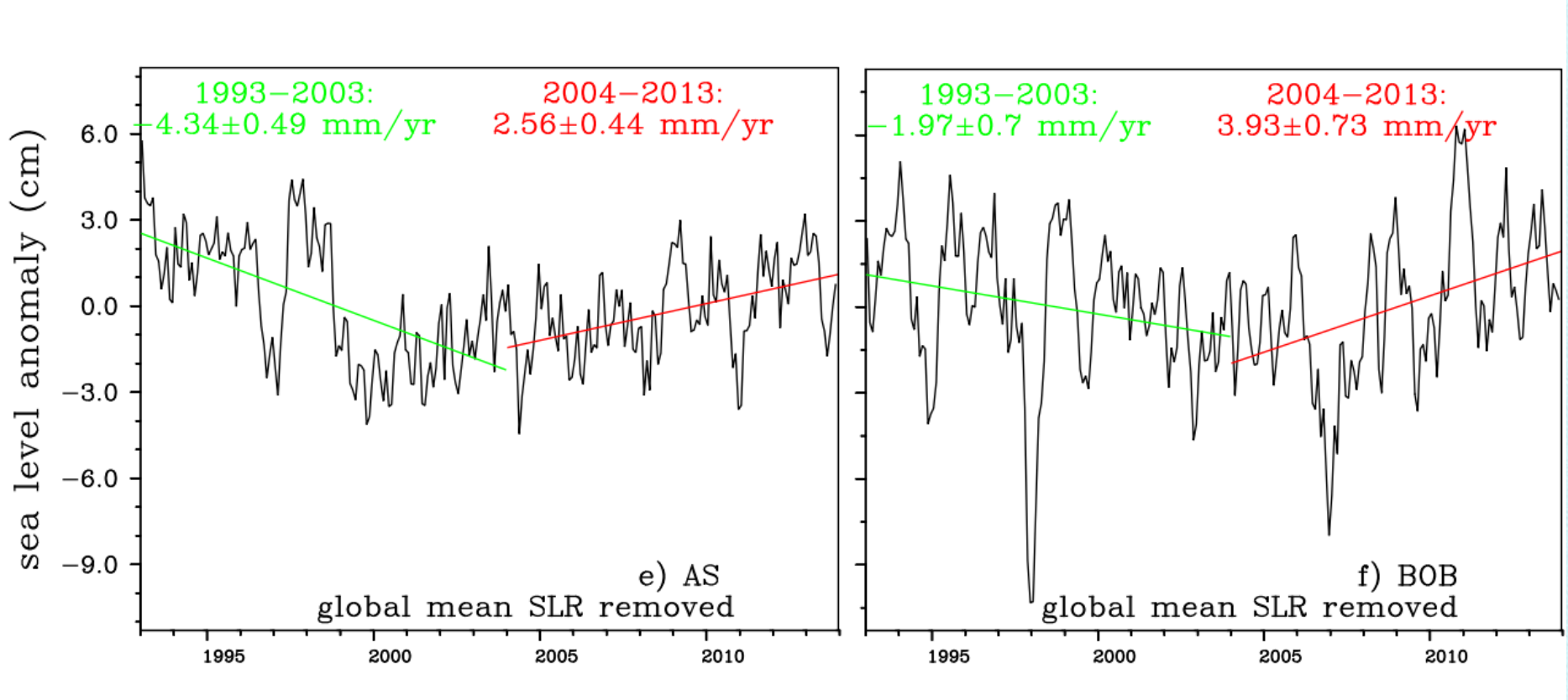
In the NIO, SL decreases at 2.94 ± 0.3 mm/yr during period I, which essentially balances the global mean SLR, but increases at 2.66 ± 0.27 mm/yr faster than the global SLR during period II.

Period I – 1993-2003

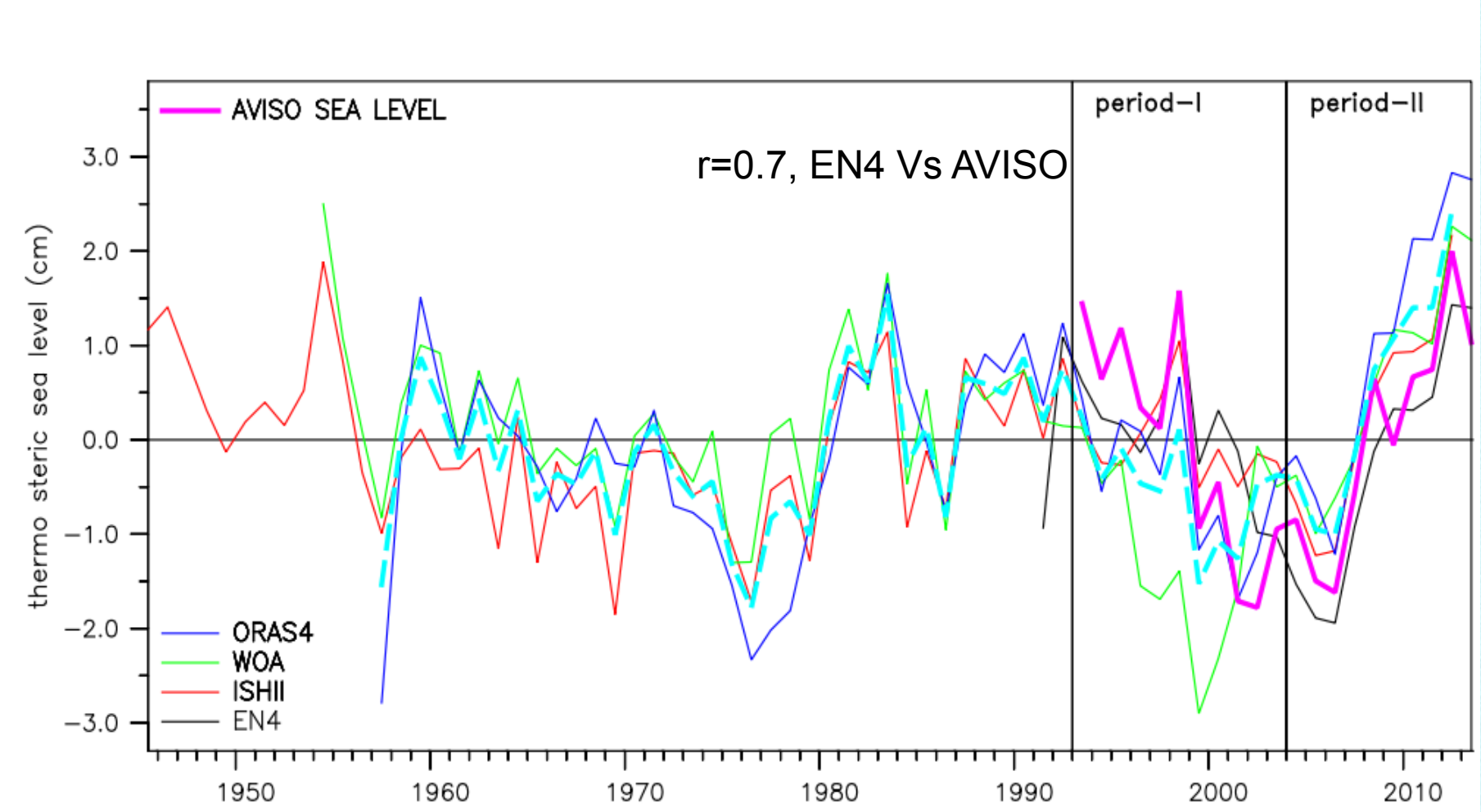
Period II – 2004-2013



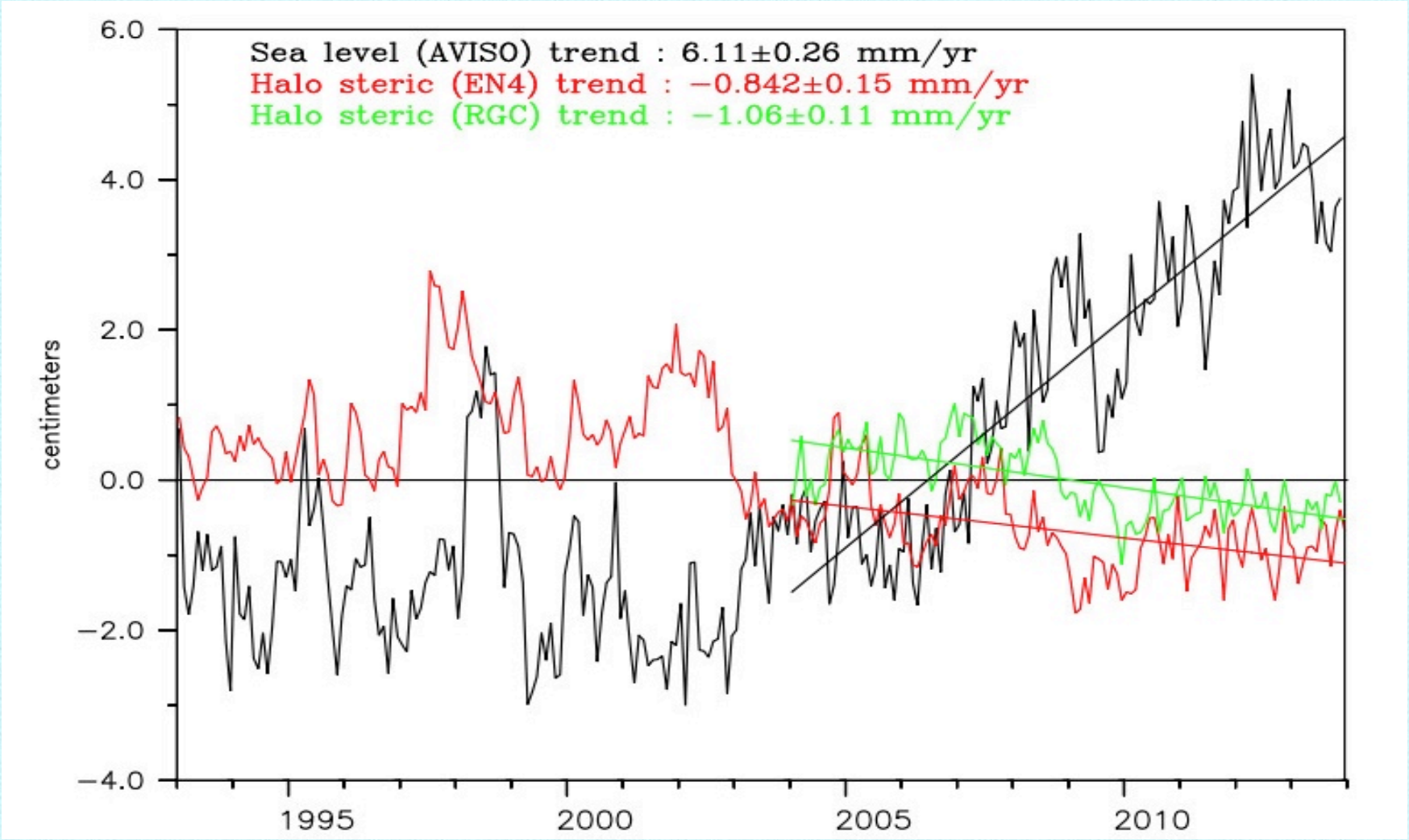
Arabian Sea and BoB



Time series of annual mean 0-700 m thermosteric sea level averaged over the NIO



Halo steric trend



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

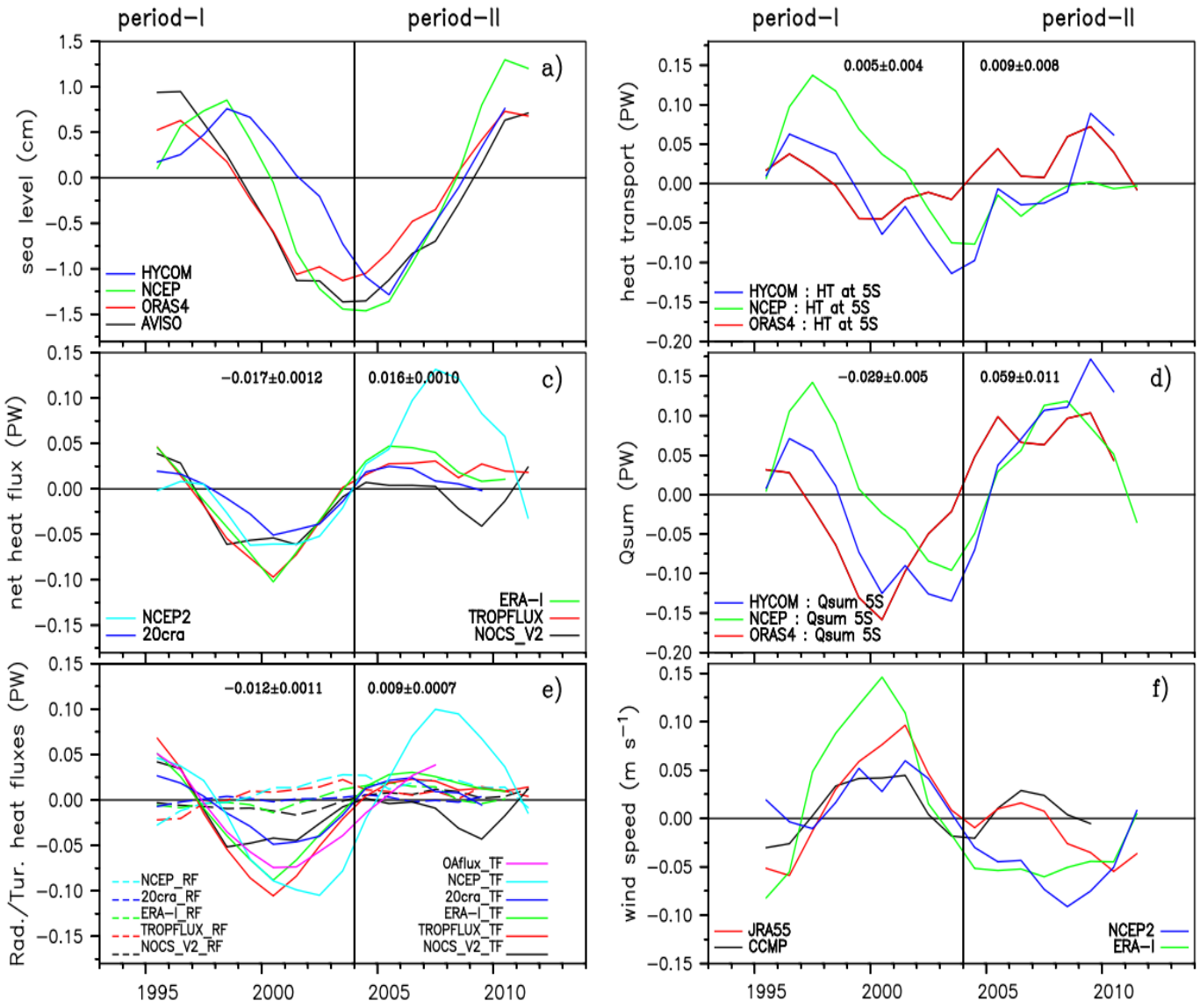
- What are the causes of this decadal reversal?

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

$$\frac{\partial HC_t}{\partial t} = \int_S^N \int_W^E Qnet\, dxdy + \int_W^E Qtr\, dx + \int_S^N \int_W^E \rho\, C_p T (P - E)\, dxdy + Rs$$

Causative mechanism



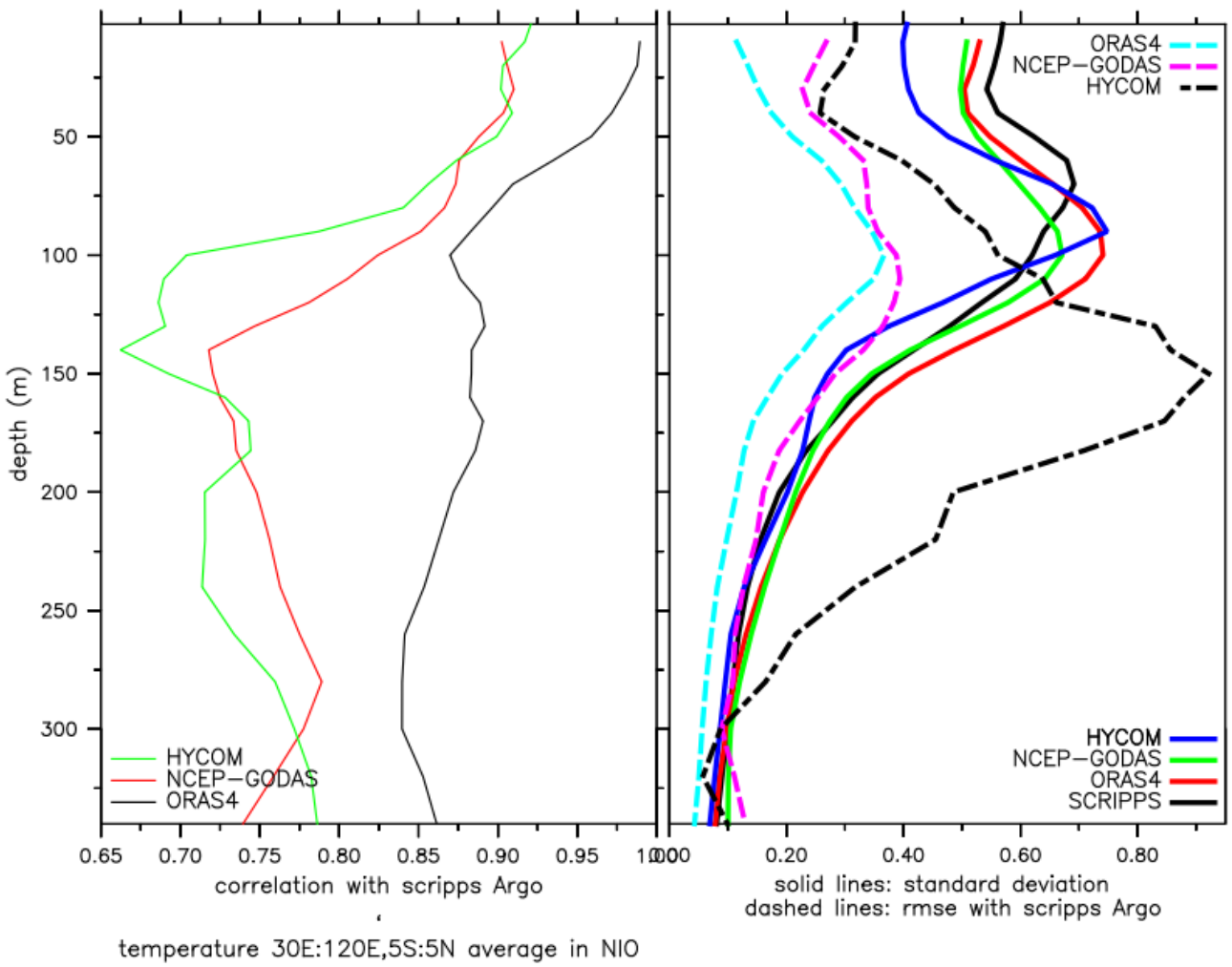
HYCOM Simulations with ITF and without ITF

NCEP-GODAS

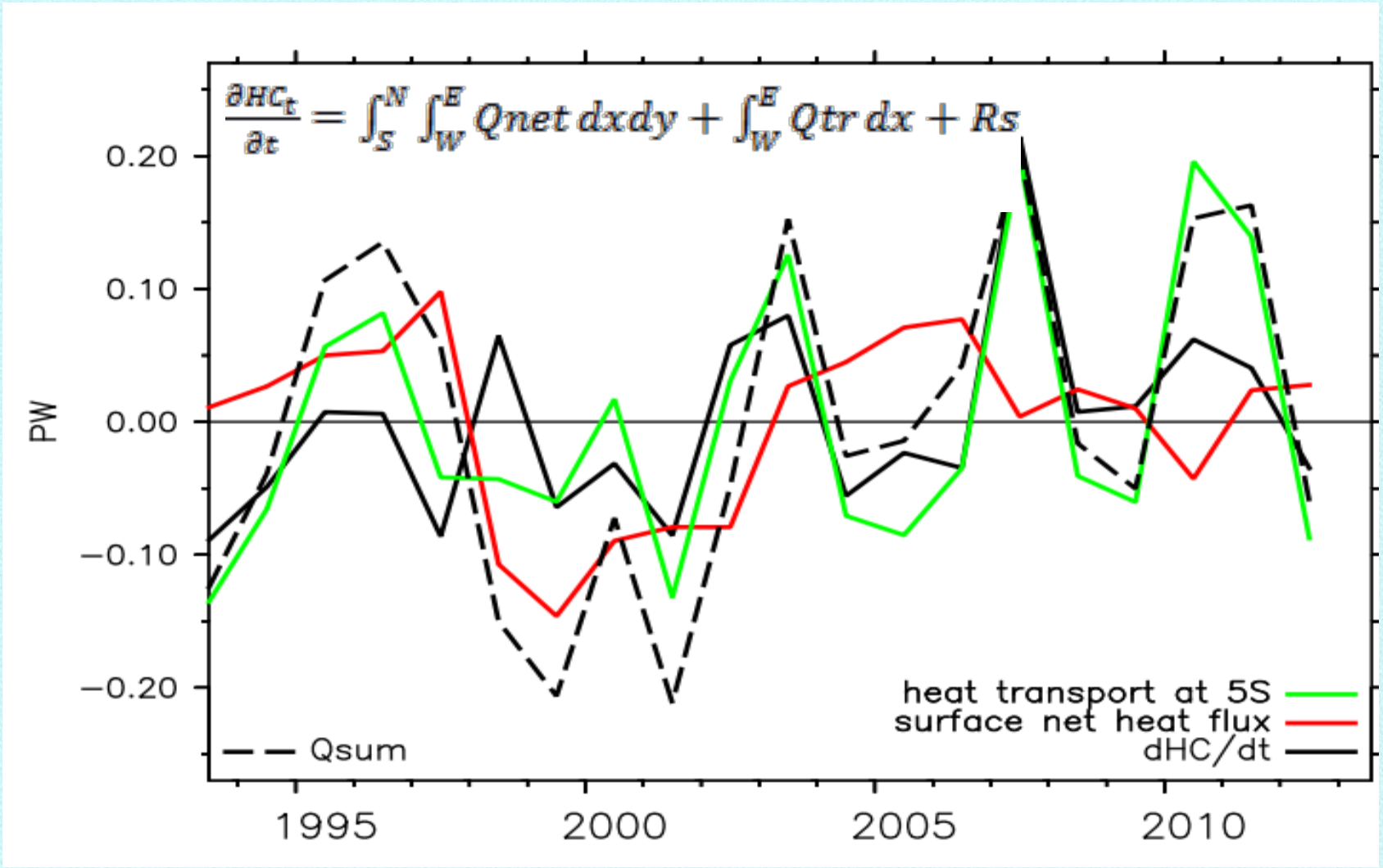
ORAS4

5 S – Southern Boundary

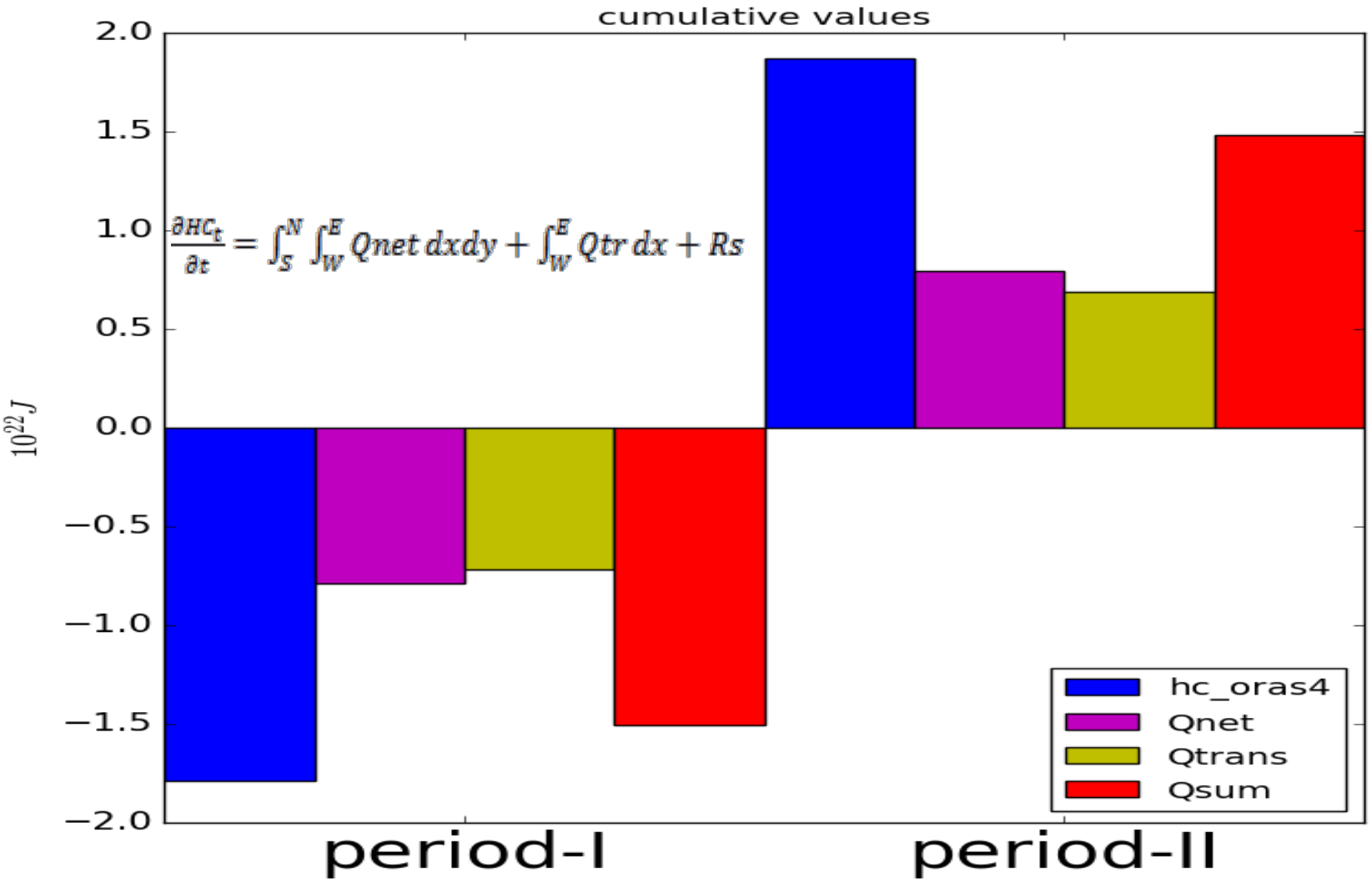
Evaluation of Subsurface currents



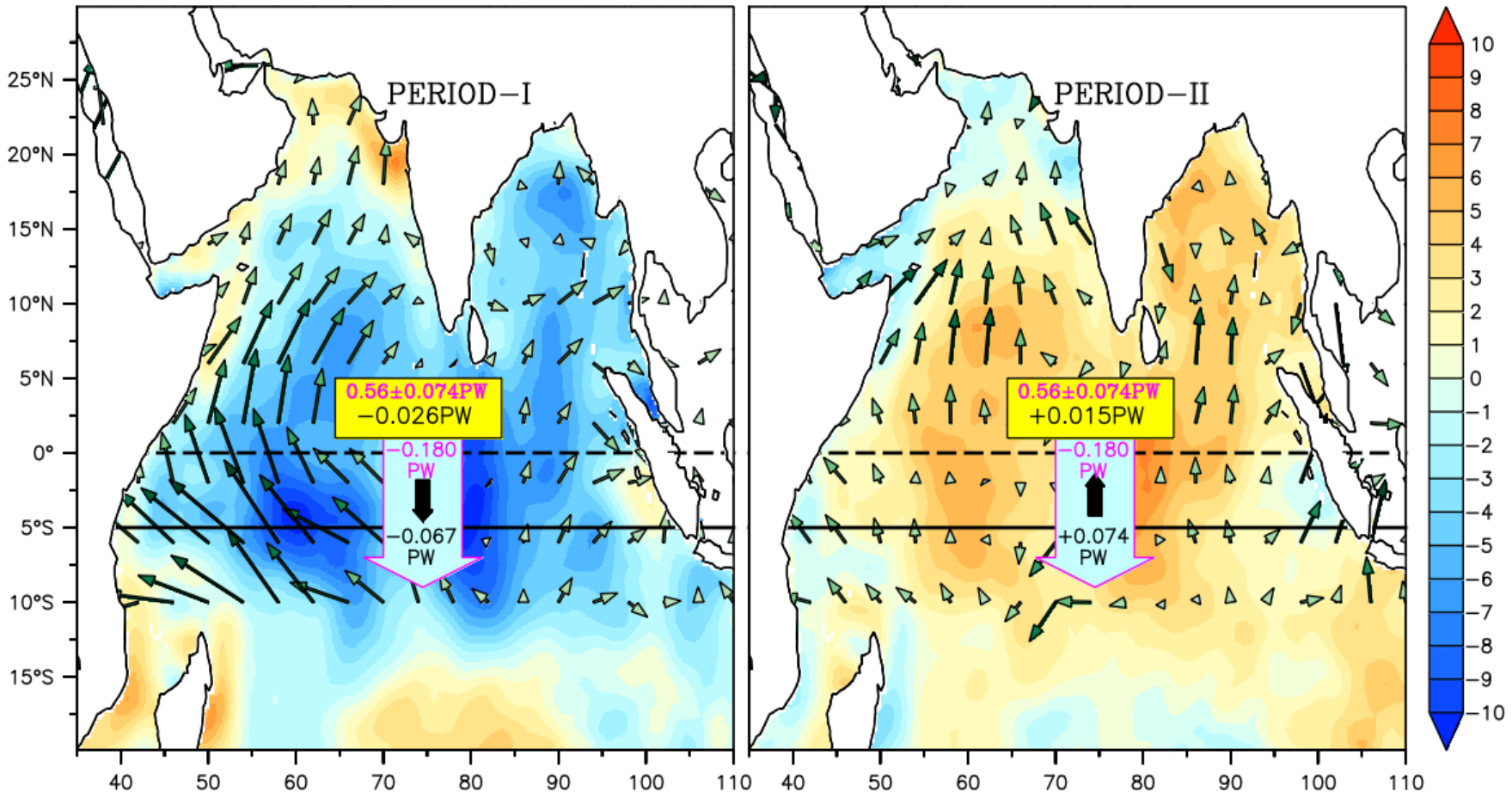
Sea level budget



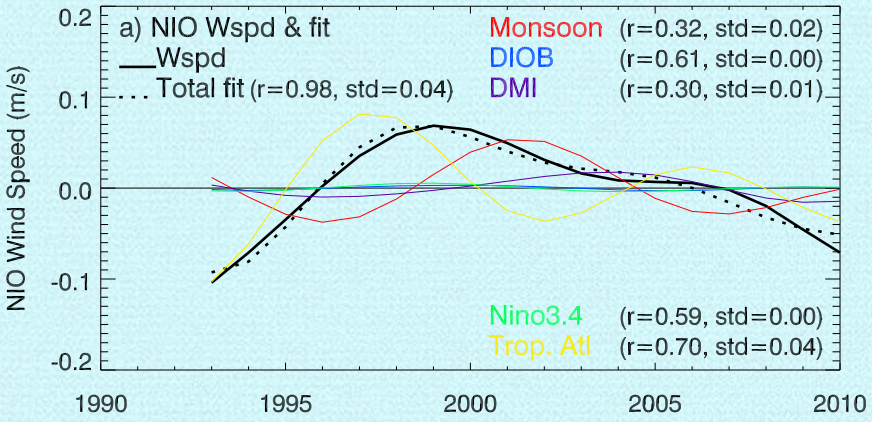
Budget terms

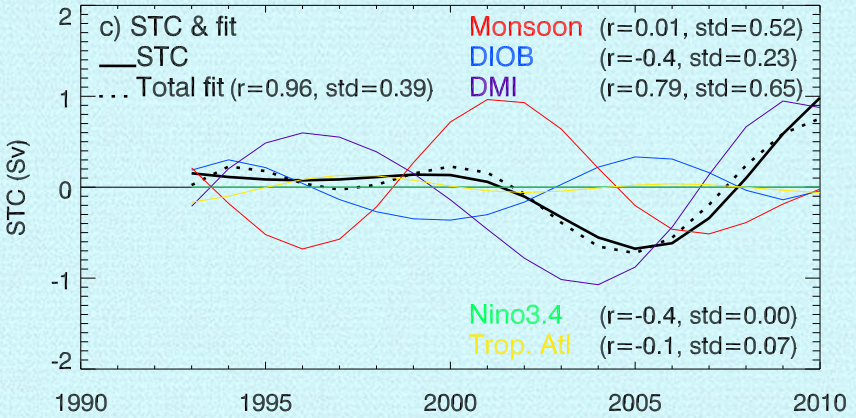


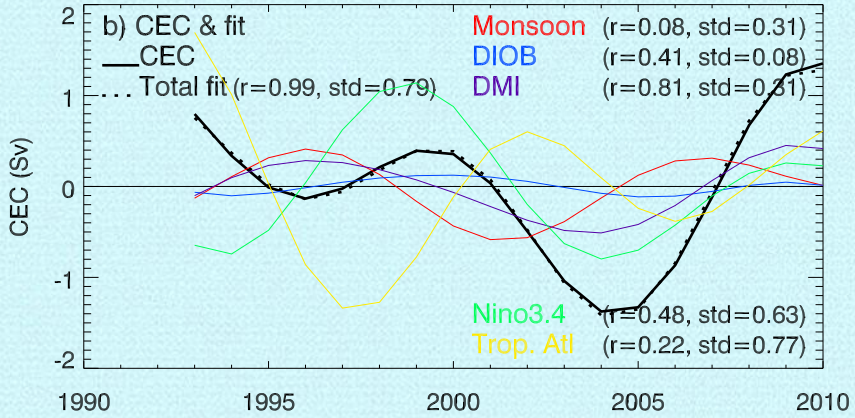
North Indian Ocean Sea Level



what causes the decadal reversal in wind over the Indian Ocean?







Climate Indices

- All-India summer monsoon rainfall
- Nino3.4 SST Anomaly (SSTA),
- Decadal Indian Ocean Basin Mode (DIOB)
- Indian Ocean Dipole (IOD)
- Tropical Atlantic SSTA

climate modes have apparent decadal changes in affecting surface winds in different regions of the Indian Ocean.

Climate Indices

	NIO wind speed		CEC		STC	
	1993-2003	2003-2010	1993-2003	2003-2010	1993-2003	2003-2010
Observed	**0.129**	**-0.115**	**-0.997**	**4.351**	**-0.290**	**2.083**
Total fit	**0.126**	**-0.115**	**-0.982**	**4.355**	**-0.252**	**2.082**
Monsoon	*0.074*	*-0.047*	*-0.808*	*0.519*	1.333	-0.857
DIOB	0.004	0.004	0.162	0.144	-0.474	-0.421
DMI	*0.019*	*-0.056*	*-0.549*	*1.618*	*-1.152*	*3.398*
NINO3.4	0.003	0.008	0.638	***1.682***	-0.000	-0.000
AMO	*0.026*	*-0.024*	*-0.426*	*0.392*	0.042	-0.038

Summary

- Satellite and in situ observations, together with ocean reanalysis products, show a distinct decadal reversal of sea level change over 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.
- Climate variability modes (the all-India summer monsoon rainfall, ENSO, Decadal Indian Ocean Basin Mode (DIOB), Indian Ocean Dipole, and tropical Atlantic SSTA) have apparent decadal changes in affecting surface winds and thus sea level over the NIO.

Thank You for your attention