# Mean sea-level-rise along the Indian coasts

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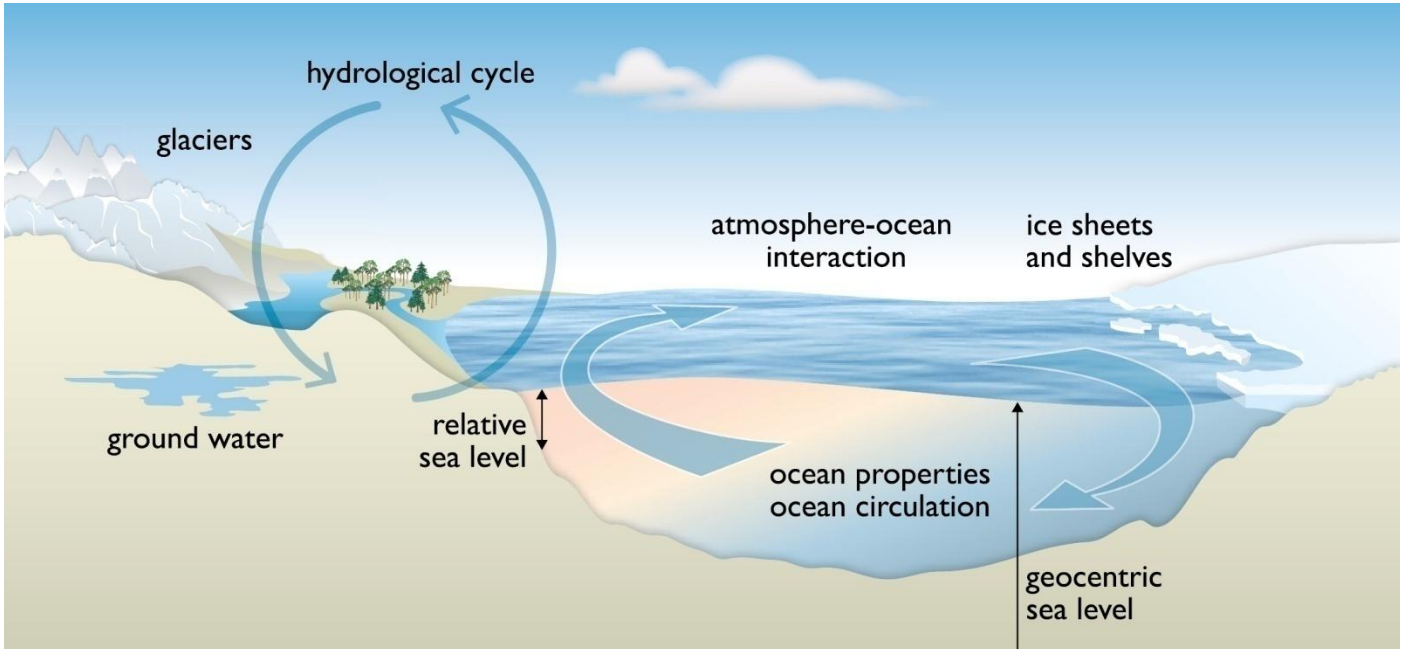
# Processes of sea-level changes

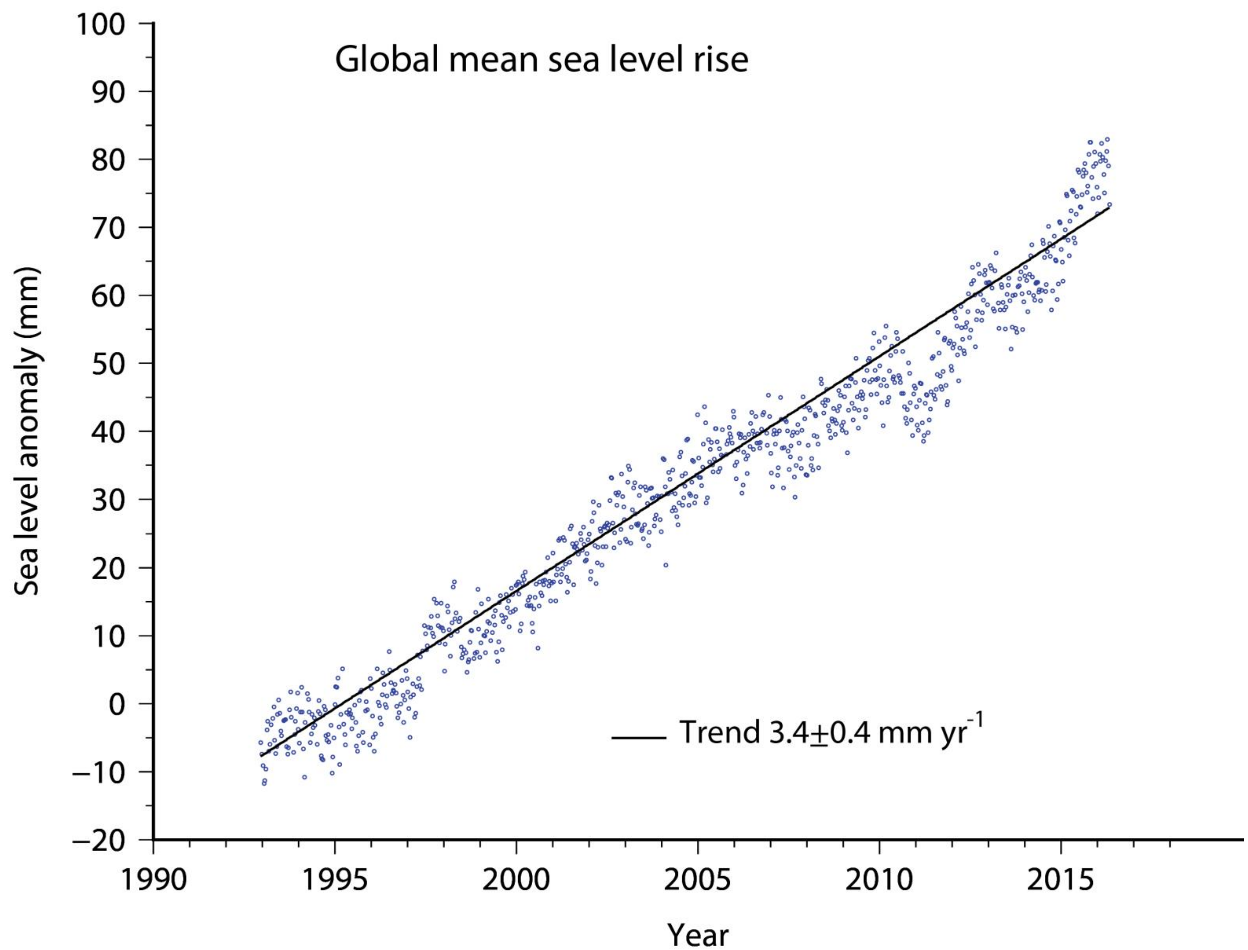



- Relative sea level is also affected by land movements, changes in ocean density, circulation and distribution of mass on the earth

# Global sea-level-rise trends

- Global sea-level rise  had been 1.7 mm $yr^{-1}$ 1901-2010 and at the rate of 3.12 mm $yr^{-1}$ during the last two decades (1993-2012) (Church et al., 2013)

# Global mean sea-level-rise trends during the last two decades




Topex/POSEIDON,
Jason-1 and Jason-2
Satellites
Data source: MSL Group
Uni. Colarado

# Mean and Extremes

- Sea level changes can be broadly of two types:
- (i) Mean sea level
- (ii) Extreme sea level (A combination of storm surges, tides, MSL rise)

The former is a global phenomenon, while the latter is a regional phenomenon

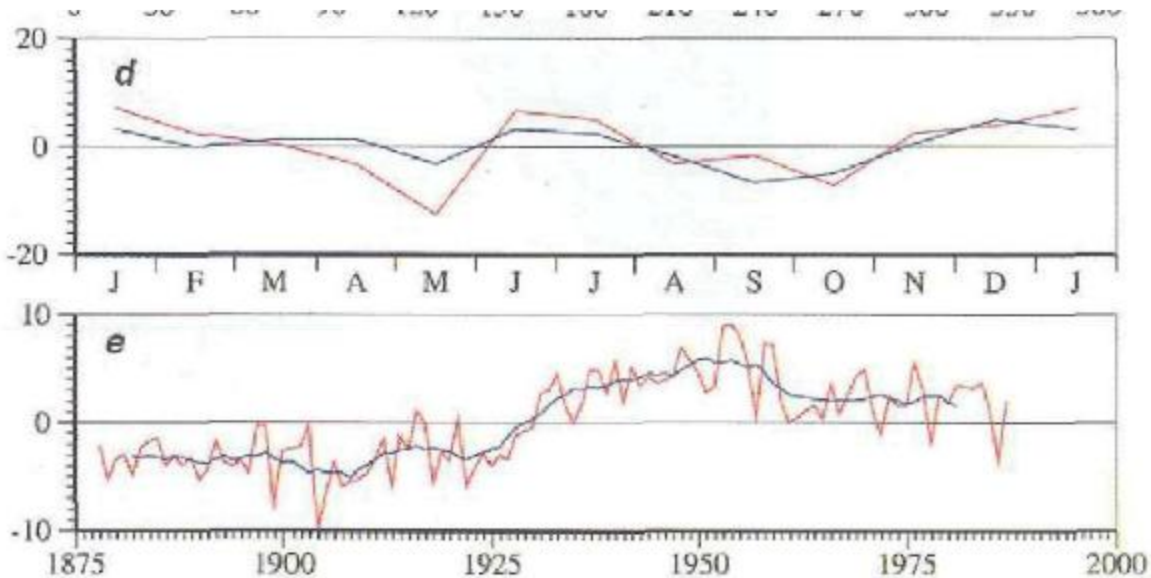
# Mean Sea Level calculation from tide-gauge data

- Daily MSL is calculated by applying a suitable filter (see IOC Manuals for details) to the measured tide gauge data (i.e. not the tidal or non-tidal parts separately, but to the measured values)
- Monthly MSL is then defined as the arithmetic average of the daily MSL values in that month
- Annual MSL is defined as the average of the daily MSL values in a year

# MSL variability

- Mean Sea level undergoes variability at different time scales, such as seasonal, inter-annual, decadal and multi decadal.

# Seasonal cycle of sea level along the Indian coast

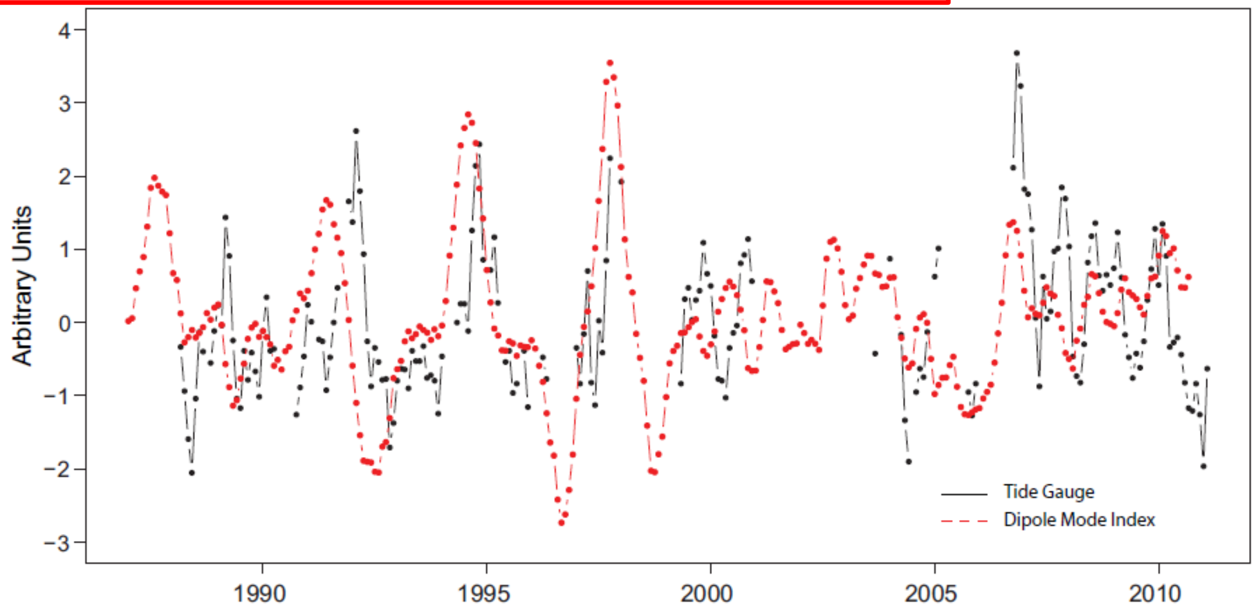



- d monthly mean data (black line –climatology)
- e annual mean data (black line- filtered 10 yr boxcar)

*Shankar et al. 2000* In: Current Science

# Inter-annual variability

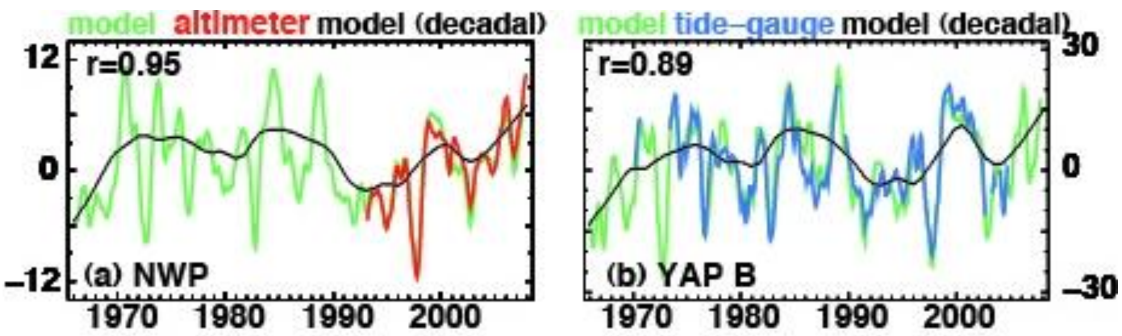
MSL at Diego Garcia (Chagos Archipelago, tropical west Indian Ocean) ; high sea level during positive phases of the IOD




- Courtesy:
- Philip Woodworth

# Decadal sea level variability

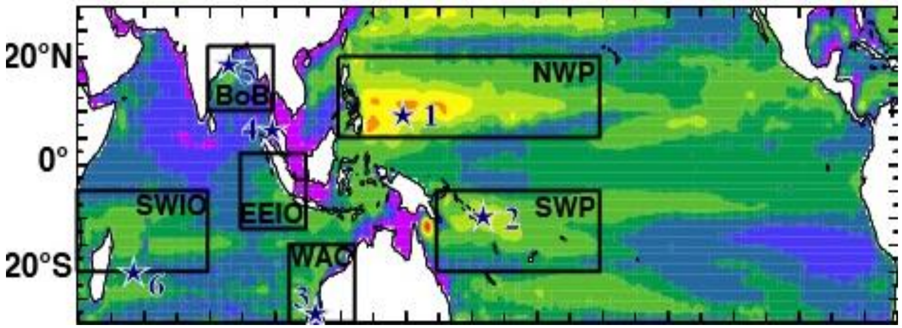
- We used observed sea level obtained from satellite altimetry and tide-gauges to validate steric sea level from simulations of an Ocean General Circulation Model (NEMO) to investigate the decadal sea level variations



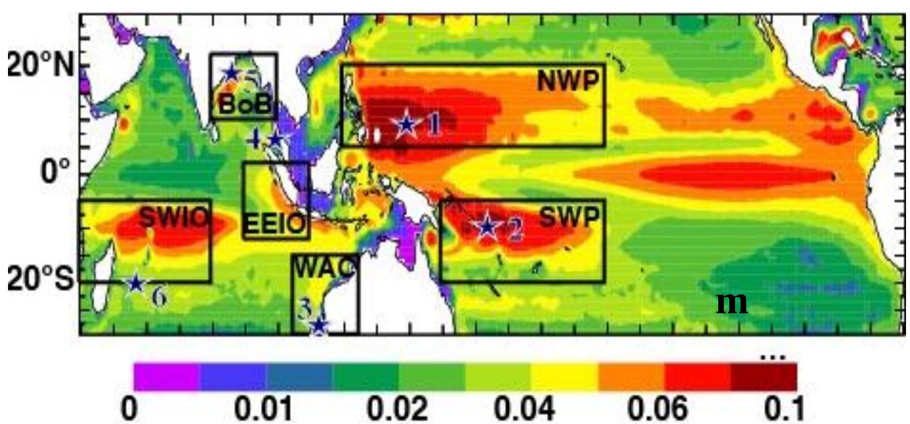

**Sea level time-series in the north-west Pacific from altimeter (red), tide-gauges (blue) and model (green).**
**Black curve is the decadal signal obtained through extraction procedure.**

# AMPLITUDE OF VARIABILITY

**Standard deviation of model decadal sea level**




**Standard deviation of model interannual sea level**




**The regions :**

**1 North west Pacific**
**2 South west Pacific**
**3 West Australian coast**
**4 Eastern equatorial Indian Ocean**
**5 Bay of Bengal**
**6 South-west Indian Ocean**

**The model was driven wind fields from various products of wind fields**
**Decadal variations in zonal wind stress causes decadal changes in sea level**
**Nidheesh et al., 2013 Climate Dynamics**

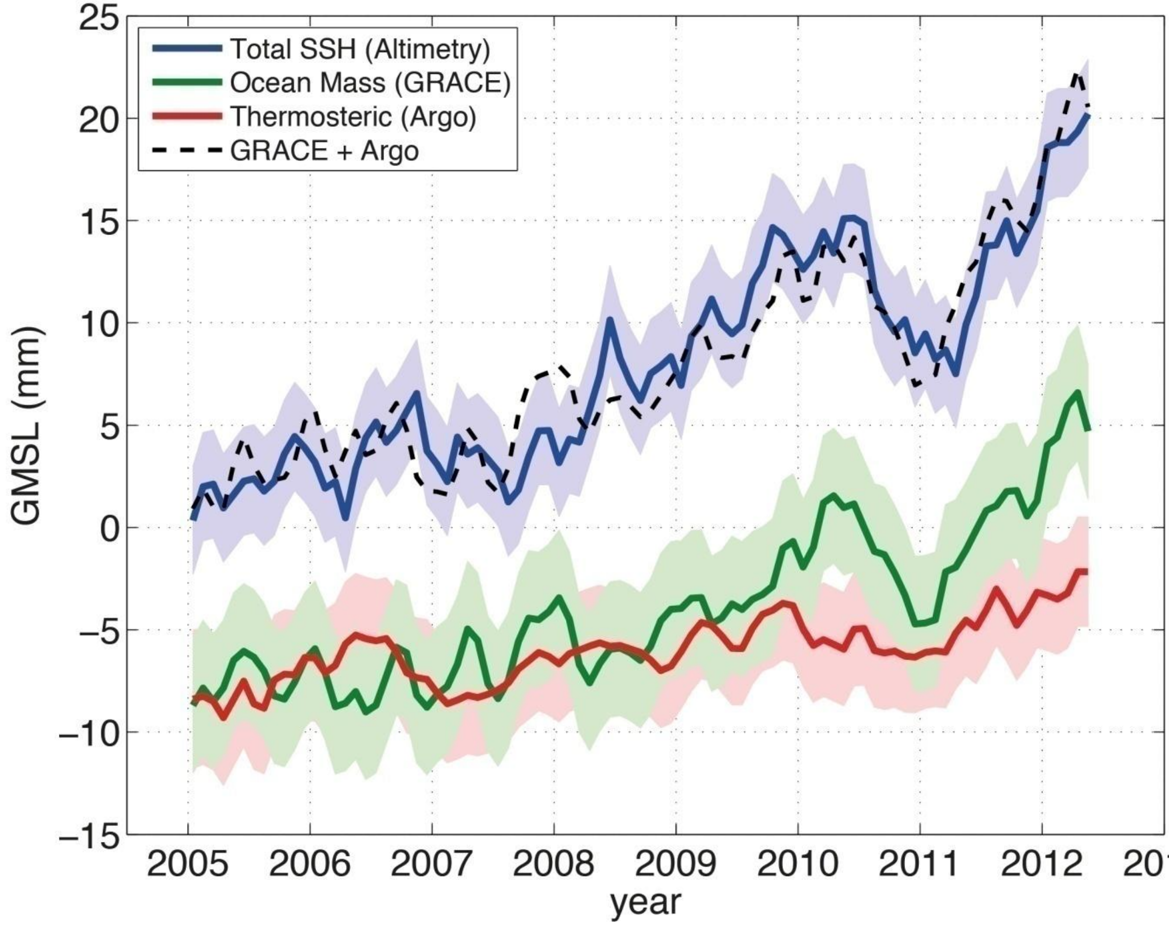
# Observational evidences for sea-level rise in recent decades

- Increase in the observational evidences for sea-level rise
- Tide gauge records
- Satellites, TOPEX/Poseidon (since 1992), Jason-1 & 2 and the Indo-French satellite, SARAL/Altika, which is currently in orbit since 2013, measures sea level using altimeters
- GRACE satellite (since 2004) measures minute changes in gravity making it possible to estimate ice sheet melting (Greenland, Antarctica)
- ARGO measurements of temperature and salinity in oceans

# Ocean observations

- During the last decade, ARGO floats have been continuous measuring  temperature and salinity in oceans.

Ocean thermal
Expansion and
mass added from
Glacier melt together
Account for the
Nearly 75 percent
Of Observed  SLR



# Trend estimation and record length

- Douglas  B. suggested a length of tide-gauge record of  > 50-60 years for trend estimation. In shorter records, decadal variability can aliase the trends.

# Regional sea-level rise

- Global sea-level rise is relatively well understood; however, regional sea level rise is less studied

# Estimates of sea-level-rise trends along the Indian coasts

- Emery and Aubrey (1989) used all the available records along the Indian coast, estimated trends showed considerable variability
- Douglas (1991) expressed apprehensions on the Indian tide gauge records

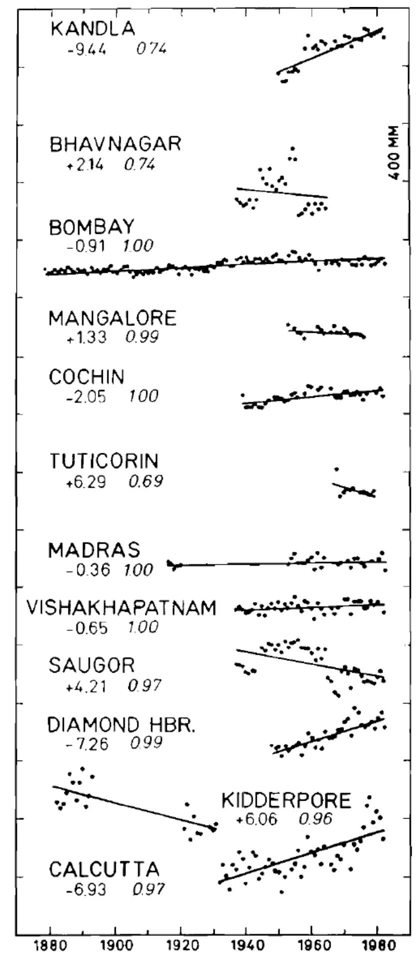
- Unnikrishnan and Shankar (2007) used selected records to estimate sea-level rise trends

# Sea-level-rise trends along the Indian coasts - Earlier studies

| Journal of Coastal Research | 5 | 3 |
| --- | --- | --- |

**Tide Gauges of India[1]**

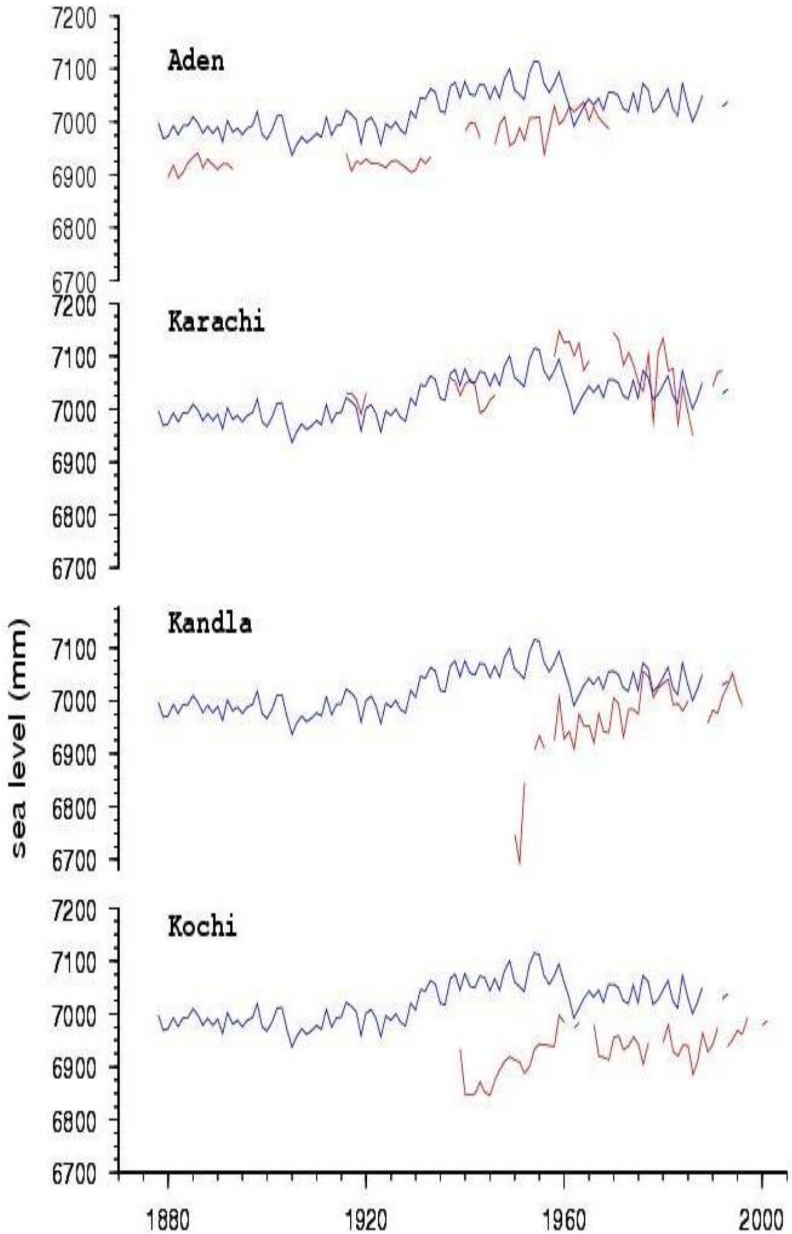
**K. O. Emery and D. G. Aubrey**



# Inter-consistency checks for the estimation of long-term trends

- Inter-consistency checks between adjacent records are needed before further analysis. This can be done using a linear correlation analysis between the two time series.
- For instance, we took the longest record at Mumbai for comparison with other records in the Arabian Sea. Along the east coast, Visakhapatnam record is correlated with other records in the Bay of Bengal.

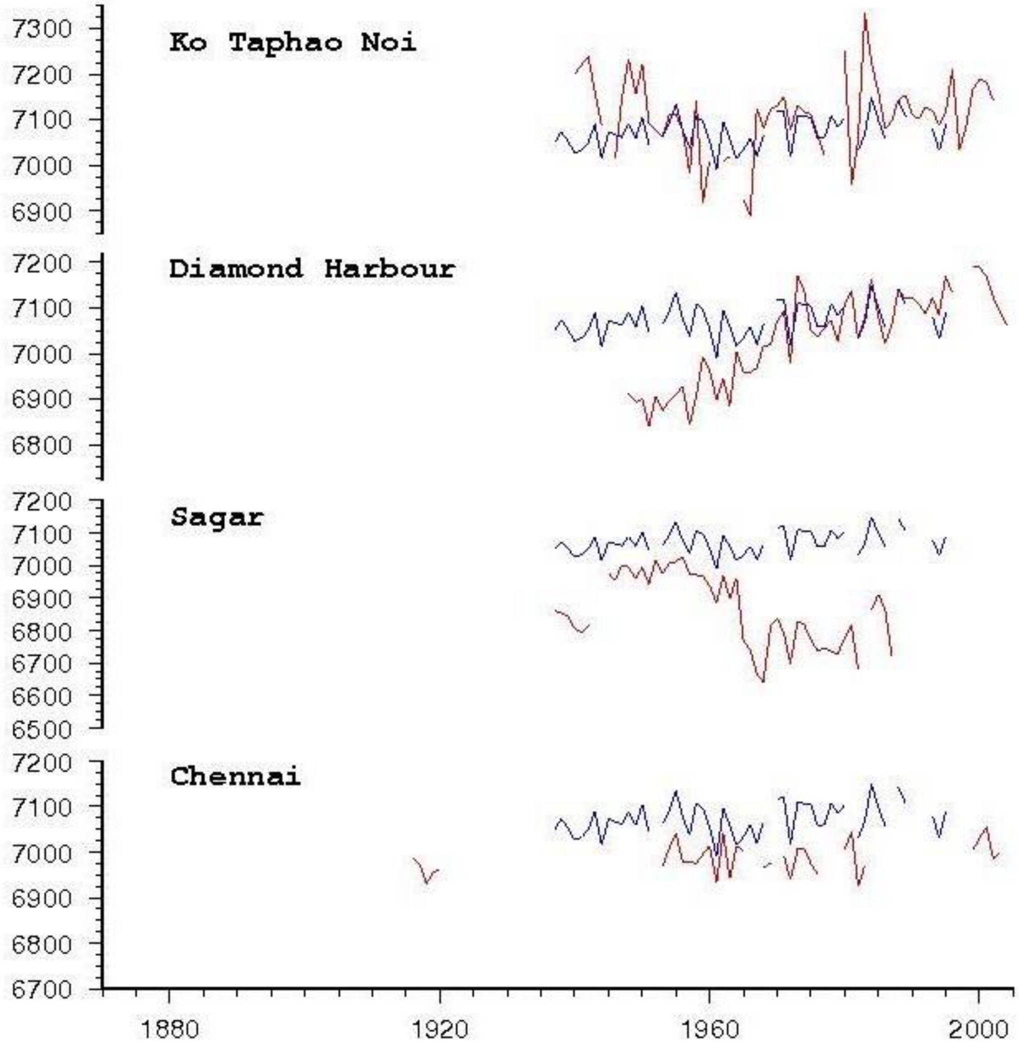
Individual tide gauge records (red) along the Arabian Sea coast compared to Mumbai record (blue)



# Linear correlation of individual records with that of Mumbai

| Station | No. of years | Reference station | Correlation coeffici | Confid. Limit (%) |
|---|---|---|---|---|
| Aden (1880-1969) | 58 | Mumbai | 0.68 | 99.9 |
| Karachi (1916-1992) | 44 | Mumbai | 0.31 | 95 |
| Kandla (1950-1996) | 43 | Mumbai | -0.04 | < 90 |
| Kochi (1939-2003) | 54 | Mumbai | -0.04 | < 90 |

Tide Gauge records (red) along the Bay of Bengal coast compared to Vishak (blue) record



# Linear correlation of individual records with that of Vishak

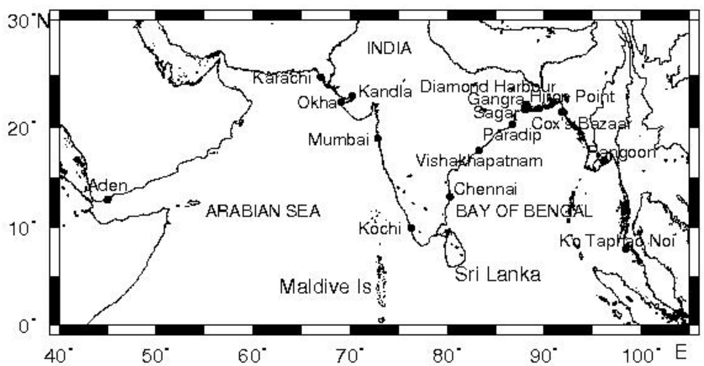
| Station | No. of years | Reference station | Linear correlation coeff. | Confid. Limit (%) |
|---|---|---|---|---|
| Kochi (1939-2003) | 54 | Vishakhapatnam | 0.43 | 99.0 |
| Chennai (1916-2003) | 39 | Vishakhapatnam | 0.62 | 99.9 |
| Sagar (1937-1987) | 48 | Vishakhapatnam | 0.22 | <90.0 |
| Diamond Harbour (Kolkata) | 55 | Vishakhapatnam | 0.46 | 99.9 |

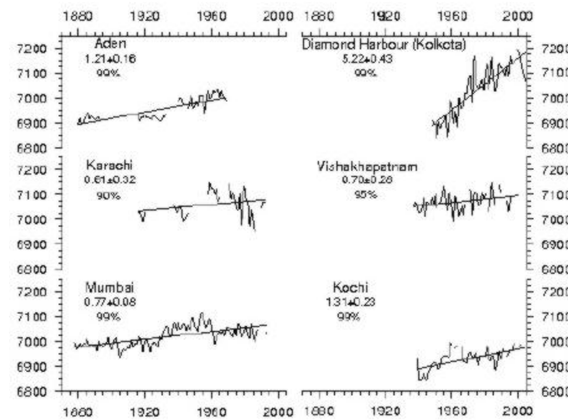
# Correction for vertical land movements

- Vertical land movements occur through various processes such as local tectonic activity, subsidence in deltaic regions, glacial isostatic adjustment (GIA), or post-glacial rebound.

- GIA corrections using model ((ICE5G- VM4, Peltier, 2004)

# Sea-level-rise trends in the north Indian Ocean



# Net sea-level-rise trends along the north Indian Ocean coast based on past tide-gauge records

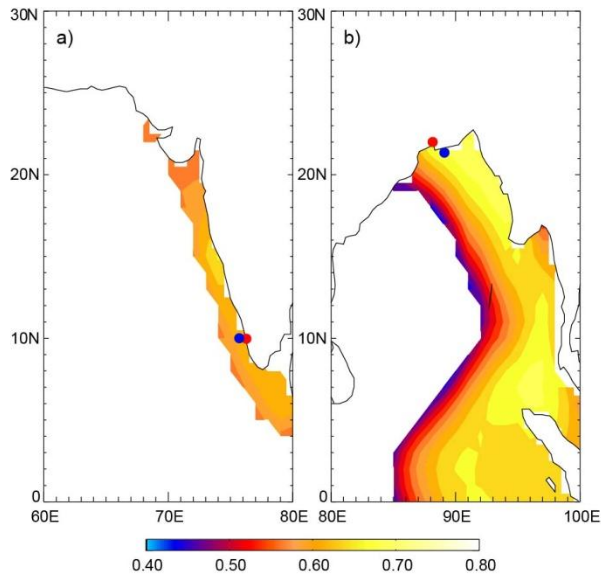
| Station | No of years | trends | GIA | Net sea-level rise trends (mm/yr) |
|---|---|---|---|---|
| Aden | 58 | 1.21 | -0.16 | 1.37 |
| Karachi | 44 | 0.61 | -0.45 | 1.06 |
| Mumbai | 113 | 0.77 | -0.43 | 1.20 |
| Kochi | 54 | 1.31 | -0.44 | 1.75 |
| Vishakhapatnam | 53 | 0.70 | -0.39 | 1.09 |
| Diamond Harbour | 55 | 5.22 | -0.52 | 5.74 |

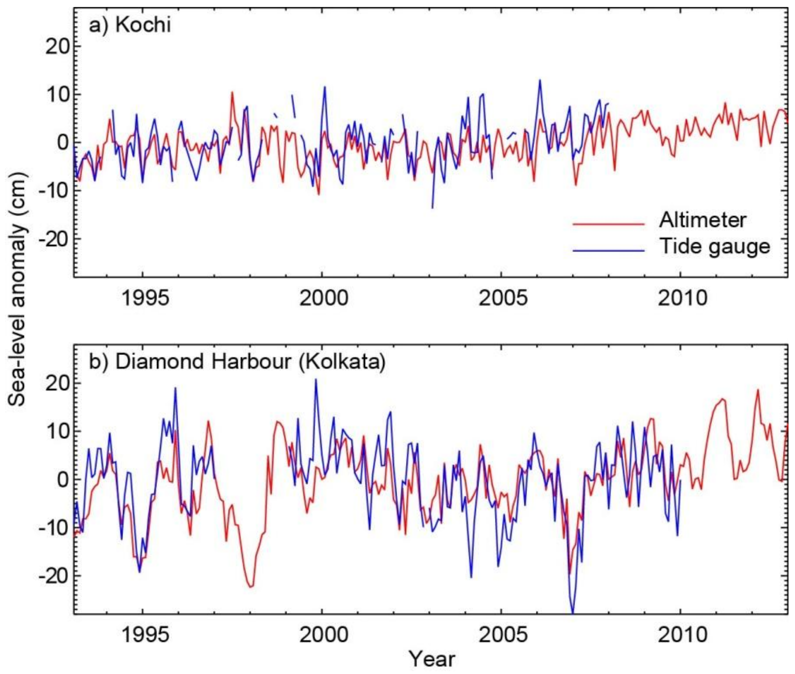
# Estimation of sea-level rise during last two decades

- Since the availability of satellite altimeter data (Topex/POSEIDON, Jason-1 and Jason-2) sea level data became available on a near global scale (except ± $66^0$ latitudes)

- Altimeter data permits to prepare spatial plots of sea-level rise trends and allows to compare with tide gauge estimates.

# Comparison between satellite altimeter data and tide-gauge data in selected stations




- Blue (red) dots show tide-gauge (altimeter) locations

Linear correlation coefficient 0.63 for Kochi
0.69 for D Harbour

# Spatial distribution of sea-level-rise trends in the north Indian Ocean from satellite altimetry

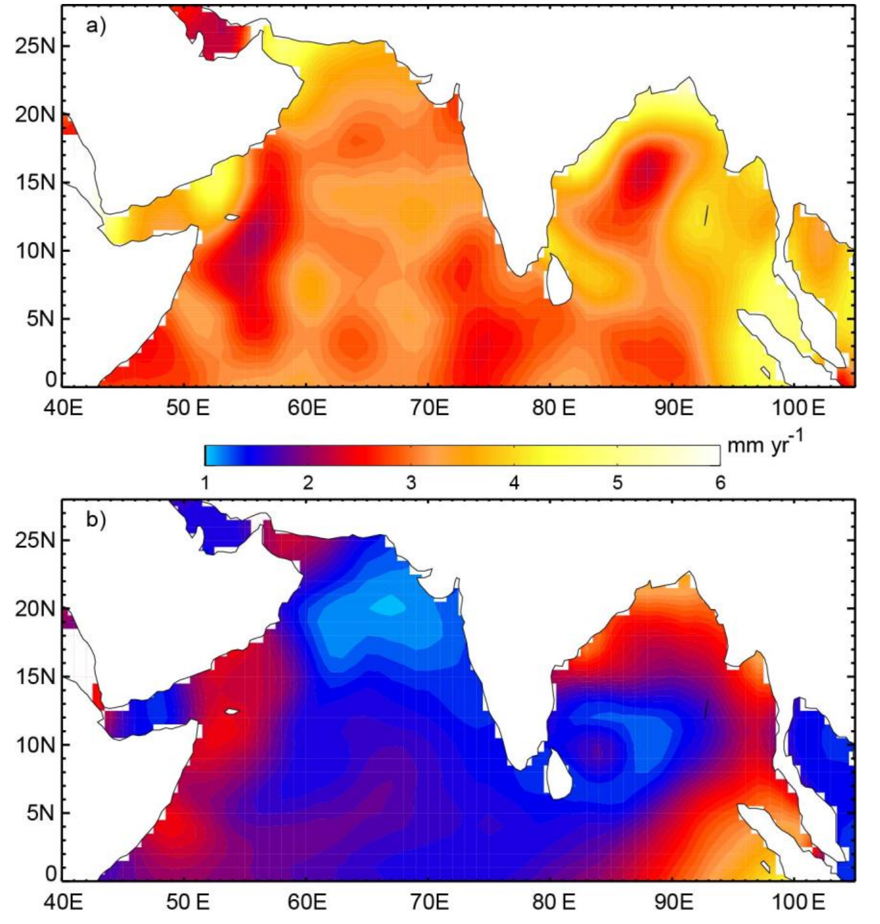
Trends are larger (3.28 mm $Yr^{-1}$ basin average) in the past two decades, compared to those in 20th century

Large trends and uncertainties in the eastern Bay of Bengal

Regions of low uncertainties are Associated with regions of low inter-annual variability (as described In previous studies, Shankar et al., Aparna et al.)

Unnikrishnan et al., (Current Science, 2015)

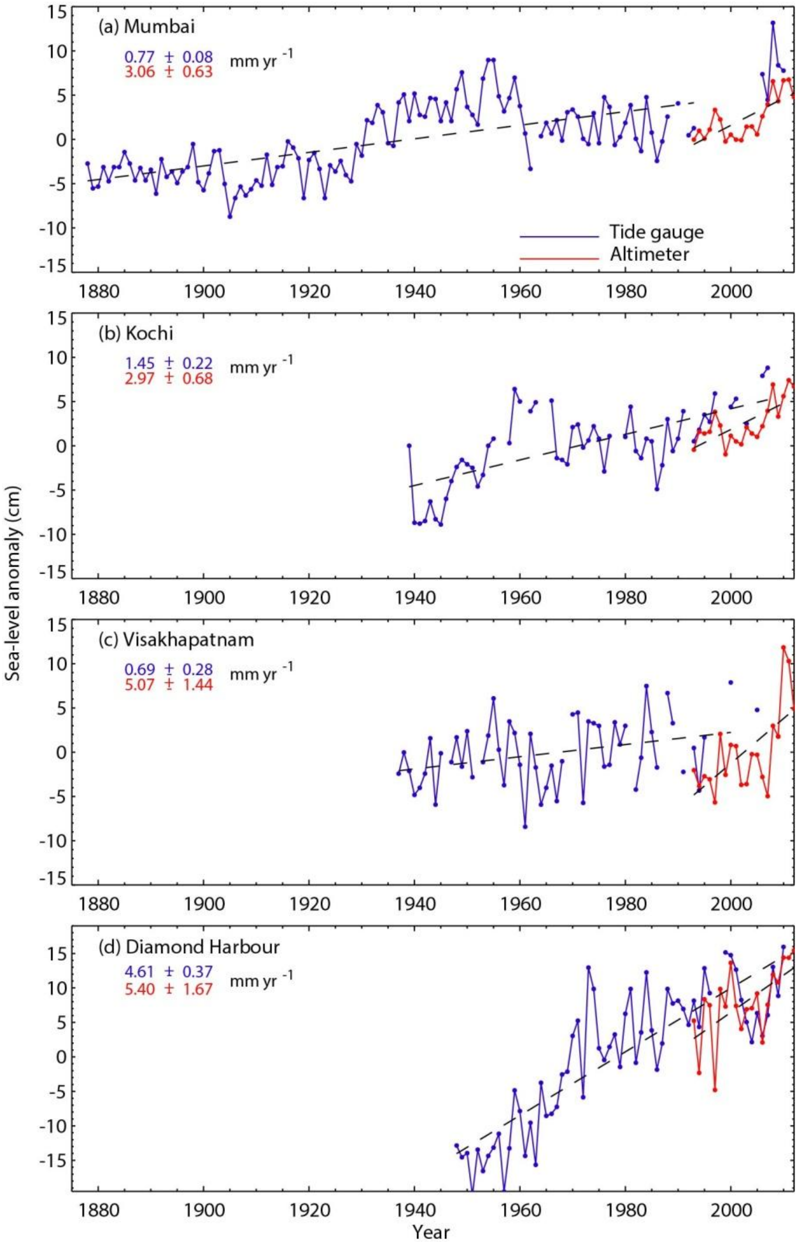
**Sea-level-rise trends(1993-2012) and related uncertainties**



# Sea-level-rise trends along the Indian coasts

- Gaps in some tide gauge-records during altimeter period

Large trends in the deltaic regions (Diamond Harbour) are partly attributed to subsidence



# Net sea-level-rise trends along the Indian coast

| Station | Period of analysis | Number of years of data availability | Trends in relative sea-level rise (mm $yr^{-1}$) | GIA Correction (mm $yr^{-1}$) | Net sea-level-rise trend (mm $yr^{-1}$ ) |
|---|---|---|---|---|---|
| Mumbai | 1878-1993 | 113 | 0.77±0.08 | -0.31 | 1.08 |
| Kochi | 1939-2007 | 56 | 1.45±0.22 | -0.36 | 1.81 |
| Visakhapatnam | 1937-2000 | 53 | 0.69±0.28 | -0.24 | 0.93 |
| Diamond Harbour (Kolkata) | 1948-2010 | 61 | 4.61±0.37 | -0.35 | 4.96 |

# Regional sea level changes

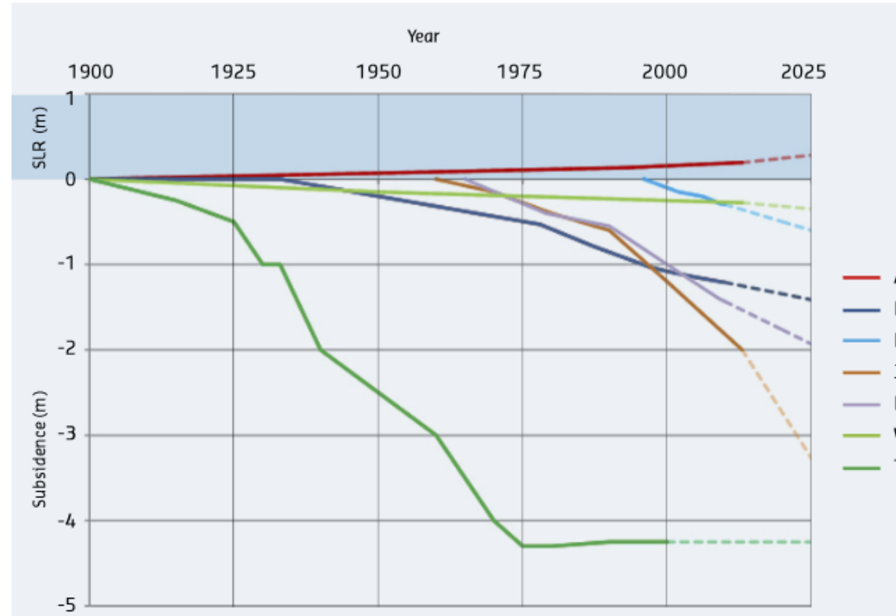
- Warming-induced sea-level rise
- Subsidence, groundwater depletion
- Changes in extremes

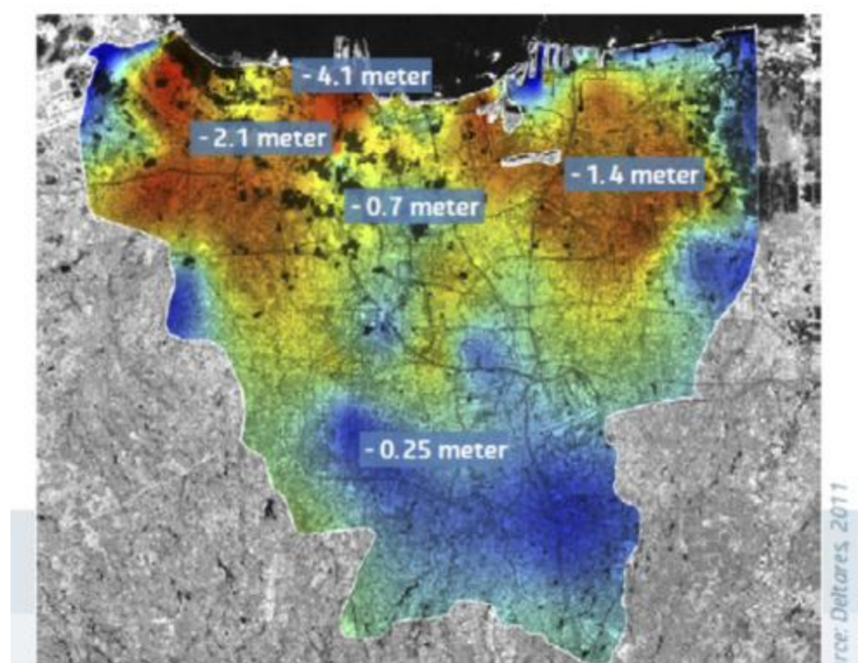
# Regional Sea level changes

Climate variability

Long-term trends in MSL

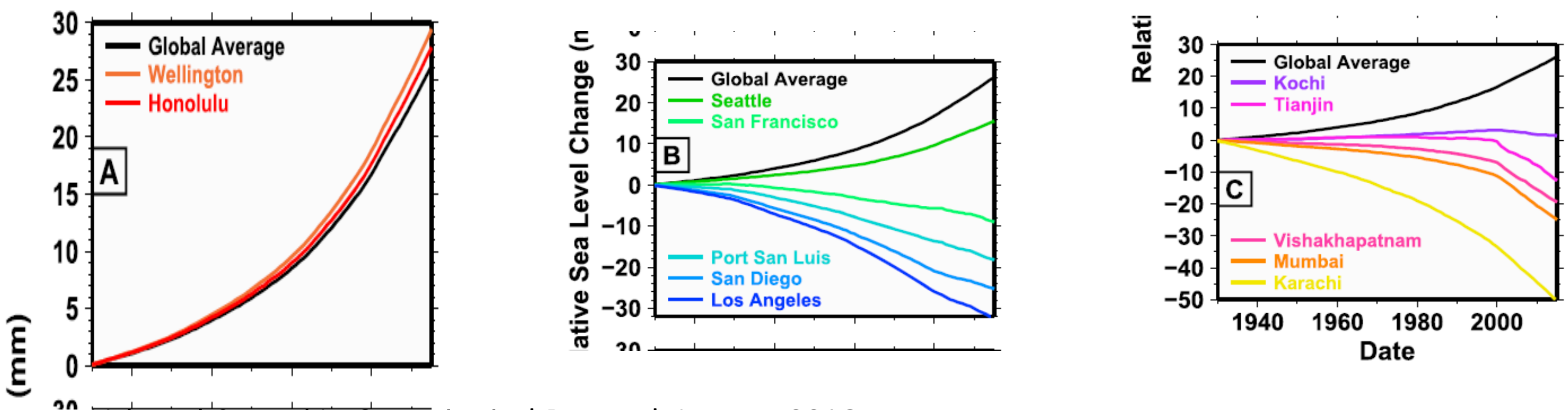
Land movements (subsidence, glacial isostatic adjustment, local tectonic activity)



# Relative sea-level change caused by groundwater depletion

Relative sea level change varies spatially due to deflections of the solid Earth and sea surfaces, computed here. On the longest wavelengths, groundwater depletion moves mass from continental sources, located mainly in the Northern Hemisphere, to the ocean basins, which are on average positioned in the Southern Hemisphere. Because this spherical harmonic degree 1 movement of water mass represents a change to the vector between Earth's center of mass and figure, the solid Earth shifts (by 8.89 mm away from 38°S, 133°W) and elevates relative sea level rise in the Pacific while depressing it southern Asia (Figure 1a). Because of this, central Pacific tide gauges (e.g., Honolulu and Wellington, Figure 2a) should measure rates of groundwater-induced sea level rise up to ~15% faster than the global average (Figure 1a).




- Veit and Conrad In Geoophysical Research Letters, 2016

# Linear sea-level rise trends for tide gauge records in North America and South Asia

**Table 1.** Linear Sea Level Trends (mm/yr, 1930–2010, Compute as in Figure 3) for Tide Gauges in Western North America and Southern Asia[a]

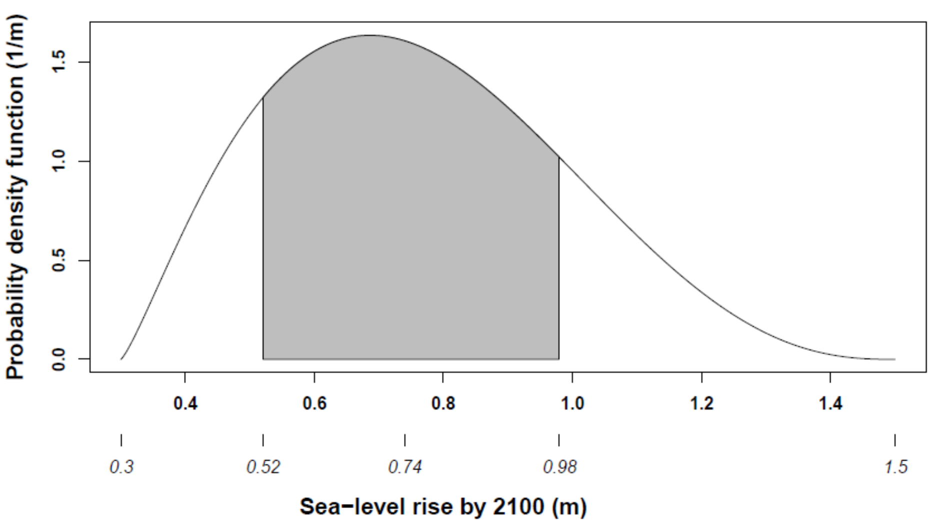
| | | Applied Corrections | | | | | |
|---|---|---|---|---|---|---|---|
| | | GIA | | Interseismic | | Groundwater | |
| Station Name | Linear Fit to Tide Gauge Data | Correction | Applied | Correction | Applied | Correction | Applied |
| | | *Western USA* | | | | | |
| Seattle | 2.14 | −0.70 | 1.44 | 0.00 | 1.44 | 0.15 | 1.59 |
| San Francisco | 1.88 | −0.42 | 1.46 | 0.23 | 1.69 | 0.40 | 2.10 |
| Alameda | 0.69 | −0.40 | 0.29 | 0.31 | 0.60 | 0.46 | 1.07 |
| Port San Luis | 0.77 | −0.33 | 0.44 | 1.20 | 1.64 | 0.52 | 2.16 |
| Santa Monica | 1.43 | −0.20 | 1.23 | 0.35 | 1.58 | 0.66 | 2.24 |
| Los Angeles | 0.89 | −0.22 | 0.67 | 0.42 | 1.09 | 0.59 | 1.68 |
| La Jolla | 2.19 | −0.23 | 1.96 | −0.12 | 1.84 | 0.53 | 2.38 |
| San Diego | 2.12 | −0.24 | 1.88 | −0.20 | 1.68 | 0.51 | 2.19 |
| Mean | **1.51** | −0.34 | **1.17** | 0.27 | **1.45** | 0.48 | **1.93** |
| Standard Deviation | **0.65** | 0.17 | **0.64** | 0.44 | **0.41** | 0.16 | **0.44** |
| | | *Southern Asia* | | | | | |
| Alexandria | 1.85 | 0.03 | 1.88 | | | 0.24 | 2.12 |
| Aden | 1.38 | 0.13 | 1.51 | | | 0.16 | 1.67 |
| Karachi | 1.83 | 0.29 | 2.12 | | | 0.51 | 2.63 |
| Mumbai | 0.25 | 0.31 | 0.56 | | | 0.46 | 1.02 |
| Kochi | 1.35 | 0.36 | 1.71 | | | 0.22 | 1.93 |
| Chennai | 0.61 | 0.28 | 0.89 | | | 0.28 | 1.17 |
| Vishakhapatnam | 0.93 | 0.24 | 1.17 | | | 0.43 | 1.60 |

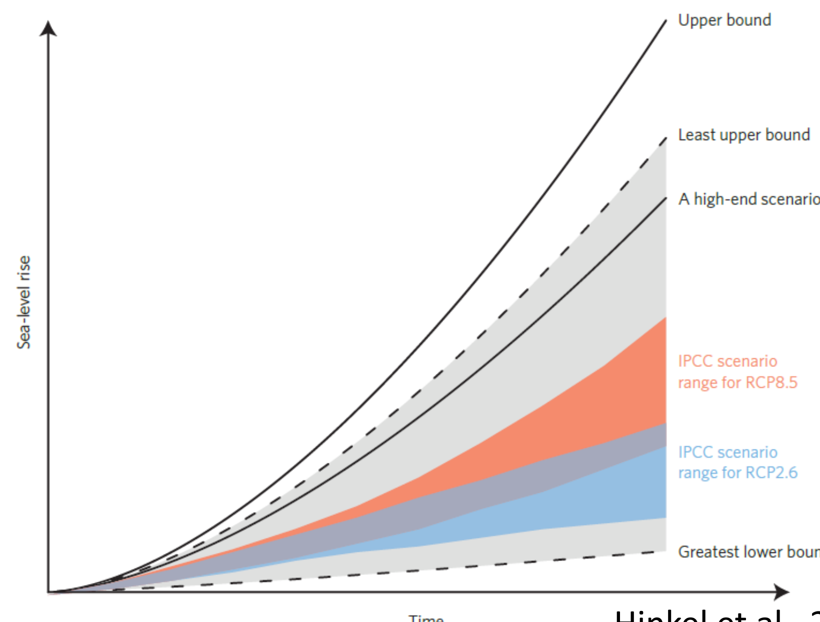
# Conclusions

- At regional scale, considerable inter-annual/decadal variability (previous studies) can aliase the trends in short records, as found in the eastern Bay of Bengal (Large uncertainties present)
- (short records depending on the phase of the decadal curve, the trends could differ)
- Except for the northern and eastern BB, the trends in the north Indian Ocean during last two decades are consistent with global trends
- Increased sea level rise trends could be due to an acceleration resulting from global warming or partly caused by aliasing by natural variability

# Challenges that need to be addressed:

- From the Science and Implementation plan:
  - **Sea level information useful for coastal management**, e.g. end-tail of SLR distributions, uncertainties
  - **Downscaling sea level variability and uncertainties** from regional to local coastal scale,
  - *Sea level rise vs **relative sea level rise** (land subsidence in coastal mega-cities and deltas can be up to one order of magnitude larger than sea level change)*
  - **Probabilistic information and return-period** from combined effects of sea level rise and changes in extremes (e.g., storm surges), in order to define *sea-level allowances* (needs for coastal defense raising to keep extreme marine submersions unchanged)
  - **Pilot studies** for mega city, delta, island state, etc. using accurate sea level products from working groups 1-4. => definition of these pilot studies (Indo-Gangetic delta….)




Hinkel et al., 2015

# WCRP's initiatives on 'Regional sea level rise and coastal impacts'

- 5-day Conference in New York 10-14 July 2017

**Conference venue**

Columbia University
Lerner Hall
2920 Broadway
New York City, NY 10027
USA

**Conference website**
www.sealevel2017.org



**Current conference sponsors**

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**Local Organization**
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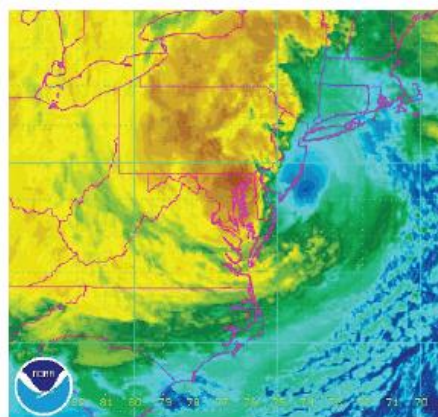
**International WCRP/IOC Conference**

## Regional Sea Level Changes and Coastal Impacts

**July 10-14, 2017**

THE EARTH INSTITUTE
COLUMBIA UNIVERSITY

**New York, NY, USA**



Sea level change is already impacting coastal communities globally and will continue to do so.

To meet urgent societal needs for useful information on sea level, the World Climate Research Program (WCRP) has established the theme "Regional Sea-Level Change and Coastal Impacts", as one of its cross-cutting "Grand Challenge" (GC) science questions.

The GC Sea Level has designed and developed an integrated interdisciplinary program on sea level research reaching from the global to the regional and coastal scales.

In particular, the program aims for close interaction with relevant coastal stakeholders to make sure that the results effectively support impact and adaptation efforts and wider coastal zone development and management.

The WCRP, jointly with the Intergovernmental Oceanographic Commission of UNESCO (IOC), is organizing an international conference on sea level research that will address the existing challenges in describing and predicting regional sea level changes, and in quantifying the intrinsic uncertainties.

It follows 11 years after the first WCRP sea level conference (Paris, 2006), and three years after the last Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). It will provide a comprehensive summary of the state of worldwide climate-related large scale sea level research.