

Is sea-level rising?

Invited Article

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The common man and the policy makers are always concerned about the report of rising sea level both globally and regionally. The present article makes a brief survey of the scientific findings on this topic. There has been considerable research on sea-level rise caused by global warming. Thermal expansion in the ocean and melting of glaciers and ice sheets mainly contribute to sea-level rise. The various reports of the Intergovernmental Panel on Climate Change (IPCC) made assessments of observed sea level rise and future projections. Figure 1 shows the global mean sea level rise of 3.4 mm/yr (with a standard error of ± 0.4 mm/yr) during the period from 1992 to 2016. These estimates have been made using data from satellite altimeters.

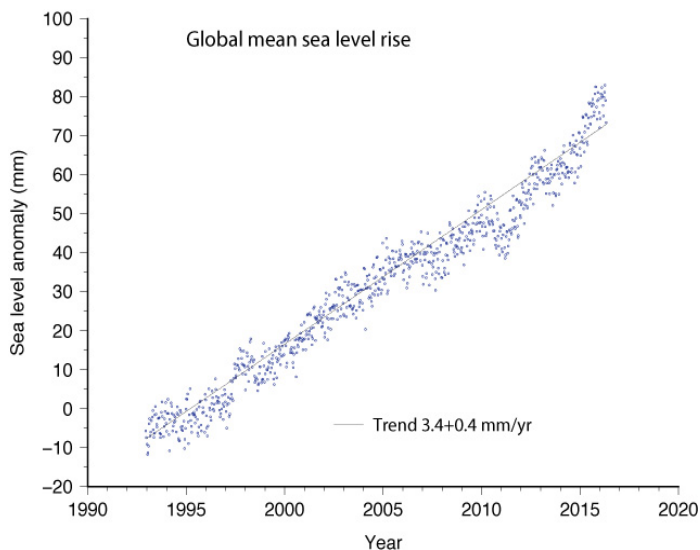


Fig. 1: Global mean sea-level time series. Dots indicate data from satellite altimeters (Topex/POSEIDON, Jason-1 and Jason-2), with seasonal signals removed. The straight line indicates the fitted trend. Data source: Mean Sea Level Group, University of Colorado

It is worth mentioning here that sea level change is influenced by changes in the hydrological cycle, melting of glaciers and ice sheets, ocean circulation, land subsidence, etc. [Figure 2]. The combination of these processes produces a complex pattern of total sea level change, which varies through time as the relative contribution of each process changes. Changes in any one of the components or processes shown in Figure 2 will result in a sea level change.

It is true that sea level has fluctuated in the past between glacial and interglacial periods. Geologists have studied these changes using proxies such as, sediment or ice

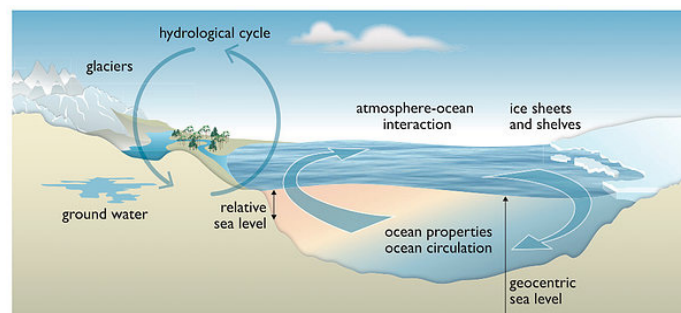


Figure 2: Climate-sensitive processes and components that can influence global and regional sea level [Source: Church et al. 2013, IPCC, Fifth Assessment Report]

cores. However, the rates of present-day sea-level rise (since the industrial period) have been considerably higher than those in the past.

It is interesting to note that a lot of research findings on sea-level rise since more than the past three decades came out based on analysis of data from instruments known as 'tide-gauges'. Tide gauges were originally installed in major ports to measure water surface elevations continuously. These instruments were earlier of 'mechanical type' and more recently of electronic type to measure and record water surface elevations at a point in the harbour area. Mechanical tide gauges use mechanical floats in a stilling well. As the water surface goes up or down, a pen attached to the float records on a chart which is fixed on a rotating drum. After a few days, the chart is removed and digitised to get instantaneous sea level. Electronic tide gauges are mainly of two types. (i) pressure gauge type and (ii) radar gauge type. The former uses a pressure sensor, which measures the hydrostatic pressure of the water column above it. The hydrostatic pressure can be converted into sea level height by using the hydrostatic equation. Radar gauge uses a radar sensor, kept at a height looking down the sea, sends out a pulse of radio waves and measures the travel time to be reflected off the surface and back to the sensor. By using the travel time and the speed of radio waves one can estimate the sea surface height.

The tide gauge data have been analysed and used to predict the time of 'high tide' and 'low tide', which are used by ships to decide the timing for entering and leaving harbours. Some of the oldest tide gauges in the world are found in Brest (France), Liverpool (U.K.) and Mumbai (India), which were operational since the late 19th century. In India, Survey of India (SOI) is responsible for maintenance of tide gauges and prediction of tides. The Indian Tide Tables, published by the SOI gives the tidal predictions at major ports along the Indian coasts and some neighbouring countries. The ports, where tide gauges are installed include those of Mumbai, Kochi, Visakhapatnam and Diamond Harbour (Kolkata).

Since 1980's, scientists started analysing these data more closely looking for long-term changes in sea level (sea-level rise). For this purpose, they started analysing the mean sea level (instantaneous water surface elevations or sea level measured by a tide gauge are averaged for a sufficiently long time such as a month or year to get monthly mean sea level or annual mean sea level. The surface waves and tides are filtered out before the averaging procedure). All the analyses using tide-gauge data showed a slow and gradual increase in mean sea level of the order of 1 to 2 mm/yr. However, there were some concerns, since the findings were based on data obtained

from some selected (based on the quality of data) tide gauges over the globe. This issue got resolved with the availability of data on sea level measured from satellite altimeters.

Since 1992, altimeters onboard satellites starting with Topex/POSEIDON and later Jason-1 and Jason-2 started measuring sea level from space. An altimeter measures two-way travel time required for a radar pulse emitted by the antenna onboard the satellite and get it reflected from the ocean surface back to the antenna. These measurements provided sea level scientists the data having a near-global coverage (except regions pole ward of 66° latitudes). These satellites repeat the track every 10 days. Various corrections need to be applied to the measured data, including the removal of tides, to obtain mean sea level data that are used for climate studies. The analysis of mean sea level data from satellites showed a good consistency with those obtained from tide gauges and the trends of the global mean sea-level rise obtained from satellite measurements, and tide gauges have been agreeing closely to each other strengthening the evidences on mean sea-level rise over the globe.

Along the west coast of India, there are two tide gauges, Mumbai and Kochi that have records of 113 and 56 years respectively. A typical record of Kochi is shown in Figure 3. The altimeter data is also superimposed on the figure. The net sea-level-rise trend for the entire period is about 1.81 mm/yr (1.45 mm/yr , as shown in Figure 3 and when corrections for glacial isostatic adjustment (GIA) of -0.36 mm/yr are subtracted becomes about 1.81 mm/yr), which is close to the global average trends (1.7 mm/yr), reported in the fifth assessment report of the IPCC. It may be noted that during the period of satellite altimeter, the trend is larger than that for the entire period including 20th century.

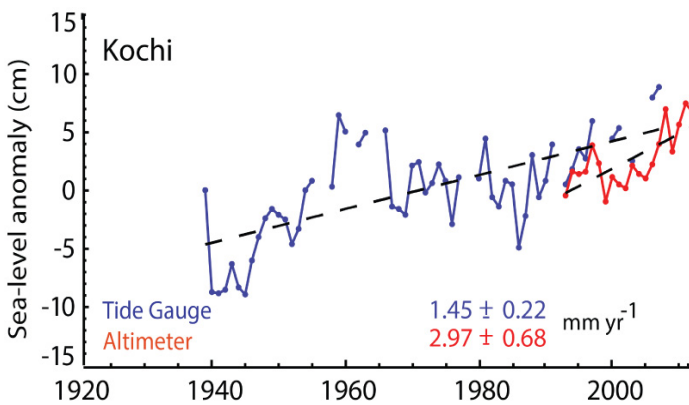


Figure 3: Tide-gauge (blue) and satellite altimeter (red) data at Kochi. The altimeter data is taken at offshore point. The figure is adapted from a published paper by Unnikrishnan et al., (2015) in Current Science. The dash indicates the fitted trend line.

Along the north east coast of India, for instance, the record at Diamond Harbour (Kolkata) shows a large trend of more than 5 mm/yr . This tide gauge is located in the deltaic region. Since the instrument is located on the land, any land movements could affect the readings. It is known that Indo-Gangetic delta is undergoing subsidence, which partly contributes to the large observed sea level rise from this tide-gauge record. Similar large trends have been reported for the records in Bangladesh as well. It may be noted that recent tide gauges also use GPS (global positioning system) measurements to determine vertical land movements. This is to account for a

correction in the estimation of trends obtained for tide gauge records.

The altimeter data permits to prepare spatial maps of sea-level rise trends. We present a map prepared for the Indian Ocean (Figure 4) north of 10°S , which shows a fairly uniform sea level rise of more than 3 mm/year for the north Indian Ocean. This estimate shows an increased sea-level-rise trend during the last 20 years compared to those obtained from tide gauge records for the past century. It is not fully understood whether this is an apparent acceleration in sea-level rise or not. This is due to a relatively short period of altimeter data (about 20 years). It may be noted that unusually large (greater than 5 mm/year) trends are found in some regions (towards the northern Bay of Bengal). We have reported this in our earlier study as uncertainties found in some regions, which are partly due to the presence of natural variability. In most of the regions, the sea-level rise is uniform and the rates are in accordance with global sea-level rise. Moreover, altimeter and tide gauge data have been complimentary to each other for the estimation of the present-day sea-level rise.

Climate models predict higher sea-level rise towards the end of the 21st century. Observations during the last two decades also show an enhanced sea-level rise. In any case, sea level will continue to rise for many hundreds of years, as already a lot of heat is absorbed in the ocean, which will continue to heat the ocean.

India has a long coastline of more than 7500 Km with several regions in the low-lying areas. Moreover, a large population in the country resides in the coastal areas. Sea-level rise and occurrence of extreme events, such as storm surges, will have a great impact in future. Long-term planning and necessary adaptation measures are needed particularly for vulnerable areas. Besides, deltaic regions, such as Sunderbans, are particularly vulnerable to sea-level rise. Subsidence, found in deltas adds to the effect of global warming induced sea level rise. Small-island nations like Maldives, which is only about 1.2 m above mean sea level, will face the consequences of

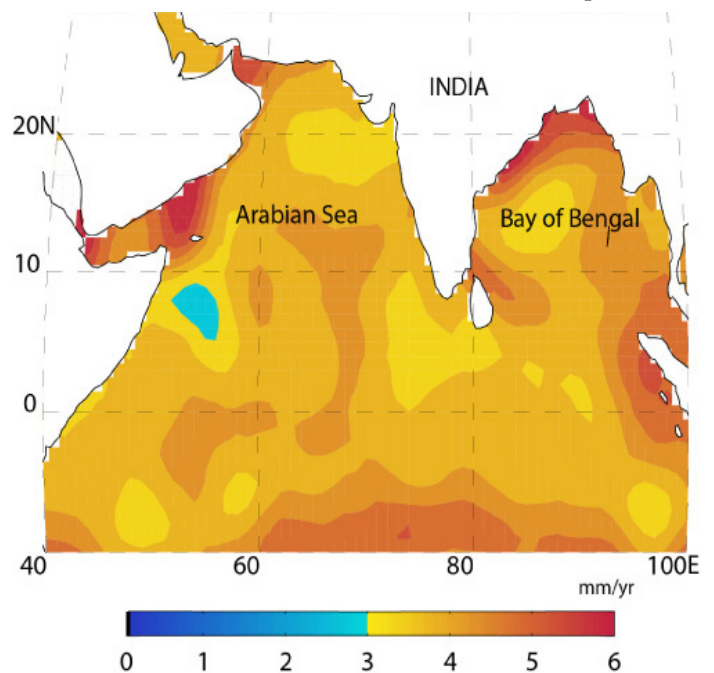


Fig.4: Spatial map of the sea-level rise trends during 1992 to 2015 in the Indian Ocean (north of 10°S)

future sea level rise. Climate change will exacerbate already existing extreme events such as unusually large high tides in Mumbai as well as storm surges along the east coast of India.

Reference:

The present article has drawn information from research papers published by the author and report of the IPCC AR5 WG1 Chapter 13: Sea Level Changes, in which the author has served as a 'Lead Author'. Figure 1 is prepared using data from the University of Colorado. Nerem, R. S., D. Chambers, C. Choe, and G. T. Mitchum. "Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions." *Marine Geodesy* 33, no. 1 supp 1 (2010): 435. Figure 2 is adapted from IPCC AR5 WG1 Chapter 13.

Data Assimilation in numerical ocean models: Indian perspective

Review Article

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Measuring the properties of global oceans has been a challenge ever since the concept of measurements is introduced. The vastness, hostile conditions and the cost factor are some of the major reasons behind the data gaps in the oceans. Satellites sense the ocean surface, however they are unable to provide much information of the ocean beneath. Since last one decade, ARGO floats have been providing wealth of ocean information which has marginally improved our understanding, however, when it comes to knowing about the regional/basin/global scale synoptic conditions we look upon the numerical ocean models.

Numerical ocean models are a set of physical and mathematical equations which are solved in time to get the complete 4-D state of the ocean. Since 4-5 decades there has been a tremendous development in the field of numerical ocean modeling. The state of the art ocean models are quite complex and have components such as bio-geochemistry coupled to it.

Due to various approximations, numerical models are prone to generate errors and these errors grow with model integration time. It is therefore quite important to check these errors and apply mid-way correction to the models. With the availability of huge amount of surface observations of temperature, salinity and sea surface height from satellites, it is now possible to extensively generate error statistics at each model grid of moderate ($0.5 \times 0.5^\circ$) to very high resolution ($1\text{km} \times 1\text{km}$). This synergy of model output and observations to optimally provide an analysis state is known as data assimilation. There can be three major objectives of data assimilation:

- Generate accurate initial conditions from which the

model can be initialized for an accurate forecast.

- Generate 4-D ocean state for several years for studying ocean processes
- Tune model parameters for improving the models.

Data assimilation techniques have evolved extensively (Malanotte-Rizzoli; 1996) since last 2-3 decades from simplest (nudging) to the most complicated ones (4-D variational method) and efforts are towards using an efficient approach to build an assimilation scheme for a chaotic system (like particle filter based method).

Due to high computational requirements it is quite impractical to use sophisticated assimilation schemes like the Ensemble Kalman filter or 4-D variational method in high resolution operational models such as those operationally being run at INCOIS or even the US navy. These operational agencies use the 3-D variational approach in their operational system.

However, in non-operational scenario where we need to optimize model parameters or we need to prepare long term hindcast analysis, one can use advanced data assimilative procedures. For the Indian Ocean several studies have been performed using simple to intermediately complex data assimilation schemes. Agarwal et. al. (2008) used simple techniques of nudging and Cressman to assimilate ARGO temperature and salinity profiles into the OGCM. Though the techniques used were simple, there was a clear improvement in the thermocline and mixed layer depth in the assimilated runs.

Chakraborty et. al. (2014, 2015) used the method of singular evolutive ensemble Kalman (SEEK) filter to assimilate satellite derived sea surface temperature, sea surface salinity and sea surface height into the OGCM. It was found that the maximum impact of assimilation comes due to the assimilation of sea surface height data which can correct the model upto thermocline depth. Ratheesh et. al. (2014) used the method of ensemble optimal interpolation (EnOI) to assimilate satellite derived sea surface temperature and sea surface height data into the sigma coordinate Indian Ocean Model. The outputs of this data assimilative model are available on www.mosdac.gov.in in near real time on a regular basis.

Though data assimilation used by various operational agencies are able to do a fairly good job in arresting model drifts and produce accurate forecasts, there is a continuous need for doing assimilation in a regular manner. Once the assimilation stops, the model solution oscillates back to its equilibrium state and errors become large. So the challenge is to use data assimilation procedures not just to improve model's initial condition, but also to estimate model parameters. Optimal setting of parameters (Menemenlis et. al. 2005) used in various procedures will lead to model improvement and the requirement of assimilating the fields may not be continuous.

Another challenge is to assimilate high resolution data sets into the model. This is once again a practical difficulty where the state vector and the observation vector size become too large to be handled. Necessary efforts are required to address this issue. Assumption of normal distribution of state variables to be assimilated can also be done away with by using stochastic data assimilation techniques such as the