Sea-Level Rise

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Key Messages

- *There is high confidence that the rate of global mean sea level (GMSL) rise has increased. Human-caused climate change has made a substantial contribution to the rise since 1900.*
- *The GMSL has risen by 1.7 (1.5 to 1.9) mm year^{-1} since 1901 and the rate of rise has accelerated to 3.3 mm year^{-1} since 1993.*
- *Sea-level rise in the Indian Ocean is non-uniform and the rate of north Indian Ocean rise is 1.06–1.75 mm year^{-1} from 1874 to 2004 and is 3.3 mm year^{-1} in the recent decades (1993–2015), which is comparable to the current rate of GMSL rise.*
- *Indian Ocean sea-level rise is dominated by the ocean thermal expansion, while the addition of water mass from terrestrial ice-melting is the major contributor to the GMSL rise.*
- *Interannual to decadal-scale variability in the Indian Ocean sea level is dominated by El Niño Southern Oscillation and Indian Ocean Dipole events.*
- *Relative to 1986–2005, GMSL is very likely to rise by ~26 cm by 2050 and ~53 cm by 2100 for a mid-range, mitigation scenario.*
- *Steric sea level along the Indian coast is likely to rise by about 20–30 cm at the end of the twenty-first century and the corresponding estimate for global mean steric sea-level rise is 18±5 cm (relative to 1986–2005), under RCP4.5 (for a mid-range emission scenario, excluding ice-melt contributions).*
- *Extreme sea-level events are projected to occur frequently over the tropical regions (high confidence) and along the Indian coast (medium confidence) associated with an increase in the mean sea level and climate extremes.*

9.1 Introduction

The global ocean plays a critical role in regulating the energy balance of the climate system. Over 90% of the anthropogenic excess heat goes into the oceans (Church et al. 2013a, b), remaining goes into melting both terrestrial and sea ice, and warming the atmosphere and land (Hansen et al. 2011; Church et al. 2011b; Trenberth et al. 2014). One of the consequences of warming of the global ocean and the melting of ice and glaciers is the rise in mean sea level. Sea-level rise can exert significant stress on highly populated coastal societies and low-lying island countries around the world. Indian Ocean region is heavily populated, comprises of many low-lying islands and coastal zones and is highly rich in marine ecosystems. The regions in and around the Indian Ocean are home to roughly 2.6 billion people, which is 40% of the global population. One-third of the Indian population and the majority of the Asian population are located near coastal regions. Therefore, the rise in sea level can pose a growing challenge to population, economy, coastal infrastructures and marine ecosystems. Despite considerable progress during recent years, major gaps remain in our understanding of sea-level changes and their causes, particularly at regional scales.

Changes in mean sea level are the result of the complex interplay of a number of factors. Even though there is an unabated rise in observed global mean sea level, the spatial distribution of sea-level trends is not globally uniform (Church et al. 2013a, b). Regionally, sea-level variations can deviate considerably from the global mean. It is very likely that in the twenty-first century and beyond, the sea-level change will have a strong regional pattern, with some places experiencing significant deviations from the global mean sea-level rise (IPCC AR5). The detailed sea-level change along coastlines can therefore potentially be far more substantial than the global mean sea-level rise. The underlying causes of regional sea-level changes are associated with dynamic variations in the ocean circulation as part of climate modes of variability, changes in the wind pattern and with an isostatic adjustment of Earth's crust to past and ongoing changes in polar ice masses and continental water storage (Stammer et al. 2013). Assessment of vulnerability to rising sea levels requires consideration of physical causes, historical evidence and projections.

This chapter reviews the physical factors driving changes in global mean sea level (GMSL) as well as those causing additional regional variations in relative sea level (RSL). Geological and instrumental observations of historical sea-level changes in the global ocean and for the RSL in the Indian Ocean are presented here. The chapter then describes a range of scenarios for future levels and rates of sea-level change, for the Indian Ocean as well as for the global ocean. Finally, an assessment of the impact of changes in sea level on extreme water levels is discussed.

9.2 Physical Factors Contributing to Sea-Level Rise

Sea level is measured either with respect to the surface of the solid Earth, known as relative sea level (RSL) or a geocentric reference such as the reference ellipsoid, known as the geocentric sea level. RSL estimates have been obtained from tide gauges and geological records for the past few centuries. Geocentric sea level has been measured over the past two decades using satellite altimetry. The sea level, when averaged globally, provides global mean sea level (GMSL). The physical processes causing GMSL rise and regional changes in RSL are not identical, although they are related. The primary contributors to current GMSL rise are the thermal expansion of sea waters, land ice loss and freshwater mass exchange between oceans and land water reservoirs and groundwater storage change. The recent trends of these contributions are most likely resulted from the climate change induced by anthropogenic greenhouse gas emissions.

9.2.1 Ocean Warming

Analyses of in-situ ocean temperature data collected over the past 50 years by ships and recently by Argo profiling floats (Argo Data Management Team 2008; Roemmich et al. 2009) reveal that ocean has been warming and increases the upper ocean heat content (OHC). Hence, the sea level, due to the thermal expansion of sea water, has significantly increased since 1950 (e.g. Levitus et al. 2009; Ishii and Kimoto 2009; Domingues et al. 2008; Church et al. 2011a). A recent study by Cheng et al. (2017) has shown that the changes in OHC were relatively small before about 1980; since then, OHC has increased fairly steadily and, since 1990, has increasingly involved deeper layers of the ocean. In the climate system, the ocean acts as a 'buffer' for the atmospheric temperature by storing a large amount of heat from the atmosphere and transporting it to deeper depths via the ocean conveyor belt. On average, over the last 50 years, 93% of the excess heat accumulated in the climate system because of greenhouse gas emissions has been stored in the ocean owing its large heat capacity, the remaining 7% warm the atmosphere and continents, and melt sea and land ice (Levitus et al. 2012; von Schuckmann et al. 2016). Consequently, ocean warming explains about 30–40% of the observed sea-level rise of the last few decades (e.g. Church et al. 2011b).

9.2.2 Glaciers Melting

Apart from the global ocean thermal expansion, melting of the continental ice storage in a warming climate is turned out to be another factor for global mean sea-level rise. Being very sensitive to global warming, mountain glaciers and small ice caps have retreated worldwide during recent decades. The contribution of glacier ice melt to sea-level rise has been estimated based on the mass balance studies of a large number of glaciers (Meier et al. 2007; Kaser et al. 2006). In fact, studies have shown that glaciers have accounted for ~21% of the global sea-level rise since 1993 (e.g. WCRP 2018).

9.2.3 Ice Sheets

The mass balance of the ice sheets was less known before the 1990s due to inadequate and incomplete observations. Different remote sensing techniques available since then have provided important results on the changing mass of Greenland and (west) Antarctica (e.g. Allison et al. 2009). These data indicate that both ice sheets are currently losing mass at an accelerated rate (e.g. Steffen et al. 2011). For the period 1993–2003, <15% of the rate of global mean sea-level rise was due to the melting of ice sheets (IPCC AR4). But their contribution has increased to ~40% from 2003 to 2004. The ice sheets mass loss explains ~25% of the rate of global sea-level rise during 2003–2010 (Cazenave and Remy 2011; Church et al. 2011a). A near-complete loss of Greenland ice sheet over a million years or more leading to the global mean sea-level rise of about 7 m can be caused by sustained global warming greater than a certain threshold above pre-industrial conditions (IPCC AR5). A schematic representation of different processes contributing to global and regional sea-level changes is shown in Fig. 9.1.

9.2.4 Regional Sea-Level Change

Sea-level rise pattern varies substantially from region to region. Geographical patterns of sea-level rise can result in different processes: changes in sea-water density due to changes in temperature and salinity (known as 'steric' sea-level changes) are the dominant process, especially in the tropical oceans. Steric sea-level changes are primarily associated with the atmosphere-ocean coupled dynamics driven mainly by surface winds and ocean circulation. Solid Earth's deformation and geoid changes in response to past and ongoing mass redistribution caused by land ice melt and land water storage changes (known as 'static' factors) also make regional changes in sea level (Stammer et al. 2013). It was shown that the dominant contribution to observed regional sea-level changes comes from steric effects caused by non-uniform thermal expansion and salinity variations (Church et al. 2013a, b; Stammer et al. 2013). Contributions from other effects, in particular, the static factors, are little in the present time but will become important in the future (Milne et al. 2009).

9.3 Mean Sea-Level Change

9.3.1 Global

At the time of the last interglacial period, about 125,000 years ago, sea level was likely 4–6 m higher than it was during the twentieth century, as polar average

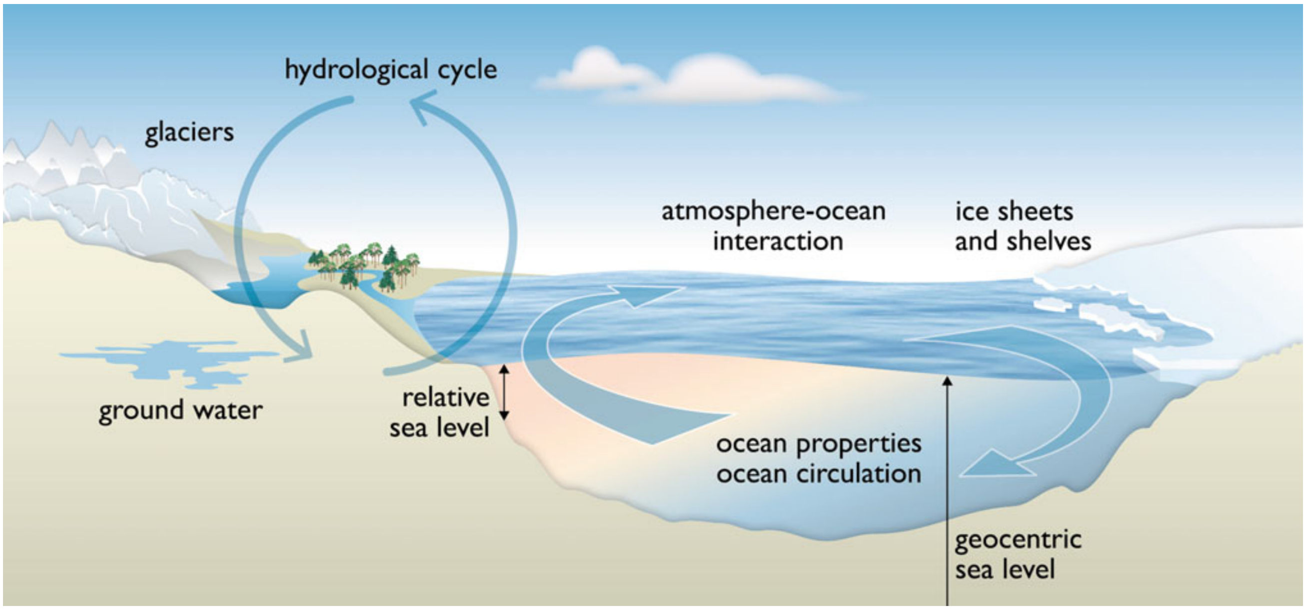


Fig. 9.1 Schematic representation of climate-sensitive processes and components that can influence the global mean sea level and regional sea level. Adapted from Fig. 13.1, IPCC AR5

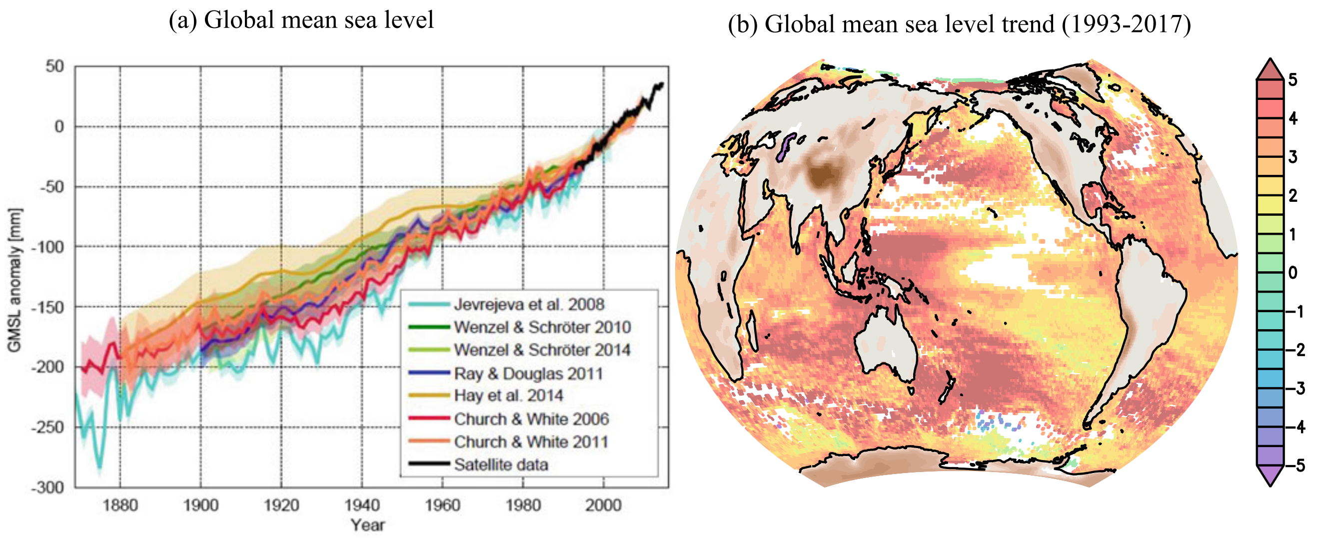
temperatures were 3–5 °C higher than present values (Dutton and Lambeck 2012). It was shown that loss of ice from the Greenland ice sheet must have contributed to about 4 m of this higher sea level and there may also have been a contribution from the Antarctic ice sheet (Shepherd et al. 2018). Sea level was 120 m or more below present-day values at the last glacial maximum about 21,000 years ago (Peltier and Fairbanks 2006). Further, the Third Assessment Report (TAR) of the IPCC reported that during the disintegration of the northern hemisphere ice sheets at the end of the last glacial maximum, sea level rose at an average rate of 1 m century^{-1}, with peak rates of about 4 m century^{-1}. Since the end of the last deglaciation about 3000 years ago, sea level remained nearly constant (e.g. Lambeck et al. 2010; Kemp et al. 2011a, b).

Proxy and instrumental sea-level data indicate a transition in the late nineteenth century to the early twentieth century from relatively low mean rates of rising over the previous two millennia to higher rates of rise as shown in Fig. 9.2a. There have been many studies of twentieth-century sea-level rise based on analysis of past tide gauge data. For example, an estimate of global mean sea-level change over the last century based mainly on tide gauge observations is 1.5 ± 0.5 mm year^{-1} (Church et al. 2001). Since the beginning of the twentieth century, the sea-level rise was at an average rate of 1.7 (1.5–1.9) mm year^{-1} between 1901 and 2010 (Church and White 2011). This rise has accelerated recently, and the rate of global sea-level rise estimated from satellite altimetry during 1993–2010 is 3.3 (2.8–3.6) mm year^{-1}, significantly higher than the rate estimated for the entire twentieth century. The spatial trend in sea-level anomalies from satellite data for the period 1993–2017 is shown in Fig. 9.2b. The most recent global mean sea-level trend during the period 1993–2017 amounts to 3.3 ± 0.5 mm year^{-1} at a 90% confidence level (WCRP 2018). This increase, however, has not happened at a constant rate and also sea-level rise is not globally uniform (e.g. Woodworth and Player 2003; Bindoff et al. 2007), i.e. sea-level variability, as well as trends, differs from region to region.

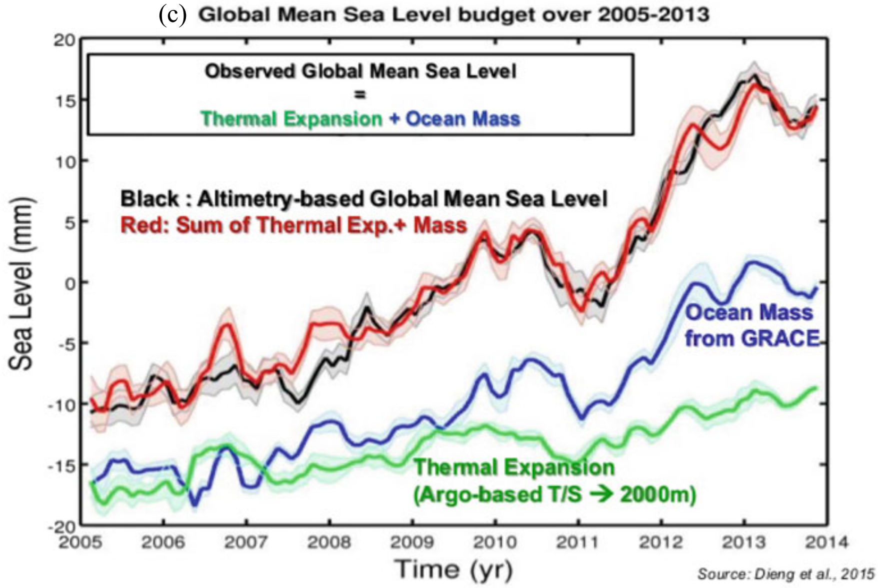
Accurate assessment of present-day global mean sea-level variations and its components (ocean thermal expansion, ice sheet mass loss, glaciers mass change, changes in land water storage, etc.) are highly essential. GMSL change as a function of time t is usually expressed by the sea-level budget equation:

$$\mathrm{GMSL}(t) = \mathrm{GMSL}(t)_{\text{steric}} + \mathrm{GMSL}(t)_{\text{ocean mass}} \qquad (1)$$

where $\mathrm{GMSL}(t)_{\text{steric}}$ refers to the contributions of ocean thermal/haline expansion/contraction to sea-level change, and $\mathrm{GMSL}(t)_{\text{ocean mass}}$ refers to the change in mass of the ocean caused mainly by the melting of ice sheets. The closure of the global sea-level budget was examined by WCRP (2018), comparing the observed global mean sea level with the sum of its components. Ocean thermal expansion, glaciers, Greenland and Antarctica contribute 42, 21, 15 and 8% to the global mean sea level over the 1993–present period (WCRP 2018). The time evolution of the global sea-level budget based on WCRP (2018) is shown in Fig. 9.2c. It can be seen from Fig. 9.2c that the sum of thermal expansion


(a) Global mean sea level

(b) Global mean sea level trend (1993-2017)


(c) Global Mean Sea Level budget over 2005-2013

Source: Dieng et al., 2015

Fig. 9.2 a Time series of global mean sea-level anomaly (mm) from sea-level reconstructions and altimetry, **b** spatial map of trend of sea-level anomalies (mm year^{-1}) from AVISO (1993–2017) and **c** time series of components of sea-level budget (mm). Adapted from Dieng et al. (2015)

and mass changes nearly explains the observed sea-level rise in recent decades.

9.3.2 Regional Changes: Indian Ocean Sea-Level Rise

Regionally, sea-level variations can deviate considerably from the global mean due to various geophysical processes. These include changes in ocean circulations, which partially can be attributed to natural, internal modes of variability in the complex Earth's climate system and anthropogenic influence. The Indian Ocean sea-level trends since the 1960s exhibit a basin-wide pattern, with sea-level falling in the south-west tropical basin and rising elsewhere (Han et al. 2010). Regionally, thermosteric changes are dominant; halosteric contributions can, however, be important in certain regions, like the Bay of Bengal and south-east Indian Ocean (e.g. Nidheesh et al. 2013; Llovel and Lee 2015). The instrumental record of sea-level change is mainly comprised of tide gauge measurements and satellite-based radar altimeter measurements.

Tide gauge records: understanding the changes in RSL is best determined based on continuous records from tide gauge measurements. The sea-level measurements by tide gauges along the west and east coast of India during the

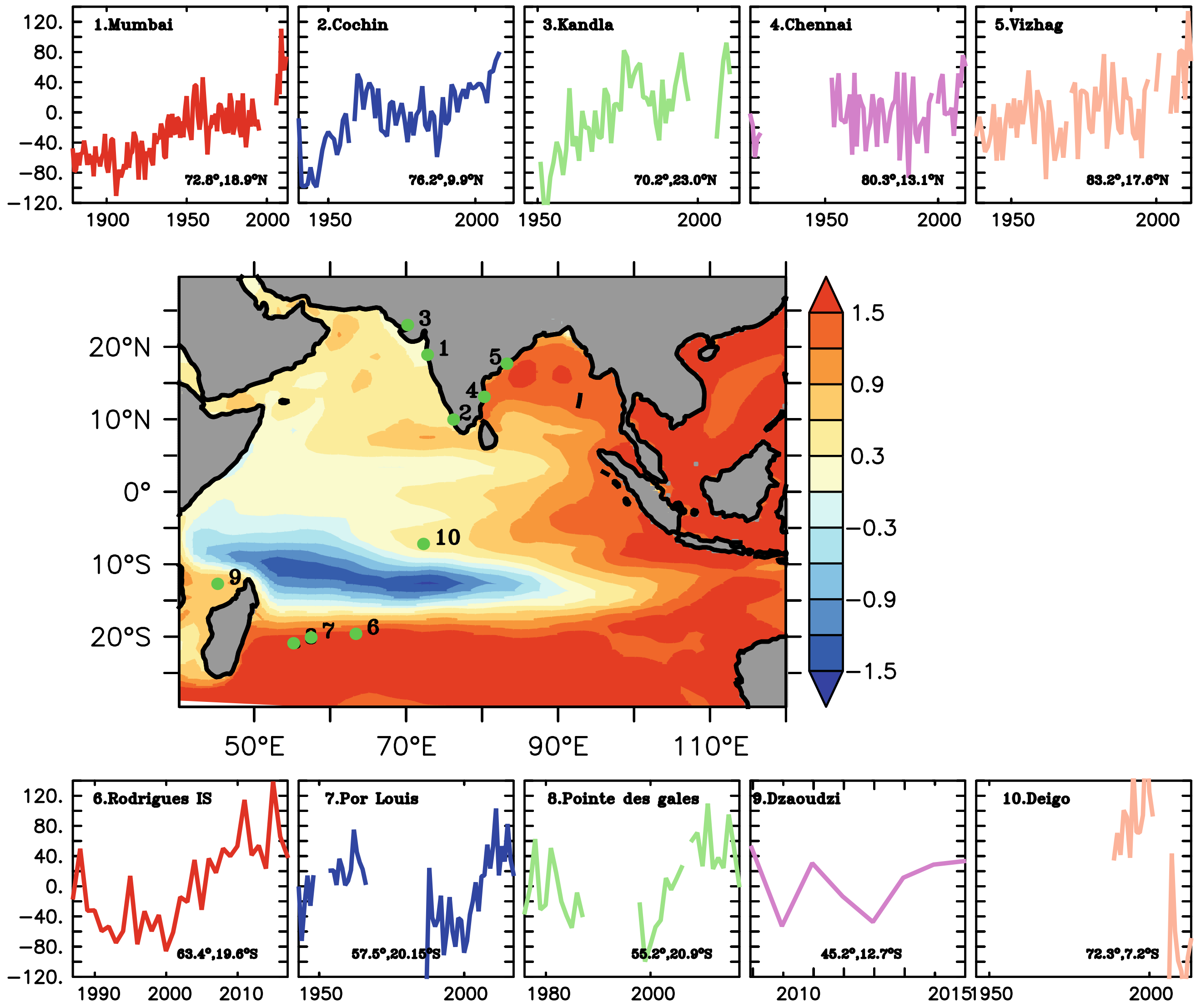


Fig. 9.3 Spatial map of sea-level trend (mm year^{-1}) in the Indian Ocean from ORAS4 reanalysis for the period 1958–2015 and time series of long-term tide gauge records along the Indian coast and open ocean. The tide gauge locations are marked by green circles. The anomalies are computed with the base period 1976–2005

twentieth century show evidence of significant sea-level rise (Fig. 9.3). Long-term sea-level trend estimates using tide gauge observations (having different time span) available along the coasts of India and the rim of the eastern Bay of Bengal show a rate of sea-level rise of about 1.06–1.75 mm year^{-1} in the Indian Ocean during 1874–2004 (Unnikrishnan et al. 2006; Unnikrishnan and Shankar 2007), similar to the global sea-level rise trend of 1.7 mm year^{-1} estimated for the period 1880–2009 (Church and White 2011). Tide gauge observations after corrections for vertical land movement from a glacial isostatic adjustment (GIA) model and for sea-level pressure changes show that sea level along the Indian Ocean coasts has increased since the 1960s, except for the fall at Zanzibar (Han et al. 2010).

Satellite Altimeter and Reanalysis With the beginning of satellite altimetry, it is possible not only to obtain a more robust estimate of global mean sea-level rise but also to examine the spatial patterns that enable assessment of regional sea-level variability. Sea level in the Indian Ocean has shown a distinct spatial pattern with a substantial increase in the north (Unnikrishnan et al. 2015; Swapna et al. 2017; Srinivasu et al. 2017; Thompson et al. 2016) and the south Indian Ocean as seen from Fig. 9.3. Mean sea-level rise in the Indian Ocean from satellite altimetry shows a rise of 3.28 mm year^{-1} during 1993 to 2017, which is higher compared to estimates from tide gauges over the historical period, but still close to the GMSL rise estimated over the same period (Unnikrishnan et al. 2015). The time evolution

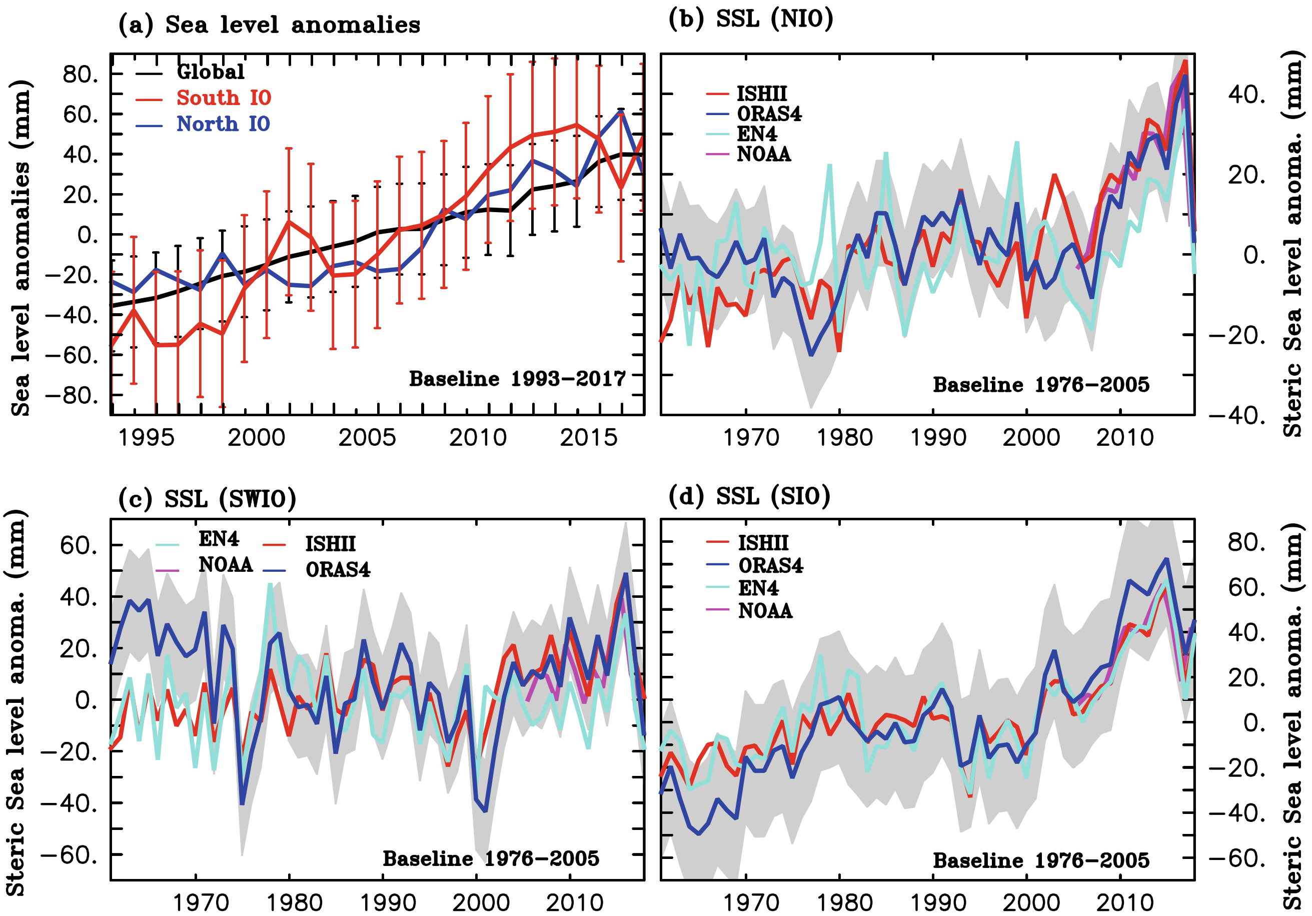


Fig. 9.4 Time series of annual mean sea-level anomalies (mm) from **a** AVISO averaged in the North Indian Ocean (blue curve; 50°E–110°E, 5°S–25°N), South Indian Ocean (red curve; 50°E–110°E, 20°S–30°S) and global mean (black curve); the error bars based on one standard deviation is shown for the global and south Indian Ocean mean sea level with respective colours; time series of steric sea level (mm) for upper the 2000 m from different reanalysis and observational datasets in the **b** North Indian ocean **c** South-west Indian Ocean and **d** South Indian Ocean. The anomalies are computed with the base period 1976–2005

of sea-level anomalies in the global ocean and the north Indian Ocean from satellite-derived Aviso data is shown in Fig. 9.4a. The north Indian Ocean sea level is rising at the same rate as that of the GMSL. In the north Indian Ocean (north of 5°S), sea level experienced a basin-wide rise from 2004 to 2013 (Srinivasu et al. 2017) with a rate of 6 mm year^{-1}. The time evolution of sea-level anomalies in the north (50°E–100°E; 5°S–25°N; NIO), south (50°E–100°E; 20°S–30°S; SIO) and in the open ocean upwelling dome (55°E–75°E; 5°S–15°S; SWIO) is shown in Fig. 9.4. We can see a sharp rise in sea level in the north and south, and a sea-level fall in the open ocean upwelling dome (SWIO). In the Indian Ocean, thermosteric sea level is the primary contributor for the spatial patterns of sea-level variability (Nidheesh et al. 2013), with halosteric sea level having apparent contributions in some regions particularly in the south-east tropical Indian Ocean and near the West Australian coast (Llovel and Lee 2015). Sea-level budget analysis performed for the Indian Ocean also indicates that more than 70% of sea-level rise in the north Indian Ocean is contributed by the thermosteric component (Srinivasu et al. 2017; Swapna et al. 2017). The halosteric sea-level changes are dominant in the south-east Indian Ocean region with a halosteric sea-level rise of about 6.41 ± 0.62 mm year^{-1}, twice as large as that of the thermosteric sea-level rise (3.72 ± 1.04 mm year^{-1}, Llovel and Lee 2015).

Temporal Variability in Indian Ocean Sea Level

Indian Ocean sea level shows large regional variability in all temporal scales, interannual to decadal and multi-decadal scales. Superimposed on the trend, the Indian Ocean sea level shows large temporal variability (Han et al. 2014). On interannual scales, steric effects are reported to be the major contributing factors to the sea-level changes in the Indian Ocean, with contribution from El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) (Parekh et al. 2017; Palanisamy et al. 2014). Co-occurrence years (years when IOD and El Niño events co-occur) contribute significantly towards the sea-level variability in the Indian Ocean and account for around 30% of the total interannual variability (Deepa et al. 2018a, b).

Decadal sea-level variability is driven primarily by the variations in the surface wind forcing over the Indo-Pacific Ocean (Lee and McPhaden 2008; Nidheesh et al. 2013; Han et al. 2017). The decadal sea-level variability of the south-western tropical Indian Ocean region known as the thermocline ridge region of the Indian Ocean or open ocean upwelling region (Vialard et al. 2009) is found to be associated with decadal fluctuations of surface wind stress (Li and Han 2015; Deepa et al. 2018a, b). Decreasing sea-level trends were noted in this region from the 1960s and are driven by the changes in the surface winds associated with combined changes in the Indian Ocean Hadley and Walker cells, which is partly attributable to the rising levels of atmospheric greenhouse gases (Han et al. 2010). In the southern tropical Indian Ocean region, decadal ENSO contribution dominates and the Pacific influence via Indonesian Throughflow (ITF; known as the *oceanic bridge* between the Indian and Pacific Oceans) mainly accounts for sea-level variability in the south-east Indian Ocean region (Han et al. 2018; Deepa et al. 2018a, b). However, Nidheesh et al. (2017) have noted that the representation of Indian Ocean decadal sea-level variability in observation-based sea-level products (reanalyses and reconstructions) is not consistent across the products due to poor observational sampling of this basin as compared to other tropical oceans. Hence, the salient features of Indian Ocean decadal sea-level variability, briefly summarized above from various studies that used any single of those sea-level products or OGCMs, need to be considered with caution.

Multi-decadal sea-level variability in the Indian Ocean is dominated by the thermosteric changes forced by changes in the winds. For example, Swapna et al. (2017) have shown that the multi-decadal rise in north Indian Ocean sea level is caused by the weakened summer monsoon circulation, which reduces the southward ocean heat transport and results in an increased heat storage and thermosteric sea-level rise of about 3.3 mm year^{-1} during 1993–2015 in the north Indian Ocean (Swapna et al. 2017).

9.4 Future Mean Sea-Level Change

9.4.1 Global

Sea level has been rising over the past century, and the rate has accelerated in recent decades. The onset of modern sea-level rise coincided with increasing global temperature (e.g. Kemp et al. 2011a, b); sea-level rise over the coming centuries is perhaps the most damaging side of rising temperature. The Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5) provided an assessment of projected global sea-level rise till the end of the twenty-first century (up to 2100) forced by different emission scenarios (Taylor et al. 2012). Projected sea-level rise under each scenario is the sum of individual contributions from steric changes and melting of glaciers and ice caps, the Greenland ice sheet, the Antarctic ice sheet and contribution from land water storage. These projections are derived from the co-ordinated modelling activities under the Coupled Model Intercomparison Project (CMIP) of the World Climate Research Programme (WCRP). CMIP5 provides projections of future climate on two time scales, near term (up to about 2035) and long term (up to 2100 and beyond). The near-term simulations (simulation over 10–30 years) are initialized with observed ocean state and sea ice, and the long-term simulations are initialized from the end of freely evolving simulations of the historical period (carried out by atmosphere-ocean global climate models—AOGCMs or Earth system models). Climate projections in CMIP models are carried out with specified concentrations of atmospheric greenhouse gases (known as 'Representative Concentration Pathways'—RCPs). The sea-level projections described here are based on a 'mitigation scenario' (RCP4.5, in which the anthropogenic emission leading to radiative forcing is limited to 4.5 Wm^{-2} in the year 2100) which is a mid-range scenario between a higher (RCP8.5) and lower (RCP2.5) scenarios (see Moss et al. 2010). Although the performance of CMIP5 models in simulating the sea level has substantially increased compared to previous versions, these models still do not account for the net ocean mass changes induced by melting ice sheets and glaciers (Flato et al. 2013). Consequently, it is not possible to evaluate the 'total' sea-level rise directly from CMIP sea-level simulations. However, the dynamic sea-level changes are given directly, and the methods by which the mass contributions are estimated (also the method of uncertainty calculation) are given in Church et al. 2013a, b (refer to their Supplementary material).

The observed global mean sea-level rise about 1–2 mm year^{-1} for 1900–2000 as inferred from tide gauges (see Fig. 9.5a) is within the range of hindcasts by CMIP models over the historical period (1870–2005; Church et al. 2013a, b), giving confidence in future projections from those models. Figure 9.5 provides the central estimates and likely ranges of projected evolution of GMSL for the twenty-first century for two emission scenarios (RCP8.5 corresponding to high emission and RCP2.6 corresponding to a very low emission scenario). Combining paleo data with historical tide gauge data confirms that the rate of sea-level rise has increased from a low rate of change during the pre-industrial period (of order tenths of mm year^{-1}) to rates of about 2 mm year^{-1} over the twentieth century, with a likely continuing acceleration during the twenty-first century

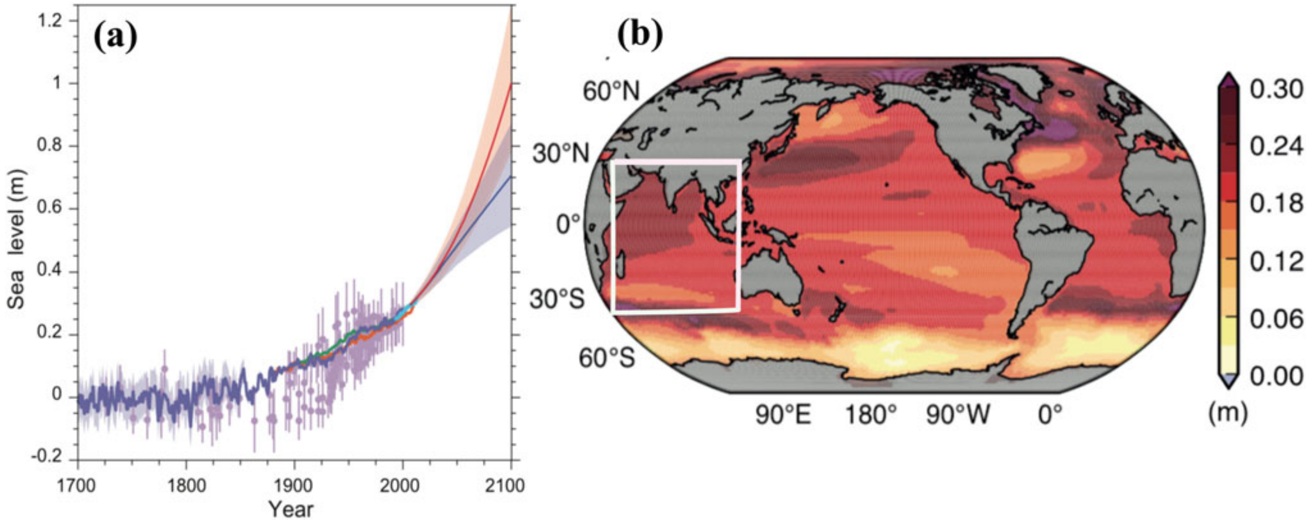


Fig. 9.5 **a** Global mean sea-level evolution derived from the compilation of palaeo sea-level data (purple), three different tide gauge reconstructions (Church and White 2011—orange, Jevrejeva et al. 2009—blue, Ray and Douglas 2011—green), altimeter data (bright blue), and central estimates and likely ranges for future projections of global mean sea-level rise for RCP2.6 (very low emissions—blue) and RCP8.5 (very high emissions—red) scenarios, all relative to pre-industrial values. **b** Ensemble mean projection of the dynamic and steric sea-level changes for the period 2081–2100 relative to the reference period 1986–2005 from 21 CMIP5 models, using the RCP4.5 experiment. Note that, these regional sea-level projections do not include the effects of terrestrial ice-melting. The Indian Ocean is highlighted by a white rectangle. Adapted from Church et al. (2013a, b)

Table 9.1 Sea level estimates based on CMIP5 RCP scenarios (*Source* IPCC AR5; Chap. 13)

Global mean sea-level rise (relative to 1986–2005)				
SSH	RCP2.6	RCP4.5	RCP6.0	RCP8.5
2081–2100 (m)	0.40 [0.26–0.55]	0.47 [0.32–0.63]	0.48 [0.33–0.63]	0.63 [0.45–0.82]
2046–2065 (m)	0.24 [0.17–0.32]	0.26 [0.19–0.33]	0.25 [0.18–0.32]	0.30 [0.22–0.38]
By the end of 2100 (m)	0.44 [0.28–0.61]	0.53 [0.36–0.71]	0.55 [0.38–0.73]	0.74 [0.52–0.98]
GMSL rise rate (mm year^{-1}) 2081–2100	4.4 [2.0–6.8]	6.10[3.5–8.8]	7.4 [4.7–10.3]	11.2 [7.5–15.7]

(Fig. 9.5a). For the high emission scenario, CMIP5 models predict a GMSL rise by 52-98 cm by the year 2100, which would threaten the survival of coastal cities and entire island nations all around the world. Even with a highly optimistic emission scenario (RCP2.5), this rise would be about 28–61 cm (Fig. 9.5a), with serious impacts on many coastal areas, including coastal erosion and a greatly increased risk of flooding. Global sea-level estimates are given in Table 9.1.

Projections incorporating Antarctic ice sheet dynamics indicate that sea levels may rise 70–100 cm under RCP4.5 and 100–180 cm under RCP8.5, though major uncertainty in sea level projections arise from the representation of ice-sheet dynamics in the models. Translating the sea-level projection into potential exposure of population, recent study by Kulp and Strauss (2019) reveals triple estimates of global vulnerability to sea-level rise and coastal flooding. However, their study is based on digital elevation model (DEM) utilizing neural networks for reducing errors in satellite-based DEM, and global coverage with widely distributed ground truth is highly essential for better understanding coastal inundations and population vulnerability.

9.4.2 Regional Sea-Level Projections for the Indian Ocean

While the global mean sea-level rise has strong societal implications, we will now see that regional sea-level changes can considerably deviate from the global mean. As shown in many studies (Zhang and Church 2012; Han et al. 2014; Hamlington et al. 2013), the observed sea-level rise over the altimeter period is indeed not uniform over the world oceans. While sea level rises at a faster rate in some oceanic regions, such as in the north Indian Ocean, sea level has shown a fall in the thermocline ridge region south of the equator in the Indian Ocean (Han et al. 2010). This contrasting spatial distribution of sea-level rise makes regional sea-level projections challenging as the attribution of projected changes requires a clear understanding of projected changes in ocean wind-driven circulation, steric changes and terrestrial ice storages (Air-sea momentum and heat fluxes variations are associated with spatially varying sea-level changes. For example, the excess surface latent heat flux associated with global warming penetrates differentially into the ocean depending on, for example, the mixed layer depth and circulation. Similarly, climate change induces changes in surface winds, which will further cause sea-level regional changes). As far as the Indian Ocean is concerned, apart from information provided in IPCC AR4/5, there is no independent studies that provide regional sea-level projections[1] and its attribution (i.e. the role of external forcing and natural variability as well as the respective contributions from global (regional) ocean steric and mass variations are still far from precise).

Figure 9.5b shows the spatial distribution of projected changes in regional sea level in the world oceans, derived from 21 CMIP models, for the RCP4.5 scenario (which is mid-range emission scenario (RCP4.5) between the high/low-end scenarios (RCPs 8.5 and 2.5). These sea-level projections reveal a clear regional pattern in sea-level changes, with complex ridge-and-trough patterns superimposed on a generally rising global mean sea level. For instance, in the Indian Ocean, the highest changes (trends) are seen in the north and western tropical Indian Ocean with a mean sea-level change of about 0.25–0.3 m at the end of the twenty-first century (Fig. 9.5b). It should be noted that north and western tropical IO is one of the few oceanic regions where maximum changes are predicted by CMIP climate models (maximum steric and dynamic sea-level rise). In a similar study, Carson et al. (2016) showed that these projected changes in mean sea level for the twenty-first century are considerably larger than the (projected) noise (natural variability) everywhere in the Indian Ocean, suggesting that the projected changes in the Indian Ocean mean sea level seen in Fig. 9.5b would have an anthropogenic origin. The contribution of thermal expansion to the GMSL rise by 2100 is estimated to be about 0.19 m for the RCP4.5 (Church et al. 2013a, b), and the slightly higher changes seen regionally in the western tropical Indian Ocean could be either related to additional changes from dynamic sea-level rise or could be resulting from an excess projected warming of this region. Note that, these projected changes (shown in Fig. 9.5b) do not include a contribution from ice-melting (mainly glaciers and ice sheets). Though, the dynamic adjustment of the world oceans to additional mass input from ice-melting is complex and occurs over decadal to century time scales (e.g. Stammer 2008), our current understandings indicate that the projected regional sea-level rise from glaciers and ice sheets is comparable to the changes from thermal expansion and circulation changes (see Church et al. 2013a, b). This is true for the Indian Ocean also, which means, combining the effects of steric changes (shown in Fig. 9.5) with mass addition may be higher than the values shown for projected Indian Ocean sea-level changes, shown in Fig. 9.5b.

9.5 Extreme Sea-Level Changes in the Indian Ocean

One of the main consequences of mean sea-level rise on human settlements is an increase in flood risk due to an increase in the intensity and frequency of extreme sea levels (ESL). Coastal areas become threatened when high tides coincide with extreme weather events and drive ESL (Wahl et al. 2017). Extreme weather (climate extremes) contributes to ESL through wind-waves and storm surges. Storm surge is an episodic increase in sea level driven by shoreward wind-driven water circulation and atmospheric pressure. Wind-waves are generated when wind energy is transferred to the ocean through surface friction and is transformed into wave energy fluxes. When waves reach the coast, they interact with the bathymetry and drive an additional increase in water levels through wave set-up and run-up. ESLs are exacerbated by tropical cyclones (TCs), which significantly intensify wind-waves and storm surge (Peduzzi et al. 2012).

ESL can be defined as a combination of surges/waves, tides and MSL, where MSL is the mean sea-level. Though there are several statistical techniques to evaluate ESL, there is no universally accepted standard or best approach for broadscale impact and adaptation analysis (Arns et al. 2013).

The IPCC AR5 (Church et al. 2013a, b; Rhein 2014) included a review of ESL reveal that the recent increase in observed extremes worldwide has been caused primarily by an increase in MSL, although the dominant modes of climate variability (particularly the El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), North Atlantic Oscillation (NAO) and other modes) also have a measurable influence on extremes in many regions. Since the IPCC AR5, there have been a number of studies relating to ESL. Wahl (2014) reported rapid changes in the seasonal cycle of MSL along the Gulf Coast of the United States. The spatial variability of ESL is found to be considerably lower than the global mean trend (Vousdoukas et al. 2018). However, recent studies have shown that global warming will induce changes in storm surges and wind-waves, while cyclonic activity may also be affected (Hemer et al. 2013; Woodruff

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[1] Future projections for the Indian Ocean are based on thermosteric component (thermal expansion only).

et al. 2013). These climate extremes along with sea-level rise will affect ESL and intensify coastal flood risk (Vousdoukas et al. 2018).

The recent evolution of extremely high waters along the severe cyclone-risk coasts of the Bay of Bengal (the east coast of India and Bangladesh) was assessed using long-term (24–34 years) hourly tide gauge data available from five stations by Antony et al. 2016. They have noticed the highest water levels above mean sea level with the greatest magnitude towards the northern part of the Bay, which decreases towards its south-west. Extreme high waters were also observed resulting from the combination of moderate, or even small, surges with large tides at these stations in most of the cases. In the Bay of Bengal, return period and return level estimations of extreme sea levels have been provided by Unnikrishnan et al. (2004) and Lee (2013) using hourly tide gauge data and Unnikrishnan et al. (2011) using storm surge models, driven by regional climate models. In the Indian Network for Climate Change Assessment Report-II, Chap. 4, Unnikrishnan et al. (2010) have shown that higher flood risks are also associated with storm surge along the southern part of the east coast of India, where tidal ranges are low. The study by Rao et al (2015) also suggested that in an extreme climate change scenario, there is a high risk of inundation over many regions of Andhra Pradesh, which is along the east coast of India. Extreme sea-level projections for Ganga-Brahmaputra-Meghna delta (Kay et al. 2015) show an increased likelihood of high water events through the twenty-first century. The First Biennial Update Report (BUR) to UNFCCC by the Government of Indian 2015 emphasized the need to promote sustainable development based on scientific principles taking into account the dangers of natural hazards in the coastal areas, and sea-level rise due to global warming.

Long and good quality tide gauge sea-level records are geographically biased towards the European and North American coasts, reflecting the historical limitations of the worldwide tide gauge dataset. Therefore, major ESL analyses cover the ocean's basin to the extent as possible, but there is a substantial lack of information especially in the Southern Hemisphere and the Indian Ocean (Marcos et al. 2015). Extreme sea levels, caused by storm surges and high tides, can have devastating societal impacts. It was shown that up to 310 million people residing in low elevation coastal zones are already directly or indirectly vulnerable to ESL (Hinkel et al. 2014). Since the extreme sea level is projected to increase with an increase in mean sea level and climate extremes, an extensive network of tide gauges with co-located GPS systems is needed along the Indian coastline, as our coastline is among the most vulnerable and densely populated regions of the globe.

The projected rise in mean sea level and ESL is a real caution for countries off the rim of north Indian Ocean, and for India, and to a large number of islands in the Indian Ocean, many of them have fragile infrastructures and population density is projected to become the largest in the world by 2030, with about 340 million people exposed to coastal hazards (Neumann et al. 2015). The sea-level rise-related coastal hazards include loss of land, salinization of freshwater supplies and an increased vulnerability to flooding. For instance, the Bay of Bengal already witnesses more than 80% of the total fatalities due to tropical cyclones, while only accounting for 5% of these storms globally (Paul 2009). The storm surges associated with the cyclone conflates with the climate change-induced sea-level rise (e.g. Han et al. 2010) to increase vulnerability. In general, the regional projections of the Indian Ocean mean sea level for the twenty-first century (see Fig. 9.5b) from climate models are high compared to other tropical oceans and the consequences could become double-fold considering the fact that the Indian Ocean basin hosts millions of people on its rim lands. In further research, an improved understanding of the factors controlling the Indian Ocean long-term sea-level rise and continuous monitoring of sea-level variability is essential for better assessing its socio-economic and environmental impacts in a changing climate.

9.6 Knowledge Gaps

Lack of long sea-level observations for the Indian Ocean is a major caveat to derive the reliable basin-scale pattern of sea-level rise and multi-decadal variability in this basin. For example, previous studies suggested that the multi-decadal oscillations in regional sea level call for a minimum of 50–60 years of sea-level data in order to establish a robust long-term trend (e.g. Douglas 1997; Chambers et al. 2012). There are only two tide gauges in the Indian Ocean that go back to the nineteenth century: Mumbai (west coast of India) and Fremantle (west coast of Australia). Figure 9.6 indeed shows that, except for a few gauge stations along the coastal India and west coast of Australia, there are no gauge records available in the interior ocean that spans over a minimum of 40 years. On the other hand, satellite altimetry provides high-resolution sea-level measurements over the entire basin since 1992, but the data are so short in terms of providing reliable estimates of regional sea-level rise trends given the presence of multi-decadal oscillations (e.g. Unnikrishnan et al. 2015; Swapna et al. 2017). In the same lines, the unavailability of long-term hydrographic profiles in the Indian Ocean limits our knowledge of long-term heat content and salinity variations in the basin and hence the steric sea level. In a recent study, Nidheesh et al. (2017) showed that representation of Indian Ocean decadal sea-level variations in observation-based sea-level datasets (reanalyses and reconstructions) is not robust and the inconsistencies are

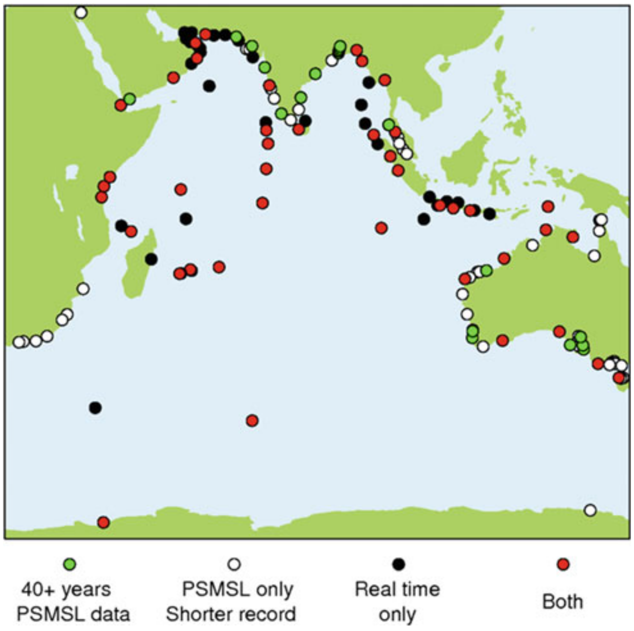

Fig. 9.6 Active tide gauge stations in the Indian Ocean. PSMSL stations are considered active if data are available for 2011 or later. Real-time stations are considered active if they have supplied data in 2017. Adapted from Beal et al. (2019)

largely attributed to the lack of past sea-level data in the interior ocean especially prior to 1980. The international venture of enhancing and sustaining the Indian Ocean Observing System (IndOOS, Beal et al. 2019) aims to fill those many knowledge gaps which arise mainly from lack of long-term observations in the Indian Ocean.

9.7 Summary

One of the major consequences of warming of the global ocean and the melting of ice and glaciers is the rise in mean sea level. There is high confidence that sea level has been rising in the global oceans as well as in the Indian Ocean. Over 90% of the anthropogenic excess heat goes into the oceans (Church et al. 2013a, b), remaining goes into melting both terrestrial and sea ice, and warming the atmosphere and land (Hansen et al. 2011; Church et al. 2011b; Trenberth et al. 2014). As a result, global mean sea level has risen by 1.7 (1.5–1.9) mm year^{-1} since 1901 and the rate of rise has accelerated to 3.3 mm year^{-1} since 1993. Sea-level rise in the Indian Ocean is non-uniform and the rate of north Indian Ocean rise is 1.06–1.75 mm year^{-1} from 1874 to 2004 and is 3.3 mm year^{-1} in the recent decades (1993–2015). Indian Ocean sea-level rise is distinct, dominated by the thermal expansion, while mass contribution is the major contributor to the GMSL rise. Steric sea level along the Indian coast is likely to rise by about 20 to 30 cm at the end of the twenty-first century and the corresponding estimate for global mean steric sea-level rise is 18 ± 5 cm (relative to 1986–2005), under RCP4.5 (for a mid-range emission scenario, excluding ice-melt contributions). Considering the fact that coasts are home to approximately 28% of the global population, including 11% living on land less than 10 m above sea level, long-term sustained observations and continued modelling are critical for detecting, understanding and predicting ocean and cryosphere change, thus providing knowledge to inform risk assessments and adaptation planning (IPCC, Special Report on Ocean and Cryosphere in a Changing Climate).

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