Chapter 7
Observation and Geophysical Causes of Present-Day Sea-Level Rise

C.K. Shum and Chung-Yen Kuo

Contents

Abstract The 2007 IPCC Fourth Assessment Report (FAR) sea-level assessment has significantly narrowed the gap between the observations and the geophysical causes of sea-level rise than the 2001 IPCC Third Assessment Report (TAR). The observed present-day (1900–current) sea-level rise is approximately 1.8–2.2 mm/year. The unexplained discrepancy (observed compared with the sum of all known geophysical contributions to sea-level rise) dropped from 1.83 to 1.29 mm/year. A post-2007 IPCC FAR sea-level assessment study covering modern satellite measurement data span (2003–2008) indicates significant narrowing of the sea-level budget disagreement over IPCC TAR, to 0.44 mm/year. However, a review of more recent studies including the mountain glacier and ice-sheet mass balance estimates and the estimated sea-level fall from human impoundment of water in reservoirs reveal that the discrepancy is now up to 1.42 mm/year, drastically larger than the current assessment (0.44 mm/year). The unexplained sea-level signal represents 71% of the

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observed sea-level rise (~2.0 mm/year). Major geophysical contributors to sea-level rise identified which potentially have the largest errors include the ice-sheet mass balance, the knowledge of glacial isostatic adjustment forward models underneath the ice-sheets and the ocean, mountain glaciers and ice caps, and the anthropogenic effect of human impoundment of water in reservoirs and dams. Integrated analysis and interpretation using modern satellite and in situ measurements could narrow the uncertainty between the observations and the explained contributions from each of the geophysical sources to sea-level rise.

Keywords Sea-level rise • Global climate change • Intergovernmental Panel for Climate Change

Abbreviations

FAR	Fourth Assessment Report
TAR	Third Assessment Report
UNEP	United Nations Environment Program
WMO	World Meteorological Organization
GIA	glacial isostatic adjustment
GRACE	Gravity Recovery and Climate Experiment
MBT	mechanical bathythermographs
PMSL	permanent service for mean sea-level
LGM	last glacial melt

7.1 Introduction

The Earth's Quaternary climate, driven by Milankovich cycles which resulted in ice ages, can be characterized on time-scales on the order of 100,000 years with interlinked changes in temperature, greenhouse gases which are dominated by CO_2, and natural water reservoirs including the ice-sheets, glaciers and ice caps, hydrosphere and ocean (e.g., Shum et al. 2008). The global sea-level during the Last Ice Age, or at the Last Glacial Maximum (LGM) 20,000 years ago, is ~130 m lower than the present (Lambeck et al. 2002). During the twentieth century and since the onset of the Industrial Revolution, anthropogenic effects from greenhouse gases have led to global warming, resulting in accelerated ice-sheet melt and an increased rate of sea-level rise (Solomon et al. 2007). Paleoclimate studies of past ice-sheets from previous Ice Ages indicate a distinct potential of future accelerated ice-sheet melt and the corresponding sea-level rise due to anthropogenic climate change (Overpeck et al. 2006). From a science perspective, it is critical to understand the complicated processes of greenhouse gas forced warming to the changes in the Earth's natural reservoirs (ice-sheet, hydrosphere and ocean) contained by the solid-Earth and their feedbacks, with the present-day global sea-level rise as one of the consequences.

More than 70% of our planet is ocean. Approximately half of the world's population or 3.2 billion people lives within 200 km of coastlines (Hinrichsen 2009, http://peopleandplanet.net), and 30% of US population lives near the coastal regions (Crowell et al. 2007). Sea-level rise, widely recognized as one of consequences resulting from anthropogenic climate change, has a substantial social and economic impact, and is a timely scientific, societal and cross-disciplinary problem. The present-day (twentieth century and to the present) sea-level rise is a measurable signal using tide gauges over the last century and a half, and using Earth-orbiting satellite measurements over the past decade and a half. Quantifying sea-level change remains a complex interdisciplinary research problem, primarily because of the small magnitude of the sea-level rise signal: at ~1–2 mm/year over the last century. However, the signal has a very long or near-planetary spatial scale, allowing averaging of measurements over large ocean basins or globally and it has already been demonstrated that this small signal can be measured with adequate accuracy using tide gauges and using satellite altimetry (Douglas 2001; Cazenave and Nerem 2004). The small rate of the twentieth century and contemporary sea-level rise could only be *partially* explained, at present, by a number of competing geophysical processes, each of which is a complex process within the Earth-atmosphere-ocean-cryosphere-hydrosphere system. Improved quantification, understanding and future projection of sea-level change remains a challenge. The understanding of geophysical and anthropogenic processes leading to sea-level rise, towards improving its future projection, is a significant contemporary geoscience and societal problem.

7.2 Intergovernmental Panel on Climate Change Assessments on Sea-Level Rise

Recognizing the problem of global climate change, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. IPCC's First Assessment Report provides an estimate of global sea-level rise of 1.0–2.0 mm/year during the twentieth century with a large uncertainty (Warrick and Oerlemans 1990). The IPCC Second Assessment Report in 1996 indicates a consensus estimate of the twentieth century sea-level rise based on tide gauges at ~2 mm/year, attributing half of the rise to glacier ablation and the other half to thermal expansion of the ocean, with a conclusion that ice-sheets contributed little to sea-level rise (Warrick et al. 1996). The IPCC Third Assessment Report (TAR) in 2001 stated that the estimated twentieth century sea-level rise is at 1–2 mm/year (Church et al. 2001), and established more certainty on the tide gauge observed rate of 1.84 ± 0.35 mm/year (Douglas 2001). The observed thermal expansion of the ocean during the last 5 decades is estimated to be 0.55 mm/year (Levitus et al. 2000), which is significantly less than the anticipated value of ~1 mm/year from the 1996 IPCC Assessment. The discrepancy between the observed and explained geophysical causes is almost as large as the observed rate of sea-level rise (1.8 mm/year) in IPCC TAR (Church et al. 2001), and the problem remains an enigma (Munk 2002). The 2007 IPCC Fourth Assessment Report (FAR), Working Group I, *The Physical Science Basis*, concluded that the warming of the climate system is unequivocal, and with high certainty that the effect of human activities since 1750 has resulted in global warming (Solomon et al. 2007). Observational evidence confirms the anthropogenic increase of average air, land and ocean temperature, melting of snow and ice, and global sea-level rise. Compared with IPCC TAR, the 2007 IPCC Fourth Assessment Report (FAR) sea-level Assessment (Bindoff et al. 2007; Lemke et al. 2007) significantly closed the gap between observations and geophysical explanations.

Figure 7.1 (updated from Shum et al. 2008) shows the current knowledge of estimated, observed and projected sea-level rise for the past two centuries and the next century (1800–2100), characterizing the "*Hockey Stick*" *of Sea-Level Rise,* indicating a significant sea-level acceleration since ~1900 (Donnelly et al. 2004; Gehrels et al. 2006; Jevrejeva et al. 2008), which coincide with the Industrial Revolution. The pre-1900 estimate is based on geological interpretation at 0.1–0.2 mm/year; Lambeck et al. 2002), the tide gauge observed sea-level rise (1900–2005) (red, uncertainty with yellow shade) and satellite altimetry observed sea-level rise (1985–2005) (blue) (Cazenave and Nerem 2004; Church et al. 2004; Kuo 2006; Shum et al. 2009). The projected twenty-first century sea-level rise (IPCC FAR), based on the natural forcing plus greenhouse gases (ALL250 or

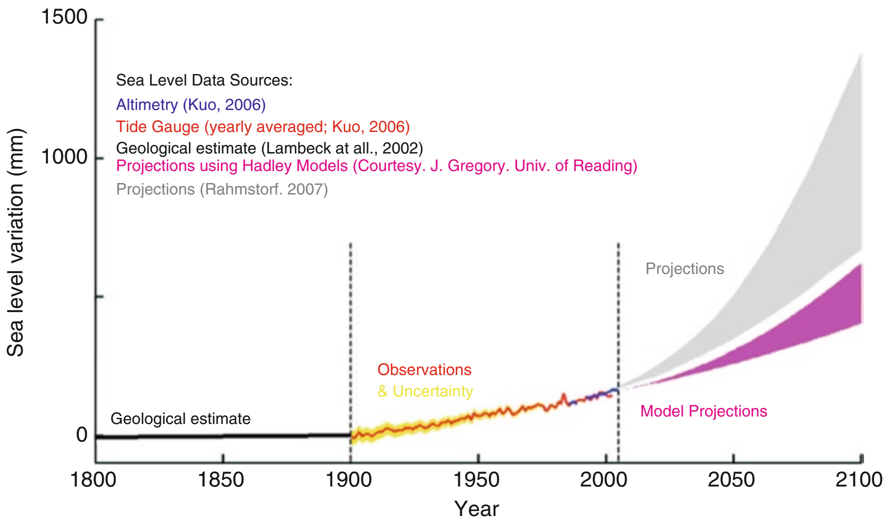

Fig. 7.1 Current knowledge of the estimated, observed and projected global sea-level rise over the past two centuries and the next century (1800–2100) (Figure updated from Shum et al. 2008)

"worse" scenario) using the HadCM3 climate model (Gregory et al. 2006) (pink envelop) is 20–60 cm. However, Rahmstorf (2007) which used empirical methods, show a much higher projected sea-level rise (70–130 cm) than the IPCC FAR projection. Siddall et al. (2009) used a climate model with ice-sheet feedbacks and assuming a maximum warming of 6.4°C and projects an end of twenty-first century sea-level rise of 82 cm (not shown here), which is in good agreement with the IPCC FAR projection. The current discrepancy of sea-level projections remains controversial and the likely improvement of model predictions depends on our enhanced understanding of the complex geophysical processes causing sea-level rise, and our ability to more accurately measure and to explain various geophysical contributions resulting in sea-level rise, including ice-sheet and glacier melt rates, oceanic thermal expansion.

7.3 Sea-Level Budget

Table 7.1 (2nd through 4th columns) summarized that the 2007 IPCC Fourth Assessment Report (FAR) sea-level assessment (Bindoff et al. 2007; Solomon et al. 2007) has significantly narrowed the gap between the observations and the geophysical causes of sea-level rise than the 2001 IPCC Third Assessment Report (TAR) (Church et al. 2001). The unexplained discrepancy (observed minus the sum of geophysical contributions) dropped from 1.83 to 1.29 mm/year, 2001 TAR to 2007 FAR assessment (Table 7.1, 2nd and 4th column), respectively. A post-2007 IPCC FAR sea-level budget assessment study by (Cazenave and Shum 2009) covering modern satellite measurement data span (2003–2008) indicates significant narrowing of the sea-level budget disagreement over IPCC TAR, to 0.44 mm/year (Table 7.1, 5th column). Here we define the sea-level trend covering time span of the twentieth century and present-day (2000–present) and provided a review of published estimates of various geophysical causes of sea-level rise and observations (Table 7.1, 6th column). We make the assumption that individual (geophysical or observed sea-level) trend estimates has mitigated long-period signals and represents "true" long-term trends for ice mass-balance or sea-level. The definition would not preclude a potential acceleration signal in the sea-level rise. The estimated rates or trends of geophysical signals (including ice-sheet mass balance) have the same definition. The result now reveals a larger discrepancy in the sea-level budget (Table 7.1, 6th column): the maximum difference between observed and explained contributions to sea-level rise is at 1.42 mm/year, which is much larger than the assessment by (Cazenave 2009) of 0.44 mm/year (Table 7.1, 5th column), and in worse agreement than the 2007 IPCC FAR assessment of 1.29 mm/year (Table 7.1, 4th column).

The unexplained sea-level signal of 1.42 mm/year represents up to 71% of the observed sea-level rise (~1.8–2.2 mm/year). This significant unraveling of our current knowledge of the sea-level budget is due primarily to a number of critical geophysical sources providing published estimates of their respective contributions

Table 7.1 Contemporary global sea-level budget (observations versus contributing geophysical sources)

Geophysical sources of sea-level rise	2001 IPCC TAR 1900–1990[a] (mm/year)	2007 IPCC FAR (mm/year) (Bindoff et al. 2007) 1961–2003	2007 IPCC FAR (mm/year) (Bindoff et al. 2007) 1993–2003	Post–FAR study[c] (mm/year) 2003–2008	This study (mm/year) 1900–2008
Thermal expansion	0.5 ± 0.2 (0.3 → 0.7)	0.42 ± 0.12 (0.3 → 0.54)	1.6 ± 0.5 (1.1 → 2.1)	0.31 ± 0.15 (0.16 → 0.46)	0.4 ± 0.2 (0.2 → 0.6)[1]
Glaciers and Ice caps	0.3 ± 0.1 (0.2 → 0.4)	0.50 ± 0.18 (0.32 → 0.68)	0.77 ± 0.22 (0.55 → 0.99)	1.1 ± 0.24 (0.86 →1.34)	0.96 ± 0.44 (0.52 → 1.4)[2]
Greenland Ice sheet	0.3 ± 0.3 (0.0 → 0.6)[a]	0.05 ± 0.12 (–0.07 → 0.17)	0.21 ± 0.07 (0.14 → 0.28)		0.3 ± 0.33 (–0.03 → 0.63)[3]
Antarctic Ice sheet	–0.1 ± 0.1 (–0.2 → 0.0)[a]	0.14 ± 0.41 (–0.27 → 0.55)	0.21 ± 0.35 (–0.14 → 0.56)	1.0 ± 0.15 (0.85 → 1.15)	0.14 ± 0.26 (–0.12 → 0.4)[4]
Terrestrial hydrology	–0.35 ± 0.75	–	–	0.17 ± 0.1 (0.07 → 0.27)	0.17 ± 0.1 (0.07 → 0.27)[5]
Water impoundment in reservoirs	(–1.1 → 0.4)	–	–	–	–0.55[6]
Sum of geophysical contributions	0.65 ± 0.84 (–0.8 → 2.1)	1.1 ± 0.5 (0.6 → 1.6)	2.8 ± 0.7 (2.1 → 3.5)	2.58 ± 0.34 (1.94 → 3.22)	1.42 ± 0.82 (0.6 → 2.24)
Observed total sea-level rise	1.5 ± 0.5 (1.0 → 2.0)	1.8 ± 0.5 (1.3 → 2.3)	3.1 ± 0.7 (2.4 → 3.8)	2.5 ± 0.4 (2.1 → 2.9)[b]	2.0 ± 0.2 (1.8 → 2.2)
Difference (observed–explained)	0.85 ± 0.98 (–0.13 → 1.83)	0.7 ± 0.7 (0.0 → 1.4)	0.30 ± 0.99 (–0.69 → 1.29)	–0.08 ± 0.52 (–0.60 → 0.44)	0.58 ± 0.84 (–0.26 → 1.42)

[a] Included natural and "climate" contributions from ice-sheets (Church et al. 2001)
[b] Observed by satellite altimetry
[c] Cazenave (2009), similar studies by Peltier (2009), Leuliette and Miller (2009), Willis et al. (2008)
[1] Antonov et al. (2005), Ishii and Kimoto (2009), Gouretski and Koltermann (2007), Domingues et al. (2008)
[2] Arendt et al. (2002), Dyurgerov and Meier (2005), Kaser et al. (2006), Meier et al. (2007), (Cogley 2009)
[3] Abdalati et al. (2001), Rignot and Thomas (2002), Krabill et al. (2004), Zwally et al. (2005), Johannessen et al. (2005), Rignot and Kanagaratnam (2006), Ramillien et al. (2006), Chen et al. (2006b), Luthcke et al. (2006), Velicogna and Wahr (2006a), Cazenave (2009), Shepherd and Wingham (2007), Slobbe et al. (2009)
[4] Thomas et al. (2004), Davis et al. (2005), Wingham et al. (2006), Zwally et al. (2005), Rignot et al. (2008), Cazenave (2009), Shepherd and Wingham (2007), Shum et al. (2008). GRACE estimâtes (Ramillien et al. 2006 ; Chen et al. 2006a, Velicogna and Wahr 2006b, Shum et al. 2008): 0.14–0.40 mm/year
[5] Milly et al. (2003), Ngo-duc et al. (2005), Ramillien et al. (2008)
[6] Chao et al. (2008), no uncertainties provided

to sea-level rise with large discrepancies, or there are still large uncertainties for these estimates. These geophysical sources include the ice-sheet mass balance estimates, the land water contributions (including terrestrial hydrology, glaciers and ice caps and human-impoundment of water in reservoir and dams), and the effect of glacial isostatic adjustment (GIA) process, or solid Earth's viscoelastic rebound due to deglaciation of ancient ice-sheets from the Last Ice Age since the LGM. The ultimate objective is to improve the individual estimates quantifying of each of these geophysical sources causing present-day sea-level rise.

7.3.1 Ice-Sheet Mass Balance Estimates

There are significant discrepancies between the various ice-sheet mass balance estimates (Table 7.1, 6th column), from −0.03 to 0.63 mm/year and from −0.12 to 0.4 mm/year (equivalent sea-level) for Greenland and for Antarctica, respectively, using data from airborne altimetry (Krabill et al. 2004) and satellite altimetry (Cazenave and Nerem 2004), from synthetic aperture radar interferometry (InSAR) (Rignot and Thomas 2002) and from Gravity Recovery and Climate Experiment (GRACE) satellite mission (Tapley et al. 2004). The discrepancy are primarily due to (1) poor knowledge of glacial isostatic adjustment (GIA) (Peltier 2004) over the ice-sheets, which is in particular critical when GRACE is used (Velicogna and Wahr 2006b): the choice of the GIA models significantly affects Antarctica mass balance estimates, adding 0.25–0.45 mm/year of equivalent sea-level rise (Shum et al. 2008), (2) firn-compaction and ice column density variations when (airborne and satellite) altimetry are used (Helsen et al. 2008), (3) short data spans (GRACE) or lack of finer than seasonal sampling (InSAR, airborne altimetry) which may bias the trend estimate, and (4) significant differences in GRACE mass balance estimates including results with different spatial resolutions and with land-sea signal leakage (Lettenmaier and Milly 2009; Guo et al. 2010). Figure 7.2 shows the satellite radar altimetry and GRACE estimated Antarctica mass balance. Notable *discrepancies* between the estimates from altimetry and GRACE are in the Antarctic Peninsula, JJ′ (altimetry shows no large mass loss); E. Antarctica, AA″ & A″B; Siple Dome, E′E″, D″D; Enderby Land, A″B, Oakes Coast, D″D′. However, there are good agreements between satellite altimetry and GRACE observed ice-sheet mass balance, for example, over the regions including: Basin GH (Amudsen Sea), W. Antarctica, and Basin BC (Lambert Glacier/Emery Ice Shelf), E. Antarctica (Fig. 7.2). In summary, the discrepancy of the ice-sheet mass balance estimates for Greenland ranges from −0.03 to 0.63 mm/year equivalent sea-level rise, and for Antarctica ranges from −0.14 to 0.40 mm/year, respectively (Table 7.1, 6th column), representing one of the largest uncertainties contributing to the current discrepancy of the sea-level budget.

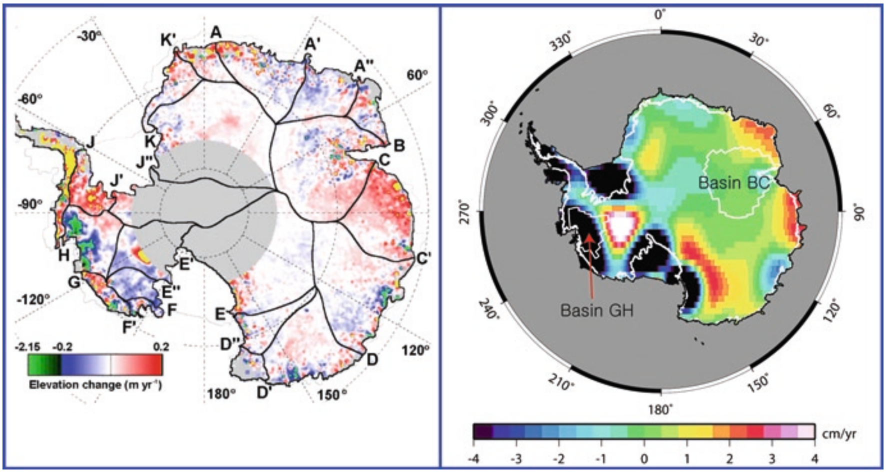

Fig. 7.2 *Left*: ERS-1–2 radar altimetry determined Antarctica ice elevation change (m/year, 1992–2003) (Figure and data courtesy, D. Wingham et al. 2006). *Right*: GRACE observed ice mass balance (cm/year, 4/2002–3/2009), GIA correction using ICE-5G (VM4) (Peltier 2004), destriped/smoothed using a 200-km radius non-isotropic Gaussian filter, with geocenter and land signal leakage corrections (Shum et al. 2008; Guo et al. 2010; Duan et al. 2009)

7.3.2 Land Water Contribution to Sea-Level

Chao et al. (2008) estimated that the sea-level fall resulting from human impoundment of water in reservoirs and dams over the last 50 years is equivalent to –0.55 mm/year. However, Lettenmaier and Milly (2009) evaluated a number of smaller land contributions to sea-level rise, and argued that since most of the large manmade reservoirs were constructed since about the 1950 and one may no longer be assumed that they contributed negatively to sea-level rise during the current time period.

The contribution of mountain glaciers and ice caps to sea-level rise is by far the largest and with a wide range of estimates: 0.52–1.4 mm/year (Arendt et al. 2002; Dyurgerov and Meier 2005; Kaser et al. 2006; Meier et al. 2007; Cogley 2009) (Table 7.1, 6th column). The latest estimate of 1.1–1.4 mm/year (Cogley 2009) is due to the revised modelling of tide water glaciers. Like Meier et al. (2007), Cogley (2009) based the estimates entirely on in situ measurements and extrapolated globally, and the estimate did not include any satellite observations (e.g., of ice cap thinning). Of the 0.8–1.1 mm/year contribution of glacier loss estimated by Meier et al. (2007) (and probably by Cogley (2009)) and the IPCC FAR study, errors are thought to be of the order of 14–23%, respectively (Milly et al. 2009). Therefore, it is critical to narrow the uncertainty of this estimate.

The contributions of terrestrial hydrologic imbalance, potentially due to global warming, to sea-level rise has been estimated to be 0.07–0.27 mm/year (equivalent sea-level rise) based on forward hydrologic models and using GRACE (Milly et al. 2003; Ngo-duc et al. 2005; Ramillien et al. 2008). This particular geophysical contribution is among the least known and further study is warranted.

7.3.3 Glacial Isostatic Adjustment

Glacial isostatic adjustment process (Peltier 2001, 2004) produces a significant signal in the solid Earth where tide gauges are located (Douglas 2001), underneath the ice-sheets and the ocean where the mass balance signal and the sea-level signal has opposite signs, respectively.

Therefore, in addition to the need of more accurate forward GIA modeling to correct tide gauge sea-level record, GIA corrections for GRACE mass change estimates over ice-sheets, and for ocean mass variations due to exchange of water fluxes from land to ocean, is critically needed. In addition the magnitude of the GIA model in terms of water thickness change over the ocean, is on the order of 1–2 mm/year (depending on whether the Paulson (2006) or the ICE-5G (Peltier 2004) GIA model is used, respectively), which has the same magnitude as the expected signal (GRACE ocean mass variations, ~2 mm/year) (Cazenave 2009; Peltier 2009; Leuliette and Miller 2009; Willis et al. 2008). On the other hand, land-water storage, according to GRACE, shows very little trend (dashed line) over 2002–2008 (Fig. 7.3, from Lettenmaier and Milly 2009). The total land water mass variations excluding Greenland and Antarctica observed by GRACE is shown here (Fig. 7.3, the shading indicates the range of estimates from the various GRACE solutions from different processing centers (data courtesy, D. Chambers), with the thick black line the mean of the three solutions). The right-hand axis shows the sea-level anomaly, which corresponds to the land equivalent water-depth anomaly. The estimated rate of land water change, ~0.3 mm/year (Cazenave 2009) (into the ocean) is "balanced" by the observed oceanic mass (~2 mm/year), *if* the GIA forward model correction (1–2 mm/year) is *perfect*. Figure 7.4 shows the ocean geoid change (mm/year) predicted by the ICE-5G(VM4) GIA model (Peltier 2004). This quantity if expressed in the form of mass variations (or water thickness change) by including self-gravitational or the elastic loading effect (e.g., Wahr et al. 1995),

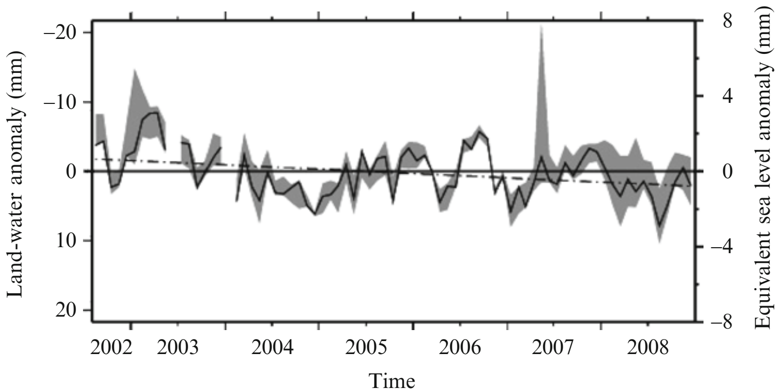

Fig. 7.3 GRACE equivalent water-depth anomalies (departures from time mean) over the global land area with exception of Greenland and Antarctica (Figure from Lettenmaier and Milly 2009)

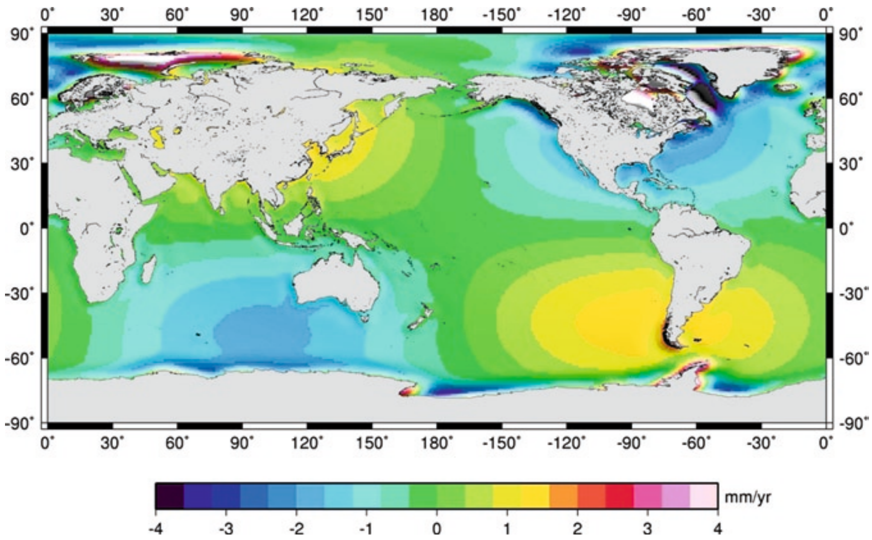

Fig. 7.4 The geoid change in the ocean predicted by the ICE-5G (VM4) glacial isostatic adjustment model (Peltier 2004)

would be amplified approximately five times of the ocean geoid change values, i.e., ~2 mm/year when averaged over the ocean (Peltier 2009). It is highly unlikely that the GIA forward model is accurate enough that an unambiguous claim is possible at present that GRACE ocean mass variations is ‘balanced’ by the observed land water fluxes flow into the ocean (Cazenave 2009; Peltier 2009; Leuliette and Miller 2009; Willis et al. 2008). Figure 7.4 also shows a see-saw positive and negative pattern in the ocean geoid change, indicative of an effect due to Earth rotational feedback. This pattern seems to be too large to be realistic and possibly this component of the modeling is in error. However, this error probably does not necessarily increase significantly the current uncertainty of predictive GIA models. In summary, there is a critical emphasis to improve the constraints of or to improve the GIA model itself, for improved estimation of oceanic mass variations and ice-sheet mass balance.

7.3.4 Thermal Expansion

Thermal expansion of the ocean, and to a less extent, the contraction of the ocean due to salt or the salinity (halosteric) effect affects the sea-level. Levitus et al. (2000) reported significant ocean heat transport from the deep ocean to the surface during the last five decades, and estimated that the thermosteric sea-level rising at 0.55 mm/year (Levitus et al. 2000). Since then, the discovery of significant instrument biases in the old mechanical bathythermographs (MBTs), the more

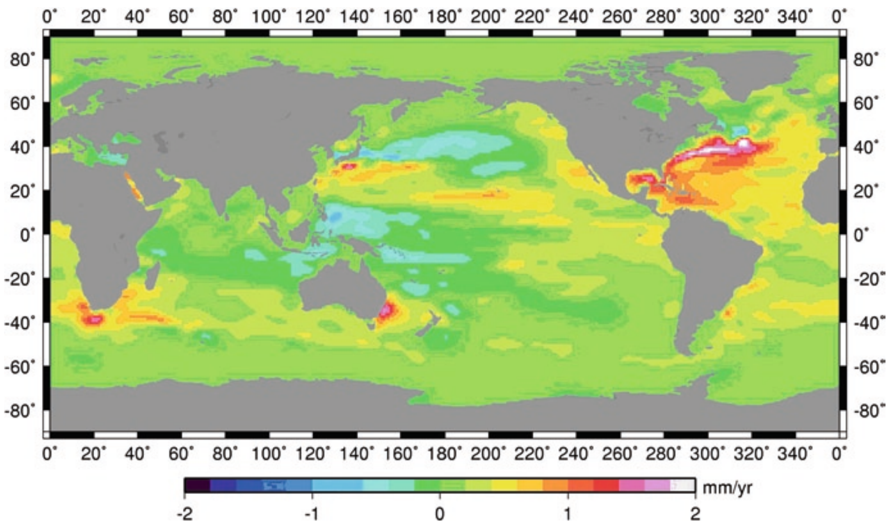

Fig. 7.5 Thermosteric sea-level trend (1955–2005): 0.24 mm/year, data based on Ishii and Kimoto (2009) data

modern expandable bathythermographs (XBTs), and the modern Argo arrays (http://sio-argo.ucsd.edu) (Willis et al. 2007), have caused several revised studies of the thermosteric sea-level rise (Antonov et al. 2005; Ishii and Kimoto 2009; Gouretski and Koltermann 2007; Domingues et al. 2008; Wijffels et al. 2008). However, the estimates still have a wide range, 0.24–0.6 mm/year (Table 7.1, 6th column). Figure 7.5 shows the thermosteric sea-level trend, 1955–2005, estimated to be 0.24 mm/year, based on the Ishii and Kimoto (2009) objectively analyzed data integrating the sea surface from 0 to 700 m depth. It is evident that more studies are needed to validate the contribution of thermal expansion to the global sea-level, and additional measurements are needed to quantify the deeper ocean (>700 m) thermosteric sea-level rise.

7.4 Sea-Level Measurements

Contemporary observations of sea-level rise (1900–2005) (WCRP Sea-Level Workshop Summary 2006) used long-term tide gauges (Douglas 2001; Miller and Douglas 2006; Holgate 2007) from Permanent Service for Mean Sea-Level (PSMSL) RLR data records (Woodworth and Player 2003), and more recently (since 1992) used satellite radar altimetry from TOPEX/POSEIDON (T/P) (Cazenave and Nerem 2004; Church et al. 2004; Kuo 2006). Tide gauges are sparsely distributed globally but have long records (>70 years). They are located near islands and continental margins, measures relative sea-level, and are suscepti-ble to uncertainty of land motion, e.g., due to glacial isostatic adjustment (GIA).

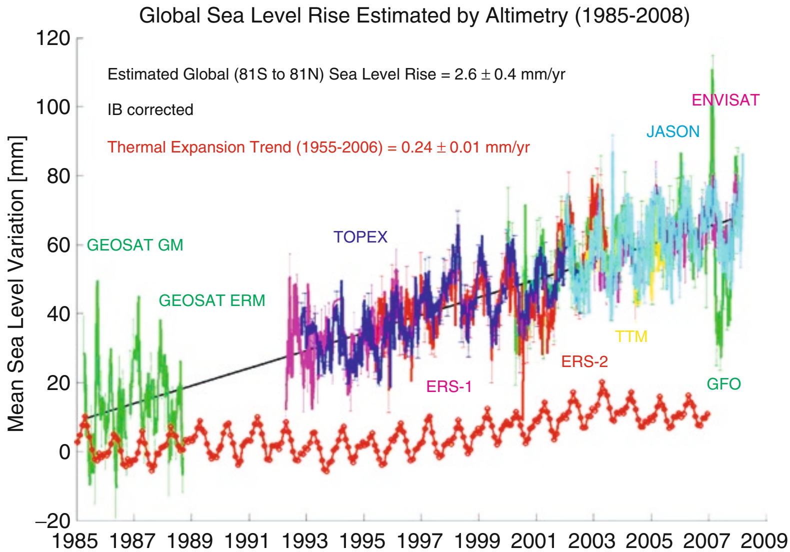

Fig. 7.6 Multiple-mission satellite radar altimetry (GEOSAT, TOPEX/POSEIDON, ERS-1/-2, JASON-1, ENVISAT and GFO, 1985–2008) observed sea-level trend (2.6 mm/year, 2.9 mm/year when GIA geoid change correction is applied using ICE-5G(VM4) model [Peltier 2004]). There is a data gap between 1989 and 1991

Satellite altimetry measures geocentric sea-level and unaffected by land motion (to a less extent, affected by changing shape of the ocean basin) and have globally coverage (Shum et al. 1995). However, they have much shorter records (10 years) than tide gauges, and require absolute calibration or monitoring for potential instrument drifts (e.g., Shum et al. 2003).

Figure 7.6 shows the multiple-mission satellite radar altimetry (GEOSAT, TOPEX/POSEIDON, ERS-1/-2, JASON-1, ENVISAT and GFO, 1985–2008) observed sea-level trend (2.6 mm/year, 2.9 mm/year when the GIA geoid correction is applied using the ICE-5G(VM4) model (Peltier 2004)). There is a data gap between 1989 and 1991. The inverted barometer correction (IB) has been applied. Also plotted is the thermosteric sea-level during the altimetry data span (data from Ishii and Kimoto, 2009). The seasonal variations are not removed. Figure 7.7 shows the sea-level trend observed by individual tide gauges (1900–2006, trend color coded and show as circles) with a global average of 1.65 ± 0.4 mm/year. Note that tide gauges sample only about a few % of the global ocean surface. The background is the satellite altimetry observed short-term (1985–2008) trend of 2.6 ± 0.4 mm/year (2.9 mm/year after corrected for the GIA effect), when averaged globally. Satellite altimetry with its global sampling reveals that the rate of sea-level rise is not uniform globally (Fig. 7.7) and that the estimated trend is potentially dominated by interannual or longer variations in the ocean. In some regions (e.g., Western Pacific), rates of sea-level rise are faster by a factor up to 3 than the global mean rate. In other regions rates are slower than the global mean (e.g., eastern Pacific). The estimated trend from altimetry (2.9 mm/year)

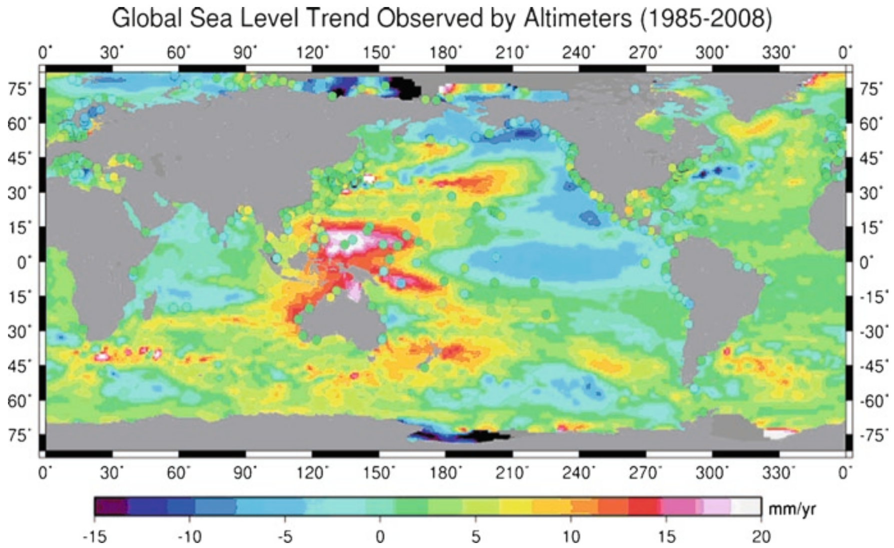

Fig. 7.7 Sea-level trend observed by individual tide gauges (1900–2006, trend color coded and show as circles) with a global average of 1.6 ± 0.4 mm/year. The background is the satellite altimetry observed short-term (1985–2008) trend of 2.6 ± 0.4 mm/year (2.9 mm/year after GIA effect is corrected), when averaged globally

which is much larger than the trend estimated by tide gauges (1.65 mm/year) may or may not necessarily indicate a recent (1990s) acceleration of sea-level rise (Woodworth et al. 2009; Merrifield and Merrifield 2009).

Figure 7.8 illustrates the differences of these two sea-level measurement types. Figure 7.8 shows the globally averaged 500 long-term (>30 years) tide gauge sea-level time series, 1900–2004 (corrected for GIA using ICE-5G model). The monthly averaged time series (grey) is shown to have significant 'false' (large) amplitudes in the seasonal signal, while the yearly averaged time series (blue) agrees between with average of satellite altimetry sea-level measurements (monthly average in green and yearly average in red). The estimated trend from tide gauges is 1.65 mm/year, compared with altimetry observed sea-level (1984–2008) trend of 2.9 mm/year (after GIA uplift correction). Figure 7.8 shows that global sampling is required to average out the variability in the sea-level trend (Fig. 7.7), and that the trend estimates using short-data span from satellite altimetry may be contaminated interannual or longer variations oceanic signals.

The Gravity Recovery and Climate Experiment (GRACE) twin-satellites measure *mass change* of the Earth (Tapley et al. 2004) (in the form of water thickness change) inferring from its temporal gravity field solutions, using the known harmonic (Stokes) coefficients, $\dot{C}_{nm}$ and $\dot{S}_{nm}$ (Wahr et al. 1998) (n is degree and m is order, equation not shown here), with monthly sampling (or finer) and spatial resolutions, ranging from 400 km (half-wavelength) (e.g., Velicogna and Wahr 2006b) to 200 km using *mascons* (e.g., Luthcke et al. 2006), from regional solutions

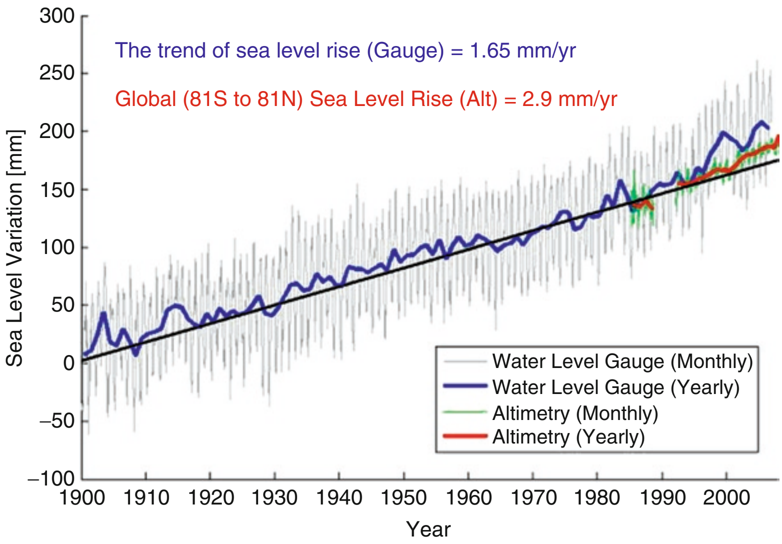

Fig. 7.8 Global sea-level trend observed by tide Gauges (1900–2006) and Altimetry (1985–2008)

including the use of spherical wavelets (Han et al. 2005; Schmidt et al. 2006), and recently achieving 200 km resolution via data post-processing (decorrelation and latitude-dependent non-isotropic filtering) (Duan et al. 2009; Guo and Shum 2009; Guo et al. 2010). The computation of mass changes involves elastic loading in the form of load Love number, k_n. GRACE is not sensitive to $n = 1$ terms (or geocenter) which has noticeable effects, e.g., on ice-sheet mass balance estimates (Chambers et al. 2007). Geocenter corrected used could be solutions from satellite laser ranging to Lageos satellites (J. Ries, pers. comm.). The smoothing or filtering and 'destripping' of Stokes coefficients representing GRACE's temporal gravity field solutions (Wahr et al. 2006) is necessary to mitigate sampling/observability problems (Swenson and Wahr 2006; Duan et al. 2009; Guo et al. 2010), and various correction algorithm for land signal leakage due to filtering near land-ocean boundaries (Velicogna and Wahr 2006b; Chen et al. 2006b; Guo et al. 2010). Figure 7.9 shows a global ocean mass (or the ocean bottom pressure) trend map estimated by GRACE. The combination of thermosteric sea-level (Fig. 7.5) and satellite altimetry (Fig. 7.7) yields the ocean mass variations (Fig. 7.9) (e.g., Kuo et al. 2008; Chambers 2006a, b).

The combination of these modern satellite and in situ data is anticipated to provide more accurate measurement of geophysical sources contributing to present-day sea-level rise, and the sea-level signal directly. In addition, the integrated analysis using these data sets allows sea-level budget studies treating each of the geophysical sources (ice-sheet, land water, ocean) separately, improving the chance to provide better quantification of the respective contributions from each of these sources to present-day sea-level rise.

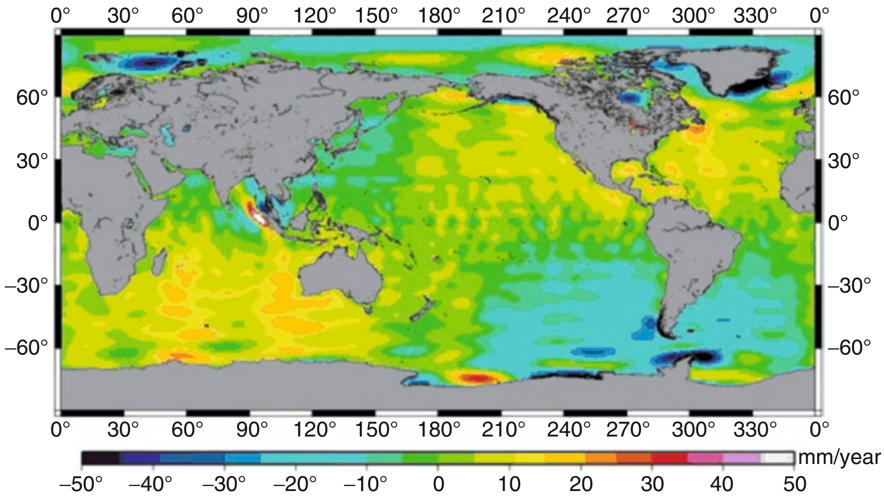

Fig. 7.9 GRACE observed global ocean botom pressure interannual variation, 2003–2008 (mm/year). CSR RL04 Level 2 data product used, water thickness change, de-striping and smoothed at 200 by 300 km by an non-isotropic filter, ICE5G(VM4) GIA geoid and seasonal signals removed, land leakage signal repaired. (Duan et al. 2009; Guo et al. 2010; Guo and Shum 2009)

7.5 Conclusions

At present, the observed and explained geophysical causes of present-day global sea-level rise appears to be worse than the assessment published by the 2007 Intergovernmental Panel for Climate Change (IPCC) Working Group I, Fourth Assessment Report (FAR). Several of the geophysical causes have been identified, including the contributions to present-day sea-level rise from ice-sheet mass balance, mountain glacier and ice caps, land water including human-impoundment of water in reservoirs, and the effect of the geodynamic process, the glacial isostatic adjustment which affects measurements of sea-level and ice-sheet mass balance using tide gauges, satellite altimetry and satellite gravimetry, GRACE. Integrated analysis and interpretation using these satellite measurements and in situ measurements including tide gauges and hydrographic data will narrow the uncertainty between the observations and the explained contributors of sea-level rise from each of these geophysical sources.

Sea-level rise is a major threat for many low-lying, highly populated coastal regions of the world (about 3.2 billion people live presently within 200 km of the coastal area (Hinrichsen 2009, http://peopleandplanet.net)). Sea-level rise exaggerates the effect of land erosion, wetland loss, storm surges associated with typhoons or hurricanes, sediment loading, land subsidence (Dixon et al. 2006) due to natural or anthropogenic (ground water pumping, oil extraction, urbanization) effects, rising water table and salt-water intrusion in freshwater aquifers (Nicholls 2002, 2007). In response to sea-level rise, in particular and for example, in Bangladesh, significant considerations should be given to the science and engineering aspects to mitigate relative sea-level rise (absolute sea-level rise adding the effect of land subsidence or vertical motion due to natural and anthropogenic effects) from the above-mentioned phenomena. In addition, the mitigation and adaptation requires an integrated approach including policy change based on scientific and engineering assessment of the risk from sea-level rise.

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