

Contemporary Sea Level Rise

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sea level rise, climate change, land ice melt, ocean warming

Abstract

Measuring sea level change and understanding its causes has considerably improved in the recent years, essentially because new in situ and remote sensing observations have become available. Here we report on most recent results on contemporary sea level rise. We first present sea level observations from tide gauges over the twentieth century and from satellite altimetry since the early 1990s. We next discuss the most recent progress made in quantifying the processes causing sea level change on timescales ranging from years to decades, i.e., thermal expansion of the oceans, land ice mass loss, and land water-storage change. We show that for the 1993–2007 time span, the sum of climate-related contributions ($2.85 \pm 0.35 \text{ mm year}^{-1}$) is only slightly less than altimetry-based sea level rise ($3.3 \pm 0.4 \text{ mm year}^{-1}$): ~30% of the observed rate of rise is due to ocean thermal expansion and ~55% results from land ice melt. Recent acceleration in glacier melting and ice mass loss from the ice sheets increases the latter contribution up to 80% for the past five years. We also review the main causes of regional variability in sea level trends: The dominant contribution results from nonuniform changes in ocean thermal expansion.

1. INTRODUCTION

Sea level is a very sensitive index of climate change and variability and, in fact, responds to change in several components of the climate system. For example, as oceans respond to global warming, sea waters warm and expand, and thus sea level rises. Coupled atmosphere–ocean perturbations, like El Niño–Southern Oscillation, affect sea level in a rather complex manner. As mountain glaciers melt because of increasing air temperature, sea level rises because of freshwater mass input to the oceans. Modification of the land hydrological cycle due to climate variability and anthropogenic forcing leads accordingly to increased or decreased runoff, and ultimately to sea level change. Change in the mass balance of the ice sheets also has a direct effect on sea level. Even the solid Earth affects sea level through ongoing processes of glacial isostatic adjustment (GIA) due to the deglaciation event of the last Quaternary ice age.

While sea level has remained almost stable during the last two to three millennia (i.e., since the end of the last deglaciation; Lambeck et al. 2004), changes have been measured shortly after the beginning of the industrial era. In fact, tide gauge measurements available since the late nineteenth century show significant sea level rise during the twentieth century (e.g., Douglas 2001). For more than 15 years now, the global mean sea level has been routinely measured at 10-day intervals over the whole oceanic domain with high-precision satellite altimetry, and such observations show clear evidence of global mean sea level rise. However, important regional variability has also been reported.

Quasi-global in situ ocean temperature data made available in recent years have allowed quantification of the contribution of ocean warming to sea level rise. In addition, mountain glacier surveys and satellite measurements of the mass balance of the ice sheets available since the early 1990s have provided new information on the land ice contribution. Finally, space-based gravity data from the recently launched GRACE mission now allow determination of the land water–storage component, while also providing important constraints on the mass balance of the ice sheets. The fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), published in 2007, summarized current observations on sea level and on contributing climate factors (Bindoff et al. 2007). In this review, we present the most recent findings on these topics, including new results published since the IPCC AR4 and the previous review by Cazenave & Nerem (2004). Most of the discussion concerns the last 50 years, with a focus on the satellite altimetry era (since 1993).

2. SEA LEVEL OBSERVATIONS

In this section, we present observations of global mean sea level changes available from tide gauges and satellite altimetry over the last century and, in particular, over the past two decades. We also discuss the regional variability in sea level trends evidenced by satellite altimetry and past sea level reconstructions.

2.1. Past Century Sea Level Rise

Our knowledge of past century sea level change comes from tide gauge measurements taken along continental coastlines and islands. The largest tide gauge database of monthly and annual mean sea level records is the Permanent Service for Mean Sea Level (PSMSL, available at <http://www.pol.ac.uk/psmsl>) (Woodworth & Player 2003), which contains data for the twentieth century from ~2000 sites maintained by ~200 nations. Unfortunately, the records are somewhat inhomogeneous in terms of data length and quality. The number and distribution of tide gauges in the past cannot compare to today's dense network, thus older data is incomplete. For long-term sea level studies, for instance, only ~10% of the data set is useable. Moreover, some tide gauges

have not functioned continuously over time, therefore large data gaps are observed for a significant number of them. Others have functioned only for a limited time span.

Another well-known difficulty arises from the fact that tide gauges measure sea level relative to the ground, hence they also monitor crustal motions. In active tectonic and volcanic regions, or in areas subject to strong ground subsidence due to other natural causes (e.g., sediment loading in river deltas) or human activities (e.g., ground water pumping and oil/gas extraction), tide gauge data are directly affected by the corresponding ground motions. Post glacial rebound (also called glacial isostatic adjustment, or GIA) is another process that gives rise to vertical land movement. Thus correction is needed to interpret tide gauge measurements in terms of absolute sea level change. In recent years, precise positioning systems, i.e., the global positioning system (GPS), have been installed at a few tide gauge sites to monitor land motions. But the equipped sites remain few and the GPS records minimal (Woppelmann et al. 2007). Geodynamic models of GIA have been developed (e.g., Peltier 2004, Paulson et al. 2007) so that tide gauge records can be corrected for this effect.

Several studies have concentrated on estimating past century sea level rise from historical tide gauges. Some authors conducted careful selection of the tide gauges, considering only those located in stable continental regions and displaying nearly continuous measurements over several decades, leading them to keep only a small number of good quality records of limited spatial coverage (e.g., Douglas 2001, Holgate & Woodworth 2004, Holgate 2007). Other studies considered larger sets of tide gauges, up to several hundreds, and developed either regional grouping or reconstruction methods (see section 2.4) to provide an historical sea level curve (e.g., Jevrejeva et al. 2006, Church et al. 2004, Church & White 2006).

Figure 1 compares two estimates of the global mean sea level since 1900 (i.e., yearly averages from Church et al. 2004 and Jevrejeva et al. 2006). We note that between 1900 and 1930 the rate of rise was modest. Since then the rate increased and amounted to $1.8 \pm 0.3 \text{ mm year}^{-1}$ over the

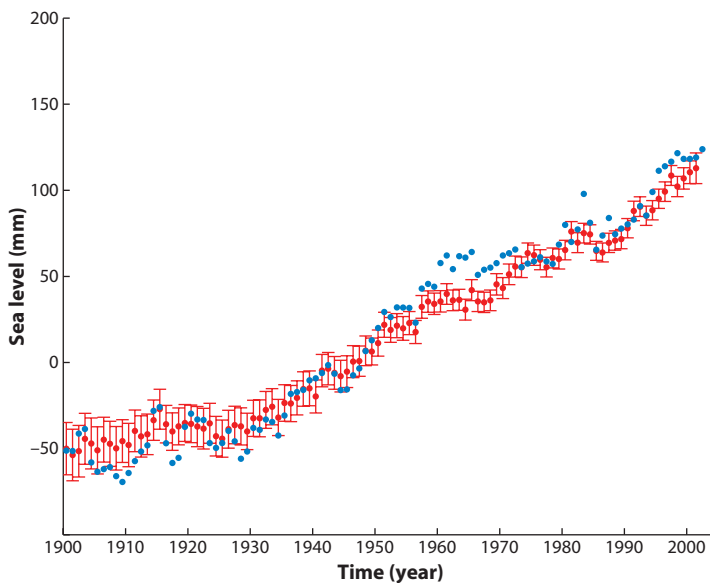


Figure 1

Observed global mean sea level (from tide gauges) between 1900 and 2001. Red dots are from Church et al. (2004). Blue dots are from Jevrejeva et al. (2006).

past 50 years. Also clearly apparent in **Figure 1** are large decadal fluctuations superimposed to the linear trend. Spectral analysis of global mean sea level rates displays high energy in the 4–8 year waveband, likely linked to El Niño–Southern Oscillation (ENSO) frequency (e.g., Chambers et al. 2002, Hebrard et al. 2008). Lower-frequency oscillations (>20 years) in global mean sea level rate have been reported (e.g., Church & White 2006, Holgate 2007, Jevrejeva et al. 2006). Church et al. (2005) and Grinsted et al. (2007) showed that major volcanic eruptions induce temporary cooling of the oceans, thus producing a small negative signature in the global mean sea level curve.

Analyzing tide gauge records from 1870 through 2004, Church & White (2006) detected an acceleration in the rate of sea level rise of $0.013 \pm 0.006 \text{ mm year}^{-2}$. Another global mean sea level reconstruction from 1700 to the present (Jevrejeva et al. 2008) reported a sea level acceleration of $\sim 0.01 \text{ mm year}^{-2}$. In a recent compilation of regional and global sea level studies for the twentieth century, Woodworth et al. (2008) conclude that significant accelerations (either positive or negative) occurred at particular epochs, but often these accelerations have a regional signature consistent with regional-scale, natural climate variability (see below).

2.2. Altimetry Era (Last Two Decades)

Since the early 1990s, satellite altimetry has become the main tool for precisely and continuously measuring sea level with quasi-global coverage and short revisit time. The concept of the satellite altimetry measurement is simple: The onboard radar altimeter transmits microwave radiation toward the sea surface that partly reflects back to the satellite. Measurement of the round-trip travel time provides the height of the satellite above the instantaneous sea surface (i.e., the range). The quantity of interest in oceanography is the sea-surface height above a reference fixed surface (typically a conventional reference ellipsoid); it is obtained by the difference between the altitude of the satellite above the reference (deduced from precise orbitography) and the range measurement. The estimated sea-surface height requires correction for various factors due to atmospheric delay and biases between the mean electromagnetic scattering surface and the sea at the air-sea interface. Other corrections due to geophysical effects, e.g., solid Earth, polar, and ocean tidal effects, are also applied. Since the mid-1970s, several altimetry missions have been launched. However, it is only two decades later, with the launch of the Topex/Poseidon mission in 1992, that errors affecting altimetry-derived sea-surface height dropped below the 10-cm level, allowing precise detection of ocean dynamics for the first time.

It is worth mentioning that global monitoring of sea level change was not initially included in the Topex/Poseidon mission goals. In effect, to measure global mean sea level rise with a <5% uncertainty, a precision of $\sim 0.1 \text{ mm year}^{-1}$ in the rate of rise is necessary, implying a precision of 1–2 cm on individual sea-surface height measurements. This requirement implies thorough control of all possible errors affecting the altimetry system (in particular, instrumental drifts) and data processing. It has pushed altimetric systems toward their ultimate performance limit (e.g., Nerem 1995). While early Topex/Poseidon precision was >5 cm for a single sea-surface height measurement (Chelton et al. 2001), further progress in the various data processing steps has decreased this error level to $\sim 1\text{--}2 \text{ cm}$ (e.g., Leuliette et al. 2004, Nerem et al. 2006), a performance also valid for the successors of Topex/Poseidon—Jason-1 and Jason-2 launched in 2001 and 2008, respectively.

Figure 2 shows the temporal evolution of the global mean sea level from satellite altimetry between January 1993 and December 2008. This curve is based on Topex/Poseidon until 2001, on combined Topex/Poseidon and Jason-1 data between 2002 and 2005, and on Jason-1 data since then. In **Figure 2** the annual cycle has been removed and a 90-day smoothing applied. The global mean sea level increases almost linearly over this 16-year time span. The positive anomaly seen

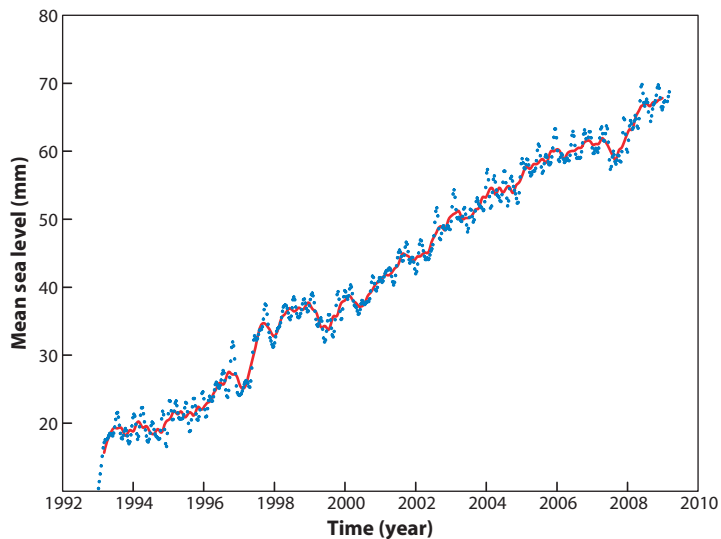


Figure 2

Global mean sea level from satellite altimetry between January 1993 and December 2008. Annual cycle has been removed. Blue dots are raw 10-day data. Red line corresponds to a 90-day smoothing of the raw data. The $-0.3 \text{ mm year}^{-1}$ GIA correction has been removed.

between 1997 and 1999 is related to the 1997–1998 ENSO event (see section 3.3). Similarly, the negative anomaly occurring by the end of 2007 is possibly related to the recent La Nina (the cold phase of ENSO). The rate of rise estimated over 1993–2008 amounts to 3.1 mm year^{-1} (with a formal uncertainty of 0.1 mm year^{-1}). Precision/accuracy of altimetry-derived rate of sea level rise has been assessed through error budget analyses and comparisons with high-quality tide gauge data (e.g., Mitchum 2000; Nerem & Mitchum 2001a,b; Leuliette et al. 2004; Ablain et al. 2009), leading to a more likely uncertainty of $\sim 0.4 \text{ mm year}^{-1}$. We modify it further. Accounting for the small correction of $-0.3 \text{ mm year}^{-1}$ due to global deformation of ocean basins in response to GIA (Peltier 2009), we thus get a rate of global mean sea level rise of $3.4 \pm 0.4 \text{ mm year}^{-1}$ over 1993–2008. Differences in estimates of altimetry-derived rate of sea level rise for the past 15 to 16 years by different investigators fall within the 0.4 mm year^{-1} range (e.g., Nerem et al. 2006; Beckley et al. 2007; Ablain et al. 2009; C.K. Shum, pers. commun.), suggesting that the 0.4 mm year^{-1} uncertainty is realistic.

2.3. Regional Sea Level Variability

Tide gauge records had previously suggested that sea level rise is not spatially uniform (e.g., last century's rate is twice as large at New York than at Buenos Aires). However, until the advent of satellite altimetry and its almost global coverage of the oceanic domain, mapping the regional variability was not possible. Satellite altimetry has revealed considerable regional variability in the rates of sea level change (**Figure 3a**). To highlight this regional variability in the rates of sea level rise, a uniform (global mean) trend of 3.4 mm year^{-1} has been removed from **Figure 3a**. **Figure 3b** shows the spatial trend patterns with respect to the global mean. In some regions, such as the western Pacific, North Atlantic around Greenland, southeast Indian, and Austral oceans, sea level rates are up to three times faster than the global mean (e.g., sea level is higher in these regions by $\sim 15 \text{ cm}$ compared to 16 years ago), while the eastern Pacific and west Indian oceans

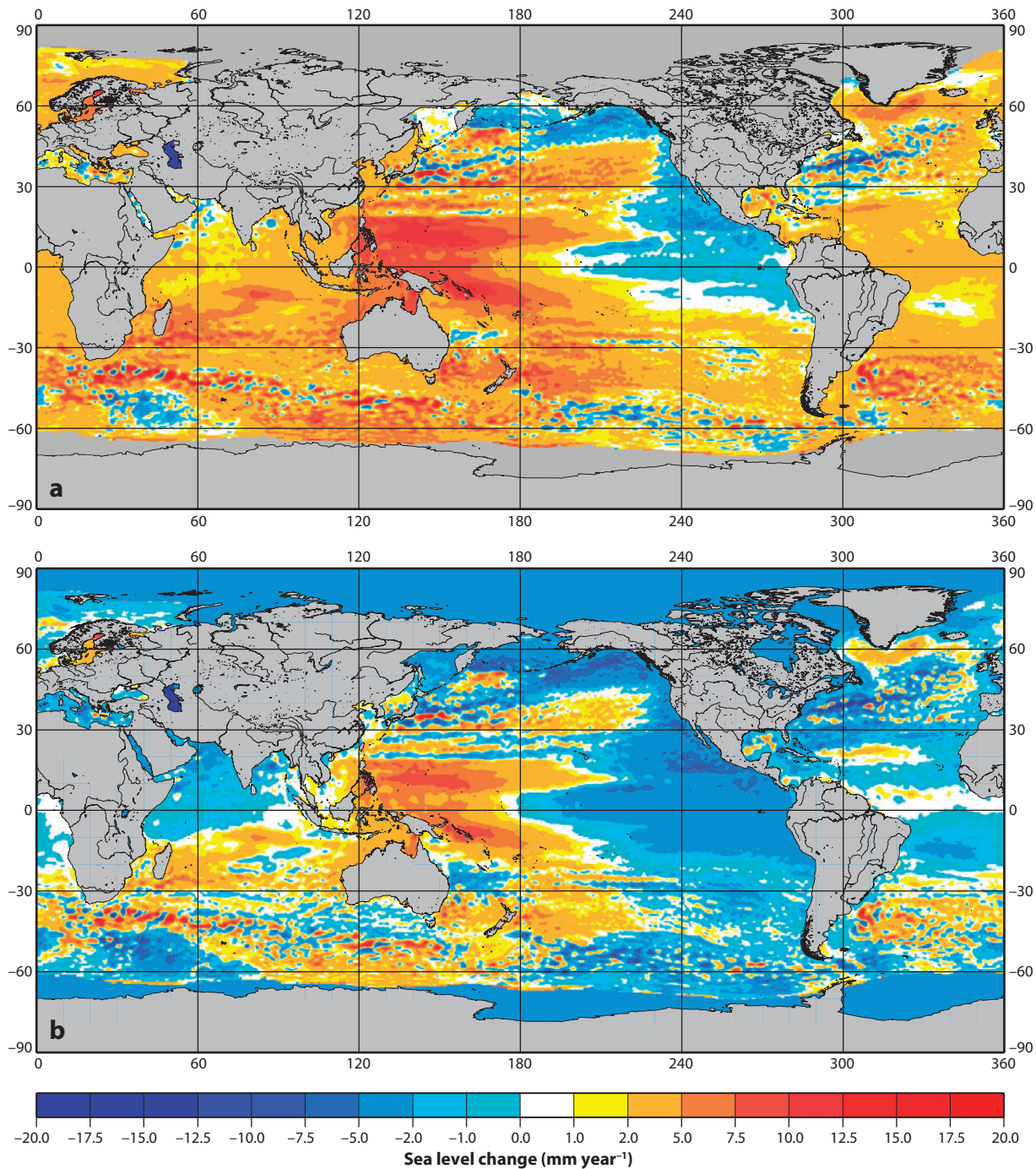


Figure 3

(a) Map of spatial trend patterns of observed sea level between January 1993 and December 2008. (b) Same as (a) but a uniform global mean trend of 3.4 mm year^{-1} has been removed.

exhibit a lower rate. In section 5, we discuss causes of nonuniform sea level change and see that ocean thermal expansion is the dominant factor at the origin of the observed spatial trend patterns (Cabanes et al. 2001, Lombard et al. 2005).

2.4. Two-Dimensional Past Sea Level Reconstructions

Trend patterns in thermal expansion were not stationary during the last few decades but fluctuated both in space and time in response to ENSO, NAO (North Atlantic Oscillation), and PDO (Pacific Decadal Oscillation) (e.g., Levitus et al. 2005, Lombard et al. 2005). This suggests that present-day sea level trend patterns, as seen in **Figure 3a,b**, are not steady features and are not necessarily representative of the distant past (e.g., last century). Yet, it is important to be aware of past regional sea level variability, in particular, to validate climate models used to predict future sea level change at regional and global scales (in fact, significant uncertainties affect sea level projections for a wide range of spatio-temporal scales, e.g., Meehl et al. 2007). Unfortunately, for the last century, information on regional sea level variability is lacking. For that reason, a number of studies have attempted to reconstruct sea level for past decades in two dimensions (2D), combining sparse but long tide gauge records with global gridded (i.e., 2D) sea level (or sea level proxy) time-series of limited temporal coverage (either from satellite altimetry or ocean general circulation model, or OGCM, reanalyses) (Chambers et al. 2002, Church et al. 2004, Berge-Nguyen et al. 2008, Llovel et al. 2009).

In this approach, the dominant modes of regional variability are extracted from the statistical information contained in altimetry data or OGCM reanalyses. **Figure 4** shows spatial trend patterns (with respect to a uniform global mean trend) for the 1950–2003 time span, based on

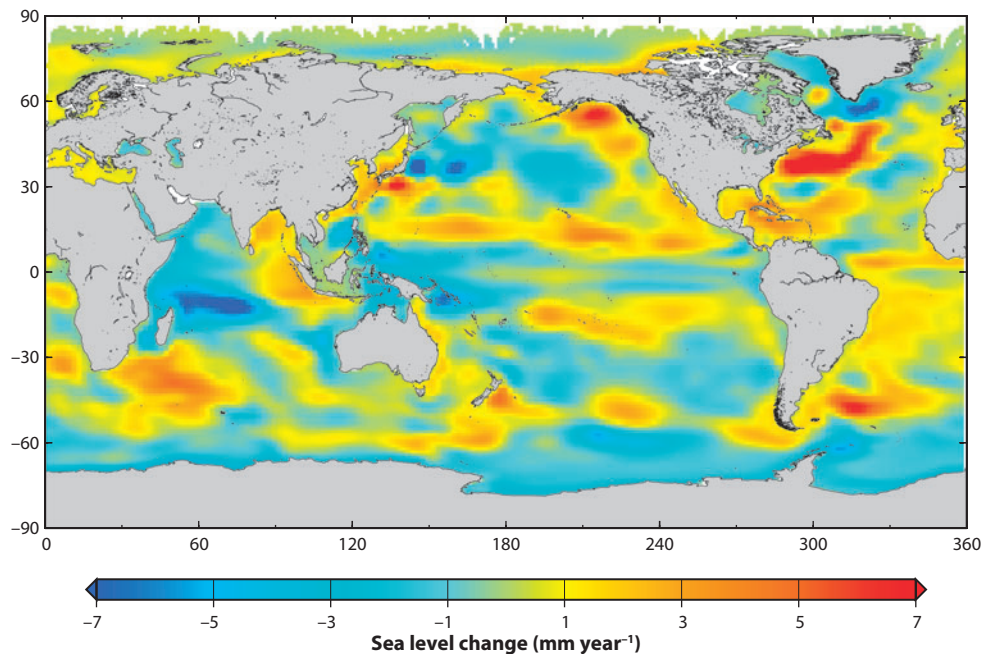


Figure 4

Map of spatial trend patterns of reconstructed sea level between 1950 and 2003 (adapted from Llovel et al. 2009).

the above-referenced paper by Llovel et al. We clearly see significant differences with the 1993–2008 patterns (**Figure 3b**), confirming that regional variability observed for the recent years is not steady. The above studies have shown that the dominant mode of temporal variability of the spatial trend patterns is related to the decadal modulation of ENSO (Chambers et al. 2002, Church et al. 2004) but lower frequency oscillations are also present (Llovel et al. 2009).

3. CAUSES OF GLOBAL MEAN SEA LEVEL CHANGE

The two main causes of global mean sea level change are the addition of freshwater to ocean basins as a result of land ice loss and water exchange with terrestrial reservoirs (soil and underground reservoirs, lakes, snowpack, etc.), and thermal expansion of the sea waters in response to ocean warming. We examine each of these contributions below.

3.1. Ice Sheets

The mass balance of the ice sheets is a topic of considerable interest in the context of global warming and sea level rise. If totally melted, Greenland and West Antarctica would raise sea level by approximately 7 and 3–5 m, respectively. Thus, even a small amount of ice mass loss from the ice sheets would produce substantial sea level rise, with adverse societal and economic impacts on vulnerable low-lying coastal regions. Observations over the past two decades show rapid acceleration of outlet glaciers in Greenland and Antarctica (Howat et al. 2007, Witze 2008). For example, marine-terminating Jakobshavn Isbrae glacier on the west coast of Greenland has experienced rapid thinning and accelerated flow velocity since the early 1990s, reaching ~ 13 km year⁻¹ in 2003 (Holland et al. 2008, Joughin et al. 2008). Glaciers draining into the Amundsen Sea, West Antarctica, have also rapidly retreated (e.g., Shepherd & Wingham 2007, Rignot et al. 2008a). These observations have been attributed to a dynamical response of the ice sheets to recent warming, with most of the ice sheet mass loss resulting from coastal glacier flow (Alley et al. 2007, 2008) (although for Greenland, surface melting also plays some role; Rignot et al. 2008b). Two main processes have been invoked to explain these observations: (a) lubrication of the ice-bedrock interface resulting from summer meltwater drainage through crevasses, and (b) weakening and breakup of the floating ice tongue, or ice shelf, that buttressed the ice stream. While the first mechanism may play some role in Greenland where substantial surface melting occurs in summer, glaciologists now favor the second mechanism as the main explanation for recent dynamical changes affecting the ice sheets (e.g., Alley et al. 2008, Holland et al. 2008). Because the ice shelf is in contact with the sea, sea water warming (e.g., Gille 2008, Holland et al. 2008) and ocean circulation changes may trigger basal melting and further breakup, accelerating ice flow (Alley et al. 2008).

Since the early 1990s, different remote-sensing techniques have offered new insight on contemporary mass change of the ice sheets (e.g., Wingham et al. 2006). Radar altimetry (e.g., ERS-1/2 and Envisat satellites) as well as airborne and satellite laser altimetry (ICESat satellite since 2003) allow monitoring ice sheet elevation change, a quantity further expressed in terms of ice volume change. The synthetic aperture radar interferometry (InSAR) technique provides measurements of glacier surface flow and, hence, ice discharge into the oceans if glacier thickness is known. When combined with other parameters of surface mass balance (mainly snow accumulation), the net ice sheet mass balance can then be derived. Space gravimetry from the GRACE space mission (since 2002) is another tool for measuring the mass balance of the ice sheets, with nearly complete coverage of the high-latitude regions up to 89°N/S. The basic quantity measured by GRACE is spatio-temporal change of the Earth's gravity field, which can be converted, over the ice sheets, into ice mass change.

Comparing results from different techniques is not easy, because each technique has its own bias and limitations, e.g., differences in spatial and temporal sampling, measurement errors, contamination from unrelated signals, and lack of direct information on ice mass (except for GRACE). For example, radar altimetry misses narrow coastal glaciers because of the large radar footprint, and measured elevations are much less reliable over steep undulated surfaces than over flat high-elevation surfaces. Ice elevation change requires correction for ice compaction; uncertainty in surface density (snow or ice) when converting elevation change into mass change is an important source of error. To be helpful for mass balance estimates, InSAR needs information on ice thickness, a quantity difficult to estimate. GRACE space gravimetry is sensitive to solid Earth mass change, in particular, that associated with GIA. Over Antarctica, where the GIA effect is of the same order of magnitude as the ice mass change, the poorly known GIA correction is a source of significant uncertainty. In spite of these problems, satellite-based sensors clearly show accelerated ice mass loss from the ice sheets over the recent years.

Greenland mass balance (last two decades). Comparison of elevation changes from successive airborne laser altimetry surveys indicated significant ice mass loss in near coastal regions of Greenland (Krabill et al. 2004). In contrast, satellite radar altimetry suggested elevation increase in Greenland's interior for the 1992–2003 period (Johannessen et al. 2005, Zwally et al. 2005). Using InSAR observations, Rignot & Kanagaratnam (2006) detected widespread glacier ice flow acceleration since 1996. Recent results from GRACE (Velicogna & Wahr 2006a, Ramillien et al. 2006, Chen et al. 2006a, Lutchke et al. 2006, Cazenave et al. 2009, Wouters et al. 2008, Peltier 2009) and ICESat (Slobbe et al. 2009) confirm other remote-sensing results (e.g., Rignot et al. 2008b), i.e., ice mass loss from coastal regions of southern Greenland, although quite large dispersion between the different investigations is noticed. GRACE results indicate accelerated ice mass loss from coastal regions of the Greenland ice sheet since 2002/2003. Many more references about the Greenland mass balance can be found in IPCC AR4 (Lemke et al. 2007).

Antarctica mass balance (last two decades). Laser airborne, laser and radar satellite altimetry, as well as InSAR surveys over West Antarctica reported accelerated ice mass loss in the Amundsen Sea sector during the past decade (Rignot & Thomas 2002, Thomas et al. 2004). Davis et al. (2005) analyzed satellite radar altimetry measurements over 1992–2003 and found significant elevation decrease, especially in the Admunsen Sea sector.

GRACE observations over West Antarctica also show important mass loss over the past few years (Velicogna & Wahr 2006b, Ramillien et al. 2006, Chen et al. 2006b, Cazenave et al. 2009, Peltier 2009). However, because of GIA contamination, GRACE results over Antarctica are more uncertain than over Greenland. Over Antarctica, the GIA effect is of the same order of magnitude as present-day ice mass change (Ivins & James 2005, Peltier 2009). However, the GIA correction depends on still poorly known parameters, e.g., Earth's mantle viscosity structure and deglaciation history. It is available from modeling only, with significant differences between models.

A recent analysis over 85% of Antarctica's coastline by Rignot et al. (2008a), combining InSAR data with regional climate modeling over 1992–2006, confirms earlier results, i.e., widespread ice mass loss in West Antarctica (Amundsen and Bellingshausen seas and Antarctica Peninsula), with loss concentrated in narrow outlet glaciers. In comparison, East Antarctica was found in near balance.

Remote sensing-based estimates of the mass balance of the two ice sheets are summarized in **Figure 5a,b** (updated from Cazenave 2006). Since approximately 2003, we note a clear acceleration of ice mass loss from the Greenland ice sheet. For 1993–2003, IPCC AR4 (Lemke et al. 2007) estimated the Greenland contribution to sea level at $0.21 \pm 0.035 \text{ mm year}^{-1}$. For 2003–2007,

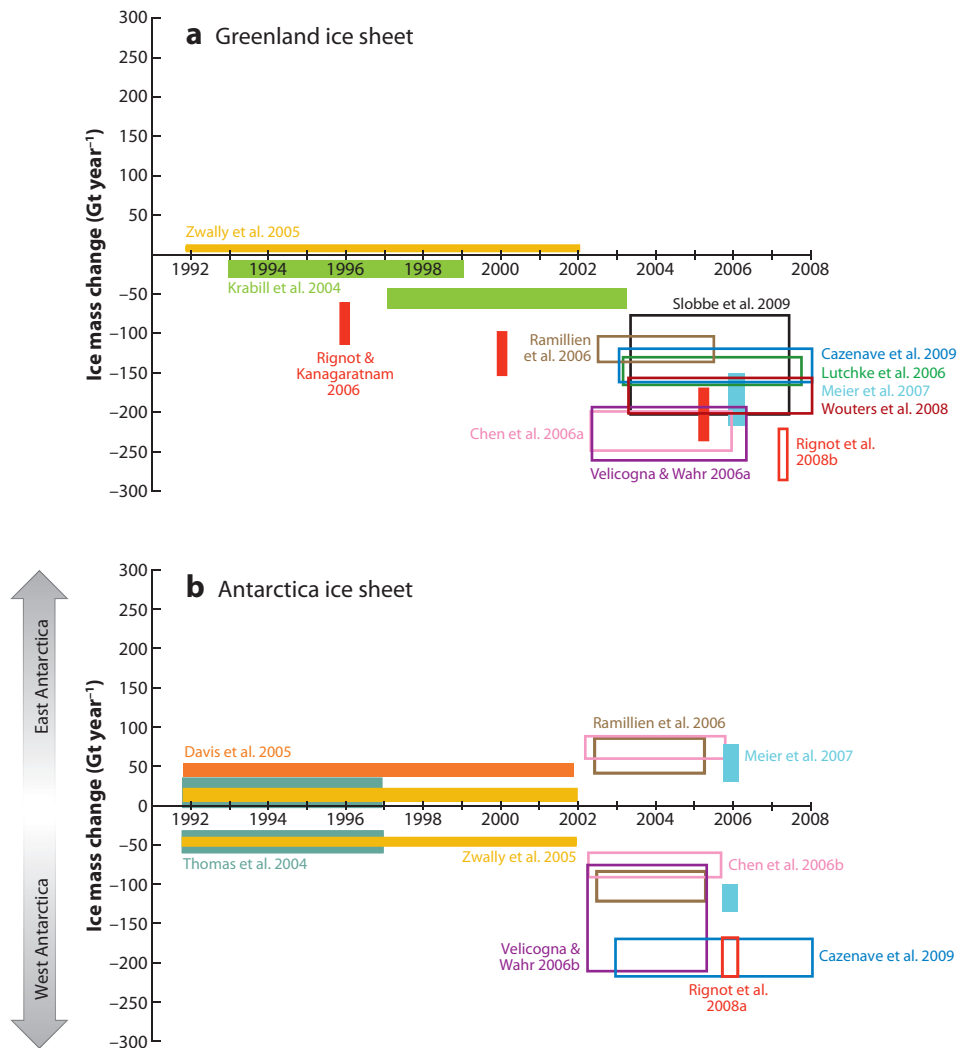


Figure 5

(a) Compilation of Greenland ice sheet mass loss based on remote-sensing observations between 1992 and 2008. (b) Same as (a) but for the Antarctica ice sheet (redrawn from Cazenave 2006).

the mean contribution of Greenland to sea level increased to $\sim 0.5 \text{ mm year}^{-1}$ (average of values shown in **Figure 5a**). In West Antarctica, acceleration is also visible but less than for Greenland. Total Antarctica contribution to sea level was estimated by IPCC AR4 at $0.21 \pm 0.17 \text{ mm year}^{-1}$ for 1993–2003.

3.2. Glaciers

Glaciers are very sensitive to global warming. Observations indicate that since the 1970s most of the world's glaciers are retreating and thinning, with noticeable acceleration since the early 1990s. Glaciers represent an $\sim 35 \text{ cm}$ sea level equivalent, potentially another significant source of freshwater mass to be added to the world's oceans, thereby raising sea level.

Mass balance estimates of glaciers are based either on in situ measurements (monitoring of the annual mean snow accumulation and ice loss from melt) or geodetic techniques (measurements of surface elevation and area change from airborne altimetry or digital elevation models). The data (available at <http://www.geo.unizh.ch/wgms/>) are collected by the World Glacier Monitoring Service (WGMS) on approximately 300 glaciers worldwide tracked over the past decades, and since 1980 include information for approximately 30 reference glaciers in nine mountain ranges since 1980.

On the basis of published results, the IPCC AR4 estimated the glaciers' contribution to sea level rise at 0.77 ± 0.22 mm year⁻¹ over 1993–2003 (Lemke et al. 2007). Since the IPCC AR4 publication (IPCC 2007), a few updated estimates of GIC loss have been proposed from traditional mass balance measurements (Kaser et al. 2006, Meier et al. 2007, Cogley 2009). A number of space-based (from GRACE and satellite imagery) indicators of glacier mass changes have also been published for particular ice fields and confirm enhanced glacier mass loss (e.g., Patagonia: Chen et al. 2007; Alaska: Chen et al. 2006c, Lutchke et al. 2008, Peltier 2009; Himalaya: Berthier et al. 2007). Kaser et al. (2006) reported a contribution to sea level rise of 0.98 ± 0.19 mm year⁻¹ for 2001–2004, a value slightly larger than during the previous decade. Using the same data as Kaser et al. (2006) and assuming that ice losses by glaciers increased linearly with time since the year 2000, Meier et al. (2007) found the glacier contribution to be 1.1 ± 0.24 mm year⁻¹ for 2006. Recently, Cogley (2009) provided an updated compilation of global average glacier mass balance up to 2005. Cogley's results indicate a contribution to sea level of 1.4 ± 0.2 mm year⁻¹ for 2001–2005, a value larger than earlier estimates due to better representation of tidewater glaciers.

3.3. Land Waters

Excluding ice sheets and glaciers, freshwater is stored in various reservoirs: snow pack, rivers, lakes, man-made reservoirs, wetlands and inundated areas, root zone (upper few meters of the soil), and aquifers (ground water reservoirs). Land waters are continuously exchanged with atmosphere and oceans through vertical and horizontal mass fluxes (evaporation, transpiration of the vegetation, surface and underground runoff) and are an integral part of the global climate system, with important links and feedbacks generated through influences on surface energy and moisture fluxes between land water, atmosphere, and oceans. Thus climate change and variability modify land water storage. Some human activities also directly affect water storage, e.g., pumping ground water out of aquifers (particularly in arid regions), damming rivers to create artificial water reservoirs, and draining wetlands. Other anthropogenic effects on land waters result from changing the physical characteristics of the land through urbanization, agriculture, and deforestation. All these effects impact sea level by either increasing or decreasing runoff.

Climatic and anthropogenic contributions of land waters to sea level (past few decades).

Variations in land water storage caused by climate change and variability over the past few decades cannot be directly estimated from observations because these are almost nonexistent at a global scale. However, global hydrological models (or land surface models) developed for atmospheric and climatic studies can be used for this purpose. The models compute the water and energy balance at the earth surface, providing water storage change in response to prescribed variations of near-surface atmospheric data (precipitation, temperature, humidity, and wind) and radiation. Using atmospheric reanalyses over 1950–2000 and the Orchidee land surface model, Ngo-Duc et al. (2005a) found no climatic long-term trend in sea level but large interannual/decadal fluctuations of several millimeters amplitude, a result also found by Milly et al. (2003) based on the Land

Dynamics model over 1980–2000. In another model-based study, Ngo-Duc et al. (2005b) showed that the positive anomaly visible in sea level in 1997–1998 (see **Figure 2**) was associated with a change in land water storage in the tropics in response to the 1997/1998 ENSO event.

Direct human intervention on land water storage and induced sea level changes have been estimated in several studies (e.g., Chao 1995, Sahagian 2000, Gornitz 2001). These results have been recently reviewed by Huntington (2008) and Milly et al. (2009). The largest contributions come from pumping ground water (for agriculture, industrial, and domestic use) and filling reservoirs. Although detailed information is lacking, and estimates vary significantly between authors, ground water depletion may have contributed to past decades' sea level rise by 0.55–0.64 mm year⁻¹ (Huntington 2008).

Over the past half-century, tens of thousands of dams have been constructed over world rivers to create artificial reservoirs, and hence negative contribution to sea level. Several attempts have been made to estimate the total volume of water stored in artificial reservoirs over the last 50 years (e.g., Chao 1995, Gornitz 2001, Vorosmarty et al. 2003). The recent study by Chao et al. (2008), which reconstructs the history of water impoundment in the nearly 30,000 reservoirs built during the twentieth century, estimates the contribution to sea level of dams and artificial reservoirs at -0.55 mm year⁻¹ during the past half-century and points out that without dam building, sea level rise would have been larger. However, opposite effects on sea level from ground water depletion may have somewhat canceled effects of water impoundment through dams.

Satellite altimetry and space gravimetry estimates of surface and total water storage contributions (recent years). While satellite altimetry has been developed and optimized for open oceans, numerous studies used this technique to monitor lake and river water levels. Water level time-series for >15 years based on Topex/Poseidon, Jason-1, and Envisat altimetry missions are now available for several hundreds of continental lakes. Using water level time-series over lakes from the HYDROWEB database (available at <http://www.legos.obs-mip.fr/soa/hydrologie/hydroweb/>), we can estimate the water volume change of the largest surface water bodies since the early 1990s. For the period 1993–2008, water storage of the Caspian and Aral seas, East African lakes, and North American lakes decreased on average. Considering the 15 largest lakes, we estimate lake water contribution to sea level rise for the period 1993–2008 at approximately $+0.1$ mm year⁻¹ (the largest contributions coming from the Caspian and Aral seas, and Lake Huron in North America, the latter two having been strongly affected by nonclimatic, anthropogenic forcing). However, lake water storage is dominated by interannual variability, therefore the contribution estimated for the past ~ 15 years does not reflect any long-term trend.

GRACE measures temporal changes of the vertically integrated water column (surface waters, soil moisture, underground waters). Thus GRACE cannot separate the contribution of individual reservoirs. In addition, GRACE does not discriminate between climate and direct anthropogenic components. Ramillien et al. (2008) estimated the water volume trend in the 27 largest river basins worldwide using GRACE data from 2003–2006 and found either positive or negative water volume change over that period, depending on the location of the river basins. The net water volume change was slightly negative (i.e., water loss), corresponding to <0.2 mm year⁻¹ sea level rise. An update of this study using a longer GRACE data set (2002–2008) over the world's 32 largest river basins gives a negative contribution to sea level of ~ -0.2 mm year⁻¹ (W. Llovel, K. DoMinh, A. Cazenave, J.F. Cretau, M. Becker, unpublished manuscript), suggesting that over a few years time span, the land water signal is dominated by interannual variability.

Figure 6 compares GRACE-based total land water storage variations (annual signal removed), expressed in equivalent sea level, with altimetry-based, detrended global mean sea level corrected for ocean thermal expansion (annual signal removed) for the years 2003–2007. A significant

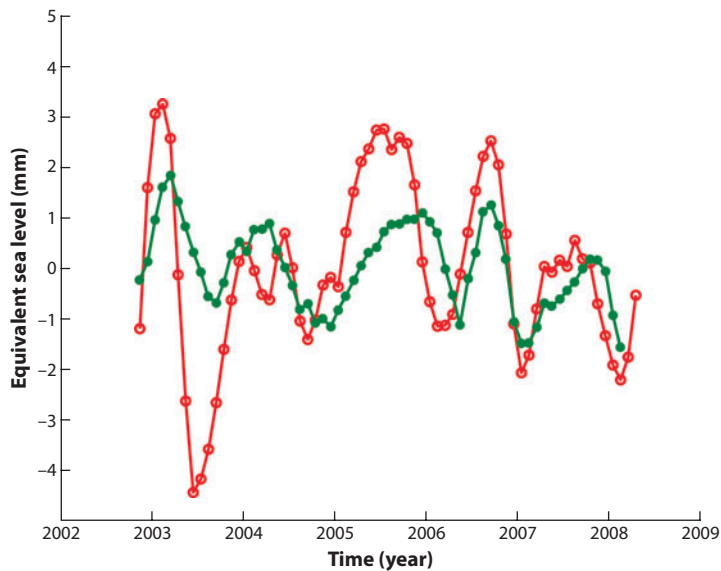


Figure 6

For the years 2003–2007, total land water storage variations from GRACE expressed in equivalent sea level (annual signal removed) are shown by the green line. Detrended global mean sea level observed by satellite altimetry, corrected for ocean thermal expansion (annual signal removed), is shown by the red line (from W. Llovel, K. DoMinh, A. Cazenave, J.F. Cretaux, and M. Becker, unpublished manuscript).

correlation is noticed between the two curves shown, suggesting that year-to-year fluctuations of the global mean sea level (corrected for ocean thermal expansion) can be at least partly explained by the effects of total land water storage oscillations.

To conclude, climate-driven change in land water storage produces mainly interannual to decadal fluctuations but (so far) no long-term trend. This is in contrast to direct human-induced change in land hydrology, which clearly has led to secular—either positive or negative—change in sea level over the past half-century. However, the two major contributions—ground water depletion and reservoir filling—could have more or less canceled each other out. But this may no longer be true in the future: While dam building is clearly decelerating (e.g., Chao et al. 2008), ground water pumping will likely continue at a sustained rate, with a positive contribution to sea level.

3.4. Ocean Temperature and Salinity Changes

Anomalies in temperature and salinity in the ocean water column change density, which further gives rise to sea level variations (classically called steric variations, or thermosteric or halosteric if associated with only temperature or salinity variations, respectively). We first discuss the contribution of temperature variations.

In situ hydrographic measurements collected mainly by ships since the middle of the twentieth century have suggested that in terms of global mean, the oceans have warmed. Since the late 1960s, ocean temperature has been essentially measured with expandable bathythermographs (XBT) along ship tracks, complemented by mechanical bathythermographs (MBT) and Conductivity-Temperature-Depth (CTD) systems. Recently, an international program of profiling floats, Argo (available at <http://www.argo.ucsd.edu>) (Roemmich & Owens 2000), has been set up, providing

temperature and salinity measurements globally down to 2000 m with a revisit time of ~ 40 days. The Argo network was almost complete by the end of 2003. Historical as well as modern in situ hydrographic measurements are stored in the World Ocean Database (WOD) with regular updates (Boyer et al. 2006). Two major problems affect XBT historical measurements: (1) systematic bias due to uncertainty in assigning a correct depth value to each temperature measurement, and (2) previously sparse data coverage, both geographically and in the deep ocean. XBT instruments do not directly measure depth as they fall within the water column. Traditionally, depth is deduced from a fall-rate equation and time elapsed since the probe entered the sea surface. Even with calibrated fall-rate equations (Hanawa et al. 1995), systematic depth errors are assumed to remain (Gouretski & Koltermann 2007). The problem of sparse data coverage in the past can hardly be overcome, unless OGCMs with data assimilation are used (see section 5). Thus estimates of ocean heat content and thermal expansion for the past are biased by lack of data in certain regions, in particular, in the Southern Hemisphere (Levitus et al. 2005, Antonov et al. 2005). In spite of these limitations, several analyses of global ocean temperature have been conducted in recent years (Domingues et al. 2008; Guinehut et al. 2004; Ishii et al. 2006; Ishii & Kimoto 2009; Levitus et al. 2005, 2009; Willis et al. 2004). Most recent analyses take special care of systematic depth bias corrections affecting XBT and MBT measurements, and here we report only the latest results (Domingues et al. 2008, Ishii & Kimoto 2009, Levitus et al. 2009).

Compared to earlier analyses, new analyses show substantial reduction of spurious large interannual anomalies in ocean heat content, in particular, during the mid-1970s. **Figure 7** shows the evolution of the ocean thermal expansion since 1955 from Levitus et al. (2009) and Ishii & Kimoto (2009) (temperature data down to 700 m). Also shown is the residual sea level, i.e., observed sea level (data from Church et al. 2004) minus thermal expansion (for each data set). The mean thermal expansion trend over 1955–2001 is $0.4 \pm 0.01 \text{ mm year}^{-1}$ and $0.3 \pm 0.01 \text{ mm year}^{-1}$

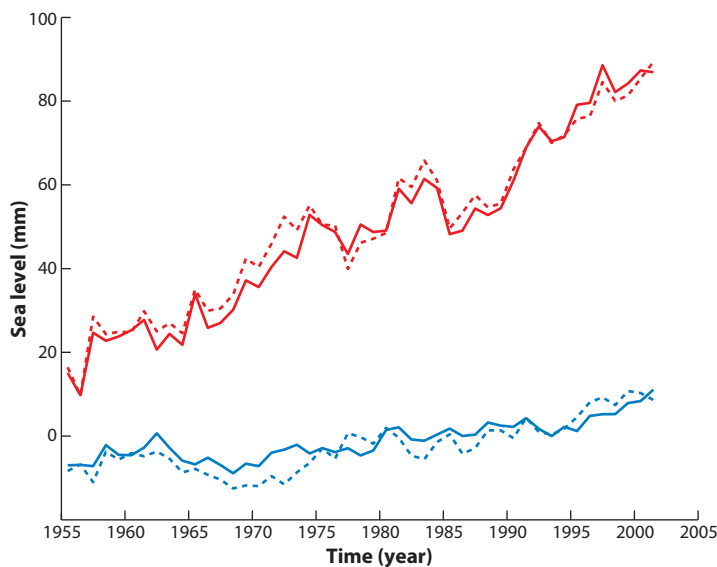


Figure 7

Blue lines: thermosteric sea level (or thermal expansion) between 1955 and 2001 from Ishii & Kimoto (2009) (solid line) and Levitus et al. (2009) (dashed line). Red lines: residual sea level, i.e., observed global mean sea level from Church et al. (2004) minus thermal expansion (solid and dashed lines refer to Ishii & Kimoto and Levitus et al. thermal expansion data, respectively).

for the Levitus et al. and Ishii & Kimoto data, respectively. Based on a reconstruction of ocean temperatures, Domingues et al. (2008) estimate the thermal expansion trend over 1961–2003 at $0.5 \pm 0.08 \text{ mm year}^{-1}$. The mean trend in residual sea level over 1955–2001 is $\sim 1.5 \text{ mm year}^{-1}$, which represents the ocean mass increase over that period (plus eventually, a deep ocean temperature contribution not accounted for in the thermal expansion curves; see, e.g., Johnson et al. 2007). This ocean mass trend is three times larger than the thermal expansion trend.

According to Levitus et al. (2001, 2009), heat stored in the oceans during the last four decades ($\sim 16 \times 10^{22} \text{ J}$) is roughly 15 times greater than heat stored on continents, and roughly 20 times that stored inside the atmosphere, indicating that $\sim 85\%$ of excess heat from the climate system over that period has accumulated in the oceans. From climate modeling with different forcing agents (greenhouse gases, solar irradiance, aerosols, albedo, and land use), Hansen et al. (2005) show that the Earth is currently in a state of energy imbalance, amounting to $0.85 \pm 15 \text{ W m}^{-2}$ (i.e., excess energy absorbed from the sun versus reemitted to space). This value is in agreement with satellite-based observations at the top of the atmosphere for 2001–2004 (Trenberth et al. 2009). Levitus' value for ocean heat storage over the last 40 years corresponds to a contribution of $\sim 0.3 \text{ W m}^{-2}$ (after scaling by the ocean surface), i.e., $\sim 1/3$ of the Earth's total energy imbalance. However, if one considers ocean heat storage over the altimetry era (in the range of $0.6\text{--}0.7 \text{ W m}^{-2}$), the ocean contribution becomes dominant.

Figure 8 shows thermosteric sea level curves since 1993 based on Ishii & Kimoto (2009) and Levitus et al. (2009) temperature data (down to 700 m). On the altimetry time span (1993–2006/2007), thermal expansion trends amount to $1.1 \pm 0.25 \text{ mm year}^{-1}$ and $0.9 \pm 0.2 \text{ mm year}^{-1}$ for Ishii & Kimoto and for Levitus et al., respectively, with a mean of $\sim 1 \pm 0.3 \text{ mm year}^{-1}$. This trend is lower than that reported by IPCC AR4 over 1993–2003, $1.6 \pm 0.3 \text{ mm year}^{-1}$ (Bindoff et al. 2007), which is likely a result of the plateau in ocean heat

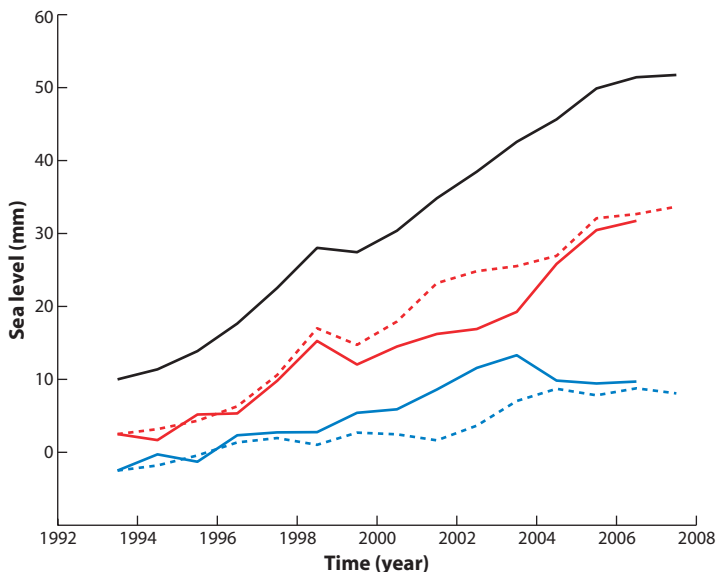


Figure 8

Blue lines: thermosteric sea level (or thermal expansion) since 1993 from Ishii & Kimoto (2009) (solid line, up to 2006) and Levitus et al. (2009) (dashed line, up to 2007). Black line: altimetry-based global mean sea level (annual averages). Red lines: residual sea level, i.e., observed global mean sea level minus thermal expansion (solid and dashed lines refer to Ishii & Kimoto and Levitus et al. thermal expansion data, respectively).

content seen beyond 2003 (see section 4). **Figure 8** also shows altimetry-based sea level (annual averages) and residual sea level curves (observed minus thermosteric sea level). The mean residual trend amounts to 2.3 mm year^{-1} and essentially represents the ocean mass increase.

Recent results based on Argo show that since approximately 2003, thermal expansion is following a plateau (after correcting for instrumental drifts of some Argo probes: Early estimates of Argo-based thermal expansion, Lyman et al. 2006 showed a negative trend as of 2003; however, instrumental problems were subsequently reported on some probes, leading to cold bias, hence artificial ocean cooling). For the recent years, thermal expansion rates range from $-0.5 \pm 0.5 \text{ mm year}^{-1}$ over 2003–2007 (Willis et al. 2008) to $+0.4 \pm 0.1 \text{ mm year}^{-1}$ over 2004–2007 (Cazenave et al. 2009) and $+0.8 \pm 0.8 \text{ mm year}^{-1}$ over 2004–2007 (Leuliette & Miller 2009). The 2003 data coverage is very sparse and it is likely that the Willis et al. (2008) value is biased low for that reason. The recent flattening of the thermal expansion curve likely reflects natural short-term variability. Similar short-term plateaus are also well visible in the past (see **Figure 7**).

Assuming constant total salt content, density changes arising from redistribution of salinity by the ocean circulation (halosteric effect) has no effect on the global mean sea level (although it does at local/regional scales, Wunsch et al. 2007). On the other hand, freshwater addition to the oceans due to increased river runoff and precipitation, as well as ice melting, modifies ocean salinity. If global measurements of salinity were available, it would be possible to estimate the global mean change of salinity and deduce the amount of freshwater added to the oceans. Ultimately, this would provide an estimate of ocean mass change and its contribution to sea level. Unfortunately, the coverage of salinity measurements is very sparse for the past decades, preventing reliable estimates of global mean ocean mass change by this method (although, because of sufficient coverage of salinity profiles over the North Atlantic, Boyer et al. 2007 were able to determine regional changes in freshwater content over 1955–2006). However, with space gravimetry data from GRACE, it is now possible to directly estimate the change in global mean mass of the oceans (see section 4).

4. SEA LEVEL BUDGET

The IPCC AR4 summarized the sea level budget for two periods (1961–2003 and 1993–2003) (Bindoff et al. 2007). For 1961–2003, the contributions of thermal expansion, glaciers, and ice sheets were estimated at $0.4 \pm 0.06 \text{ mm year}^{-1}$, $0.5 \pm 0.1 \text{ mm year}^{-1}$, and $0.2 \pm 0.2 \text{ mm year}^{-1}$, respectively (quoted error bars are one standard deviation from the mean). Their sum of $1.1 \pm 0.25 \text{ mm year}^{-1}$ was compared to the 1.8 mm year^{-1} rate of sea level rise observed over that period. The IPCC AR4 concluded that the sea level budget of the past four decades was not closed. For the 1993–2003 decade, the contribution of thermal expansion, glaciers, and ice sheets was estimated at $1.6 \pm 0.25 \text{ mm year}^{-1}$, $0.8 \pm 0.11 \text{ mm year}^{-1}$, and $0.4 \pm 0.2 \text{ mm year}^{-1}$, respectively, with a sum of $2.8 \pm 0.35 \text{ mm year}^{-1}$ —in rather good agreement with the altimetry-based rate of rise, $3.1 \pm 0.4 \text{ mm year}^{-1}$.

Since the IPCC AR4 publication (IPCC 2007), new results have appeared in the literature, in particular, for thermal expansion. Recently reprocessed ocean temperature data (Domingues et al. 2008, Levitus et al. 2009, Ishii & Kimoto 2009) do not lead to any important revision for the thermal expansion rate of the past four to five decades (see section 3.4), although the interannual variability has been greatly reduced. Because there are no new estimates for the land ice contribution for the past few decades, we concentrate instead on the altimetry period (since 1993), for which several new results are available. **Table 1** presents sea level budget since 1993. Two time spans are considered: 1993–2007 and 2003–2007.

Table 1 Sea level budget for two time spans (1993–2007, 2003–2007)*

| Sea level rise (mm year ⁻¹) | 1993–2007 | 2003–2007 |
|--|---|---|
| Observed | 3.3 ± 0.4 | 2.5 ± 0.4 (Ablain et al. 2009) |
| Thermal expansion | 1.0 ± 0.3 (mean of Levitus et al. 2009 and Ishii & Kimoto 2009 values) | 0.25 ± 0.8 (Argo) (mean of Willis et al. 2008, Cazenave et al. 2009, and Leuliette & Miller 2009 values) |
| Ocean mass | 2.3 ± 0.5 (observed rate minus thermal expansion) | 2.1 ± 0.1 (GRACE with a –2 mm year ⁻¹ GIA correction, Cazenave et al. 2009) |
| Glaciers | 1.1 ± 0.25 (based on Kaser et al. 2006 and Meier et al. 2007) | 1.4 ± 0.25 (Cogley 2009) |
| Total ice sheets (Greenland & Antarctic) | 0.7 ± 0.2 0.4 ± 0.15 0.3 ± 0.15 (compilation of published results) | 1.0 ± 0.2 0.5 ± 0.15 0.5 ± 0.15 (compilation of published results) |
| Land waters | — | –0.2 ± 0.1 (W. Llovel, K. DoMinh, A. Cazenave, J.F. Cretaux, M. Becker, unpublished manuscript) |
| Sum of (2 + 4 + 5 + 6) | 2.85 ± 0.35 | 2.45 ± 0.85 |
| Observed rate minus sum | 0.45 | –0.05 |

* Quoted errors are one standard deviation. The observed sea level rate is GIA corrected (–0.3 mm year⁻¹ removed).

1993–2007. Over 1993–2007, the altimetry-based rate of sea level rise was 3.3 ± 0.4 mm year⁻¹. Mean thermal expansion rate (average of Levitus et al. 2009 and Ishii & Kimoto 2009 values over their common time span) is 1.0 ± 0.3 mm year⁻¹. The rate difference between observed sea level rise and mean thermal expansion is 2.3 mm year⁻¹. This represents the ocean mass increase (plus eventually a deep ocean thermal contribution). For the glaciers' contribution since 1993, we use Kaser et al. (2006) and Meier et al. (2007) updates, leading to a value of 1.1 ± 0.25 mm year⁻¹. Although ice sheet mass loss is clearly not linear (see **Figure 5a,b**), we deduce from a compilation of published results a mean contribution to sea level of ~0.7 mm year⁻¹ for the two ice sheets (~0.4 mm year⁻¹ for Greenland and ~0.3 for Antarctica). This leads to a total ice component of ~1.8 mm year⁻¹, lower than the 2.3 mm year⁻¹ residual rate. As in IPCC AR4 for 1993–2003, the sea level budget is not totally closed. But over 1993–2007, the mass component dominates the thermal component (unlike over 1993–2003).

Recent developments: 2003–2008. As indicated above, Argo-based data on ocean thermal expansion indicate a less rapid increase since 2003 than during the previous decade, although sea level has continued to rise, but at a reduced rate of 2.5 ± 0.4 mm year⁻¹ (Ablain et al. 2009). GRACE data averaged over the oceans provide a measure of the ocean mass change (e.g., Chambers et al. 2004). However, GRACE is also sensitive to GIA and the latter effect averaged over the oceanic domain is still uncertain, ranging from –1 mm year⁻¹ (Paulson et al. 2007) to –2 mm year⁻¹ (Peltier 2009). Depending on the assumed GIA correction, estimated ocean mass change over 2003–2007 ranges from 1.1 mm year⁻¹ (Leuliette & Miller 2009) to 2.1 mm year⁻¹ (Cazenave et al. 2009).

Independent estimates of glaciers and ice sheet contributions to sea level over the same time span can help discriminate between the two values. Meier et al. (2007) as well as Cogley (2009)

report accelerated glacier melting since 2003, leading to 1.4 ± 0.25 mm year⁻¹ equivalent sea level rise in year 2006.

The mass balance of the ice sheets has been recently reevaluated using GRACE and other remote-sensing techniques. For example, Rignot et al. (2008a) find an Antarctica contribution to sea level of 0.56 mm year⁻¹ for year 2006, in good agreement with the GRACE-based Antarctica mass balance estimate of 0.55 ± 0.06 mm year⁻¹ (Cazenave et al. 2009). GRACE data also suggest an increased contribution from Greenland of 0.4 ± 0.05 mm year⁻¹ (Wouters et al. 2008). Using ICESat laser altimetry, Slobbe et al. (2009) estimated the Greenland contribution over 2003–2008 at 0.39 ± 0.2 mm year⁻¹.

Summing all land ice components leads to 2.4 ± 0.35 mm year⁻¹ equivalent sea level rise over 2003–2007, only slightly larger than the GRACE-based ocean mass increase if the largest GIA correction is considered. These new observations report accelerated land ice loss, which may have contributed to ~80% of the sea level rise in recent years, as compared to a 50% contribution over 1993–2003 (IPCC 2007).

Chambers (2006) and Lombard et al. (2007) showed that combining satellite altimetry and GRACE data provides an estimate of the steric component. In effect, satellite altimetry represents the sum of thermal expansion and ocean mass change, while GRACE averaged over the oceans measures the ocean mass change component only. The altimetry-derived contribution minus mass factors (using values presented in **Table 1**) shows a slightly positive trend of 0.3 mm year⁻¹ over 2003–2007, in agreement with the Argo-based reduced thermosteric rate over that same period.

5. REGIONAL VARIABILITY IN SEA LEVEL TRENDS

Satellite altimetry has revealed strong regional variability in sea level trends (**Figure 2a,b**). Several studies have shown that nonuniform ocean warming, hence nonuniform thermal expansion, is most responsible for the observed spatial trend patterns in sea level (e.g., Lombard et al. 2005). Recent studies based on ocean general circulation models, either with data assimilation (e.g., Carton & Giese 2008, Kohl & Stammer 2008, Wunsch et al. 2007) or without (Lombard et al. 2009), confirm that regional sea level trend patterns reported by satellite altimetry are mainly due to regional variability in thermal expansion. However, salinity changes are not negligible at regional scale. For example, using the ECCO (Estimating the Circulation and Climate Experiment of the Ocean) ocean circulation model with atmospheric data forcing and assimilation of a good deal of ocean data (in situ temperature and salinity, altimetry-based sea level, sea surface temperature, satellite-based surface winds, etc.), Wunsch et al. (2007) reproduced local sea level trend patterns observed by satellite altimetry over 1993–2004. They showed that thermal expansion change in the upper ocean is the dominant contribution to observed spatial trend patterns but also that approximately 25% of the temperature contribution is locally compensated by salinity. Lombard et al. (2009) were also able to reproduce spatial trend patterns using the high-resolution (0.25°) NEMO (Nucleus for European Models of the Ocean) ocean circulation model without data assimilation over 1993–2001.

Figure 9 (from Lombard et al. 2009) compares sea level trend patterns over 1993–2001 observed by satellite altimetry and computed by the NEMO model. A striking agreement is noticed between observations and model results. In **Figure 10a,b** are shown the separate contributions from temperature and salinity computed by the model. In some regions (e.g., equatorial Pacific and North Atlantic), effects of temperature and salinity are opposite and cancel each other, but in most other regions thermosteric trend patterns closely resemble observed trend patterns, as noted earlier by Wunsch et al. (2007).

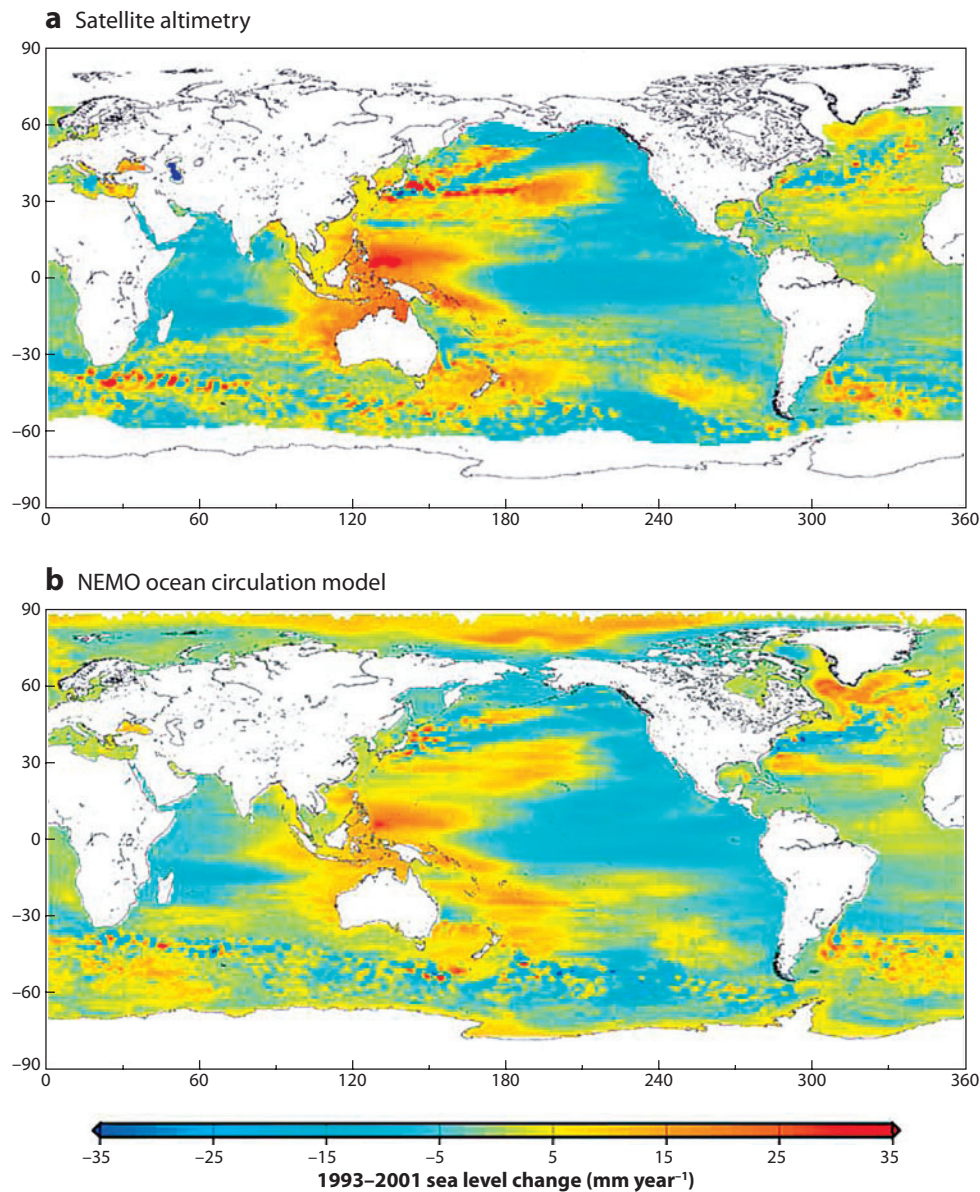


Figure 9

Spatial patterns in sea level trends over 1993–2001 observed by satellite altimetry (*a*) and computed by the NEMO ocean circulation model (*b*) (from Lombard et al. 2009).

Wunsch et al. (2007) discuss attribution of observed local/regional sea level trend patterns: (*a*) ocean warming and cooling, (*b*) freshwater exchange with the atmosphere and land via evaporation, precipitation, and runoff, and (*c*) redistribution of water mass via ocean advection. To these processes should also be added solid Earth processes due to gravity and ocean volume changes (discussed below). Concerning factors (*a*) through (*c*), Wunsch et al. (2007) showed that observed trend patterns result from a complex dynamical response of the ocean, involving forcing terms

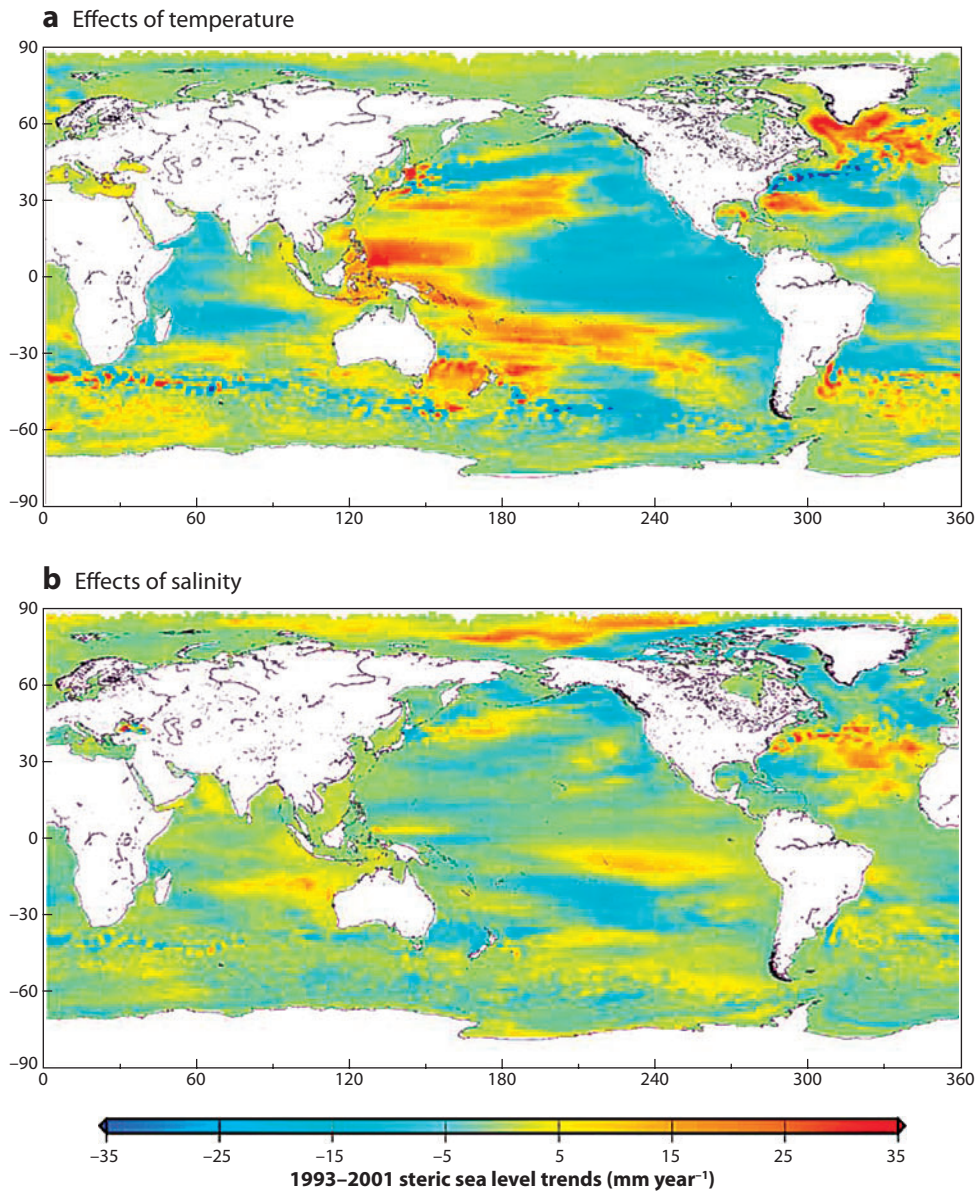


Figure 10

(*a*) Thermosteric (i.e., due to temperature only) sea level trend patterns over 1993–2001 computed by the NEMO ocean circulation model. (*b*) Same as (*a*) but for the effects of salinity only (from Lombard et al. 2009).

as well as water movements associated with wind stress. These authors also stressed that given the long memory time of the ocean, observed patterns reflect not only forcing patterns over the period considered but also forcing and internal changes that occurred in the past. This suggests that distribution of sea level trends observed by satellite altimetry over the last 16 years may not be steady but will eventually adjust, over much longer time spans, toward different geographical

patterns than those currently observed. Concerning the response of the ocean circulation to freshwater forcing associated with Greenland and Antarctic ice melting, using ECCO simulations, Stammer (2008) showed that significant sea level rise would be expected along the western coast of the North Atlantic in response to Greenland ice melting.

We have seen above that steric sea level change is the dominant contributor to the observed spatial trend patterns observed for sea level. However, other processes are expected to also give rise to regional sea level variations. This is the case for the response of the solid Earth to the last deglaciation (GIA) and to ongoing melting of land ice in response to global warming. These processes give rise to secular change of the geoid (an equipotential surface of the Earth's gravity field that coincides with the mean surface of the oceans at rest) and gravitational deformations of ocean basins and of the sea surface (Mitrovica et al. 2001, Plag 2006, Peltier 2009). Recently, Mitrovica et al. (2009) showed that rapid melting of the ice sheets and glaciers will lead to nonuniform sea level rise because of the changing mutual gravitational attraction between the ice sheet and the nearby ocean as well as the elastic deformation of the solid Earth to the load redistribution. Such regional sea level changes are broadscale but different for each melting source (Greenland, Antarctica, glaciers). To give an order of magnitude, they can reach up to 30% of the melt contribution to sea level rise.

Now that high-quality in situ temperature and salinity measurements with global coverage are available from the Argo observation system, it may become possible to detect the fingerprint of land ice melt (due to both gravitational and dynamical effects) using satellite altimetry data corrected for steric sea level (e.g., Milne et al. 2009).

6. SEA LEVEL PROJECTIONS

IPCC AR4 projections indicated that sea level should be higher than today's value by ~ 35 cm by the year 2100 (within a range of ± 15 cm due to model results dispersion and uncertainty over future greenhouse gas emissions) (Meehl et al. 2007). However, this value is likely a lower bound because physically realistic behavior of the ice sheets was not taken into account. As discussed in section 3.4, a large proportion of ice sheet mass loss results from coastal glacier flow into the ocean through dynamical instabilities. Such processes are only beginning to be understood and were not taken into account in the IPCC AR4 sea level projections. Recent studies by Rahmstorf (2007) and Horton et al. (2008) provided semi-empirical sea level projections based on a simple relationship established for the twentieth century between global mean sea level rate and global mean temperature. Using mean temperature projections from climate models, these studies extrapolated future global mean sea level. Projected range of sea level rise in 2100 by Rahmstorf (2007) (i.e., between ~ 50 and ~ 120 cm) directly reflects the temperature projections range. The middle value (~ 85 cm) is roughly twice the IPCC AR4 value. Whereas future sea level rates may not be as closely associated with global mean temperature as they are today (especially if ice sheet dynamics play a larger role in future), an approach such as Rahmstorf's offers independent insight on plausible ranges of future sea level rise and an interesting alternative to still uncertain coupled climate model projections.

Figure 11 shows the evolution of the global mean sea level between 1800 and 2100 based on observations for the nineteenth and twentieth centuries and model projections [from IPCC (2007) AR4 and the semi-empirical method by Rahmstorf 2007] for the twenty-first century.

We have seen that observed sea level rates present high regional variability around the global mean (**Figure 3b**), and thus regional variability is expected in the future. The mean regional sea level map for 2080–2099 (**Figure 12**) provided by IPCC AR4 (Meehl et al. 2007) from an ensemble mean over 16 coupled climate models shows higher than average sea level compared to 1980–1999 in the Arctic Ocean in response to increasing ocean temperature and decreasing salinity. On the

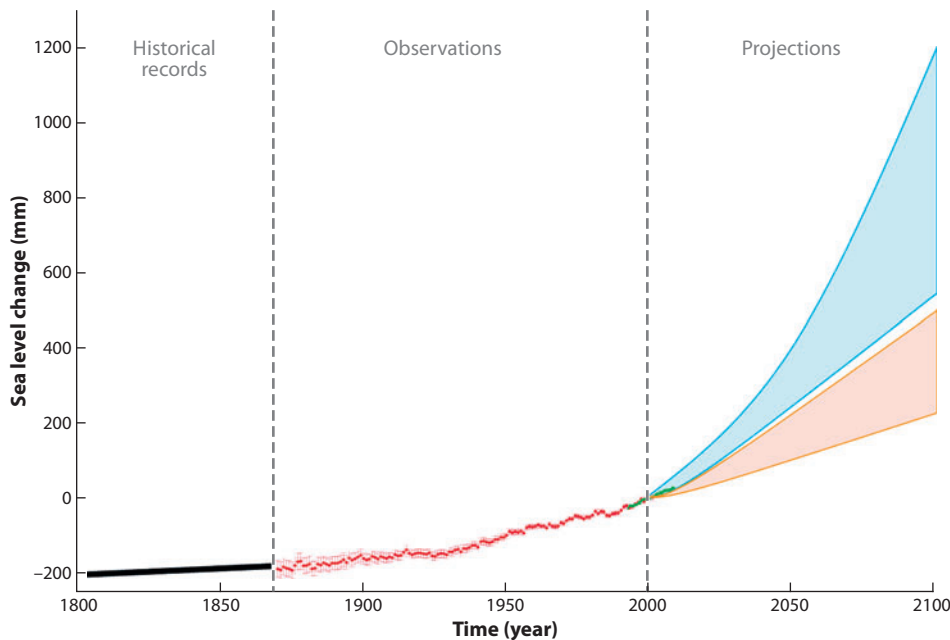


Figure 11

Evolution of the global mean sea level between 1800 and 2100 from observations (for the nineteenth and twentieth centuries) and model projections for the twenty-first century. The thick black line represents the long-term sea level based on various observations for the nineteenth century. The red line is based on tide gauge data (from Church et al. 2004). The green line is from satellite altimetry since 1993. The pink shaded region includes projections from coupled climate models [from IPCC (2007) AR4]. The light blue shaded region includes projections from Rahmstorf (2007).

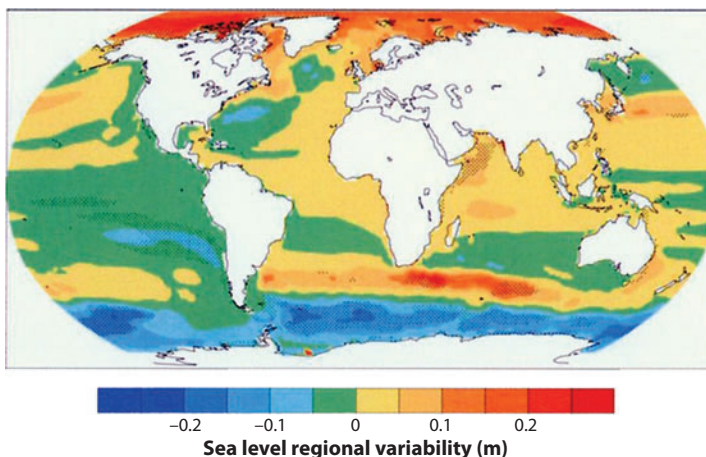


Figure 12

Regional sea level change (in metres) by the end of the twenty-first century due to ocean density and circulation changes, relative to the global average. This regional variability is calculated as the difference between averages for 2080–2099 and 1980–1999 under SRES scenario A1B, from an ensemble mean of 16 AOGCMs (Atmosphere–Ocean General Circulation Models). Reproduced from IPCC (2007) AR4.

other hand, a lower sea level is projected in the Austral Ocean. These model-based projections essentially reflect that part of the regional variability due to long-term climate signals but still poorly account for decadal/multidecadal natural variability. On a decadal timescale, spatial trend patterns may differ by a factor of 2 to 3 from the global mean sea level rise (see section 2.3). Regional sea level projections at 10- to 20-year intervals should be proposed by climate models. To evaluate future regional impacts, this information is of crucial importance.

7. COASTAL IMPACTS

Main physical impacts of sea level rise are rather well known (e.g., Nicholls 2002, 2007). These include (a) inundation and recurrent flooding in association with storm surges, (b) wetland loss, (c) shoreline erosion, (d) saltwater intrusion in surface water bodies and aquifers, and (e) rising water tables. In many coastal regions of the world, the effects of rising sea level act in combination with other natural and/or anthropogenic factors, such as decreased rate of fluvial sediment deposition in deltaic areas, ground subsidence due to tectonic activity, or ground water pumping and hydrocarbon extraction. Change in dominant wind, wave, and coastal current patterns in response to local or regional climate change and variability may also impact shoreline equilibrium.

Deltas are dynamical systems linking fluvial and coastal ocean processes (Ericson et al. 2006). Over the last 2000 years, agriculture has accelerated the growth of many world deltas (McManus 2002). But in recent decades, dam and reservoir construction and river diversion for irrigation considerably decreased sediment supply along numerous world rivers, destroying the natural equilibrium of many deltas.

Accelerated ground subsidence due to local groundwater withdrawal and hydrocarbon extraction is another problem that affects numerous coastal megacities. For example, during the twentieth century, Tokyo subsided by 5 m, Shanghai by 3 m, and Bangkok by 2 m (Nicholls 2007). Hydrocarbon extraction in the Gulf of Mexico causes ground subsidence along the Gulf Coast in the range of 5–10 mm year⁻¹ (Ericson et al. 2006). Whatever the causes, ground subsidence produces effective (relative) sea level rise that directly interacts with and amplifies climate-related sea level rise (i.e., long-term trend plus regional variability).

In terms of impacts, what is important is relative sea level rise, i.e., the combination of the climate-related sea level rise and ground subsidence. In many coastal regions of the world, these two factors are currently of the same order of magnitude, and hence produce higher relative sea level rise than the climate component alone. If sea level continues to rise at current rates, or more likely accelerates, then climate change impacts (sea level rise) may dominate. As mentioned in section 6, future sea level projections from coupled climate models are likely underestimated. In addition, climate models are not yet able to provide reliable data on regional variability (that superimposes positively or negatively on the global mean rise in sea level) for the next 20, 30, and 50 years. It is therefore very difficult to quantify future sea level rise in specific regions, and this should be among the priorities for the climate-modeling community. In parallel, multidisciplinary studies of sea level rise impacts that take an integrated approach involving all factors (climate change, anthropogenic forcing, solid earth processes, etc.) need to be developed.

8. CONCLUSION

Most recent developments indicate that sea level is currently rising, slightly faster since the early 1990s than during the previous decades. Owing to the recent progress in understanding the causes of present-day sea level rise, we can nearly close the sea level budget for the period 1993–2007. Approximately 30% of the rate of sea level rise is due to ocean thermal expansion in response to

ocean warming. Mass loss in mountain glaciers and ice sheets accounts for approximately another 55%. Since 2003 ocean thermal expansion rate has slightly reduced while sea level has continued to rise. Direct and indirect estimates of land ice contribution indicate that ocean mass increase explains roughly 80% of the past 5-year observed sea level rate. If, as most likely, recent thermal expansion pause is temporary, and if land ice shrinking continues to accelerate, the prevailing sea level may be the source of some surprise in the near future.

The recently launched Jason-2 satellite, the successor to Jason-1, will provide continuity in the monitoring of sea level variations from space, at least for the coming years. In addition to ocean temperature and salinity measurements from Argo, mass balance of the ice sheets from GRACE and other remote-sensing techniques, GRACE-based land water-storage change and in situ and remote observations of mountain glaciers are absolutely crucial for understanding sea level evolution with time and its response to climate change and variability. These observations also offer invaluable constraints to the climate models developed for future sea level projections.

Sea level is a climate parameter difficult to determine by climate models because it involves interactions of all components of the climate system (oceans, ice sheets and glaciers, atmosphere, land water reservoirs) on a wide range of spatial and temporal scales. Even the solid Earth through its elastic response to changing crust and mantle parameters, as well as water mass redistribution, affects sea level. Systematic monitoring of oceans, cryosphere, and land waters from in situ and space-observation systems are thus crucial to validate climate models, and hence improve future sea level projections. Considering the highly negative impact of future sea level rise for society, the multidisciplinary aspects of sea level rise (observations, modeling, coastal impact studies) should remain a major area of future climate research.

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Errata

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