

REVIEW

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Key Points:

- We summarize the most up-to-date knowledge about sea level rise and its causes
- Sea level rise is not uniform and displays regional variability
- Impacts of sea level rise on coastal hazards will depend on many local factors

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Sea level rise and its coastal impacts

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Abstract Global warming in response to accumulation of human-induced greenhouse gases inside the atmosphere has already caused several visible consequences, among them increase of the Earth's mean temperature and ocean heat content, melting of glaciers, and loss of ice from the Greenland and Antarctica ice sheets. Ocean warming and land ice melt in turn are causing sea level to rise. Sea level rise and its impacts on coastal zones have become a question of growing interest in the scientific community, as well as in the media and public. In this review paper, we summarize the most up-to-date knowledge about sea level rise and its causes, highlighting the regional variability that superimposes the global mean rise. We also present sea level projections for the 21st century under different warming scenarios. We next address the issue of the sea level rise impacts. We question whether there is already observational evidence of coastal impacts of sea level rise and highlight the fact that results differ from one location to another. This suggests that the response of coastal systems to sea level rise is highly dependent on local natural and human settings. We finally show that in spite of remaining uncertainties about future sea levels and related impacts, it becomes possible to provide preliminary assessment of regional impacts of sea level rise.

1. Introduction

In the recent years, sea level rise induced by global warming and its impacts on coastal zones has become a question of growing interest in the scientific community, as well as the media and public. It is now well established that the Earth's climate is warming and that the main cause is the accumulation of greenhouse gases (GHGs) inside the atmosphere, produced by anthropogenic fossil fuel combustion and change in land use (mostly deforestation) [IPCC AR4, 2007; IPCC AR5, 2013]. Global warming has already given rise to several visible consequences, in particular increase of the Earth's mean surface temperature [e.g., Morice et al., 2012] and of ocean heat content [Levitus et al., 2012; Hobbs and Willis, 2013], melting of sea ice [Wadhams et al., 2011] and glaciers [Cogley, 2009; Gardner et al., 2013], and loss of ice mass from the Greenland and Antarctica ice sheets [Shepherd et al., 2012]. Ocean warming causes thermal expansion of sea waters, hence sea level rise. Similarly, water from land ice melt ultimately reaches the oceans, thus also causes sea level rise. Direct sea level observations available since the mid-to-late nineteenth century from in situ tide gauges and since the early 1990s from high-precision altimeter satellites indeed show that sea level is rising [Jevrejeva et al., 2008; Nerem et al., 2010; Church and White, 2011; Mitchum et al., 2010]. Observations also show that the rate of rise displays strong regional variations [Lombard et al., 2005; Meyssignac and Cazenave, 2012]. Modeling of future climate change under different radiative forcing scenarios indicates that sea level will continue to rise during the next decades and even centuries [IPCC AR5, 2013; Levermann et al., 2013]. Adverse effects of sea level rise in coastal areas are generally considered as a major threat of climate change if we consider that 10% of the world population is living in coastal areas less than 10 m above sea level [McGranahan et al., 2007]. Twentieth century observations report shoreline erosion in many areas of the world coastlines [Bird, 1987] but it remains unclear whether this is due to climate-related sea level rise [Vellinga and Leatherman, 1989] or to more local nonclimatic factors such as ground subsidence (causing relative sea level rise), coastal management, land use and land use changes, waves and currents, deficit in sediment supply, etc., or to the combination of all factors [e.g., Bird, 1996]. Nevertheless, it is virtually certain that in the coming decades, the expected acceleration of sea level rise in response to continuing global warming will exacerbate the vulnerability of many low-lying, densely populated coastal regions of the world, and very likely will become a major threat in the near future for a significant fraction of human beings.

In this review article, we first summarize the most up-to-date observations about sea level change and variability at global and regional scales, focusing on the twentieth century and last two decades. We also discuss the various climatic and nonclimatic factors responsible for the sea level variations at global and regional scales. We further present global mean and regional sea level projections for the 21st century. Finally, we briefly discuss the implications of recent and future sea level rise, placing them in the context of the numerous natural and anthropogenic factors affecting coastal zones, such as coastal erosion and marine submersion.

2. Sea Level Observations and Causes

2.1. Global Mean Sea Level Observations and Causes: Twentieth Century and Last Two Decades

2.1.1. Observed Sea Level Rise During the Twentieth Century

Our knowledge of past century sea level change comes from tide gauge measurements located 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, www.pol.ac.uk/psmsl/) [Woodworth and Player, 2003], which contains data for the twentieth century from ~2000 sites. However, only ~10% of this data set is useable for historical sea level studies because of data gaps and limited tide gauge distribution in the past. Tide gauges measure sea level relatively to the ground, hence monitor ground motions also. In active tectonic and volcanic regions, or in areas subject to strong ground subsidence due to natural causes (e.g., sediment loading in river deltas) or human activities (groundwater and oil/gas extraction), tide gauge data are directly affected by corresponding ground motions. Post glacial rebound, the viscoelastic response of the Earth crust and mantle to last deglaciation (also called glacial isostatic adjustment, GIA) is another process that gives rise to vertical land movement, e.g., crustal uplift in high latitudes of the Northern Hemisphere [e.g., Peltier, 2004; Paulson et al., 2007; Milne et al., 2009; Tamisiea, 2011]. If one is interested in the climate-related components of sea level rise, vertical land motions need to be removed. On the other hand, for studying coastal impacts of sea level rise, it is the relative (i.e., including vertical land motion as measured by tide gauges) sea level rise that is of interest.

Most recent analyses of long, good-quality tide gauge records (corrected for GIA and when possible for other vertical land motions by the Global Positioning System, GPS) indicate a mean rate of sea level rise of 1.6–1.8 mm/yr over the twentieth century [Jevrejeva et al., 2006, 2008; Wöppelmann et al., 2007, 2009; Church and White, 2011]. Figure 1 (left panel) shows the tide gauge-based sea level evolution between 1900 and 2011, with associated uncertainty (data set from Church and White [2011]). Over this time span, the mean rate of rise amounts to 1.65 ± 0.2 mm/yr.

2.1.2. Satellite Altimetry Era

Since the early 1990s, sea level is routinely measured with quasi-global coverage and a few days/weeks revisit time (called “orbital cycle”) by high-precision altimeter satellites such as Topex/Poseidon (1992–2006) and its successors Jason-1 (2001–2013) and Jason-2 (2008–), as well as Envisat (2002–2011), Cryosat (2010–), and SARAL/Altika (2013–). Compared to tide gauges which provide sea level relative to the ground, satellite altimetry measures “absolute” sea level variations in a geocentric reference frame. The concept of the satellite altimetry measurement is simple [Chelton et al., 2001]: the onboard radar altimeter transmits microwave radiation toward the sea surface which partly reflects back to the satellite. Measurement of the round-trip travel time of the electromagnetic signal provides the height of the satellite above the instantaneous sea surface (called “range”). The sea surface height (SSH) above a fixed reference surface (typically a conventional reference ellipsoid) is then simply computed from the difference between the altitude of the satellite above the reference (deduced from precise orbit computation) and the range measurement. The SSH measurement needs to be corrected for various factors due to ionospheric and tropospheric delays, instrumental biases and drifts, and effects of the electromagnetic scattering of the radar signal at the air-sea interface. Other corrections due to solid Earth, pole and ocean tides and atmospheric loading are also applied [see Chelton et al., 2001 for details]. The precision of an individual SSH measurement has now reached the 2–3 cm level. Further averaging over the oceanic domain during an orbital cycle leads to a precision of ~0.4 mm for a single global mean sea level measurement. In terms of multiyear linear trend, error budget analyses of all sources of

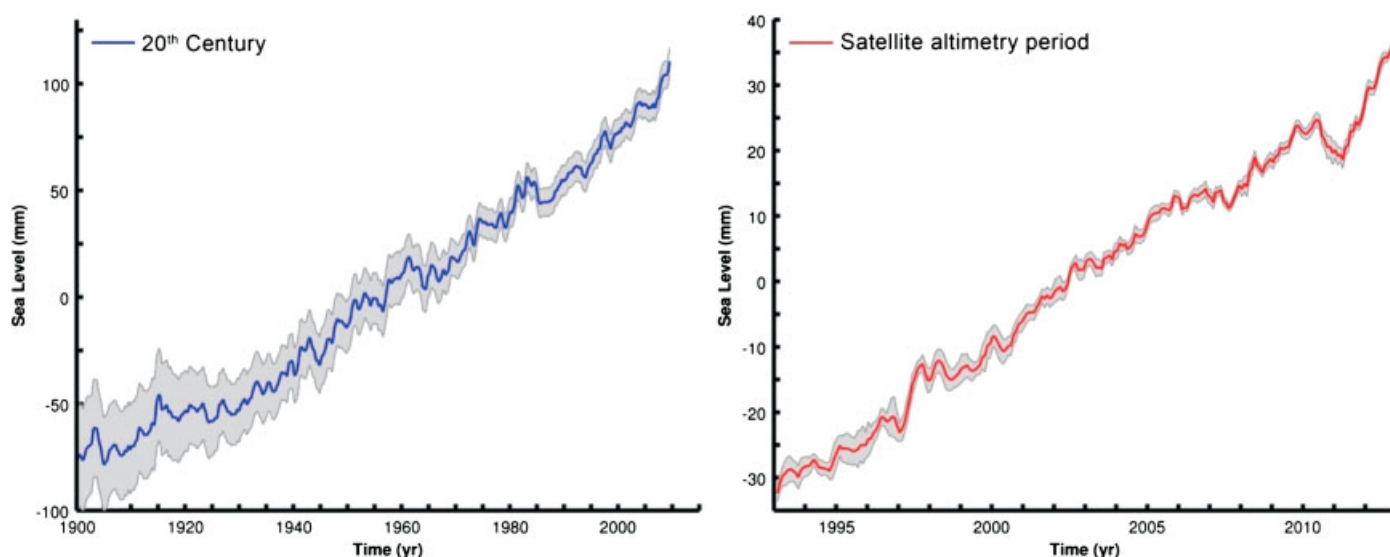


Figure 1. Global mean sea level time series and associated uncertainty based on tide gauge data over the twentieth century (left panel; data from Church and White [2011] and satellite altimetry data over 1993–2012; average data from different groups; see text).

errors affecting the altimetric system, as well as comparisons with tide gauge-based sea level measurements, suggest errors in the order of 0.4 mm/yr [Ablain et al., 2009; Mitchum et al., 2010; Nerem et al., 2010].

The temporal evolution of the global mean sea level from satellite altimetry between January 1993 and December 2012 is shown in Figure 1 (right panel). This curve is based on an average of six sources of sea level data: data from the five satellite altimetry processing centers (AVISO: <http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/>, Colorado University: <http://sealevel.colorado.edu/>, CSIRO: http://www.cmar.csiro.au/sealevel/sl_data_cmar.html, GSFC: http://podaac.jpl.nasa.gov/Integrated_Multi-Mission_Ocean_AltimeterData, and NOAA: http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/LSA_SLR_timeseries_global.php) plus the new data set from the ESA Climate Change Initiative (CCI) “Sea Level” project (ftp://ftp.esa-sealevel-cci.org/Products/SeaLevel-ECV/V1_11092012/). Associated uncertainty is based on the dispersion of individual time series around the mean. A small correction of -0.3 mm/yr is applied to account for the GIA effect on the global mean absolute sea level [Peltier, 2004; Tamisiea, 2011]. The altimetry-based sea level curve shows an almost linear increase since 1993, except for some temporary anomalies associated with ENSO (El Niño–Southern Oscillation) events (e.g., positive/negative anomalies associated with the 1997–1998 El Niño/2011 La Niña). Over this 20-year-long time span, the rate of global mean sea level rise amounts to 3.2 ± 0.1 mm/yr (the 0.1 mm/yr uncertainty is based on individual point errors; as mentioned above, a more realistic value accounting for systematic errors is closer to 0.4 mm/yr).

2.1.3. Is Present-Day Rate of Sea Level Rise Unusual Compared to Last Centuries/Millennia Variations?

As shown in Figure 1 (left panel), the twentieth century sea level curve is not purely linear. Sea level rate appears to increase with time. This led a number of investigators to estimate the acceleration at the multidecadal to century time scale [e.g., Church and White, 2006; Jevrejeva et al., 2008; Woodworth et al., 2009, 2011; Ray and Douglas, 2011; Gehrels and Woodworth, 2013]. Results are highly scattered (in the range of 0–0.019 mm/yr/yr), with the computed acceleration being highly dependent on the record length and the considered data set. Nevertheless, most studies conclude to a slight acceleration of the global mean sea level in the course of the twentieth century.

The rate of sea level rise of the last two decades is double the mean rise of the twentieth century. It has been suggested that this higher rate cannot be attributed to decadal variations but rather reflects a recent acceleration of the global mean rise (since the early 1990s) [Merrifield et al., 2009]. However, this was questioned by other studies stating that because of low-frequency, multidecadal sea level fluctuations, any

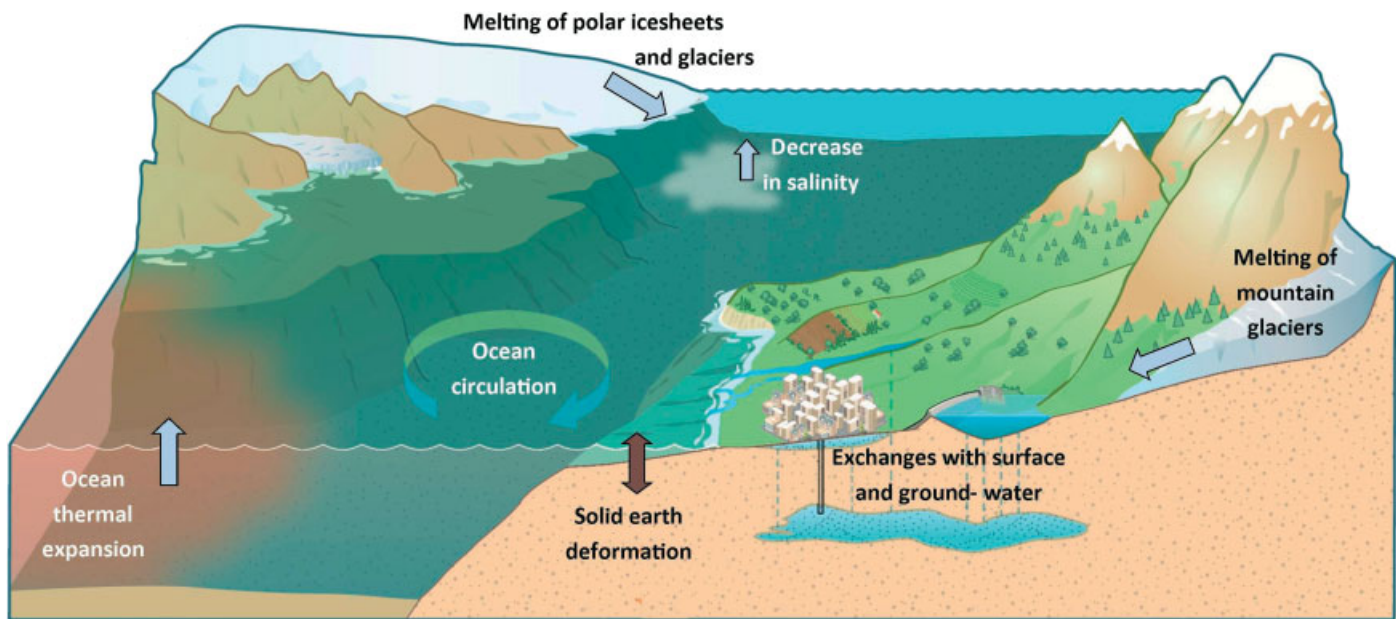


Figure 2. Sketch showing the main factors causing sea level changes.

recent acceleration is hard to detect [e.g., *Chambers et al.*, 2012]. While this is well possible considering the still short length of the altimetry record, it is worth mentioning that the altimetry-based rate of sea level rise is remarkably stable: since more than a decade, regular extent of the sea level time series gives a nearly constant rate value in the range of 3.1–3.3 mm/yr.

Recent studies based on Paleo sea level data (coral reef cores, geological and archeological data, etc.) have shown that since 2–3 millennia, the mean sea level has remained quasi stable [e.g., *Lambeck et al.*, 2004, 2010; *Miller et al.*, 2009, 2013]. Using biomarkers of ancient sea levels in salt marsh environments, *Kemp et al.* [2011] showed that the rate of sea level change did not exceed 0.5 mm/yr during the last 2000 years, a conclusion confirmed by other studies showing that no acceleration occurred until the mid-to-late nineteenth century or even later [e.g., *Gehrels et al.*, 2006; *Jevrejeva et al.*, 2008; *Gehrels and Woodworth*, 2013]. Thus, compared to the late Holocene period, the twentieth century and last two decades' rates of sea level rise are unusually high. However, the mean rate of rise during the last deglaciation (between ~20 000 years and early Holocene) amounted 12 mm/yr [e.g., *Bard et al.*, 2010; *Lambeck et al.*, 2010], a value significantly higher than today. Moreover, during short periods of only 300 years, the rate of sea level rise reached 40 mm/yr (e.g., during the Melt Water Pulse 1A, 14,000 years ago) [Bard et al., 2010; *Deschamps et al.*, 2012]. Although involved land ice volume was much greater than nowadays, these Paleo-observations indicate that very high sea level rates are not impossible.

2.1.4. Can We Explain Present-Day Global Mean Sea Level Rise?

The main factors causing current global mean sea level rise are thermal expansion of sea waters, land ice loss, and fresh water mass exchange between oceans and land water reservoirs (see Figure 2). These contributions vary in response to natural climate variability and global climate change induced by anthropogenic GHG emissions.

Ocean warming. Analyses of in situ ocean temperature data collected over the past ~50 years by Expandable Bathy Thermographs (XBT) from ships [e.g., *Levitus et al.*, 2005, 2009; *Ishii and Kimoto*, 2009] and about the last 10 years by automatic profiling floats from the Argo system [Roemmich et al., 2012] have shown that ocean heat content, and hence ocean thermal expansion, has significantly increased, in particular since 1970, although not linearly [e.g., *Domingues et al.*, 2008; *Ishii and Kimoto*, 2009; *Levitus et al.*, 2012]. A steep increase was observed in thermal expansion during the 1993–2003 decade [e.g., *Bindoff et al.*, 2007], but since about 2003, thermal expansion has increased less rapidly [Llovel et al., 2010; *Lyman et al.*, 2010; *Von Schuckmann and Le Traon*, 2011]. The recent slower rate of thermal expansion likely

reflects short-term natural variability rather than a new long-term trend. Although very sparse, the few available deep ocean temperature measurements (below ~ 1000 m) indicate that the deep ocean has also warmed [e.g., Purkey and Johnson, 2010] in the recent decades but its exact contribution to sea level rise remains uncertain. On average, over the satellite altimetry era (1993–2012), the contribution of upper ocean warming to global mean sea level rise accounts for $\sim 30\%$ [Cazenave and Llovel, 2010; Church et al., 2011; IPCC AR5, 2013].

Glaciers melting. Being very sensitive to global warming, mountain glaciers and small ice caps have retreated worldwide during the twentieth century, with significant acceleration since the early 1990s [e.g., Meier et al., 2007]. From volume and mass balance studies of a large number of glaciers based on various in situ and remote sensing observation methods, estimates have been made of the contribution of glacier melt to sea level rise [Kaser et al., 2006; Meier et al., 2007; Cogley, 2009; Jacob et al., 2012; Gardner et al., 2013; IPCC AR5, 2013]. For the period 1993–2009/2012, glaciers and ice caps have accounted for $\sim 30\%$ of the global mean sea level rise [Gardner et al., 2013].

Ice sheets. If totally melted, Greenland and West Antarctica (the instable part of the continent) would raise sea level by about 7 m and 3–5 m, respectively. Thus, even a small amount of ice mass loss from the ice sheets is able to produce substantial sea level rise. Since the early 1990s, different remote sensing observations (airborne, and satellite laser and radar altimetry, Synthetic Aperture Radar Interferometry, InSAR, and since 2002, space gravimetry from the GRACE mission) have provided important observations of the mass balance of the ice sheets. These data indicate that Greenland and West Antarctica are losing mass at an accelerated rate. Several tens of articles have been published in the recent years on that topic, leading to important dispersion between the various mass balance results [e.g., Steffen et al., 2010; Zwally and Giovinetto, 2011; Hanna et al., 2013]. Such a dispersion results from systematic errors of the observing systems and the different time spans considered by the investigators. However, the recent paper by Shepherd et al. [2012], involving a large number (47) of world experts in the different remote sensing systems, provides a reconciled estimate for the ice sheet mass balance since 1992. On average the ice sheet contribution to sea level rise over the altimetry era amounts to roughly 20% [Shepherd et al., 2012]. The space-based observations unambiguously show acceleration of ice sheet mass loss in the recent years [e.g., Rignot et al., 2011]. For the period 1993–2003, less than 15% of the rate of global sea level rise was due to the ice sheets (IPCC AR4, 2007), but their contribution has increased since 2000–2003 [Shepherd et al., 2012; IPCC AR5, 2013].

Observational evidence indicates that the recent negative mass balance partly results from accelerated glacier flow along some coastal margins of the ice sheets (in the proportion of 50% for Greenland and 100% for Antarctica), and further iceberg discharge into the surrounding ocean [e.g., Pritchard et al., 2009; Rignot et al., 2011; Hanna et al., 2013]. This dynamical instability process is generally observed in regions where coastal glaciers are grounded below sea level. Thinning and subsequent break-up of floating ice tongues or ice shelves that buttressed the glaciers result in rapid grounding line retreat and accelerated glacier flow [Pritchard et al., 2012; Hanna et al., 2013]. Several recent observations have suggested that warming of subsurface ocean waters may trigger these dynamical instabilities [Hanna et al., 2008; Holland et al., 2008; Jenkins et al., 2010; Rignot et al., 2012].

Land water storage. Change in land water storage due to natural climate variability and human activities (i.e., anthropogenic changes in the amount of water stored in soils, reservoirs, and aquifers as a result of dam building, groundwater mining, irrigation, urbanization, and deforestation) is another potential contributor to sea level change. No global data exist to estimate the historical land water component but model-based estimates of land water storage change caused by natural climate variability do not report any long-term trend during the second half of the twentieth century [Ngo-Duc et al., 2005]. Since 2002, space gravimetry observations from the GRACE mission now allow direct determination of the total land water storage variations (i.e., due to the combination of climate variability and human activities) [e.g., Llovel et al., 2011]. Observations as well as model-based results show that the land water signal is dominated by large interannual variability, especially during ENSO events, leading to 2–4 mm sea level fluctuations over ~ 2 -year-long time span [Boening et al., 2012; Cazenave et al., 2012; Fasullo et al., 2013].

Human-induced activities have a direct impact on land water storage, and hence sea level [e.g., Milly *et al.*, 2010]. Chao *et al.* [2008] showed that dam building along rivers and associated reservoir impoundment has lowered sea level by ~ -0.5 mm/yr during the second half of the twentieth century. Inversely, groundwater extraction for crop irrigation in regions of intensive agriculture has led to a few tenths of mm/yr sea level rise [Wada *et al.*, 2013]. Although subject to considerable uncertainty, estimates for the past few decades suggest near cancellation between net groundwater depletion and dam/reservoir contribution [Konikow, 2011; Pokhrel *et al.*, 2012; Wada *et al.*, 2012]. The situation may change in the future however, because of expected increasing groundwater depletion and decreasing dam building, leading to a net positive contribution to sea level [Konikow, 2011; Wada *et al.*, 2012, 2013].

Global mean sea level budget over the altimetry era. In the IPCC 5th Assessment report [IPCC AR5, 2013], the observed rate of global mean sea level rise over the 1993–2010 time span is compared to estimates of the sum of individual components. Contributions for thermal expansion (including a small, poorly known contribution from the deep ocean), glaciers, Greenland, and Antarctica (in % of the observed rate of global mean sea level rise, equal to 3.2 mm/yr) are 34%, 27%, 10%, and 8.5%, respectively. This means that ocean warming and total land ice melt explain 34% and 45.5% of the global mean rise for the altimetry period, leaving a residual term of about 20%. Contribution uncertainties are in the order of 10% of the observed global mean sea level rate for thermal expansion and glaciers, and of about 15% for the ice sheets. IPCC AR5 [2013] considers an additional contribution of 12% for the anthropogenic land water storage change (net effect of groundwater depletion and dam/reservoir retention). But this component based on the difference between two large numbers of opposite signs is also subject to some uncertainty. The IPCC AR5 numbers (values and associated uncertainties) are in good agreement with those reported by Church *et al.* [2011] and Hanna *et al.* [2013] for thermal expansion and ice sheets over nearly the same time span (1993–2008/2011). However, Hanna *et al.* [2013] propose a larger value for the glacier contribution (43% of the observed global mean sea level rise) based on results from Cogley [2009] and Gardner *et al.* [2013], and a nearly zero net value for the land water contribution [based on Church *et al.*, 2011 and Wada *et al.*, 2012]. In all cases, adopted values lead to quasi closure of the sea level budget over the altimetry era but the combination of systematic errors and/or lack of information on some components hinders perfect closing of the sea level budget.

New observational systems available since about a decade (e.g., Argo for thermal expansion, GRACE space gravimetry for glacier and ice sheet mass balance, total—natural climate plus anthropogenic—land water storage change and direct ocean mass change estimates, Icesat laser altimetry for glaciers, and ice sheet mass change) have been extensively used for sea level budget studies. However, the various publications concentrating on this recent period display significant dispersion in their individual numbers, even though each study supports closure of the sea level budget [Willis *et al.*, 2008; Cazenave *et al.*, 2009; Peltier, 2009; Leuliette and Miller, 2009; Leuliette and Willis, 2011; Chen *et al.*, 2013; Hanna *et al.*, 2013; Von Schuckmann *et al.*, 2013]. Sources of dispersion are numerous: for example, differences in data length (the interannual variability strongly affects the linear trend estimates over few-years-long time spans), data processing methodology for satellite altimetry [e.g., Masters *et al.*, 2012; Henry *et al.*, 2014] and Argo [Llovel *et al.*, 2010; Von Schuckmann and Le Traon, 2011], and ocean depth range for Argo data integration [Von Schuckmann and Le Traon, 2011]. Other sources of differences come from GRACE data processing and GIA corrections applied to the GRACE-based ocean mass and Antarctica mass balance [e.g., Chambers *et al.*, 2010; Chen *et al.*, 2013; Velicogna and Wahr, 2013]. Understanding and reducing these sources of errors (on altimetry-based sea level time series and components) is currently an active research area. Several international projects are or have been recently conducted on that topic, e.g., the ESA Climate Change Initiative “Sea Level,” “Glaciers” and “Ice Sheet” projects, the “Ice2sea” project of the 7th European framework programme, and the “Ice Sheet Mass Balance Exercise”—IMBIE—supported by ESA and NASA. Similar initiatives, e.g., on Argo data processing should also be implemented shortly. Thus, important progress is expected in the near future in global sea level research.

Studies of the historical sea level budget (twentieth century or since 1960) using a combination of observations and model data have also been attempted [Church *et al.*, 2011; Moore *et al.*, 2011; Gregory *et al.*, 2013]. The largest contribution to the twentieth century sea level rise comes from glaciers, followed by ocean warming. While historical information about the Antarctica ice sheet is lacking, these studies suggest its contribution was small.

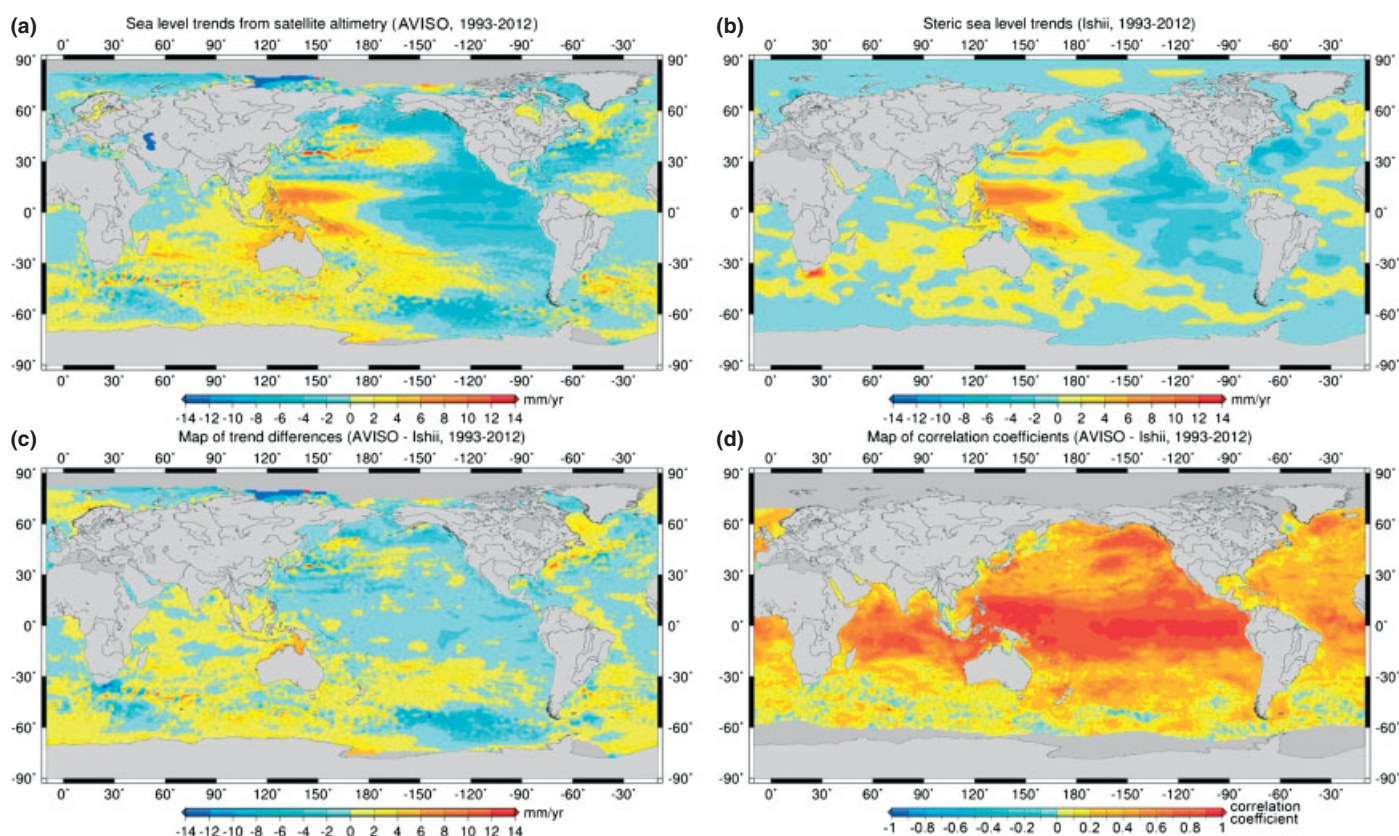


Figure 3. (a) Spatial trend patterns in altimetry-based sea level over 1993–2012 (data from AVISO; global mean trend removed); (b) spatial trend patterns in steric sea level over 1993–2012 (updated version of *Ishii and Kimoto* [2009] data; global mean trend removed); (c) difference map between (a) and (b); and (d) correlation map between altimetry-based and steric sea level variability (global mean trends removed from each data set).

2.2. Regional Variability in Sea Level Trends (Last Decades): Observations and Causes

2.2.1. Climate-Related Regional Variability

Satellite altimetry has revealed that sea level is not rising uniformly; this is illustrated in Figure 3a showing the spatial trend patterns in sea level with respect to the global mean rise over 1993–2012 (gridded sea level time series from AVISO, www.aviso.oceanobs.com, are used for that purpose; these are based on Topex/Poseidon, Jason-1 and Jason-2 altimetry data complemented by ERS-1 and 2, and Envisat data, the latter allow high-latitude coverage up to 82°N/S). Over this 20-year time span, in some regions like the western Pacific, rates of sea level rise were about three times faster than the global mean rate. In other regions, rates were slower than the global mean (e.g., eastern tropical Pacific).

Observed spatial patterns in sea level trends mainly result from changes in the density structure of the oceans associated with temperature and salinity variations (called steric effects) [Bindoff *et al.*, 2007]. Except for the Arctic region, the largest contribution comes from ocean temperature variations. Salinity also plays a role (in particular in the Arctic) and, in many regions, partly offsets thermal expansion [Wunsch *et al.*, 2007; Kohl and Stammer, 2008; Stammer *et al.*, 2013]. Figure 3b shows the spatial trend patterns due to steric effects over the 1993–2012 time span, after removing the global mean steric sea level rise (an updated version of ocean temperature and salinity data from *Ishii and Kimoto* [2009] was used and vertical integration performed between the surface and 700 m depth). As is now well known, observed and steric regional sea level trends agree well both in amplitude and location. Figure 3c shows the residual map (altimetry-based minus steric sea level trends). The residual signal is very small almost everywhere (in the range ± 2 mm/yr, value to be compared to observed and steric trends, in the range ± 10 mm/yr or more), indicating that upper ocean (0–700 m) temperature and salinity changes dominate the regional sea level signal. Other signals such as deep ocean temperature changes and regional water mass redistribution are likely small. Figure 3d shows a correlation map between the altimetry-based and steric interannual

variabilities after removing their respective global mean trend. The correlation is close to 1 almost everywhere in the tropics as well as in the northeast Pacific and north Atlantic, suggesting that besides trends, the year-to-year regional fluctuations of the two signals are also well correlated. The lack of correlation in the Southern Ocean possibly reflects the poorer coverage of steric data in this region.

Owing to geostrophy, local changes in the water density distribution due to temperature and salinity anomalies, and hence in SSH, cause associated horizontal pressure gradients to be balanced by ocean currents. Thus, regional sea level patterns mostly reflect changes in ocean circulation and associated redistribution of heat, salt, and water mass [Landerer *et al.*, 2007; Stammer *et al.*, 2013]. Using a numerical ocean model covering part of the altimetry period, Fukumori and Wang [2013] tried to discriminate changes in ocean circulation, hence regional sea level trends, due to external fluxes of heat, fresh water, and momentum from those due to internal redistribution of preexisting heat and salt anomalies. They showed that internal redistribution accounts for most regional sea level trends especially in regions of strong currents, except in the western tropical Pacific where external sources dominate the signal. This is in agreement with other studies that showed that the large sea level trends observed in this region during the altimetry era (see Figure 3a) are due to deepening of the thermocline in response to decadal increase of Pacific trade winds [Timmermann *et al.*, 2010; Merrifield *et al.*, 2012].

Observations of ocean temperature data available since the mid-1950s show that trend patterns in thermal expansion are not stationary but fluctuate in space and time in response to natural (internal) modes of the climate system, such as ENSO, NAO (North Atlantic Oscillation), and PDO (Pacific Decadal Oscillation) [e.g., Lombard *et al.*, 2005; Bindoff *et al.*, 2007]. So the same is expected for the sea level. Thus, trend patterns observed by satellite altimetry over the last 20 years do not reflect long-term features but rather fluctuations of decadal/multidecadal life time associated with internal climate variability. Past sea level reconstructions that statistically combine long tide gauge records with spatial information about natural/internal ocean modes [e.g., Church *et al.*, 2004; Hamlington *et al.*, 2011; Ray and Douglas, 2011; Meyssignac *et al.*, 2012a], as well as numerical ocean circulation models [e.g., Carton and Giese, 2008; Kohl and Stammer, 2008] correctly reproduce not only the spatial sea level trend patterns observed by satellite altimetry, but also show that sea level trend patterns over longer time spans (e.g., since 1950) are quite different than those of the last two decades. They also confirm that characteristic modes of sea level variability follow those of the natural/internal ocean modes (i.e., ENSO, PDO, and NAO) [see also Stammer *et al.*, 2013]. Similar results have been reported using climate models from the Coupled Model Intercomparison Projects (CMIP3 and CMIP5) [Meyssignac *et al.*, 2012b, 2013]. These decadal trend patterns are superimposed onto longer trend patterns due to gradual anthropogenic global warming, but for the present and recent past, the decadal patterns dominate the observed signals [Meyssignac *et al.*, 2012b, 2013]. However, in the future, the regional trends due to global warming will likely emerge from the decadal (natural) variability.

2.2.2. Nonclimatic Causes of Regional Variability in Sea Level Trends

In addition to the climate-related factors (thermal expansion, salinity effects, and internal mass redistributions), other effects (called “static”) related to the elastic/viscous response of the solid Earth to present-day land ice melt and last deglaciation (the latter being called GIA) also produce regional sea level changes [Milne *et al.*, 2009; Tamisiea and Mitrovica, 2011; Stammer *et al.*, 2013]. In effect, the melted water from the former and present-day ice sheets and glaciers does not get redistributed uniformly over the oceans because of several processes: self-gravitation between ice and water masses, gravity change and solid Earth’s deformations associated with the viscoelastic or elastic response of the Earth to the changing load, as well as changes of the Earth’s rotation due to water and ice mass redistribution [Peltier, 2004, 2009; Chambers *et al.*, 2010; Tamisiea *et al.*, 2010; Spada *et al.*, 2012]. These regional sea level changes are broad-scale but their regional fingerprint is different for each melting source (i.e., last glaciation ice sheets, Greenland, Antarctica, and glaciers). Amplification by several percent of the global mean rise is expected far from the melting source while significant sea level reduction may occur around the melting bodies [Mitrovica *et al.*, 2001; Lambeck *et al.*, 2010; Riva *et al.*, 2010; Tamisiea and Mitrovica, 2011; Spada *et al.*, 2012].

2.2.3. Relative Sea Level Changes Due to Vertical Land Motions

At the local scale, vertical land motions such as uplift or subsidence of the ground due to GIA, tectonic and volcanic activity, sediment loading, groundwater pumping, and oil and gas extraction can produce sea level variations relative to the seafloor [Peltier, 2004; Ballu *et al.*, 2011; Wöppelmann and Marcos, 2012]. Such local phenomena may either amplify or reduce the climate-related and static components. For example, using GPS-based precise positioning, Ballu *et al.* [2011] showed that a coastal site in the Torres islands (north Vanuatu and southwest Pacific) experienced very large subsidence of ~ 12 cm between 2007 and 2009. This subsidence was caused by the 1997 earthquake that generated sudden coseismic vertical ground motions, followed by interseismic ground motions. Accounting for the climatic component, this led to a relative sea level rise of ~ 20 mm/yr between 1997 and 2009, a value 6 times higher than the current climate-related global mean sea level rise. At many other coastal sites worldwide, ground subsidence resulting from groundwater extraction (e.g., in Manila [Raucoles *et al.*, 2013] and Bangkok [Phien-wej *et al.*, 2006]) or sediment loading in river deltas [e.g., Ericson *et al.*, 2006] similarly causes relative sea level rise. For coastal management purposes, what is of interest is the "total" relative sea level change, i.e., the sum of three components: (1) the climatic component expressed by the sum of the global mean rise plus the regional variability discussed above, (2) static effects causing regional sea level changes, and (3) the local vertical land motion component. Recent studies have shown that the sum of these three components leads to large deviation of the local relative sea level change with respect to the global mean rise [Becker *et al.*, 2012; Palanisamy *et al.*, 2012; Peng *et al.*, 2013].

2.3. Future Sea Level Rise (Global and Regional Scales)

There is little doubt that sea level will continue to rise in the future decades and centuries [Meehl *et al.*, 2007]. Most recent projections of the future sea level rise from ensemble means of process-based climate models indicate that by 2100, global mean sea level should be on average higher than today in the range of 40–75 cm, depending on the radiative forcing scenario [IPCC AR5, 2013]. Accounting for model dispersion leads to a larger range from ~ 25 to 95 cm. Medium warming scenarios (RCP4.5 and RCP 6.0) project a global mean sea level elevation of ~ 50 cm by 2100 while a value of ~ 75 cm is projected for the high warming scenario (RCP8.5). Ocean warming, glaciers melting, and ice sheet mass loss will contribute $\sim 45\%$, 26% , and 23% , respectively, the remaining being attributed to land water storage change. This proportion is almost the same for all scenarios.

Processes causing recent-past and present-day regional sea level variations will continue in the future but of a proportion possibly significantly different from that of today. The largest regional variations by 2100 will come from steric effects in response to changes in wind stress as well as heat and fresh water fluxes [Lowe and Gregory, 2006; Pardaens *et al.*, 2010; Yin *et al.*, 2010; Suzuki and Ishii, 2011]. Increased sea water freshening in the Arctic region due to sea and land ice melt is expected to enhance sea level rise in this region. Higher than average sea level rise is also projected along the eastern coast of North America, as a result of decreasing deep water formation in the Labrador Sea and associated slowing down of the Atlantic meridional overturning circulation [e.g., Yin *et al.*, 2009; Sallenger *et al.*, 2012].

Deformation of ocean basins and self-gravitation (static effects) due to future land ice melt and other water mass redistributions (e.g., due to land water storage) will also give rise to regional sea level changes, causing amplification of the global mean rise by up to 30% in some regions (e.g., in the tropics) and large negative contributions in the vicinity of the melting bodies [e.g., Mitrovica *et al.*, 2009; Tamisiea and Mitrovica, 2011; Spada *et al.*, 2012; Riva *et al.*, 2010]. Until very recently, projections of future regional variability were limited to effects of thermal expansion and salinity changes in response to climate change [e.g., IPCC AR4, 2007]. Static effects and human-induced changes in land hydrology were not included. Attempts were recently made to produce total relative sea level projections by 2100 accounting for all sources of regional variability including static effects [Slangen *et al.*, 2012; IPCC AR5, 2013]. Summing all regional effects led to large departure from the global mean rise in many regions, in a proportion roughly independent of the warming scenario. Amplification of up to 20%–30% of the global mean rise is projected in several regions, in particular in the tropics. Knowledge of the future total relative sea level is important for assessing future regional impacts. However, as mentioned above, the regional projections only concern the long-term signal due to anthropogenic climate change and associated static effects. The decadal

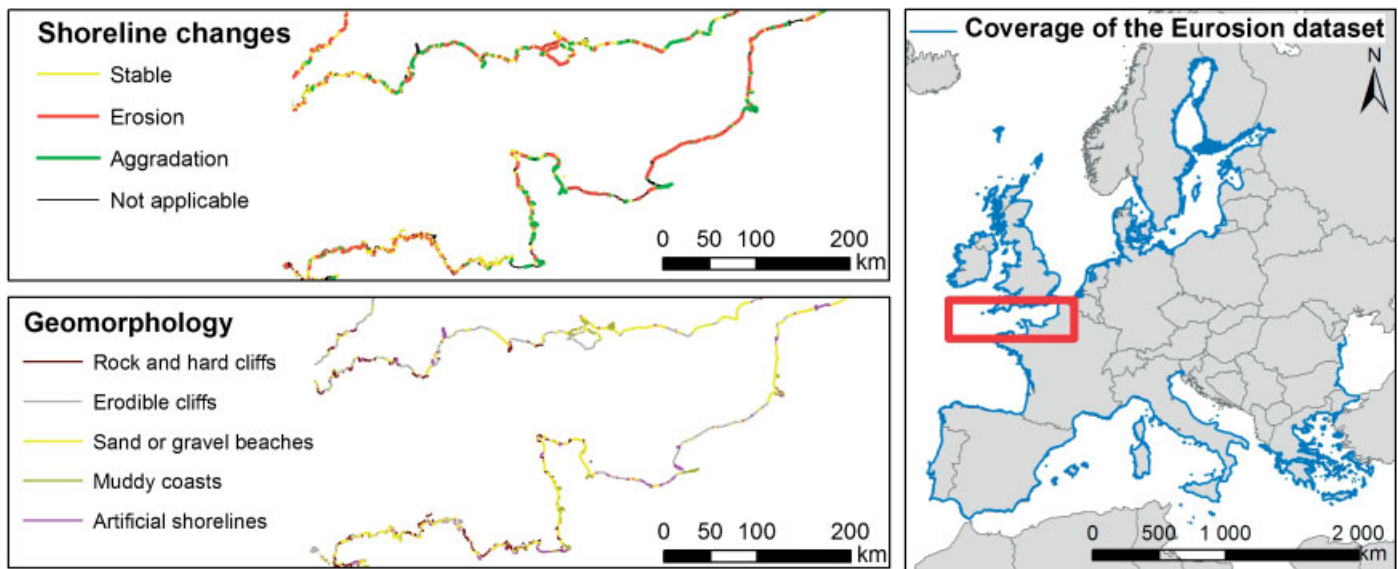


Figure 4. Example of the “EuroSION” coastal dataset (www.euroSION.org) providing quantitative information on shoreline changes and coastal geomorphology. This figure highlights the coverage of the existing dataset (right) as well as the high spatial variability of shoreline changes and geomorphology. Because of this high variability, sea level rise impacts can only be evaluated at local scales.

signal caused by internal climate variability is generally not included as it requires precise initial conditions of the ocean state. This missing factor adds significant uncertainty to projected future regional sea level changes [Hu and Deser, 2013]. Future vertical ground motions are also generally ignored although some attempts have been made recently for the northwest coast of the USA based on tectonic setting information [National Research Council, 2012].

3. Coastal Impacts of Sea Level Rise

Sea level rise is expected to aggravate coastal erosion, extreme marine flooding, or saltwater intrusion in coastal aquifers [Nicholls and Tol, 2006; Nicholls et al., 2007; Nicholls and Cazenave, 2010]. For each type of impact, the dynamic response of coastal systems remains highly uncertain. This has motivated numerous studies on the evolution of shorelines, as well as on potential causes, among them, sea level rise.

3.1. Observations of Contemporary Shoreline Changes Over the Last Decades

Our knowledge of shoreline changes over the past few decades comes primarily from in situ observations or from the analysis of ancient aerial photographs. By collecting such observations worldwide, a survey undertaken under the auspices of the International Geographic Union revealed that a majority of shorelines are experiencing an erosive crisis [Bird, 1987]. This study stated that 70% of world beaches were eroding, whereas only 10% were accreting. It also reported continuous retreat of erodible cliffs and erosion of many coastal swamps and deltas. Since the pioneering study of Bird [1985], many local observations of shoreline changes have been published worldwide. However, in most regions, shoreline monitoring remains sparse, such that neither consolidated nor quantified information about global shoreline change is available today. A few studies exist nevertheless from country to continental scale [e.g., Queleennec et al., 1998; Thieler and Hammar-Klose, 1999] (EuroSION, www.euroSION.org). They provide quantitative information on shoreline changes and geomorphology gathered in coastal databases through geographical information systems. As an example, the content and coverage of the European coastal database “EuroSION” is provided in Figure 4. Existing coastal databases highlight the heterogeneity of coastline behaviors depending on their geomorphological settings. For example, the European database shows that about 30% of European beaches are currently eroding, whereas 60% of wetlands are accreting. In addition, status of European coastlines significantly differs from the global case: Excluding Scandinavia coasts currently uplifting in response to GIA, only 40% of beaches are found in erosion, which is significantly less than the 70% found at global scale by Bird [1987]. While there are obviously regional differences in coastal erosion, the representativeness of coastal sites included in any global study is limited by the amount of available

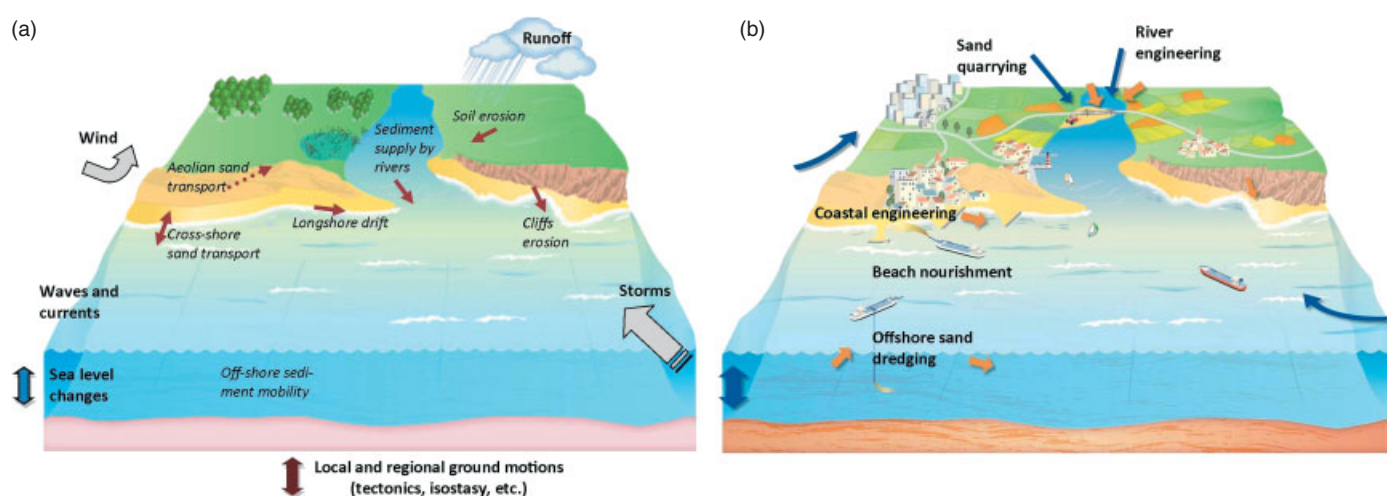


Figure 5. Sketch showing processes involved in coastal sediment transports and shoreline changes in the absence of human intervention (a), and with direct and indirect anthropogenic actions affecting sediment mobility (b).

local observations. This highlights the need for more observations on contemporary shoreline changes. This could be achieved by collecting new precise coastal data, updating current databases, and sharing the information among the scientific community.

3.2. Role of Sea Level Rise in Shoreline Changes Over the Last Decades

Because global mean sea level has been rising for several decades, it has been suggested that a link exists between global coastal erosion and sea level rise [Vellinga and Leatherman, 1989]. Consequently, the issue of identifying a possible role of sea level rise in shoreline changes in specific coastal localities has been the topic of numerous studies [e.g., Allen, 1981; Inman and Dolan, 1989; Zhang et al., 2004; Corbella and Stretch, 2012]. However, conclusions remain controversial:

1. Several studies show examples of rapid relative sea level changes leading to shoreline retreats. For example, in the Chao-Phraya river delta (Thailand), the combined effects of sediment reduction and rapid subsidence due to groundwater pumping have led to shoreline retreat of up to 1 km in some places [Uehara et al., 2010]. However, even in rapidly subsiding coasts, other processes (e.g., the effects of waves, storms, or of human activities) may still dominate. For example, the Barrier islands in the Mississippi delta are affected by rapid subsidence, but the processes involved in causing their disintegration seem mostly related to sand dredging and sediment availability [List et al., 1997; Morton, 2007].
2. Other studies have attempted to check whether decadal to multidecadal coastal erosion is more likely when sea level is rising faster. For that purpose, the studies used observations of shoreline evolution in areas where sea level significantly deviated from the global average during the past decades. In several sites, a relation between shoreline or beach changes, and rates of relative sea level rise has been found, e.g., along the eastern coast of the USA [Zhang et al., 2004; Gutierrez et al., 2011], at beaches of two islands of Hawaii [Romine et al., 2013], and in two deltas of Papua New Guinea [Shearman et al., 2013] and in Europe [Yates and Le Cozannet, 2012]. Other studies have provided evidence that even in areas affected by fast sea level rise (e.g., western tropical Pacific) [Becker et al., 2012], the effects of sea level rise cannot be detected so far because they are masked by the effects of waves, currents, cyclones, and anthropogenic forcing agents [e.g., Le Cozannet et al., 2013; Yates et al., 2013].
3. Finally, in areas where sea level rise is close to the global average, there is evidence that other processes account for shoreline changes: natural factors such as the effects of waves and storms [e.g., Webb and Kench, 2010; Ford, 2013] or factors directly due to human actions such as coastal land reclamation or embankments [Webb and Kench, 2010]. Moreover, even in areas not directly affected by human activities, indirect anthropogenic actions may impact the shorelines. This is the case in New Caledonia, where the dominant process affecting estuarine shorelines is related to mining activities, fine sediments from degraded soils quickly migrating to the estuaries [Garcin et al., 2013].

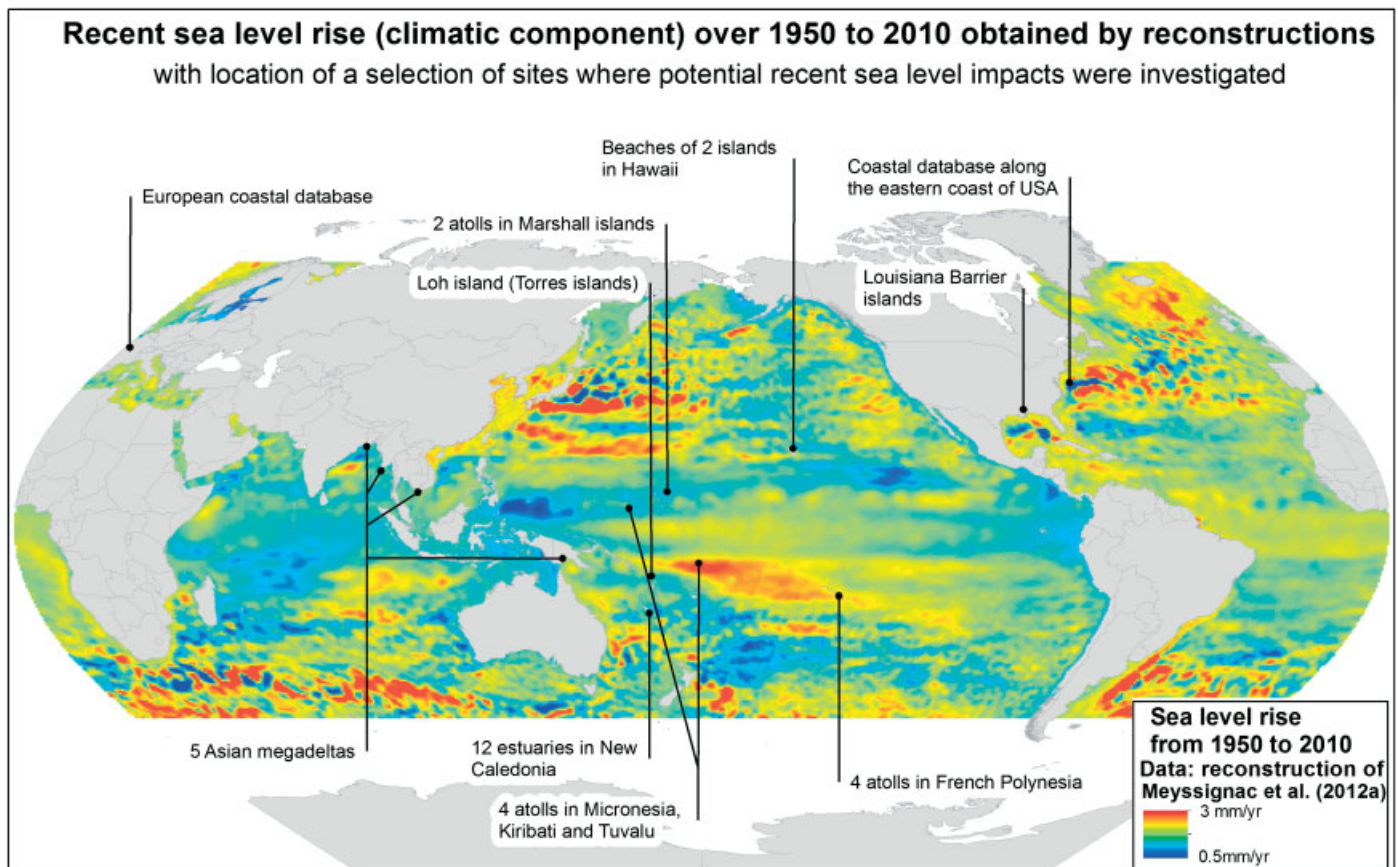


Figure 6. Spatial trend patterns in past sea level (climatic component only) over 1950–2010 based on the Meyssignac et al. [2012a] reconstruction. A selection of sites where potential recent impacts were investigated are also shown (studies quoted in this paper only). These sites refer to the following studies: Louisiana Barrier islands: List et al. [1997] and Morton [2007]; coastal database in the eastern coast of the USA: Zhang et al. [2004] and Gutierrez et al. [2011]; western Pacific atoll islands: Webb and Kench [2010] and Ford [2012 and 2013]; beaches of two islands of Hawaii: Romine et al. [2013]; French Polynesia high islands and atolls: Yates et al. [2013] and Le Cozannet et al. [2013]; Loh Island: Ballu et al. [2011]; five Asian megadelta: Shearman et al. [2013]; and European coastal database (EuroSION, www.euroSION.org) and Yates and Le Cozannet [2012].

If no consensus exists on the actual role of sea level rise in contemporary shoreline erosion, this could be either because each coastal site is differently responding to sea level rise or because of lack of observations on both shorelines and dynamical phenomena acting at the coast [Ford, 2013].

3.3. Modeling the Coastal Response of Sea Level Rise

The previous section shows that all studies based on analysis of shoreline observations recognize the importance of local coastal factors: low-lying coasts are neither simply submerged as sea level rises nor systematically responding as predicted by simple conceptual schemes (e.g., the Bruun rule assuming landward translation of a fixed cross-shore profile) [Bruun, 1962; Cooper and Pilkey, 2004]. A remaining option to evaluate the impacts of sea level rise would be to model these coastal processes, namely hydrometeorological, biological, and geodynamic factors, and effects of human activities [e.g., Bird, 1996; Stive et al., 2002] (Figure 5). These processes are interacting nonlinearly on different spatiotemporal scales, e.g., as the nearshore bathymetry evolves during storms, seasons, and over decades, wave and surge propagations are in turn changed, thus modifying sediment transport [e.g., Coco and Murray, 2007]. However, although present-day coastal changes or their evolution at geological timescales can be well understood, many uncertainties remain about shoreline changes at decadal to centennial timescales [e.g., Woodroffe and Murray-Wallace, 2012]. Noteworthy are the current efforts to improve current coastal morphodynamics modeling tools [e.g., De Vriend et al., 1993; Amoudry and Souza, 2011], to better take into account effects of sea level rise [e.g., Stive, 2004; Davidson-Arnott, 2005; Ranasinghe et al., 2012, 2013; Grady et al., 2013], and to gain insight into the coupled impacts of natural effects and anthropogenic factors [e.g., McNamara

Future sea level rise and a review of vulnerable coastal cities

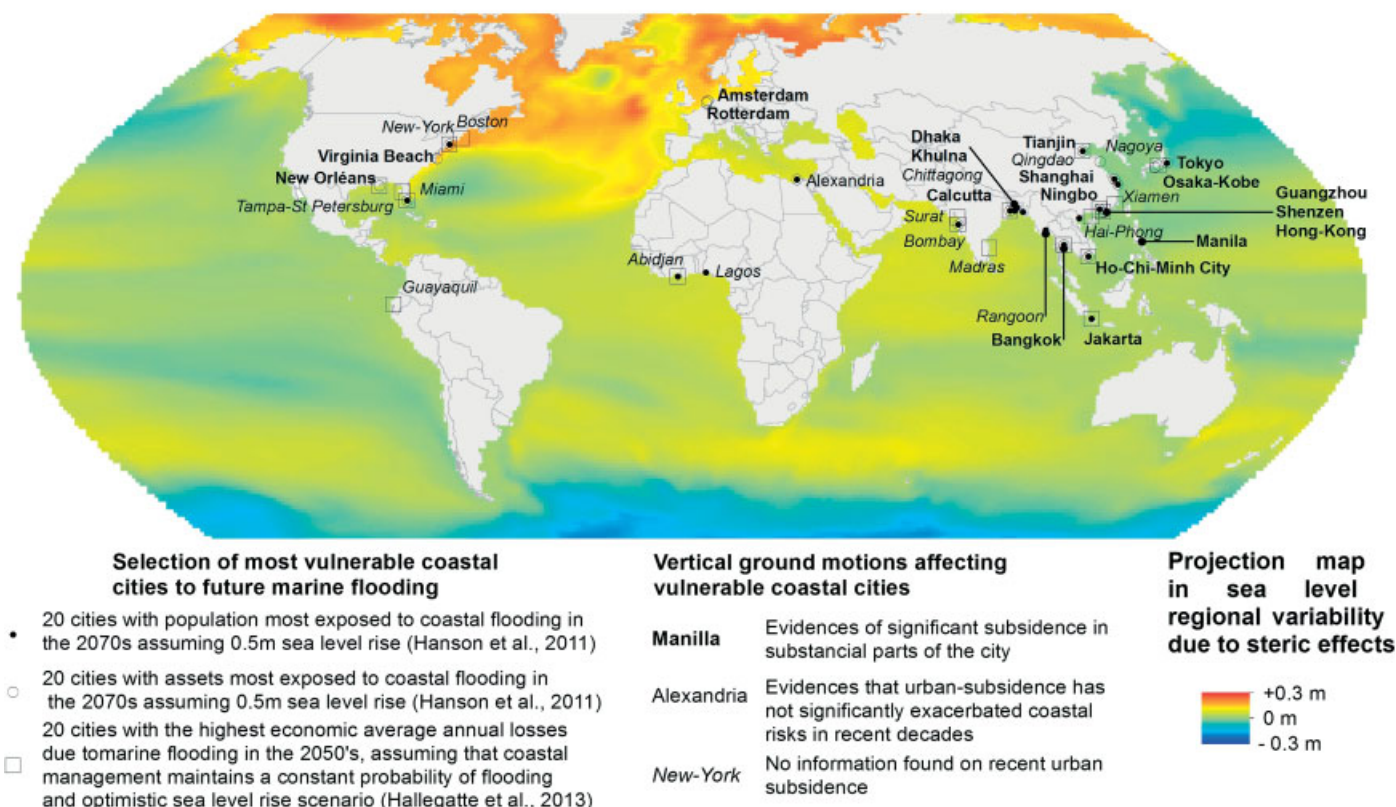


Figure 7. Projection map in sea level regional variability due to steric effects (differences between the 2080–2100 and 1980–2000 periods, with the global mean difference removed; output of the CNRM-CM5 run rcp8.5 r11p1 climate model [Voltaire et al., 2013]) on which are superimposed sites of most vulnerable coastal cities [Hanson et al., 2011; Hallegatte et al., 2013]. This map highlights that by the end of the 21st century, many vulnerable cities are located along the eastern coast of the USA and in southeast Asia. There is evidence of ground subsidence in some areas of several of these cities but systematic measurements by precise positioning techniques are lacking. Coastal cities are selected according to two global assessments of flood risk in world coastal cities [Hanson et al., 2011; Hallegatte et al., 2013]. Information on ground motions is available in the following studies: Nicholls [2011]; Wang et al. [2012a, 2012b]; Hu et al. [2004]; Chatterjee et al. [2007]; Dixon et al. [2006]; Chen et al. [2010]; Cuenca et al. [2007]; Wöppelmann et al. [2013]; Chaussard et al. [2013]; Ho-Tong-Minh-Din (personal communication).

and Werner, 2008; Lazarus et al., 2011; McNamara and Keeler, 2013]. Clearly, further research is needed to better appraise the consequences of sea level rise on coastal morphological changes.

3.4. Future Impacts of Sea Level

Considering the most recent regional sea level projections [e.g., IPCC AR5, 2013], preliminary conclusions on future regional impacts can be drawn. First, almost all coastlines worldwide will be affected by sea level rise by the end of the 21st century. Moreover, in some regions, the combination of steric and static effects will cause significant amplification of the global mean rise (see section 2.3). For example, climate models project that because of steric effects, sea level rise will be higher than the global average along the eastern coast of the USA by 2100 (see Figure 6). This is particularly of concern as this region is already subject to relative sea level rise because of GIA effects—as shown by several studies [e.g., Zhang et al., 2004; Gibbons and Nicholls, 2006; Miller et al., 2013].

Climate model projections indicate that most of the midlatitudes should experience a sea level elevation close to the global mean in the range of a few decimeters to ~1 m by 2100 depending on model dispersion and warming scenario. In the tropics, the combined steric and static effects will amplify sea level rise by 20%–30% with respect to the global mean. In this range of sea level elevation (decimeters to 1 m), it is difficult to accurately assess the response of coastal systems (see section 3.1), and mapping regional impacts of sea level at global scale is therefore difficult. However, it is still possible to provide a map of potential vulnerable localities (hotspots) affected by future sea level rise. Figure 7 shows such

urban hotspots superimposed on a projection map of regional variability due to steric effects (sea level projections from the Centre National de la Recherche Météorologique—CNRM—CMIP5 model) [Voldoire *et al.*, 2013]. This selection of urban hotspots is based on a number of previous studies about coastal cities [Hanson *et al.*, 2011; Hallegatte *et al.*, 2013], using complementary information for assessing subsidence. Figure 7 highlights the fact that Southeast Asia concentrates many locations highly vulnerable to relative sea level rise. Similar maps can be found for vulnerable coastal wetlands and small islands in Webb *et al.* [2013] and Nicholls and Cazenave [2010], respectively. They provide first-order level of future regional impacts of sea level rise.

Importantly, sea level rise is not the only factor of risk for the hotspots presented in Figure 7. For example, in an assessment of the exposure of world coastal cities to extreme flooding by 2070, Hanson *et al.* [2011] highlighted that at global scale, population and economic growth was the most important predictable driver of coastal risk increase, therefore dominating sea level rise. This reminds that coastal zones are experiencing drastic environmental changes since decades, including rapid population growth in coastal urban areas and megacities, and also more scattered urban development. Therefore, sea level rise and climate change will act as additional threats in already largely degraded coastal environments. In this respect, an important role of sea level scientists will be to help coastal managers to define realistic scenarios of sea level changes, including target projections and high-end scenarios [Katsman *et al.*, 2011].

4. Conclusion

In this paper, we first summarized the most up-to-date knowledge about present-day sea level observations and the various contributions causing global mean sea level rise and regional sea level variations. We highlighted the importance of the regional variability that superimposes the global mean rise. We showed that we are not far from closing the sea level budget and also reported that significant uncertainties still exist on sea level observations as well as on the steric and mass contributions. Reducing these errors (on altimetry-based sea level time series and components) is currently an active area of research implying a number of international projects. Monitoring sea level changes at global and regional scales and understanding the causes of these changes are indeed highly important to constrain and validate the climate models developed to project future changes, not only in terms of global mean but also at regional scale. This paper also briefly discusses the coastal impacts of sea level rise. In the recent decades, observations indicate that coasts have generally experienced erosion. Whether this is due to sea level rise or not remains presently controversial. Nevertheless, the local settings of coastal systems are obviously extremely important to characterize their response to sea level rise. Considering regional patterns of sea level variations in the future, we note that vulnerable areas along the eastern coast of the USA should be affected by more rapid sea level rise because of ocean circulation changes and static effects. Southeast Asia is another region that should be affected by the adverse effects of sea level rise because of the high exposure of populations to risks of flooding and erosion.

Although considerable progress has been realized during the past one to two decades in measuring sea level change globally and regionally, and in understanding the climate-related causes of observed changes, we are still faced to new challenges in terms of observations, modeling, and impact studies. Continuity of space-based and in situ observing systems of sea level variations and components as well as of coastal changes is clearly a major need. Besides, high priority should be given to the development of integrated, multidisciplinary studies of present-day sea level changes (global and regional), accounting for the various factors (climate change, ocean/atmosphere forcing, land hydrology change—both natural and anthropogenic, solid Earth processes, etc.) that act on a large variety of spatiotemporal scales. Sea level projections from climate models need to include all factors causing regional sea level changes. In addition, as local (relative) sea level rise is among the major threats of future global warming, it is of primary importance to develop multidisciplinary studies to understand and discriminate causes of current sea level changes in some key coastal regions, integrating the various factors that are important at local scales (climate component, oceanographic processes, sediment supply, ground subsidence, anthropogenic forcing, etc.). Ultimately, such studies would be useful for coastal scientists and stakeholders concerned by relative sea level rise, at it can be felt at the coast.

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