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Review

Sea level: A review of present-day and recent-past changes and variability

Benoit Meyssignac*, Anny Cazenave

LEGOS-CNES, Toulouse, France

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ABSTRACT

In this review article, we summarize observations of sea level variations, globally and regionally, during the 20th century and the last 2 decades. Over these periods, the global mean sea level rose at rates of 1.7 mm/yr and 3.2 mm/yr respectively, as a result of both increase of ocean thermal expansion and land ice loss. The regional sea level variations, however, have been dominated by the thermal expansion factor over the last decades even though other factors like ocean salinity or the solid Earth's response to the last deglaciation can have played a role. We also present examples of total local sea level variations that include the global mean rise, the regional variability and vertical crustal motions, focusing on the tropical Pacific islands. Finally we address the future evolution of the global mean sea level under ongoing warming climate and the associated regional variability. Expected impacts of future sea level rise are briefly presented.

Contents

1. Introduction

Sea level variations spread over a very broad spectrum. The largest global-scale sea level changes (100-200 m in amplitude) occurred on geological time scales (on the order of ~100 million years) and depended primarily on tectonic processes (e.g. large-scale change in the shape of ocean basins associated with seafloor spreading and mid-ocean ridges expansion) (e.g. Haq and Schutter, 2008; Mueller et al., 2008; Miller et al., 2011). With the formation of the Antarctica ice sheet about 34 million years ago, global mean sea level dropped by about 50 m. More recently, cooling of the Earth starting about 3 million years ago, led to glacial/interglacial cycles driven by incoming insolation changes in response to variations of the Earth's orbit and obliquity (Berger, 1988). Corresponding growth and decay of northern hemisphere ice caps on time scales of tens of thousand years produced large

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* Corresponding author.
E-mail address: benoit.meyssignac@legos.obs-mip.fr (B. Meyssignac).

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oscillations of the global mean sea level, on the order of >100 m (e.g. Lambeck et al., 2002; Rohling et al., 2009; Yokoyama and Esat, 2011). On shorter (decadal to multi centennial) time scales sea level fluctuations are mainly driven by climate change in response to natural forcing factors (e.g. solar radiation variations, volcanic eruptions) and to internal variability of the climate system (related for example to atmosphere–ocean perturbations such as El Niño-Southern Oscillation – ENSO, North Atlantic Oscillation – NAO, Pacific Decadal Oscillation – PDO). Since the beginning of the industrial era, about two centuries ago, mean sea level is also responding to anthropogenic global warming. In effect, sea level is a very sensitive index of climate change and variability. For example, as the ocean warms in response to global warming, sea waters expand, and thus sea level rises. As mountain glaciers melt in response to increasing air temperature, sea level rises because of fresh water mass input to the oceans. Similarly, ice mass loss from the ice sheets causes sea level rise. Corresponding increase of fresh water into the oceans changes water salinity, hence sea water density as well as ocean circulation that in turn affects sea level at a regional scale. Modification of the land hydrological cycle due to climate variability and direct anthropogenic forcing leads to changes in precipitation/evaporation regimes and river runoff, hence ultimately to sea level changes. Thus global, regional and local climate changes affect sea level (e.g. Bindoff et al., 2007).

In this article, we review observations of sea level variations, globally and regionally, focusing on the 20th century and the last 2 decades (Sections 2–4). We also examine the causes of sea level variations, and discuss successively components of the global mean sea level rise over the past two decades, and the contributions to the interannual global mean sea level (Section 5). Regional variability in sea level is addressed in Sections 6 and 7. In Section 8, we show examples of total sea level changes measured over the past 5–6 decades. In the last section (Section 9) we briefly address the future evolution of the global mean sea level under warming climate and associated regional variability. Concluding remarks are proposed in Section 10.

2. Paleo sea level (since the last glacial maximum and last 2000 years)

Quaternary ice ages caused large-scale fluctuations of the global mean sea level, of >±100 m amplitude, as a result of the growing and decay of northern hemisphere ice caps (Rohling et al., 2009). Since about 800,000 years, the characteristic periodicity of these fluctuations is ∼100,000 years. At the last glacial maximum, ∼20,000 years ago, global mean sea level was −130 m below present level (Lambeck et al., 2002). Subsequent melting of the northern hemisphere ice caps caused by insolation changes led to sustained sea level rise during more than 10,000 years, as illustrated in Fig. 1 (from Lambeck et al., 2002). Due to the complex history of ice cap melting (e.g. Peltier, 2004), the rate of sea level rise was not constant, as evidenced by several paleo sea level indicators of geological and biological origin (e.g. coral data, micro-atolls, beach rocks, notches, etc.). For example, episodes of rapid rise (>1 m per century) have been reported at about −14,000 years (Bard et al., 2010). At the beginning of the Holocene (11,000 years ago), the rate of rise decreased significantly and sea level stabilized between −6000 years and −2000 years ago (Lambeck et al., 2010).

There is no evidence of large fluctuations of the global mean sea level during the past two millennia. Dating of microfossils in salt-marsh environments (Lambeck et al., 2010; Kemp et al., 2011) and archaeological evidence (e.g. from Roman fish tanks, Lambeck et al., 2004) indicate that sea level rise did not exceed 0.05–0.07 m per century over the past 2000 years (see also Miller et al., 2009). Fig. 2 (from Kemp et al., 2011) illustrates this fact. It shows the sea level evolution of the last two millennia based on salt-marsh microfossils analyses along the eastern coast of North America. According to this study, sea level was a few decimeters higher/lower during the Middle Age (12th–14th century)/Little Ice Age (16th–18th century), but rates of rise remained very low until the beginning of the industrial era (late 18th to early 19th century) when a large upward trend of the mean sea level becomes well apparent (Kemp et al., 2011; also Gehrels et al., 2005, 2006; Woodworth et al., 2011a). This epoch corresponds to the beginning of the instrumental era that allowed direct sea level measurements with tide gauges (Woodworth et al., 2008, 2011b) and now satellites (e.g. Fu and Cazenave, 2001; Church et al., 2010), unlike during the previous centuries/millennia for which sea level variations are deduced indirectly from proxy records.

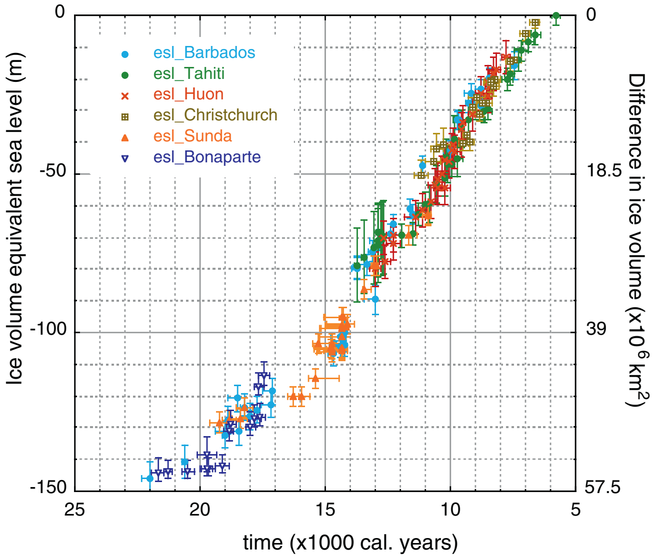

Fig. 1. Changes in global ice volume and sea level equivalent from the last glacial maximum to the present. The figure shows ice-volume equivalent sea level for the past 20 kyr based on isostatically adjusted sea-level data from different localities (updated from Lambeck et al., 2002 with a revised dataset for the Sunda shelf from Hanebuth et al., 2009).

3. The tide gauge-based instrumental record (20th century)

The very first tide gauges were installed in ports of northwestern Europe to provide information on ocean tides (e.g. Mitchum et al., 2010). Tide gauges records from Amsterdam (the Netherlands), Stockholm (Sweden) and Liverpool (UK) extend back to the early to mid-18th century, while those from Brest (France) and Swinoujscie (Poland) started in the early 19th century. In the southern hemisphere, tide gauge records at Sydney and Freemantle (Australia) are among the longest (starting in the late 19th century). Progressively, the tide gauge network extended (see for example Fig. 5.2 from Mitchum et al., 2010) but for long term sea level studies, the number of records remains nevertheless very small and the geographical spread is quite inhomogeneous. Besides, tide gauge records often suffer from multi-year- or even multi-decade-long gaps. The sparse and heterogeneous coverage of tide gauge records, both temporally and geographically, is clearly a problem for estimating reliable historical mean sea level variations.

Tide gauges measure sea level relatively to the ground, hence monitor also ground motions. 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 (ground water pumping and oil/gas extraction), tide gauge data are directly affected by the corresponding ground motions. Post

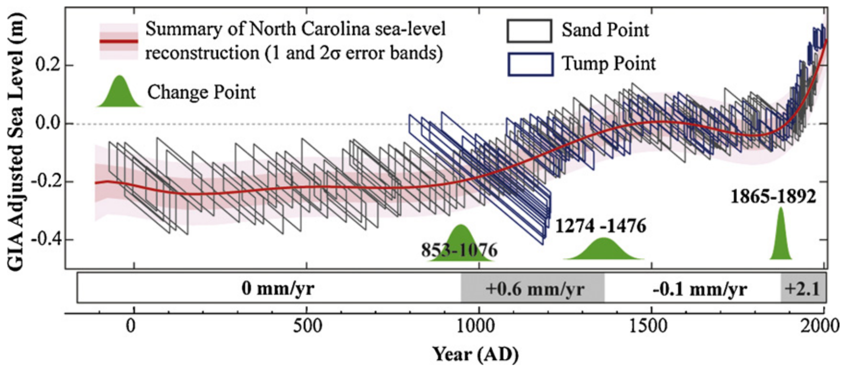

Fig. 2. Relative sea level reconstruction for the last 2000 years from salt-marsh data analyses. (From Kemp et al., 2011.)

glacial rebound, the visco-elastic response of the Earth crust to last deglaciation (also called Glacial Isostatic Adjustment – GIA) is another process that gives rise to vertical land movement. While vertical ground motions need to be considered when estimating total local (relative) sea level change (see Section 8), to compare observed sea level variations with climate-related components, the ground motions need to be subtracted.

To provide a reliable historical sea level time series based on tide gauge records, various strategies have been developed. Some authors only considered a few tens of long (>60 years) good quality tide gauges records from tectonically stable continental and island coasts, and corrected the data for GIA only (e.g. Douglas, 1991, 2001; Peltier, 2001; Holgate, 2007). Other authors used a larger set of records from a variety of regions, covering different time periods, and developed different approaches to derive the mean sea level curve. For example, Jevrejeva et al. (2006, 2008) used a regional coherency criterium among tide gauge records in order to exclude outliers (e.g. tide gauge affected by large local vertical ground motions). Church et al. (2004) and Church and White (2006, 2011) developed a 'reconstruction' method (see Section 6) to determine a 'global mean' sea level curve from sparse tide gauge records since 1870. In these studies, the only vertical motion corrected for is GIA. Since a few years, the availability of GPS-based precise positioning at some tide gauge sites has allowed direct measurements of vertical ground motion. This is the approach used by Woppelmann et al. (2007, 2009). GPS-based vertical ground motions are still based on short records (10–15 year-long only) but it is generally assumed that these are representative of long-term trends. In spite of a variety of approaches, the results based from these studies are rather homogeneous and give a mean rate 20th century rise in the range of 1.6–1.8 mm/yr. The Church and White (2011)'s tide gauge-based mean sea level curve since 1870 is shown in Fig. 3. According to this figure, 20th century sea level rise was not linear. In fact, interannual to decadal variability (in addition to shorter-term fluctuations not considered here) are superimposed on the mean trend. These will be discussed in Section 5.2.

4. The altimetry era

Since the early 1990s, sea level variations are measured by altimeter satellites (Chelton et al., 2001; Fu and Cazenave, 2001). The satellite altimetry measurement is derived as follows (see Fig. 4): the onboard radar altimeter transmits microwave radiation towards the sea surface which partly reflects back to the satellite. Measurement of the round-trip travel time provides the height of the satellite above the instantaneous sea surface. The sea surface height measurement is deduced from the difference between the satellite distance to the Earth's centre of mass (deduced from precise orbitography) and the satellite altitude above the sea surface

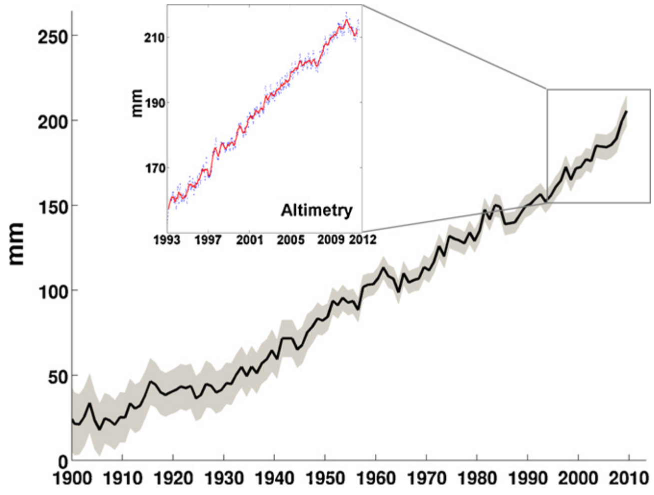

Fig. 3. 20th century sea level curve (in black and associated uncertainty in light gray) based on past sea level reconstruction using tide gauge data and additional information (from Church and White, 2011). In the box: altimetry-based sea level curve between 1993 and 2011 (data from AVISO; http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/msla/index.html) (blue points: data at 10-day interval; the red curve is based on a 3-month smoothing of the blue data).

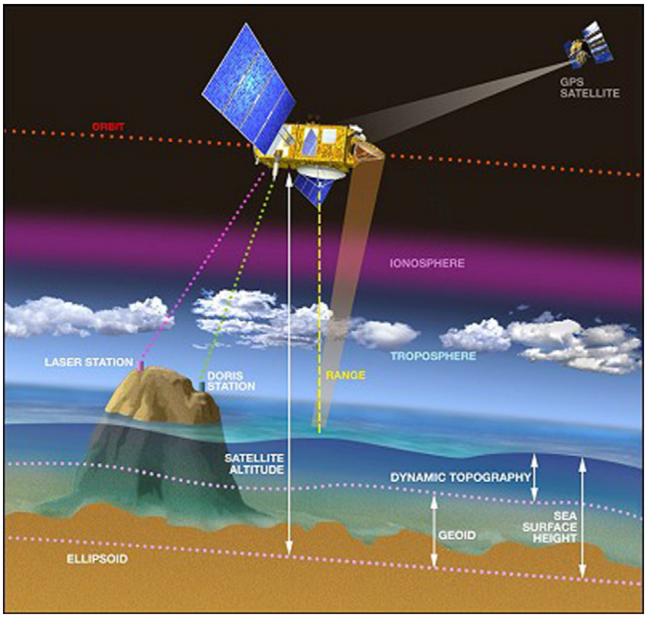

Fig. 4. Principle of the satellite altimetry measurement.

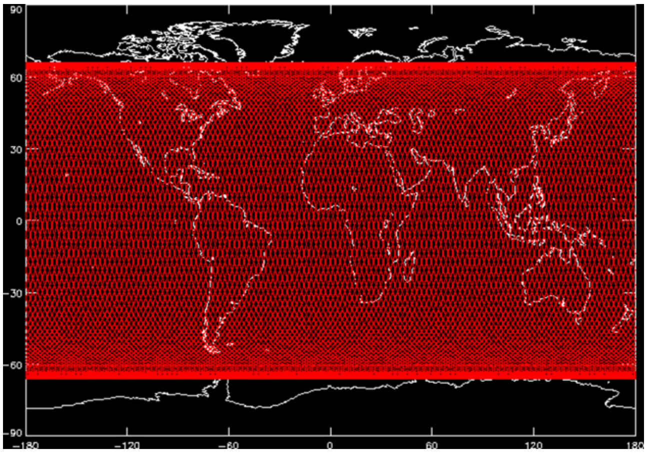

Fig. 5. Earth's coverage by the Topex/Poseidon, Jason-1 and Jason-2 altimeter satellites during an orbital cycle of 10 days.

(deduced from the radar altimeter measurement). The sea surface height measurement needs to be corrected for various factors due to ionospheric and tropospheric delay, and for biases between the mean electromagnetic scattering surface and the sea surface at the air-sea interface. Other corrections due geophysical effects, such as solid Earth, pole and ocean tides are also applied. Altimeter satellites cover the whole Earth surface within a few days – called orbital cycle (see Fig. 5). Geographical averaging of all individual sea surface heights measurements during an orbital cycle allows determining a global mean sea level value, and further constructing a global mean sea level time series. As the satellite flies over the same areas from one orbital cycle to another, it is also possible to construct a 'local' sea level time series, hence deduce regional variability in sea level.

High-precision satellite altimetry began with the launch of the Topex/Poseidon satellite in 1992 and its successors, Jason-1 (2001) and Jason-2 (2008). The precision of an individual sea surface height measurement based on these missions has now reached the 1–2 cm level (e.g. Nerem et al., 2010; Beckley et al., 2010; Mitchum et al., 2010). Precision on the global mean rate of rise is currently of ~0.4–0.5 mm/yr. This value is based on error budget analyses of all sources of error affecting the altimetry system or on comparisons with tide gauge-based sea level measurements (e.g. Ablain et al., 2009). In Fig. 3, the altimetry-based global mean sea level curve since early 1993 is superimposed on the tide-gauge-based 20th century sea level curve. We note an almost linear increase (except for temporary anomalies associated with the 1997/1998 El Niño and the 2007/2008 and 2010/2011 La Niña events). Over this 18 year-long period, the rate of global mean sea level rise amounts to 3.2 ± 0.5 mm/yr (e.g. Cazenave and Llovel, 2010; Nerem et al., 2010; Mitchum et al., 2010). This rate is significantly higher than the mean rate recorded by tide gauges over the past decades, eventually suggesting sea level rise acceleration (Merrifield et al., 2009).

5. Causes of present-day GMSL changes

5.1. Global mean 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. The recent trends of these contributions most likely result from global climate change induced by anthropogenic greenhouse gases emissions.

5.1.1. Ocean warming

Analyses of in situ ocean temperature data collected over the past 50 years by ships and recently by Argo profiling floats (Argo Data Management Team, 2008; Roemmich et al., 2009) indicate that ocean heat content, and hence ocean thermal expansion, has significantly increased since 1950 (e.g. Levitus et al., 2009; Ishii and Kimoto, 2009; Domingues et al., 2008; Church et al., 2011a). Ocean warming explains about 30%–40% of the observed sea level rise of the last few decades (e.g. Church et al., 2011b). A steep increase was observed in thermal expansion over the decade 1993–2003 (e.g. Lyman et al., 2010; Levitus et al., 2009; Ishii and Kimoto, 2009), but since about 2003, thermal expansion has increased less rapidly (Lyman et al., 2010; Llovel et al., 2010; von Schuckmann and Le Traon, 2011). The recent slower rate of steric rise likely reflects short-term variability rather than a new long-term trend. On average, over the satellite altimetry era (1993–2010), the contribution of ocean warming to sea rise accounts for ~30% (Cazenave and Llovel, 2010; Cazenave and Remy, 2011; Church et al., 2011b).

5.1.2. Glaciers melting

Being very sensitive to global warming, mountain glaciers and small ice caps have retreated worldwide during the recent decades, with significant acceleration since the early 1990s. From mass balance studies of a large number of glaciers, estimates have been made of the contribution of glacier ice melt to sea level rise (Meier et al., 2007; Kaser et al., 2006). For the period 1993–2010, glaciers and ice caps have accounted for ~30% of sea level rise (e.g. Cogley, 2009; Steffen et al., 2010; Church et al., 2011b).

5.1.3. Ice sheets

While little was known before the 1990s on the mass balance of the ice sheets because of inadequate and incomplete observations, different remote sensing techniques available since then (e.g. airborne and satellite radar and laser altimetry, Synthetic Aperture Radar Interferometry – InSAR, and since 2002, space gravimetry from the GRACE mission) have provided important results on the changing mass of Greenland and (west) Antarctica (e.g. Allison et al., 2009). These data indicate that both ice sheets are currently losing mass at an accelerated rate (e.g. Steffen et al., 2010). Most recent mass balance estimates from space-based observations unambiguously show ice mass loss acceleration in the recent years (e.g. Chen et al., 2009; Velicogna, 2009; Rignot et al., 2008a, b, 2011). For the period 1993–2003, <15% of the rate of global sea level rise was due to the ice sheets (IPCC AR4). But their contribution has increased up to ~40% since 2003–2004. Although not constant through time, on average over 2003–2010 ice sheets mass loss explains ~25% of the rate of sea level rise (Cazenave and Remy, 2011; Church et al., 2011a).

There is more and more evidence that recent negative ice sheet mass balance mainly results from rapid outlet glacier flow along some margins of Greenland and West Antarctica, and further iceberg discharge into the surrounding ocean (Alley et al., 2007, 2008; Steffen et al., 2010). This dynamical thinning process is generally observed in coastal regions where glaciers are grounded below sea level (e.g. in northeast and southwest Greenland, and Amundsen Sea sector, West Antarctica). 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. Several recent observations have shown that warming of subsurface ocean waters could trigger these short-term dynamical instabilities (e.g. Holland et al., 2008).

Fig. 6 (updated from Cazenave and Llovel, 2010) compares the observed global mean sea level rise to the different components and their sum over the altimetry era.

5.2. Interannual variability of the global mean sea level

If the (linear) global mean trend is removed from the altimetry-based sea level curve shown in Fig. 3, significant interannual

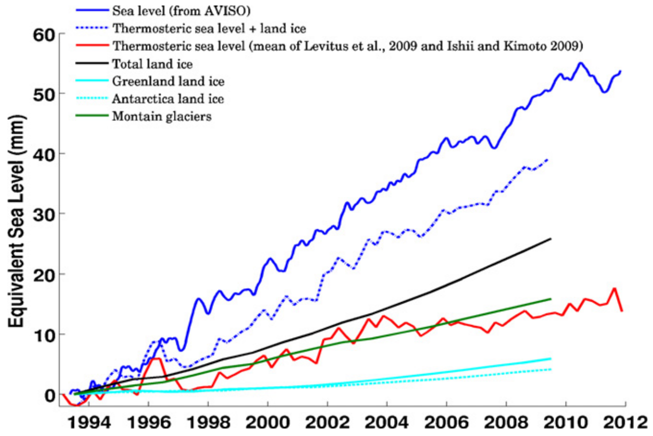

Fig. 6. Observed sea level from satellite altimetry over 1993–2010 (blue solid curve). Thermal expansion (red curve; mean value based on temperature data from Levitus et al., 2009; Ishii and Kimoto, 2009). Contribution from Greenland and Antarctica (cyan curves) and glaciers (green curve). The black curve represents the total land ice contribution while the blue dotted curve represents the total climatic contribution (sum of thermal expansion and land ice) (updated from Cazenave and Llovel, 2010).

variability is visible in the (detrended) global mean sea level (Fig. 7). Nerem et al. (2010) noticed that this detrended global mean sea level is highly correlated with ENSO, with positive/negative sea level anomalies observed during El Niño/La Niña. For example, in Fig. 7 a large positive anomaly in the global mean sea level, of several mm amplitude, is observed during the 1997–1998 El Niño (the warm phase of ENSO) and negative anomalies during the 2007–2008 La Niña (ENSO cold phase). The ENSO influence on the global mean sea level might result from changes in either global ocean heat content or global ocean mass. Llovel et al. (2011) reported that interannual global mean sea level variations are inversely correlated with ENSO-driven variations of global land water storage (with the Amazon basin as a dominant contributor to the latter), thus favouring the second option. In Fig. 7, the total land water storage – expressed in equivalent sea level (updated from Llovel et al., 2011) – is superimposed to the detrended global mean sea level. A high correlation (0.7) is noticed between the two curves. This correlation can be understood as follows: ENSO events produce large scale changes in precipitation regimes in the tropics, with more rainfall over oceans and less rainfall over land during El Niño, and opposite variations during La Niña (e.g. Gu and Adler, 2011). Recent investigations suggest in addition that positive/negative global mean sea level anomalies during El Niño/La Niña essentially result from positive/negative mass anomalies in the north tropical Pacific Ocean, possibly associated with reduced/increased transport of Pacific waters into the Indian Ocean through the Indonesian straits (Cazenave et al., under revision).

6. Causes of present-day and past-decade regional variability

The global coverage of satellite altimetry allows mapping the regional variability of the sea level rates. This has led to the discovery that sea level rise is far from being uniform. In some regions (e.g. western Pacific), the rates of sea level rise have been faster by a factor up to 3–4 the global mean rate over the past two decades. In other regions rates are slower than the global mean or even slightly negative (e.g. eastern Pacific). Fig. 8a shows the altimetry-based spatial trend patterns in sea level over 1993–2010. This variability is emphasized when we remove the global mean sea level trend of 3.2 mm/yr (Fig. 8b). In some regions such as the western and northern Pacific, the southern Indian Ocean or south of Greenland, the local departures from the global mean trend are so large that they actually dominate the sea level rate signal over the short period 1993–2010. Besides the global mean sea level rise and its causes, it is essential to understand the regional variability in sea level rates (i.e. its evolution with time and space and its drivers) if we want to assess for example the potential impacts of the sea level rise in coastal areas.

All processes that influence the global mean sea level (see Section 5.1) actually exhibit a time and space varying signature. For example, local changes in the ocean temperature and salinity fields lead to local sea level changes through associated variations of the

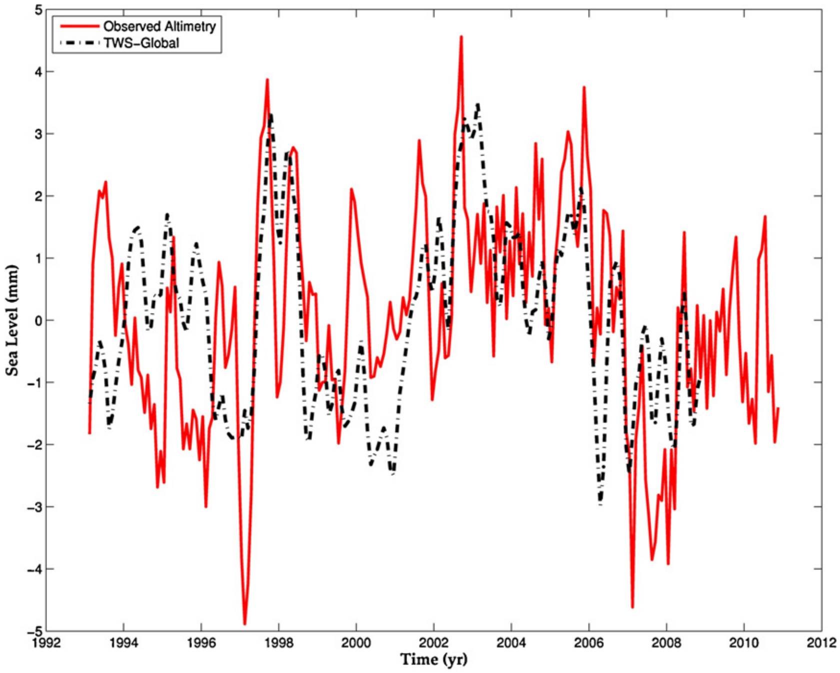

Fig. 7. Detrended global mean sea level curve (from satellite altimetry) over 1993–2010 (in red); total land water storage (noted TWS) expressed in equivalent sea level (black dashed curve) (updated from Llovel et al., 2011).

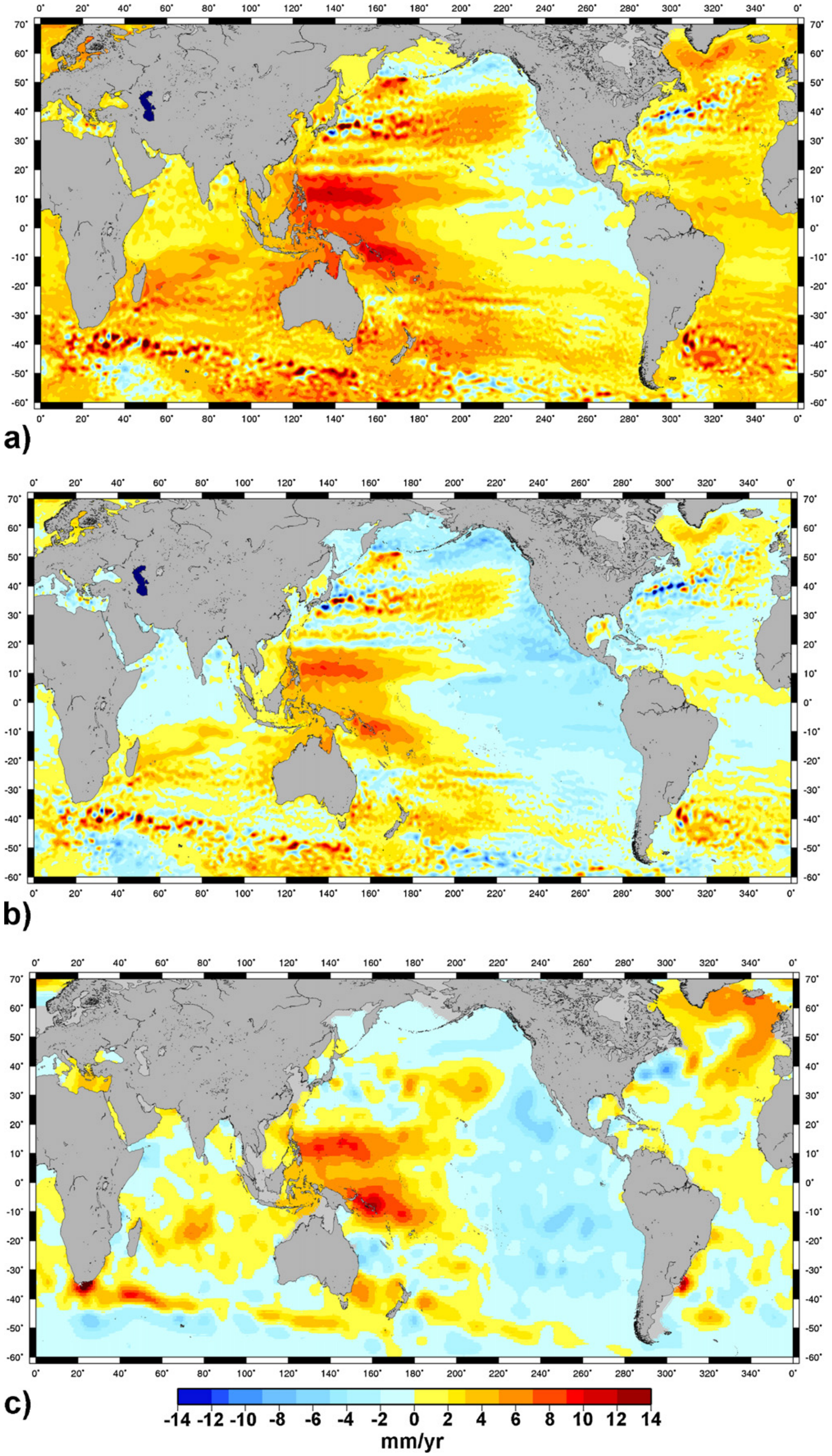

Fig. 8. (a) spatial trend patterns in sea level from satellite altimetry data over 1993–2010. (b) Spatial trend patterns in sea level from satellite altimetry data over 1993–2010 but with the global mean trend of 3.2 mm/yr removed. (c) Spatial trend patterns in thermosteric sea level over 1992–2010. (data from Levitus et al., 2009) (global mean trend removed).

water columns density and volume (thermosteric and halosteric effects respectively) (Bindoff et al., 2007; Wunsch et al., 2007; Lombard et al., 2009; Levitus et al., 2009). These variations are tightly linked to atmosphere–ocean interactions (mostly through wind stress, especially in the tropical Indo-Pacific region, but also through exchanges of heat and fresh water) and associated changes in the ocean flow field (Kohl and Stammer, 2008; Timmermann et al., 2010). Hence they produce regional variability in the rates of sea level change.

Ongoing land ice melting also gives rise to regional variability in sea level change. This comes from two processes. First the influx of freshwater in the ocean from land changes the density structure of the ocean and hence the ocean circulation (Stammer, 2008; Stammer et al., 2011). This results in regional dynamical adjustments of the sea level on inter-annual to multi-decadal time scales (Okumura et al., 2009; Stammer, 2008; Stammer et al., 2011). Second, the transfer of water mass from land into the ocean induced by land ice loss causes an elastic response of the solid Earth that deforms ocean basins. In addition, this mass redistribution produces changes of the geoid (an equipotential of the Earth's gravity field that coincides with the mean sea level) and of the Earth's rotation with a gravitational feedback. These processes (large-scale deformations of the ocean basins and gravitational changes) give rise to regional variability in sea level (Gomez et al., 2010; Milne et al., 2009; Mitrovica et al., 2001, 2009; Tamisiea and Mitrovica, 2011). Such effects associated with present-day land ice loss are still small and hard to detect in the altimetry-based observations of regional variability (Kopp et al., 2010). However, future land ice loss may produce large changes in regional sea level (Mitrovica et al., 2009; Slangen et al., 2011).

The gravitational and deformational (i.e. change in shape of ocean basins) effects associated with the visco-elastic Earth response to the last deglaciation (GIA) also produce non uniform sea level rise, in particular in the vicinity of regions occupied by the continental ice caps that covered the northern hemisphere during the Last Glacial Maximum (~20,000 years ago). But far-field sea level changes also occur (Milne and Mitrovica, 2008; Mitrovica et al., 2001; Tamisiea and Mitrovica, 2011).

Other phenomena such as erosion, deposition and compaction of sediments play some role locally, through the response of ocean floor to loading (Blum and Roberts, 2009). Finally the deformation of the Earth due to convective flow of the mantle and tectonic processes (with the exception of earthquakes) can add an extra contribution to sea level rates at regional scale but it is very low on average (<0.1 mm/yr in sea level equivalent, Moucha et al., 2008).

During the altimetry era (since 1993), the main contribution to the regional variability in sea level rise comes from the ocean temperature and salinity changes (Bindoff et al., 2007). This is evidenced by the comparison between altimetry-based and steric (i.e. the sum of thermosteric and halosteric effects) trend patterns deduced from in situ hydrographic measurements (Ishii and Kimoto, 2009; Levitus et al., 2009; Lombard et al., 2005a, b) and ocean circulation models (OGCMs) outputs (Wunsch et al., 2007; Kohl and Stammer, 2008; Carton and Giese, 2008; Lombard et al., 2009). This is illustrated in Fig. 8c showing the thermosteric trend patterns over 1993–2010 (sea level trends due to temperature variations only) computed from hydrographic measurements collected by ships and Argo profiling floats (data from Levitus et al., 2009). This figure shows that the thermosteric component is the most important contribution to the observed sea level regional variability. OGCM runs with or without data assimilation confirm that point. However salinity changes also play some role at regional scale, e.g. in the Atlantic ocean, partly compensating temperature effects (e.g. Wunsch et al., 2007; Kohl and Stammer, 2008; Lombard et al., 2009). It is worth noticing however that steric effects estimated in open oceans may be significantly different from those estimated in adjacent coastal zones because of the presence of boundary currents (Bingham and Hughes, 2012).

In the tropics, thermosteric trends are principally caused by changes in the surface wind stress and associated changes in the ocean circulation, hence heat redistribution (Timmermann et al., 2010; Merrifield and Maltrud, 2011). Merrifield (2011) noticed that in the most western part of the tropical Pacific, trade winds increased in the early 1990s, leading to a large upward trend in sea level in that region.

Prior to the altimetry era, very sparse measurements of sea level are available because it was only monitored by tide gauges on coastal areas. Moreover, for historical reasons, the tide gauge dataset is largely biased towards the northern hemisphere, leaving large gaps in the southern hemisphere. Hence it is not possible to get a satisfactory global picture of the regional variability in sea level over the past decades from the tide gauge records alone.

One approach to get information on the regional variability in sea level over the last 5 decades consists of analysing sea level time series produced by ocean circulation models and ocean reanalyses (i.e. OGCMs with data assimilation) (e.g. Carton and Giese, 2008; Kohl and Stammer, 2008). OGCMs and ocean reanalyses deduce sea level from the sum of the thermosteric and halosteric components, to which is added a small barotropic component. This allows mapping the spatio-temporal behaviour of both temperature and salinity contributions to the sea level under a prescribed external meteorological forcing. Over the altimetry era, OGCMs and ocean reanalyses reproduce fairly well the regional variability in sea level trends observed by altimetry. They confirm the thermosteric origin of the patterns (Wunsch et al., 2007; Lombard et al., 2009) and the predominant role of the wind stress in their formation (Kohl and Stammer, 2008; Timmermann et al., 2010).

Over the past 5–6 decades, however, the sea level trend patterns are quite different from those observed over the altimetry era with much lower amplitude (on the order of 3–4 times smaller). On such time scales, the predominant contribution of wind-driven thermosteric effects still holds (Kohl and Stammer, 2008) in particular in the tropical Pacific (Timmermann et al., 2010) and Indian Ocean (Han et al., 2010).

Another approach that partly relies on tide gauge data was developed in the recent years to derive spatial sea level trend patterns before the altimetry era (i.e. last 5–6 decades). It combines information from the tide gauges with spatial patterns from altimetry or OGCMs (e.g. Church et al., 2004; Berge-Nguyen et al., 2008; Llovel et al., 2009; Church and White, 2011; Hamlington et al., 2011; Ray and Douglas, 2011; Meyssignac et al., in press-a). Unlike OGCMs and ocean reanalyses, this approach (called past sea level reconstruction) does not allow separating the various contributions (e.g. from temperature and salinity) to the sea level. But, since it uses tide gauge observations, it is expected to carry more information on the regional variability than OGCMs, and thus is complementary to the latter.

This method interpolates (in an optimal way) the long tide gauge records with Empirical Orthogonal Functions (EOFs here after; Preisendorfer, 1988) representative of the principal modes of variability of the ocean deduced from the altimetry record or OGCMs (see Kaplan et al., 1998, 2000 for more details on the method). It gives 2-dimensional past sea level reconstructions back to around the early 1950s. Reconstructions are then evaluated by comparison with independent tide gauge records that were not used in the reconstruction process. Fig. 9 shows the reconstructed sea level trend patterns over 1960–2009 from Meyssignac et al. (in press-a) with and without the global mean sea level trend (Fig. 9a and 9b respectively).

Reconstruction methods rely strongly on the assumption that the principal modes of variability of the ocean deduced from the

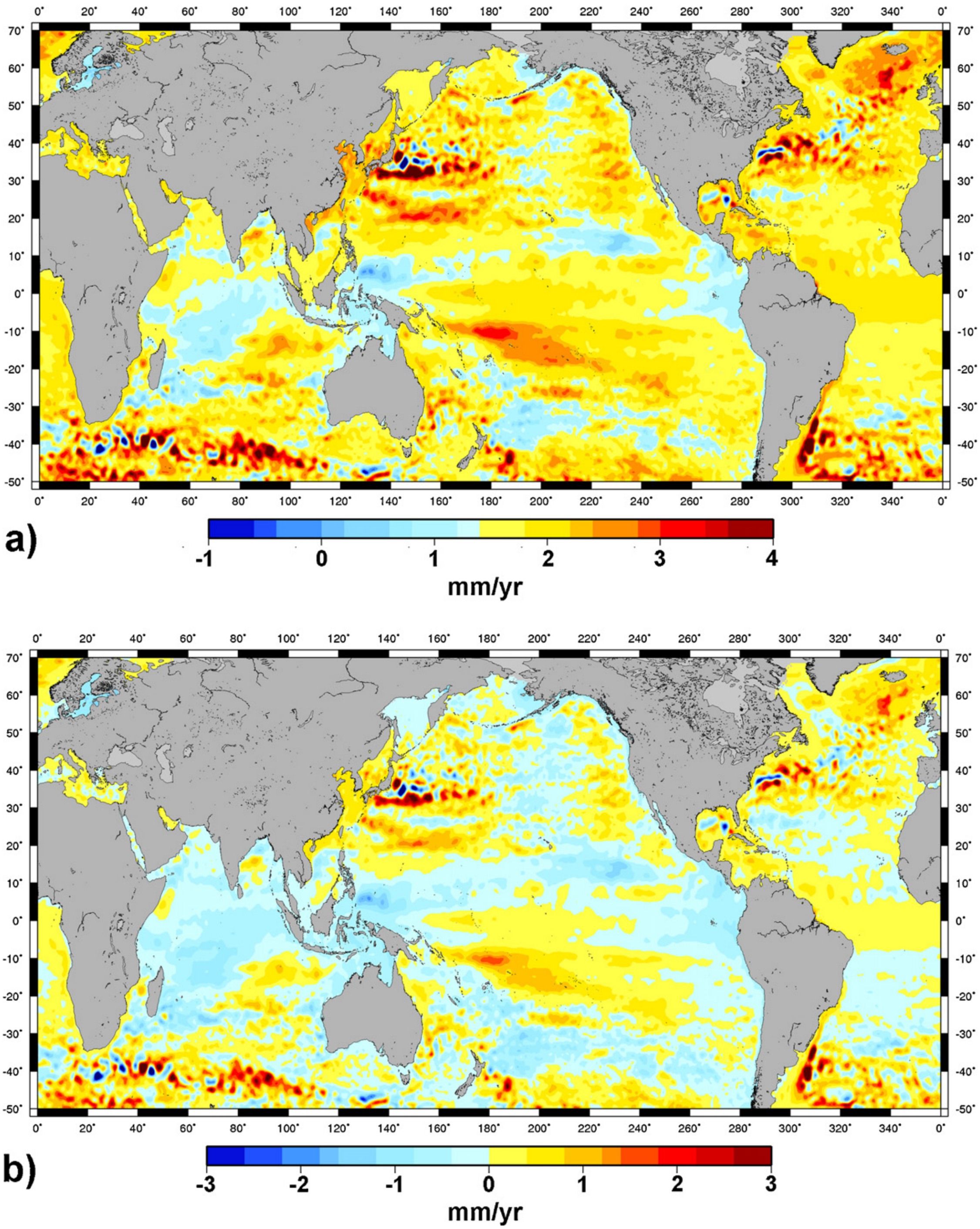

Fig. 9. (a) Spatial trend patterns in sea level over 1950–2009 from Meyssignac et al. (in press-a) reconstruction. (b) Spatial trend patterns in reconstructed sea level over 1950–2009 but with the global mean trend of 1.8 mm/yr removed.

relatively short altimetry record or from imperfect OGCMs (little information on the meteorological forcing is available before 1980) are stationary with time and representative of the modes of variability of the ocean over the long reconstructed period 1950–2010. In this respect, each type of reconstruction shows advantages and drawbacks. Reconstructions based on long EOFs (1958–2007) computed from OGCMs better capture the low-frequency oceanic signal. In that sense, they better stick to the assumption of stationarity. But reconstructions based on the EOFs from altimetry seem to give more realistic modes of variability of the ocean. Finally the various reconstructions give more or less similar results and no case appears to perform better over the globe (Meyssignac et al., in press-a). Over a given region, the best reconstruction available will be the reconstruction that compares well with local independent tide gauge records (see for example Becker et al., 2012).

Despite these differences, all past sea level reconstructions show, like OGCMs and ocean reanalyses, significantly different trend patterns over the last 60 years than those observed over the altimetry era (compare Figs. 8 and 9), with smaller amplitudes (between 3 and 4 times). Comparison with thermal expansion trends (not shown) indicates that on multidecadal time scale, the regional variability in sea level rates has also a dominant thermal origin.

7. Non stationarity of spatial trend patterns and internal variability of the ocean–atmosphere system

We have seen in the previous section that past sea level either from OGCMs and ocean reanalyses or reconstructions, exhibit regional long-term trend patterns (over the last 5–6 decades) that differ significantly from the short-term ones observed over the altimetry era. This suggests that contemporary sea level trend patterns (from altimetry) are not long-lived features. This point is also supported by the thermosteric origin of the sea level regional variability. Indeed, observations have shown that thermosteric spatial patterns are not stationary but fluctuate in time and space in response to driving mechanisms such as ENSO, NAO, and PDO. (Lombard et al., 2005a; Di Lorenzo et al., 2010; Lozier et al., 2010). Thus thermosteric trend patterns and hence regional sea level trend patterns are expected to be different prior to the altimetry era compared to those observed over the altimetry period, as confirmed by OGCMs, reanalyses and reconstructions.

Past sea level reconstructions by Meyssignac et al. (in press-b) have shown that in the Pacific ocean, altimetry era patterns can be observed in the past at various periods with a changing amplitude. The amplitude appears to fluctuate with time following a low-frequency modulation of ENSO. This suggests that the local regional variability in sea level rates observed by altimetry is actually tightly linked to natural modes of the climate system. This link is further confirmed by coupled Atmosphere–Ocean Climate Model runs (AOCM) without and with external forcing (i.e. anthropogenic greenhouse gas emissions plus aerosols, volcanic eruptions and solar radiation changes). Comparisons of model-based sea level regional variability without and with external forcing enabled Meyssignac et al. (in press-b) to analyze the role of the internal variability of the climate system with respect to the forcing factors, in particular the anthropogenic forcing. The impact of the latter on the observed regional variability of the tropical Pacific is still not visible suggesting that only the intrinsic variability of the climate system is still the main driver of the spatial patterns in sea level observed by satellite altimetry. But further analyses are required to confirm this.

8. Local sea level changes in a few selected regions

Satellite altimetry provides an absolute sea level measurement with respect to the Earth's center of mass while tide gauges, attached to the Earth's surface, give relative sea level measurements that include vertical crustal motions. The latter have a large variety of causes, e.g. GIA, tectonic and volcanic activity causing either uplift or subsidence, ground subsidence due to sediment loading (in particular in large river deltas) or due to ground water and hydrocarbon extraction, etc. (Milne et al., 2009; Woppelmann et al., 2009). If one is interested in estimating sea level change at a given site, it is the 'total' relative sea level that needs to be considered. The word 'total' here means the sum of two components: (1) the climatic component expressed by the sum of the global mean rise plus the regional variability discussed above, and (2) the vertical crustal motion component. Recent studies have shown that each of these components (and their sum) can give rise to very large deviation of local sea level change with respect to the global mean (see for example Braitenberg et al., 2011 or Fenoglio-Marc et al., 2012; Ballu et al., 2011; Becker et al., 2012).

Using GPS precise positioning, Ballu et al. (2011) showed that the Torres islands (north Vanuatu, southwest Pacific) experienced very large subsidence (of about −10 mm/yr) of seismic origin during the past ~2 decades. Because of earthquake-related vertical land motion, the local rate of sea level rise is about three times the absolute, climate-related sea level rise (of 3.3 mm/yr of that period).

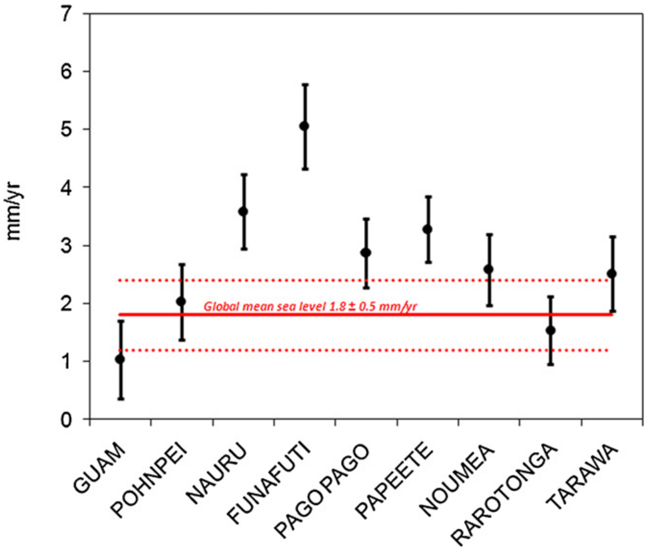

Fig. 10. Total rate of sea level rise at Guam, Pohnpei, Nauru, Funafuti, Pago Pago, Papeete, Noumea, Rarotonga and Tarawa estimated over 1950–2009 due to climate components and vertical crustal motion. The horizontal lines represent the global mean sea level trend over this period (1.8 mm/yr) and its uncertainty range (from Becker et al., 2012).

Becker et al. (2012) estimated the total relative rate of sea level change since 1950 at selected islands of the western tropical Pacific, as a result of the climate-related sea level change (uniform-global mean-sea level rise plus regional variability) and vertical crustal motion estimated from GPS. This allowed them to determine the amount of "total" sea level change effectively felt by the populations over the last ~60 years. They found that at Guam, Pohnpei and Rarotonga Islands the 'total' sea level trend is about equal to global mean sea level rise (of ~1.8 mm/yr between 1950 and 2010). At Nauru, Funafuti (Tuvalu), Papeete (French Polynesia), Noumea (New Caledonia), the 'total' sea level trend was found to be significantly higher than the global mean. This is illustrated in Fig. 10 (from Becker et al., 2012). At Funafuti, the capital atoll of the Tuvalu Archipelago, the total rate of sea level rise was found to be >5 mm/yr over the last 60 years. This corresponds to a sea level elevation of ~30 cm during this time span. These results corroborate that at this particular location, sea level rise is not insignificant – as felt by the population, even if such a rate does not necessarily produce shoreline erosion as shown by Webb and Kench (2010). In effect, other local factors such as changes in sediment deposition, coastal waves and currents are yet the main drivers of shoreline morphological changes; in the future, higher rates of sea level rise may however have larger impacts.

9. Global warming and future large-scale sea level changes

There is little doubt that global warming will continue and even increase during the future decades as green house gas emissions, the main contributor to anthropogenic global warming, will likely continue to grow in the future. A recent update by Friedlingstein et al. (2010) in carbon dioxide (CO_2) emissions due to fossil fuel burning shows a steep increase during the 2000s, even though global economic crises can produce slight temporary decline. From the total CO_2 emissions due to fossil fuels and cement industry, plus deforestation and land use changes (about 9.1 Gt/yr presently), about 45% accumulate into the atmosphere (ocean and vegetation uptake accounting for 25% and 30% of CO_2 sinks respectively) (Durand et al., 2011). There are different scenarios of emissions and responses of the climate system (expressed in terms of radiative forcing and global Earth's temperature increase) for the coming decades (IPCC, 2007). All correspond to an increase in global mean sea level during the 21th century and beyond because of expected continuing ocean warming and land ice loss (e.g. Meehl et al., 2007). IPCC AR4 projections indicated that sea level should be higher than today's value by ~40 cm by 2100 (within a range of ±15 cm due to model results dispersion and uncertainty on emissions) (Meehl et al., 2007). After the publication of the IPCC 4th Assessment Report, it has been suggested that this value could be a lower bound because the climate models used at that time essentially accounted for ocean warming, glaciers melting and ice sheet surface mass balance only. As discussed above, a large proportion of current Greenland and West Antarctica ice mass loss results from coastal glacier flow into the ocean through complex dynamical instabilities. Such processes became quite active during the last decade and were not taken into account in IPCC AR4 sea level projections. Recent studies have thus suggested that ice sheet mass loss could represent a much larger contribution than expected to future sea level rise. For example, Pfeffer et al. (2008) infer possible contributions to 2100 sea level of 16 cm–54 cm for Greenland and 13 cm–62 cm for Antarctica (although preferred values by these authors are 16 cm and 15 cm for Greenland and Antarctica respectively). Extrapolating the presently observed acceleration of Greenland and Antarctica ice mass loss, Rignot et al. (2011) suggest a total (Greenland plus Antarctica) contribution to sea level rise of ~56 cm by 2100.

Clearly, the total land ice contribution to 21st century sea level rise remains highly uncertain. But values around 40–50 cm by 2100 may not be ruled out for the sum of glaciers and ice sheets contributions. If we add the ocean warming contribution (in the range 10–40 cm; IPCC, 2007), global mean sea level could eventually exceed present-day elevation by 50–80 cm.

Alternative approaches based on semi-empirical modeling have been proposed to estimate sea level rise in the 21st century (e.g. Rahmstorf et al., in press; Jevrejeva et al., 2010, 2011). These are based on simple relationships established for the 20th century (or longer time spans) between observed global mean sea level rate of rise and observed global mean Earth's temperature (or radiative forcing). Using global mean temperature projections (the most precisely modeled climate parameter by coupled climate models) or radiative forcing, future global mean sea level can be extrapolated using the simple relationship valid for the past. This method leads to higher ranges of sea level rise by 2100 than climate model projections. Such a discrepancy remains so far poorly understood.

Present-day sea level rise is not uniform. This is also expected for the future. Geographical patterns of future sea level changes are dominated by non uniform steric effects (i.e. ocean thermal expansion and salinity changes) (e.g. Pardaens et al., 2010; Yin et al., 2010; Suzuki and Ishii, 2011). Although some differences in projected regional variability exist among the different coupled climate models, the patterns agree rather well. Ensemble means indicate higher sea level rise (with respect to the global mean) in the Arctic ocean due less salty waters caused by fresh water input in that region (from sea ice melting and Greenland ice loss increased precipitation ad Arctic river runoff). Strong compensation between thermosteric and halosteric effects is predicted in the Atlantic Ocean, with a slight dominating effect from thermal expansion. In the Southern Ocean, at latitudes centered near 60°S, there is a tendency for sea level fall compared to the global mean, just south of a band of sea level rise; such a dipole-like behaviour is associated with changes of the Antarctic Circumpolar Current. In the Indian Ocean, projections generally indicate sea level to rise slightly higher than the global mean.

Other factors give rise to regional variability, in particular gravitational effects and solid Earth's viscoelastic or elastic response to large-scale water mass redistribution associated with past and on-going land ice melt (see Section 6). For the first time, these factors have been taken into account in regional sea level projections for different scenarios of future climate warming (Slangen et al., 2011). These authors indeed model local relative sea level rise accounting for steric effects plus last deglaciation-induced GIA and additional deformational and gravitational effects due to future land ice melt. While steric effects dominate the regional variability as in the IPCC AR 4 projections, past and on-going land ice melt can lead to strong deviation around the global mean rise in the vicinity of the melting bodies where negative sea level changes are noticed. In some regions of the Arctic Ocean, this

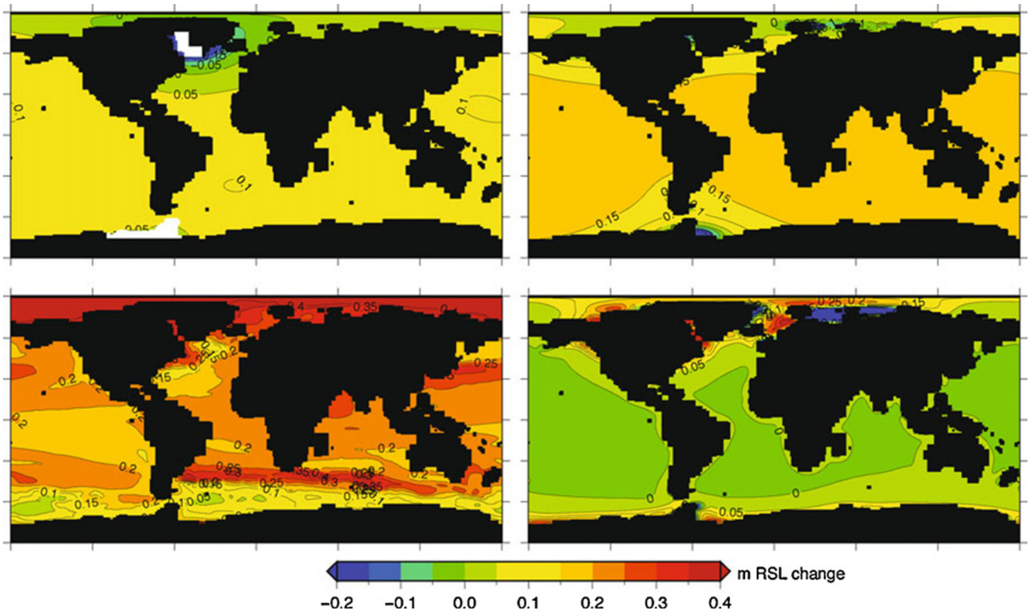

Fig. 11. Individual contributions (from an ensemble mean of 12 climate models) to regional (relative) sea level changes for the decade 2090–2099 relative to 1980–1999 and A1B warming scenario (i.e. global mean Earth's temperature increase of +2.8 °C over this period range; IPCC, 2007. Upper left panel: future ice sheet melting; upper right panel: glacier melting; lower left panel: steric effects; lower right panel: GIA effect. (from Slangen et al., 2011).

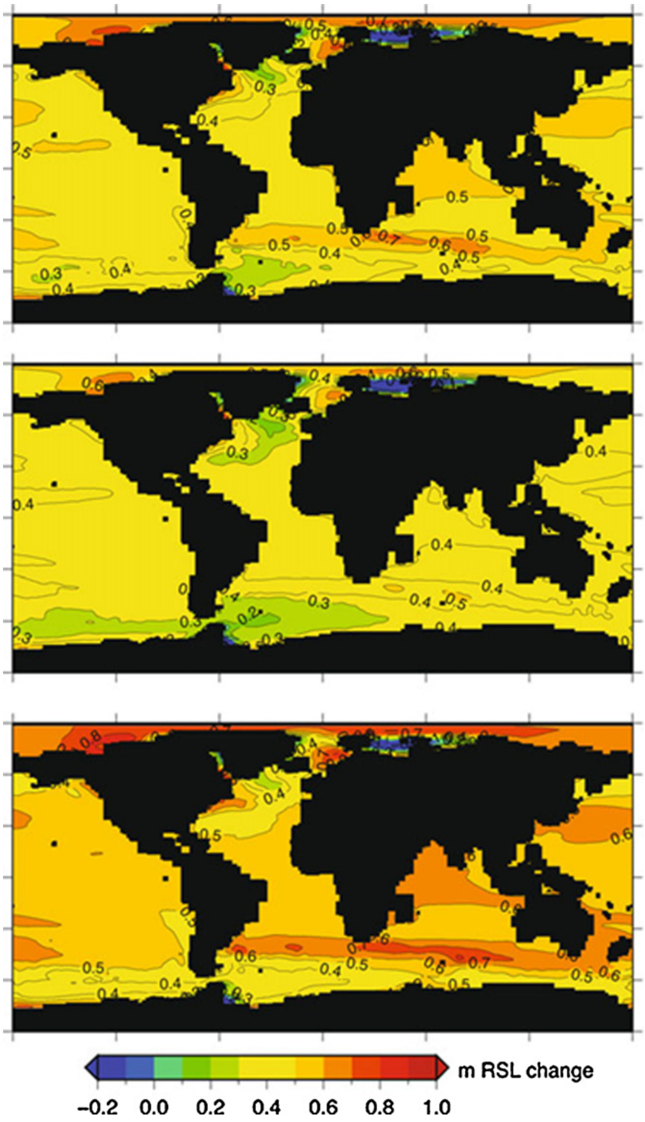

Fig. 12. Maps of the regional sea level variability (in m) between 1980–1999 and 2090–2099 (ensemble mean of ∼12 climate models) due the sum of all factors shown in Fig. 11, for three different warming scenarios: A1B (top panel), B1 (1.8 °C mean temperature increase) – middle panel, and A2 (+3.4 °C mean temperature increase) – lower panel. Global mean rise included (amounting ∼50 cm for A1B, ∼40 cm for B1 and 55 cm for A2) (from Slangen et al., 2011).

factor compensates sea level rise due to freshening. Fig. 11 from Slangen et al. (2011) shows individual contributions (i.e. future ice sheet and glacier melting, last deglaciation – induced GIA and steric effects) to regional (relative) sea level changes for the decade 2090–2099 relative to 1980–1999 and A1B warming scenario (i.e. global mean Earth's temperature increase of +2.8 °C over this period range; IPCC, 2007). These maps are based on an ensemble mean of 12 climate models. The corresponding global mean rise in this case is ∼50 cm. But local relative sea level rise ranges from ∼−4 m (nearby the ice sheets) to +80 cm. Fig. 12, also from Slangen et al. (2011), presents maps of the regional variability (ensemble mean of ∼12 climate models) due the sum of all factors and three different warming scenarios: A1B as for Fig. 11, B1(+1.8 °C mean temperature increase), and A2 (+3.4 °C mean temperature increase). As in Fig. 11, the global mean rise is included in Fig. 12 (amounting ∼40 cm for B1 and 55 cm for A2). These figures clearly demonstrate the utmost importance of regional variability of the rates of sea level change.

10. Outlook

Particular attention has been paid to the sea level rise problem during the recent years because it clearly represents a major threat of global warming. The physical impacts of sea level rise on coastal zones are well identified (Nicholls et al., 2007; Nicholls and Cazenave, 2010; Nicholls, 2010). The immediate effect is submergence and increased flooding of coastal land, as well as saltwater intrusion of surface waters. Longer-term effects also occur as the coast adjusts to the new conditions, including increased erosion and saltwater intrusion into groundwater. The coastal impacts are primarily produced by relative sea level rise as the sum of climate-related and non climate-related processes (as discussed above). For example, relative sea level is rising more rapidly than climate-induced trends on subsiding coasts. In many regions, human activities are exacerbating subsidence on susceptible coasts including most river deltas (e.g. the Ganges–Brahmaputra and Mekong deltas, Ericson et al., 2006). During the 20th century, several near coastal megacities have suffered ground subsidence of several meters because of groundwater withdrawal (e.g. Phienwej et al., 2006). The non-climate components of sea level change have in general received much less attention than climate components, because they are considered as a local issue. However, they are so common that they need to be studied more systematically. Besides the very local issues, regional variability of sea level change due to ocean thermosteric and halosteric factors may considerably amplify the global mean rise. This was the case over the past few decades in the low islands such as the Tuvalu or in the future in the Maldives island region in the Indian Ocean. As we have discussed above, additional factors such as changes in shape of ocean basins because of land ice loss and water mass redistribution are additional causes of regional variability. The combination of all these factors produces complex regional sea level patterns with important deviation with respect to the global mean rise in some areas.

Until recently, the consequences of anthropogenic global warming on sea level were essentially addressed in terms of the global mean trend. However, more and more consideration is given to the large-scale regional variability and to more local factors (of non climatic origin). While the latter are difficult – if not impossible – to predict, significant progress has been made recently to provide realistic regional sea level projections that account for the climate-related contributions and associated large-scale water mass redistribution. Such new projections should help to develop realistic climate mitigation policies for coastal management and adaptation to future climate change. In parallel, sustained and systematic monitoring of sea level and other climate parameters causing sea level rise (ocean heat content, land ice loss, etc.) from space-based and in situ observing systems is crucial (e.g. Wilson et al., 2010). This will help in improving our understanding of present-day sea level rise and variability, and ultimately will contribute to improve model projections of future sea levels.

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