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Contemporary sea level changes from satellite altimetry: What have we learned? What are the new challenges?

Anny Cazenave [a,b,*], Hindumathi Palanisamy [a], Michael Ablain [c]

[a] *LEGOS, Toulouse, France*
[b] *ISSI, Bern, Switzerland*
[c] *CLS, Ramonville St Agne, France*

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Abstract

Since the early 1990s, high-precision multi-mission satellite altimetry has provided a 25-year-long sea level record from which global mean sea level rise and superimposed interannual and regional variability can be derived. Most recent results show that the global mean sea level is rising at a mean rate of 3.1 ± 0.3 mm/yr since January 1993. A clear acceleration is also visible on this 25-year time span, estimated to 0.10 mm/yr^2. Mapping of spatial trend patterns continue to show deviation from the global mean rise in a number of regions. However, as the altimetry record lengthens, the ratio of regional trends to the global mean rise tends to decrease, with a factor of amplification of only 2, compared to 3 to 4 some years ago. Estimates of thermal expansion from Argo and ocean mass change from GRACE show that over the GRACE and Argo time span (since 2005) the sea level budget is almost closed. Assessment of the sea level budget over the entire altimetry era (since 1993) based on estimates of individual mass components for the glaciers and the ice sheets provides some upper bound for the still poorly known contribution from water storage on land. At regional scale, ocean thermal expansion is still the main cause of the spatial trend patterns observed by satellite altimetry. However, removing the steric component reveals residual signal that still needs interpretation. In the remaining of this review, we briefly discuss future sea level changes and associated coastal impacts. Finally, we address the issue of remaining gaps in sea level studies, in particular the need for producing coastal sea level products from dedicated satellite altimetry processing of sea level data in global coastal zones.

Keywords: Sea level; Satellite altimetry; Climate change; Sea level budget

1. Introduction

Sea level rise and its impacts in coastal zones has become recently a question of growing interest in the scientific community, as well as the media and the public. In effect with extreme events (e.g., floods, droughts, cyclones), sea level rise is generally considered as a major threat of current global warming in the highly populated low-lying coastal regions of the world. Today about 600 million people live nearby the sea (mostly concentrated in several of the largest world megacities) and this number is expected to double by 2060 (Nicholls, 2010). Because of obvious importance for adaption purposes and associated socio-economic issues, understanding present-day sea level rise and accurately projecting changes for the coming decades under different global warming scenarios stand among priority scientific objectives in ocean and climate research. The Earth's climate is currently warming, a result of accumulation of greenhouse gases (GHG) inside the atmosphere from anthropogenic fossil fuel combustion and land use change (mostly deforestation) (IPCC, 2013). Global

* Corresponding author at: LEGOS, Toulouse, France.
E-mail address: anny.cazenave@legos.obs-mip.fr (A. Cazenave).

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warming has already several visible consequences, in particular the increase of the Earth's mean surface temperature and of ocean heat content, the melting of sea ice and glaciers, and the loss of ice mass from the Greenland and Antarctica ice sheets. On average over the last 50 years, 93% of the heat excess accumulated in the climate system because of GHG emissions has been stored into the ocean, the remaining 7% warm the atmosphere and continents, and melt sea and land ice (von Schuckmann et al., 2016). Ocean warming and land ice melt further cause sea level rise. After about 3000 years of stability since the end of the last deglaciation (Lambeck et al., 2010; Kemp et al., 2011), direct observations from in situ tide gauges available since the mid-to-late 19th century show that the 20th century global mean sea level has been rising at a rate of 1.2 to 1.9 mm/yr (Church and White, 2011; Jevrejeva et al., 2014a; Hay et al., 2015; Dangendorf et al., 2017). Since the early 1990s, sea level changes at global and regional scales are measured by high-precision altimeter satellites. In terms of global mean, the altimetry-based rate of rise is estimated to about 3.1 mm/yr with a 0.3 mm/yr uncertainty within a 90% confidence interval (Ablain et al., 2015; 2017a; Legeais et al., 2018), a value twice as large as the 20th average. Strong regional variability in sea level rates is also observed.

In this article, we present most up-to-date observations of present-day sea level changes at global and regional scales, based on the high-precision altimeter satellites constellation operating since the early 1990s (Stammer and Cazenave, 2018; Escudier et al., 2018). We also discuss the causes of global mean and regional sea level changes over the 25-yr long altimetry record. Observations of sea level rise and components allow detecting spatio-temporal temporal changes occurring in the climate system in response to natural and anthropogenic forcings, as well as to internal climate variability. These observations can also serve to validate the climate models used to simulate future changes. Finally, we discuss the need for further observational improvements, at all spatial scales, from global to local, including the coastal areas.

2. Measuring contemporary sea level changes at global and regional scales

Historical sea level measurements come from tide gauges unevenly distributed around the world. The records are somewhat inhomogeneous in terms of data length and quality, and suffer from data gaps. Various statistical approaches have been developed to estimate, from tide gauge records, the rate of sea level rise during the 20th century (Church and White 2011; Meyssignac et al., 2012; Ray and Douglas, 2011; Jevrejeva et al., 2014a; Hay et al, 2015; Dangendorf et al., 2017). Results are substantially different from one author to another, and range from 1.2 mm/yr to 1.9 mm/yr. Thompson et al. (2016) showed that the result is highly dependent on the selected tide gauge distribution. While tide gauge data remain extremely useful for a variety of applications, sea level variations at global and regional scales are now routinely derived from satellite altimetry. This technique has revolutionized ocean dynamics in providing high-precision, high-resolution measurements of the ocean surface topography with global coverage and a revisit time of a few days. The launch of the TOPEX/Poseidon satellite in 1992 opened the era of high-precision altimetry allowing for the first time mapping of the sea surface height with a decimetre precision for a single measurement (Fu et al., 1994). This precision is nowadays close to 1-cm due to improved radar technology and continuous efforts developed through time by the space agencies and the scientific community to decrease all sources of errors affecting sea surface height measurements (e.g., Lemoine et al., 2010; Couhert et al., 2015; Quartly et al., 2017; Legeais et al., 2018; Escudier et al., 2018). By averaging the ~half-million individual measurements of the sea surface height (assuming 1-cm accuracy), collected at 1-s interval by the satellite during an orbital cycle (the duration of a complete coverage of the Earth), leads to an uncertainty of 4–5 mm for a global mean sea level estimate over a given orbital cycle (e.g., Escudier et al., 2018).

With the data of the TOPEX/Poseidon successors, Jason-1 (2001–2013), Jason-2 (2008-present), Jason-3 (2016-present), as well as those from ERS-1&2 (1992–2011), Envisat (2002–2010), SARAL/Altika (2013-present), Cryosat-2 (2010-present), HY-2A (2011-present), Sentinel-3a (2016-present) and Sentinel-3b (launched in April 2018), we now have at our disposal a sea level record more than 25-year long, of very high value for studying sea level globally and regionally, from sub-seasonal to multi-decadal time scales. Detailed descriptions of the satellite altimetry system, measurements and geophysical corrections, as well as altimetry mission characteristics are provided in Escudier et al. (2018). Additional information on long-term altimetry calibration required for providing an accurate sea level record can also be found in Fu and Haines (2013).

A number of groups in the world are currently processing data from the various altimetry missions and provide sea level products (e.g., global mean sea level and/or gridded time series at 10-day or monthly intervals): NOAA (http://www.star.nesdis.noaa.gov), University of Colorado (http://sealevel.colorado.edu) and NASA (http://www.star.nesdis.noaa.gov) in the USA, CSIRO (www.cmar.csiro.au) in Australia and AVISO (http://www.aviso.altimetry.fr) in France. In the past few years, a consistent and continuous space-based sea level record (at global and regional scales) has been produced in the context of the Climate Change Initiative (CCI) programme developed by the European Space Agency (ESA) (http://www.esa-sea-level-cci.org/products). It is based on complete reprocessing of altimetry data from nine missions of the high precision altimetry era (since 1993), with improved geophysical corrections to apply to the altimetry measurements, reduced instrumental bias and drifts, and improved linkage between missions (Ablain et al., 2015, 2017a, Quartly et al., 2017, Legeais et al., 2018). This new sea level data set, mostly dedicated to climate studies, approaches the requirements of the Global Climate Observing System (GCOS, 2011). It is provided as gridded time series (between 60°N-60°S latitude) at monthly interval between January 1993 and December 2015. The global mean sea level (GMSL) is derived from geographical averaging of the gridded data with area weighting. As shown in Ablain et al. (2017a) and Legeais et al. (2018), the GMSL trend uncertainty of the CCI sea level is about 0.3 mm/yr within a confidence interval of 90%, while the regional trend uncertainties are ranging from 1 to 3 mm/yr depending on the areas.

The altimetry-based GMSL record is shown in Fig. 1. It is based on the CCI sea level data up to December 2015 extended with sea level data from AVISO. The time series is corrected for GIA (Glacial Isostatic Adjustment), subtracting a -0.3 mm/yr value (Peltier, 2004). The seasonal signal is also removed by fitting sinusoids of 6-month and 12-month periods to the data. On Fig. 1, the first 6 years of the GMSL record are corrected for the instrumental drift affecting the TOPEX-A altimeter of the TOPEX/Poseidon mission, using the correction proposed by Watson et al. (2015) and Dieng et al. (2017). This TOPEX-A instrumental drift, known for long time, was supposed up to recently to have negligible effect on the GMSL. However, some studies based on various approaches (comparison of the TOPEX-A-based sea level with tide gauges data: Valladeau et al., 2012; Watson et al., 2015; Ablain et al., 2017b; analysis of the sea level budget: Dieng et al., 2017a; suppression of the onboard calibration mode correction: Beckley et al., 2017) have demonstrated that it has important implication on the GMSL record and its interpretation. To a first approximation, this drift is linear and leads to overestimating the GMSL rate by ~1.5 mm/yr during the first 6 years of the altimetry record. However, according to the recent study by Ablain et al. (2017b) based on comparison with tide gauges, it may be better described by a V-shape function which trend amounts to -1.0 ± 1.0 mm/yr between January 1993 and July 1995, and $+3.0 \pm 1.0$ mm/yr between August 1995 and February 1999 (uncertainty at the 90% confidence level). Note that all proposed approaches lead to nearly similar sea level curves (see Fig. 2 in The World Climate Research Programme/WCRP Sea Level Budget Group, 2018). Accounting for the TOPEX A instrumental drift significantly modifies the shape of the GMSL time series, from purely linear (as shown in many previously published publications) to quadratic. This suggests that the GMSL has accelerated over the altimetry era. The estimated acceleration over January 1993 to March 2018 amounts to 0.10 mm/yr^2 (The WCRP Sea Level Budget Group, 2018). This value agrees well with Nerem et al. (2018a)'s estimate, of 0.085 mm/yr^2, after removing the interannual variability of the GMSL.

Regional sea level trends are shown in Fig. 2a and b for the 1993–2017 time span, with and without the global mean trend. In a number of regions, sea level trends deviate from

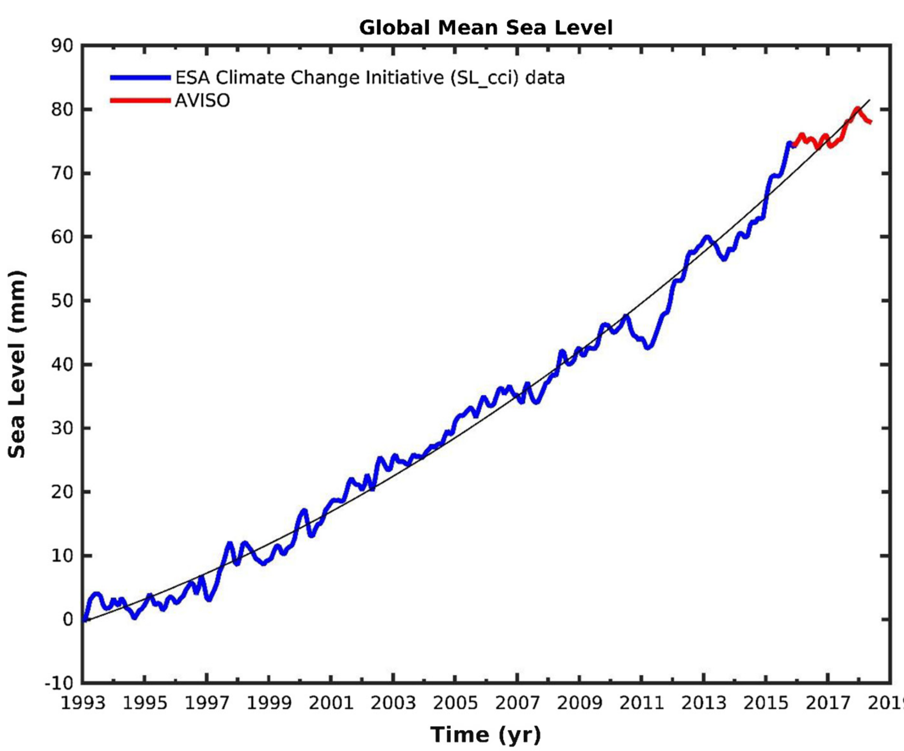

Fig. 1. Global mean sea level time series between January 1993 and June 2018 based on satellite altimetry data from CCI (https://www.esa-sealevel-cci.org/products) up to December 2015 and AVISO (https://www.aviso.altimetry.fr/) as of January 2016. The black curve is the quadratic function fitted to the data.

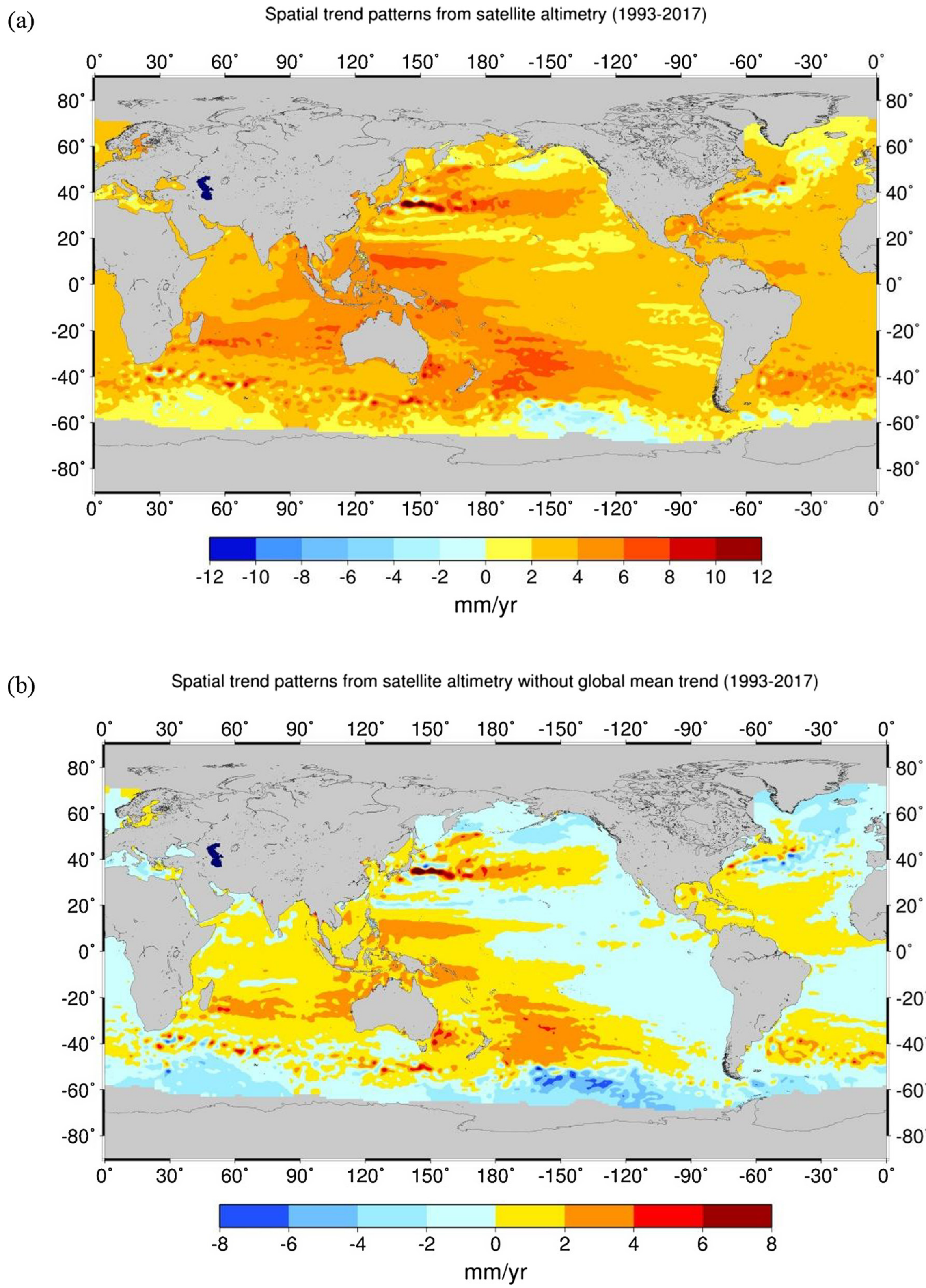

Fig. 2. (a) Spatial trend patterns in sea level from satellite altimetry between January 1993 and November 2017 based on AVISO data (https://www.aviso.altimetry.fr/l); (b) same as Fig. 2a but with the global mean sea level rise removed (using a value of 3 mm/yr).

the global mean by a factor up to 2. This is particularly the case along the northern hemisphere western boundary currents (Gulf Stream and Kuroshio) and the Austral Current around Antarctica. These regions display strong mesoscale signal that superimposes to the global mean sea level trend. Trends larger than the global mean are also observed in the southern Indian Ocean and in the south Pacific, east of Australia. The western tropical Pacific as well as the north-east Pacific also show significantly high trends.

3. Understanding present-day sea level rise at global and regional scales

The physical processes causing global mean sea level rise and regional changes are not identical, although they are related. Global mean rise primarily results from increase in ocean thermal expansion, land ice melt and land water storage change.

Geographical patterns of sea level change result from the superposition of 'fingerprints' caused by different processes: changes in sea water density due to changes in temperature & salinity, and changes in ocean circulation (these phenomena are called 'steric' effects), solid Earth's deformation and geoid changes in response to past and ongoing mass redistribution caused by land ice melt and land water storage changes (called 'static' factors, Stammer et al., 2013). Surface mass redistributions associated with these changing loads cause visco-elastic/elastic adjustment of the solid Earth, producing changes of the gravity field and deforming ocean basins. These phenomena give rise to regional changes in sea level. The collapse of the large ice sheets following the Last Glacial Maximum, and the subsequent loading of the ocean basins, resulted in deformation of the ocean floor and changes in the gravity field. This is the so called GIA effect. With a life time of a few thousand years, it is still active today and will continue to affect regional sea level variations in the future (Peltier, 2004). Present-day ice sheet melting also leads to a characteristic pattern of relative sea level fall close to the melting bodies, as well as larger than average sea level rise in the tropics (Milne et al., 2009). Non-uniform solid Earth responses are also expected from glacier melting and changes in land water storage. The 'static' sea-level variations associated with past and present ice/water mass redistributions are currently estimated using specific models that solve the so-called 'Sea Level Equation' for a deformable Earth, accounting for the gravitational interactions between the solid Earth, the ice bodies and the oceans, and for variations in the Earth rotation under the changing ice load (Peltier, 2004; Bamber and Riva, 2010; Tamisiea and Mitrovica, 2011; Spada, 2017). In addition to the steric and static effects, atmospheric loading can also produce small regional variations in sea level (Stammer et al., 2013).

At present, as shown below, the dominant contribution to observed regional sea level changes comes from non-uniform thermal expansion and salinity variations (Church et al., 2013; Stammer et al., 2013). Other effects, in particular the static factors today little contribute to the regional variability but will become important in the future (Milne et al., 2009).

In terms of global mean, the primary mechanisms leading to current GMSL rise consist of (1) ocean mass changes due to ice melting and discharge from ice sheets, glaciers, and ice caps, changes in land water storage (i.e., surface waters, soil moisture and ground waters), in the snowpack and permafrost, and in atmospheric water content; and (2) ocean volume change due to thermal expansion of sea waters and salinity variations. It is usually expressed by the sea level budget equation:

$$\mathrm{GMSL}(t) = \mathrm{GSSL}(t) + \mathrm{M}_{\mathrm{ocean}}(t) \tag{1}$$

where GSSL (t) refers to the global steric sea level change (i.e., the contributions of ocean thermal expansion and salinity changes) and $\mathrm{M}_{\mathrm{ocean}}$ (t) refers to the change in mass of the oceans. t is time.

Because of water mass conservation in the climate system, ocean mass change (i.e., $\mathrm{M}_{\mathrm{Ocean}}$ (t)) is such that:

$$\begin{aligned}&\mathrm{M}_{\mathrm{Ocean}}(t) + \mathrm{M}_{\mathrm{Glaciers}}(t) + \mathrm{M}_{\mathrm{Greenland}}(t) + \mathrm{M}_{\mathrm{Antarct.}}(t)\\ &\quad + \mathrm{M}_{\mathrm{LWS}}(t) + \mathrm{M}_{\mathrm{Atm}}(t) + \mathrm{M}_{\mathrm{snow}}(t) + \text{missing terms} = 0\end{aligned} \tag{2}$$

where $\mathrm{M}_{\mathrm{Glaciers}}(t)$, $\mathrm{M}_{\mathrm{Greenland}}(t)$, $\mathrm{M}_{\mathrm{Antarct.}}(t)$, $\mathrm{M}_{\mathrm{LWS}}(t)$, $\mathrm{M}_{\mathrm{Atm}}(t)$ and $\mathrm{M}_{\mathrm{snow}}(t)$ represent temporal changes in mass of glaciers, Greenland and Antarctica ice sheets, land water storage (LWS), atmospheric water vapor and snow mass changes. Missing terms include for example larger-scale permafrost melting (there are currently no data to estimate it).

At regional scales, the regional sea level (RSL) budget writes: RSL (t) = RSSL (t) + $\mathrm{RM}_{\mathrm{Ocean}}$ (t) + atmospheric loading + static terms, where RSSL (t) and $\mathrm{RM}_{\mathrm{Ocean}}$ (t) are time-variable regional changes in steric sea level and ocean mass. As discussed in the introductory part, the static terms consist of GIA and other solid Earth & gravitational effects due to present-day mass redistributions.

At local scale (i.e., coastal areas), in addition to the global mean plus regional components, vertical motions of the ground cause 'relative' sea level variations (where 'relative' means 'with respect to the ground'). Besides, in coastal areas, small-scale processes occurring at the land-sea interface (i.e., wind-driven ocean circulation changes, fresh water input from rivers in estuaries, trend in wave height, etc.) may superimpose to the larger-scale open-ocean sea level changes. As a result, coastal sea level changes may possibly be different from what is observed away in open ocean (see Section 8).

4. Data sets used to estimate the components of the sea level budget

As discussed in Section 2, the GMSL record at global and regional scales is essentially based on multi-mission satellite altimetry. To estimate from observations the other components of the sea level budget, other types of measurements are used.

The ocean thermal expansion component is estimated from in situ temperature measurements for different depth levels. Until the mid-2000s, temperature data were essentially based on shipboard measurements by expandable bathythermographers (XBTs). These upper-ocean in situ temperature measurements are limited to the upper 700 m depth. Although the coverage has been improved through time, large regions characterized by difficult meteorological conditions remained under-sampled, in particular the southern hemisphere oceans and the Arctic area (Abraham et al., 2013). The global ocean in situ observing system has been dramatically improved in the early years 2000 through the implementation of the international Argo program of a set of ~3800 autonomous floats, delivering a unique inside of the interior ocean from the surface down to 2000 m depth of the ice-free global ocean (Roemmich et al., 2012). Different research groups worldwide regularly produce gridded time series of temperature data for different depth levels from which steric sea level time series can be derived.

Global glacier mass changes are derived from in situ measurements of glacier mass (monitoring of the annual mean snow accumulation and ice loss from melt) and glacier length changes. Remote sensing methods are also used. These include elevation changes over entire glaciers based on differencing digital elevation models (DEMs) from satellite imagery between two epochs (or at points from repeat altimetry), surface flow velocities for determination of mass fluxes, and glacier mass changes from GRACE space gravimetry (Tapley et al., 2004). Laser altimetry from ICESat is another important method to estimate glacier mass change. A review of these different methods is given in Marzeion et al. (2017).

To estimate ice sheet mass balances and their contribution to sea level, three main methods are used: (1) measurement of changes in elevation of the ice surface over time (dh/dt) either from imagery or altimetry; (2) the mass budget or Input-Output Method (IOM) which involves estimating the difference between the surface mass balance and ice discharge, the latter being measured by SAR interferometry (InSAR); and (3) direct mass change estimate based on GRACE space gravimetry since 2002. A review is provided in the WCRP Sea Level Budget Group (2018).

Finally land water storage changes can estimated either from GRACE space gravimetry or using global hydrological models.

5. Sea level budget

5.1. Global scale

Accurate assessment of present-day global mean sea level variations and its components (ocean thermal expansion, ice sheet mass loss, glaciers mass change, changes in land water storage, atmospheric water vapour content, etc.) is important for many reasons. The global mean sea level is an integrator of changes occurring in the climate system in response to unforced climate variability as well as natural and anthropogenic forcing factors. Its temporal evolution allows detecting changes (e.g., acceleration) in one or more components. Study of the sea level budget provides constraints on missing or poorly known contributions, such as the unsurveyed deep ocean or the land water component.

Several previous studies have addressed the sea level budget over different time spans and using different data sets (e.g., Cazenave et al., 2009; Leuliette and Miller, 2009; Leuliette and Willis, 2010; Church and White, 2011; Llovel et al., 2014; Yi et al., 2015; Chambers et al., 2017; Dieng et al., 2017a; Chen et al., 2017; Nerem et al., 2018a, 2018b). Assessments of the published literature have also been performed in past IPCC (Intergovernmental Panel on Climate Change) reports (e.g., Church et al., 2013).

Recently, in the context of the Grand Challenge entitled "Regional Sea Level and Coastal Impacts" of the World Climate Research Programme, an international effort involving the sea level community worldwide has been carried out with the objective of assessing the various data sets used to estimate components of the sea level budget during the altimetry era (1993 to present) (the WCRP Sea Level Budget Group, 2018). Here we briefly summarize the main findings of this global mean sea level budget assessment.

Almost all available quality data sets have been used to estimate each component. This resulted in a large number of considered products (11 for thermal expansion, 5 for glaciers, 8 for the Greenland ice sheet and 11 for Antarctica). For each component, an ensemble mean has been considered for the budget (details can be found in the WCRP Sea Level Budget Group, 2018).

Comparing individually all components (thermal expansion, glaciers, ice sheets, etc.) shows that ocean thermal expansion remains the dominant contribution to the GMSL trend over the altimetry era. The mean thermal expansion trend is estimated to 1.3 ± 0.4 mm/yr over 1993–2015 and 2005–2015. The 0–700 m ocean depth layer contributed by 70% over 1993–2015 and 65% over 2005–2015 (Argo era), indicating that more heat has reached the 700–2000 m depth layer in the most recent decade relative to the entire 23-year period. To this value, the abyssal ocean only contributes to 0.1 mm/yr (update from Purkey and Johnson, 2010) but it is worth reminding that measurements in the deep ocean remain very sparse.

Most recent updated estimates for the glaciers, Greenland and Antarctica mass balances lead to trend contributions of 0.65 ± 0.10 mm/yr, 0.48 ± 0.10 m/yr and 0.25 ± 0.10 mm/yr over 1993–2005 and 0.74 ± 0.10 mm/yr, 0.76 ± 0.10 mm/yr and 0.42 ± 0.10 mm/yr for 2005–2015. For the latter period, Greenland and Antarctica mass balances are essentially based on GRACE. We note that the Greenland ice sheet contribution is larger than the other two, with a significant increase in ice mass loss in the recent years. Overall, the total land ice contribution (sum of glaciers, Greenland and Antarctica) dominates the ocean thermal expansion over the two considered time spans.

Fig. 3a and b shows the individual contributions (expressed in mm/yr of sea level equivalent) to the GMSL rise for 1993–2015 (rate of 3.1 mm/yr) and for 2005–2015 (rate of 3.5 mm/yr). This figure does not include the terrestrial water component that results from water storage changes on land in response to natural climate variability and direct human intervention (dam building on rivers, groundwater extraction, deforestation, land use, wetland drying, etc.). Its estimate so far remains uncertain. Direct observations of the net land water storage exist since 2002 through the use of GRACE space gravimetry (Llovel et al., 2010; Becker et al., 2010; Reager et al., 2016; Scanlon et al., 2018). Most recent GRACE-based estimates (Reager et al., 2016; Scanlon et al., 2018) provide a negative contribution to sea level, on the order of −0.3 mm/yr. On the other hand, estimates from hydrological models tend to give values of opposite sign. However, both approaches suffer significant uncertainties. The coarse resolution of GRACE (∼300 km) may lead signal unrelated to land hydrology to leak into river basins areas, which introduces bias in land water storage estimates (e.g., Yi et al., 2017). Besides, hydrological models also suffer bias

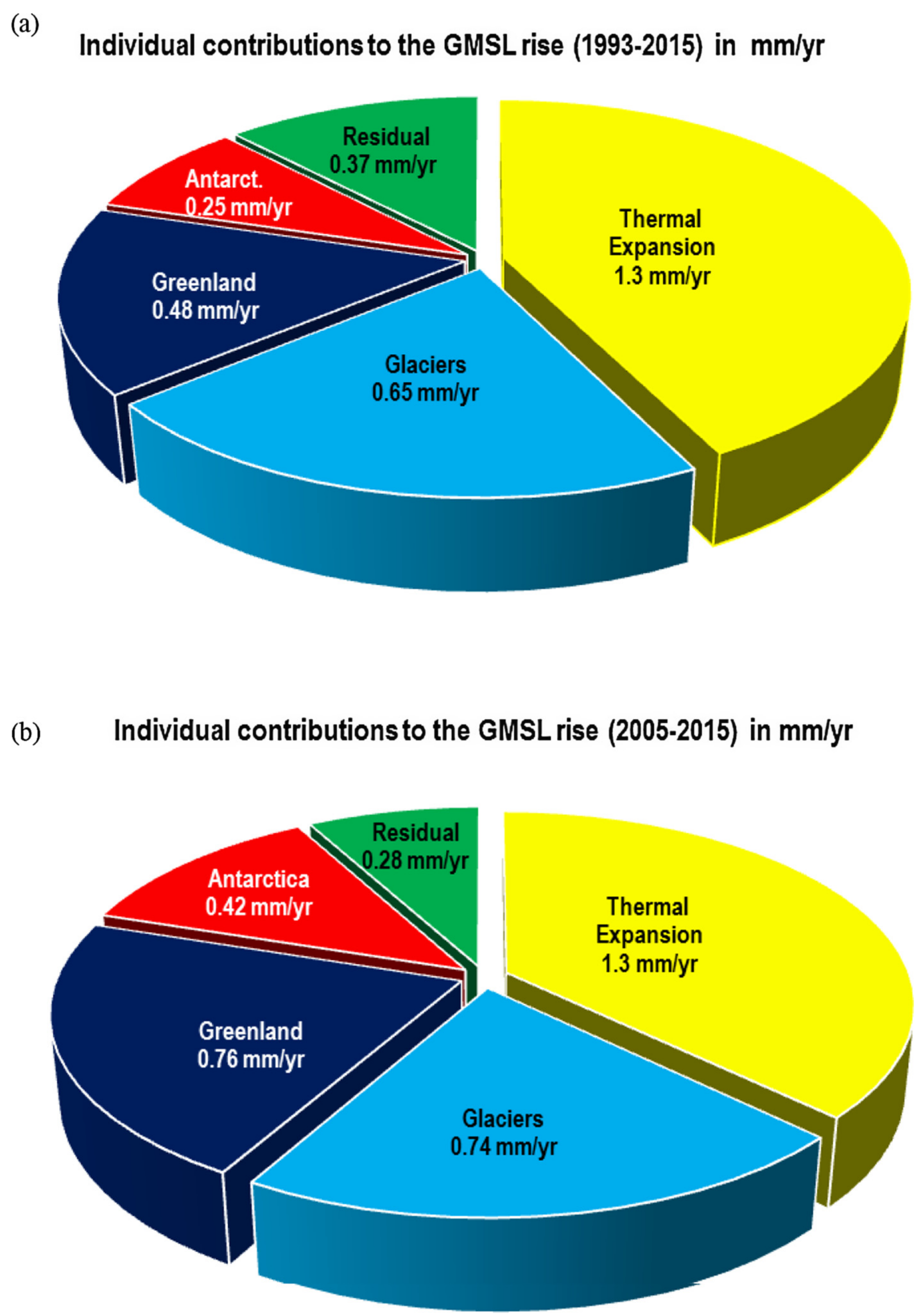

Fig. 3. (a) Individual contributions to the GMSL rise in mm/yr sea level equivalent for the 1993–2015 time span based on the assessment of The WCRP Mean Sea Level Group (2018). Colors correspond to components (yellow = thermal expansion, light blue = glaciers, dark blue = Greenland, red = Antarctica; green = residual); (b) same as (a) but for the 2005–2015 time span. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

due to uncertainty in meteorological forcing, inadequate modelling of some water reservoirs (e.g., Doll et al., 2017), and for some of them, lack of account of human interventions such as dam building and groundwater depletion.

The sea level budget approach as illustrated in Fig. 3a and b suggests that the land water component contributed to 13% and 8% to the global mean sea level over 1993–2015 and 2005–2015 respectively, assuming that the difference between observed sea level rise and sum of components is totally attributed to the land water contribution.

Since 2002, GRACE space gravimetry provides direct estimates of ocean mass changes. This approach allows more precise quantification of the total mass contribution to sea level compared to summing individual mass contributions. Fig. 4 shows the annual sea level budget for years 2005 to 2015 based on the comparison between yearly averages of the GMSL and sum of ocean thermal expansion and GRACE-based ocean mass. Yearly residuals are also shown. All values are referenced to year 2003. Quite good agreement is noticed, indicating closure of the sea level budget over this time span, within a few mm for yearly averages. This result also suggests that there is not yet any significant contribution to deep ocean warming to the global mean sea level rise.

5.2. Regional scale

Several studies published during the past decade have clearly established that the regional variability in sea level trends is mainly due to changes in temperature and salinity-related density structure of the oceans, in response

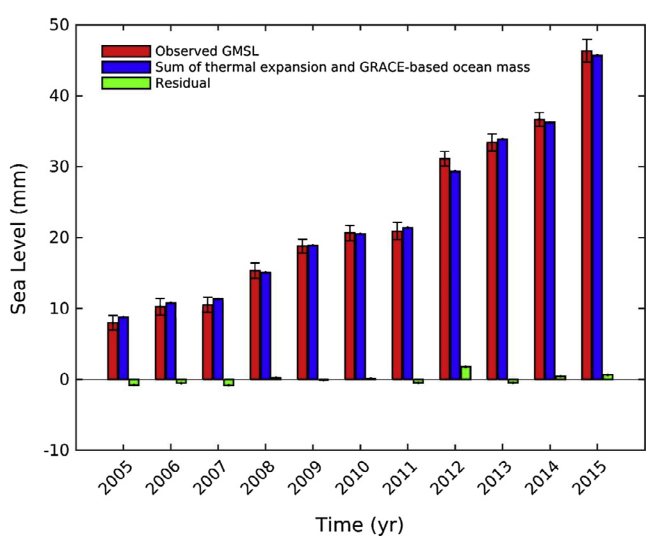

Fig. 4. Annual sea level (blue bars) and sum of thermal expansion (full depth) and GRACE ocean mass component (red bars) (All values are set to zero in 2003, the year of reference). Black vertical bars are associated uncertainties. Annual residuals (green bars) are also shown. From the assessment of the WCRP Global Mean Sea Level Group (2018). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to forcing factors (e.g., heat and fresh water exchange at the sea-air interface and wind stress-driven circulation changes) (e.g., Bindoff et al., 2007; Stammer et al., 2013; Church et al., 2013). While in most regions, regional changes in sea level largely result from ocean temperature change, in a few others, change in salinity can also be important.

Fig. 5a, b and c shows spatial trend patterns in altimetry-based and steric sea level (based on Argo data processed in Dieng et al., 2017a) over the 2005–2015 time span, and the trend difference between these two maps. The considered period is characterized by several ENSO (El Niño – Southern Oscillation) events. This is visible on both the observed and steric trend maps that show the clear ENSO signature in the eastern tropical Pacific, with high sea level and high thermal expansion. The difference map confirms that in the majority of regions, observed trends are steric in origin. However, in a few areas, residual trend signal remains, e.g., along western boundary and Austral currents. This is likely due to the inability of Argo coverage to adequately monitor the mesoscale circulation. A similar remark holds for the Indonesian region where Argo measurements are very sparse. On the other hand, the positive residual trend observed in the tropical band of the Pacific and Atlantic oceans, as well as the negative trend signal seen south of Greenland in the north Atlantic may have a different explanation. These may partly reflect the static effects due to ongoing ice sheet melting (e.g., Tamisiea and Mitrovica, 2011; Tamisea, 2011).

As shown by Piecuch and Ponte (2014), heat and mass exchanges with the atmosphere are dominant in the north Atlantic while wind stress forcing mostly explains regional sea level trends in the tropics. For example, sea level trends observed in the western tropical Pacific during the altimetry era have been attributed to increased wind-stress and associated deepening of the thermocline (e.g. Timmermann et al, 2010; Thompson and Merrifield, 2014; Palanisamy et al., 2015a, 2015b). If the inferred steric trends are removed from the altimetry trends, the residual signal of the western tropical Pacific is negligible within data uncertainties.

There is little doubt that the global mean sea level rise and its current acceleration result from anthropogenic forcing on the global climate (e.g., Becker et al., 2014; Marcos et al., 2017; Slangen et al., 2017). On the other hand, the regional trends may still be dominated by the internal climate variability and its response to natural modes of the coupled ocean–atmosphere system, such as ENSO, North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO). This has been highlighted in a number of recent studies (e.g., Zhang and Church, 2012; Stammer et al. 2013; Palanisamy et al., 2015b, Meyssignac et al., 2017). However, others suggest that the fingerprint of anthropogenic forcing is already detectable in some regions, such as the southern ocean (e.g., Hamlington et al. 2014). The debate is still open.

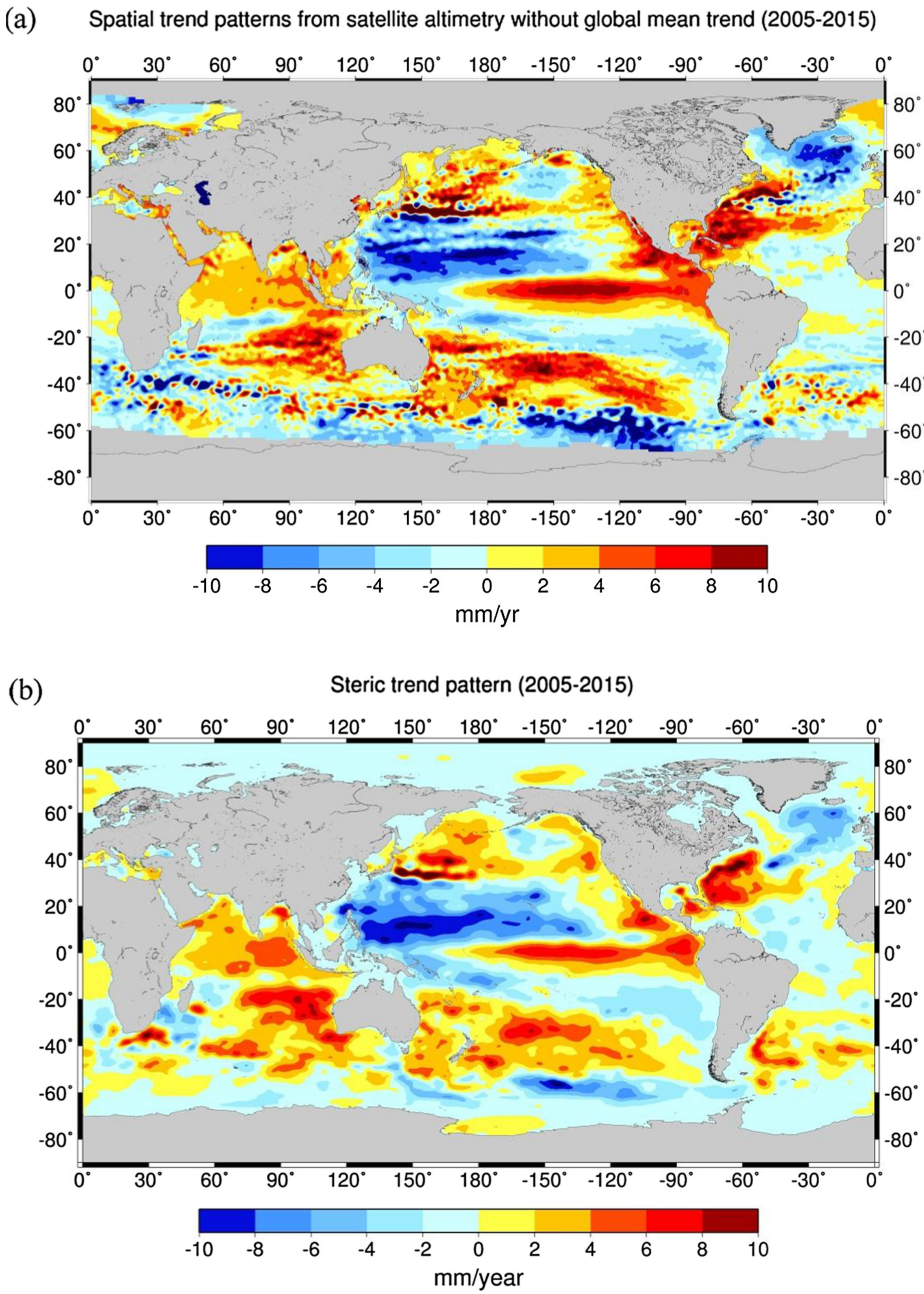

Fig. 5. (a) Spatial trend patterns in sea level from satellite altimetry between January 2015 and December 2015 based on AVISO data (https://www.aviso.altimetry.fr/); (b) Spatial trend patterns in steric sea level between January 2005 and December 2015 based on an ensemble mean of Argo data (data from Dieng et al., 2017a); (c) Residual trend map (difference between observed and steric trends).

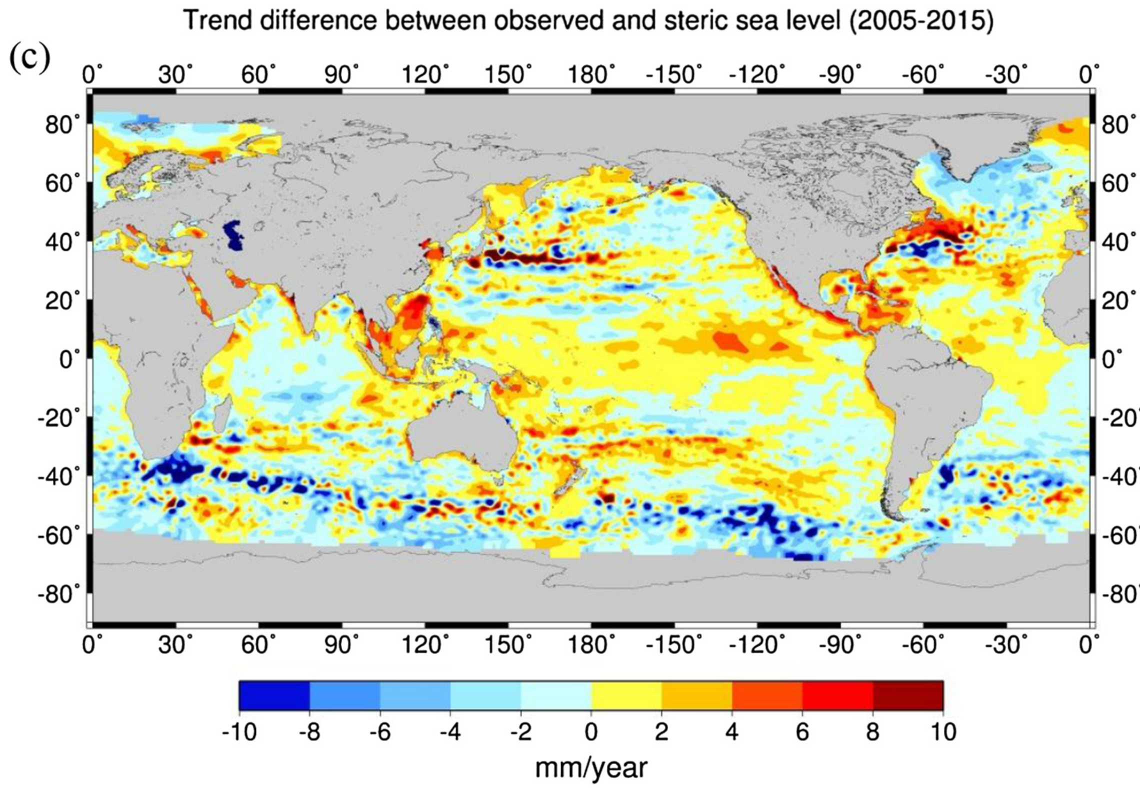

Fig 5. *(continued)*

6. Projecting future sea level changes and their coastal impacts

Compared to extreme events, sea level rise is a slow process but it has long-term consequences. In effect, it is almost certain that whatever future GHG emissions, sea level will continue to rise during the next decades and even centuries (Church et al., 2013; Levermann et al., 2013). While future global mean sea level elevation is related to future trajectories of GHG emissions, it also depends on potential runaway of some components of the climate system such as the ice sheets. Above a given warming threshold, parts of the ice sheets may undergo irreversible melting leading to several meters of sea level rise (e.g., Robinson et al., 2012; Collins et al., 2013). In addition, as it is already the case today, future sea level rise will not be uniform, amplification with respect to (*wrt*) the global mean being expected in several oceanic regions due steric and static factors (Church et al., 2013; Slangen et al., 2014). In addition, at local scale, a number of factors may also give rise to sea level changes. The quantity of interest for coastal populations is the total sea level rise relative to the ground, i.e., the climate-related global mean rise plus the regional changes due to climate and non-climate factors, plus local changes due to small scale ocean circulation and other processes. The latter are dominated by non-climate-related factors. They may result from vertical ground motions caused by tectonic and volcanic phenomena, sediment load and/or groundwater & oil extraction. Withdrawal of water from aquifers can produce dramatic relative sea level rise, especially in coastal megacities. During the second-half of the 20th century, Tokyo, Shanghai, Bangkok and Jakarta subsided by 5 m, 3 m, 2 m and 1 m respectively, because of groundwater withdrawal (Nicholls, 2010). Ground subsidence, hence relative sea level rise, is also widely observed in highly-populated deltaic areas, in particular in Asia (e.g., Ericson et al., 2006). Other factors affecting sea level in coastal areas include small-scale shelf currents, fresh water input from rivers in estuaries, and coastal morphological and bathymetric changes due sediment transport, engineering, urbanization, land use changes, etc. Very close to the shore, trend in wave regime can also impact sea level (Melet et al., 2018).

The IPCC 5th Assessment Report/AR5 (Church et al., 2013) provided sea level rise projections at global and regional scales for the 21st century and beyond. It projected a global mean sea level elevation of ∼50–100 cm for 2086–2100 wrt 1986–2000 for the RCP (Representative Concentration Pathway) 8.5 scenario. However, since the IPCC AR5 publication in 2013, some studies have suggested that these projections may be underestimated. For example, accounting for as yet unobserved ice sheet instability mechanisms, the study by De Conto and Pollard (2016) suggests that Antarctica may contribute >1 m global mean sea level rise by 2100 (wrt to year 1950) and 15 m in 2500 (for the RCP 8.5 scenario). Several other recent studies based on probabilistic and 'empirical' projections also suggest higher sea level rise projections than IPCC AR5 (Jevrejeva et al., 2014b; Kopp et al., 2014; Mengel et al., 2016). As mentioned above, at regional scale, in addition to the global mean rise, a series of factors will give rise to regional sea level trends. These include the steric component, as well as GIA and fingerprints of future land ice melt (Church et al., 2013; Carson et al., 2016). The latter effects will lead to an amplification of the global mean rise by 20% to 30% in the tropics (Church et al., 2013).

Adverse effects of sea level rise in coastal areas, such as inundation, shoreline erosion, increased flooding during storm surges, salinization of wetlands and aquifers, etc., are generally considered as a major threat, considering that coastal zones are the most densely populated and economically active areas of the world (Nicholls and Cazenave, 2010). They concentrate important infrastructures such as harbors and industries. Local conditions, e.g. low altitude above sea level, existence of deltaic areas, land subsidence due to sediment load and underground water and oil extraction may worsen the direct impacts of sea level rise. It is now well established that at local scale, the coastal response to sea level rise depends on several non-linearly-related factors such as coastal morphology, near shore bathymetry, sediment supply from rivers, changing waves & currents, etc. (Fitzgerald et al., 2008; Cazenave and Le Cozannet, 2014; Passeri et al. 2015). While for the 20th century, most coastal change was a response to multiple drivers (Nicholls, 2010; Passeri et al., 2015), expected sea level rise by the end of the 21st century and beyond, will make sea level rise the dominant forcing factor of future coastal systems changes (Wong et al., 2007; Nicholls, 2010). Detailed projections of future regional sea levels under different warming scenarios have been carried out for the coasts of North Western America (NRC, 2012), Western Europe (Katsman et al., 2011) and Australia (McInnes et al., 2015). However, it is not yet the case everywhere, e.g., Western Africa or South East Asia. The West African megacities are situated at sea level, hence are highly exposed to sea level rise. Similarly, southeast Asia coastlines are highly vulnerable to the effects of climate change (droughts & floods, cyclones, sea level rise) due to their geology and geography, growing density population, infrastructure and urban development (e.g., Yuen and Kong, 2009). Especially at risk are the large deltaic regions of Myanmar, Thailand and Viet Nam, and some low-lying areas of Indonesia, Malaysia and Philippines (Ericson et al., 2006; Nicholls et al., 2012).

7. Lessons learned from current sea level monitoring from space at global and regional scales

In terms of global average, sea level is one of the best indicators of climate change. In effect, it integrates changes occurring in the Earth's climate system in response to unforced climate variability as well as natural and anthropogenic forcing factors, e.g., net contribution of ocean warming, land ice melt, and changes in water storage in continental river basins. Temporal changes of some components are directly reflected in the global mean sea level time series. Study of the sea level budget provides constraints on missing or poorly known contributions, e.g., the deep ocean undersampled by current observing systems, or still uncertain changes in water storage on land due to human activities (e.g. ground water depletion in aquifers).

Most recent studies (e.g., Dieng et al., 2017a; Chen et al., 2017; Nerem et al., 2018b; The WCRP Sea Level budget Group, 2018) show that the GMSL is accelerating, and that this acceleration mostly arises from accelerated Greenland and Antarctica ice mass loss. Closure of the global mean sea level budget (within 0.1–0.2 mm/yr) over the GRACE and Argo era suggests that the deep ocean below 2000 m, not monitored by Argo, does not yet contribute significantly to the GMSL, while it may have already stored enough heat to have significant impact on the Earth's energy imbalance.

Assessment of the sea level budget also indicates that the most uncertain contribution to the GMSL is the net land water storage. More work is needed using both sea level and mass budget approaches, as well as using GRACE data and hydrological modelling to estimate this component.

Global mean sea level corrected for ocean mass change allows one to independently estimate temporal changes in total ocean heat content, from which the Earth's energy imbalance can be deduced, as shown in Dieng et al. (2017b) who found that this approach agrees well with independent estimates of the current Earth's energy imbalance.

This global mean sea level, as well as the global sea level budget, are now considered as key climate indicators for the ocean, as shown in the Statement on the State of the Global Climate delivered on a yearly basis by the World Meteorological Organization to inform governments, international agencies, and the general public about the global climate (e.g., World Meteorological Organization, 2018).

At regional scale, most recent studies confirm that spatial trend patterns observed in altimetry maps are mostly steric in origin. But, as illustrated in Fig. 5 above, some signals have a different source. Possibly, these may reflect the fingerprints of ongoing land ice melt predicted theoretically but until recently hardly detectable when XBTs data down to 700 m were used to remove the steric component.

8. Remaining uncertainties and key gaps in sea level monitoring

The altimetry record is unanimously recognized as an invaluable product that informs on how much sea level is rising globally in response to global warming and how it changes regionally in response to the natural internal climate variability. For that reason, it is extremely important to ensure sustained and ever more accurate observations of global and regional sea level variations from space. A longer sea level record with increased accuracy (fulfilling the GCOS requirements) will help answering still imperfectly understood scientific questions such as: Does the recently recorded sea level rise acceleration represent a long-term shift towards a new climate regime? How large and possibly abrupt near future changes in the contributions of the ice sheets will affect the global sea level? How much heat has already reached the deep ocean? Can we constrain the Earth's energy imbalance and its temporal variations with improved global mean sea level observations? Is the regional variability in sea level only due to internal climate variability or can we already detect the fingerprint of anthropogenic forcing? When should the anthropogenic signal emerge out of the natural variability? What regions will be affected first?

In addition to the above need for long-term sea level change monitoring from space at global and regional scales, a major key gap remains. It concerns coastal sea level changes.

In coastal regions, sea level variations result from a combination of different processes that act at different spatial and temporal scales. In addition to the global mean rise and superimposed large-scale regional variability, small-scale ocean processes (waves, meso-scale currents) and dynamical atmospheric forcing (air pressure and surface winds) also affect sea level in coastal regions. As these processes impact the coast differently, evaluating their relative importance is essential for assessment of the local coastline vulnerability. So far, we do not know if sea level at the coast rises at the same rate as in open ocean (Cipollini et al., 2017; 2018).

In principle, tide gauges and satellite altimetry data can be used to answer this important question. Unfortunately, this is not yet the case. Long, accurate tide gauges records are very sparse in many regions of the world, e.g., along the coasts of Western Africa. Besides, classical Ku-band nadir altimetry missions mentioned above provide valid data up to 10–20 km from the coast only. This is due to land contamination that modifies in a complex way the standard Brown-type radar waveforms, typical over open ocean surface. This prevents from accurately estimating the altimeter range. This is also due to uncertainty in some geophysical corrections, particularly important in coastal regions (e.g., the wet tropospheric correction, sea state bias, ocean tides and dynamic atmospheric correction). Imperfect knowledge of the reference mean sea surface nearby the coast leads to additional uncertainty. Ka-band altimetry on SARAL/AltiKa allows getting closer to the coast (up to 2–3 km) and increased along-track resolution of SAR altimeters on CryoSat-2 and Sentinel-3 are able to provide sea level measurements up to few hundred meters to the coast depending on the shore coast line configuration (Cipollini et al., 2018). But in both cases however, improved geophysical corrections are also needed.

Providing as precise as possible observation-based estimates of present-day (relative) sea level variations at the coast is crucial to understand processes at work and further achieve realistic evaluation of the impacts of sea level rise in coastal environments. To achieve this, accurate monitoring from space of sea level changes along the world coastal zones, highly under-sampled by tide gauges and currently un-surveyed (within 10–20 km to the coast) by conventional altimetry missions, need to be undertaken. This implies the development of an easy-to-use data base of homogeneous, multi-decade-long, multi-mission gridded coastal altimetry products, with as global as possible coverage. Today such a global coastal-altimetry-based sea level record does not exist although it could be developed by dedicated reprocessing of conventional nadir altimetry missions (e.g., the Jason series and Envisat), as well as by systematic use of new SAR technology implemented in recent ESA missions (e.g., CryoSat-2 and Sentinel-3a, 3b) and also planned for the Jason-CS/Sentinel-6 mission, scheduled to launch in 2020.

9. Conclusion

The 25-year long record of altimetry-based sea level is now recognized as a key climate variable that needs to be monitored on the long term to inform on global warming and its evolution. Study of the global mean sea level budget is also considered as highly valuable to inform on which components are responsible for accelerated sea level rise and on how partitioning between ocean warming and land ice melt impacts the sea level budget. Near closure of the sea level budget indicates that deep ocean warming (below 2000 m) is not yet an important contributor to the global mean sea level but continuing global mean sea level monitoring will allow detecting changes in deep ocean heat content. There is also indication that at regional scale, the anthropogenic mean sea level rise is becoming as important as the signature of internal climate modes. But this has to be confirmed using a longer sea level record.

Continuing monitoring of the sea level at global and regional scales is more than ever an important goal for understanding how the global climate is evolving in response to external forcing factors and natural variability. Together with the global mean Earth's temperature and the total ocean heat content, sea level is a key indicator of the state of the Earth's climate. Moreover, as sea level rise counts among the most threatening consequences of ongoing global warming, precisely measuring sea level changes in coastal zones and understanding associated forcing factors are newly recognized priorities in sea level research. Tools to do this exist but this is still an emerging research issue that needs stronger involvement from the research community and the supporting agencies.

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