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Present-day sea-level change: A review

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Abstract

Understanding of sea-level change has improved considerably over the last decade. Present-day knowledge of sea-level change is derived from tide gauge observations and satellite altimetry measurements. The average rate of sea-level change obtained from tide gauges over the last 50 years is $+1.8 \pm 0.3$ mm yr^{-1}. In comparison, altimeter measurements from TOPEX/Poseidon and Jason-1 have shown an average rise of $+3.1 \pm 0.4$ mm yr^{-1} since 1993. It is not clear yet whether the larger rate of rise of the last decade reflects acceleration or decadal fluctuation. The causes of the present-day rate are a combination of increases in ocean temperatures and land ice melt from mountain glaciers, Greenland, and Antarctica. Regional variability in sea-level change, as evidenced by the quasi global coverage of altimeter satellites, appears dominated by non uniform change of thermal expansion. New satellite technologies, such as InSAR, ICESat, and GRACE make significant contributions to understanding sea-level change. ***To cite this article: R.S. Nerem et al., C. R. Geoscience 338 (2006).***

Résumé

Les variations actuelles du niveau de la mer : une synthèse. Depuis quelques années, d'importants progrès ont été réalisés quant à la connaissance de la hausse actuelle du niveau moyen global de la mer. Les marégraphes indiquent, pour les 50 dernières années, une hausse moyenne de $+1{,}8 \pm 0{,}3$ mm an^{-1}. Depuis 1993, les satellites altimétriques TOPEX/Poseidon et Jason-1 enregistrent une hausse de $+3{,}1 \pm 0{,}4$ mm an^{-1}. On ne sait pas, pour l'instant, s'il s'agit d'une accélération ou d'une simple fluctuation décennale. De récentes observations des variations de température des océans et des bilans de masse des glaces continentales montrent que la hausse actuelle du niveau de la mer résulte de l'effet combiné de l'expansion thermique des océans et de la perte de masse des glaciers de montagne et des calottes polaires. La variabilité régionale des vitesses de variations du niveau de la mer, mise en évidence grâce à la couverture quasi globale des satellites altimétriques, résulte pour l'essentiel des variations géographiques de l'expansion thermique. De nouvelles techniques spatiales, telles que INSAR, ICESat et GRACE, offrent depuis peu d'importantes contraintes sur la contribution des glaces et eaux continentales aux variations du niveau de la mer. ***Pour citer cet article : R.S. Nerem et al., C. R. Geoscience 338 (2006).***

Keywords: Sea level; Climate change; Thermal expansion; Ice sheets mass balance; Land waters; Satellite altimetry

Mots-clés : Niveau de la mer ; Expansion thermique ; Bilan de masse des calottes polaires ; Eaux continentales ; Altimétrie spatiale

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1. Introduction

Measuring the amount of sea-level change has been an objective of scientists for over a century. Long-term sea-level change is a well-known indicator of climate variations and determining the causes of sea-level change can therefore provide insight into how the Earth is responding to climate change. Determining the rate of sea-level change is also important for determining the socioeconomic effects on coastal populations. The primary source of information on sea-level change over the past century are tide-gauge measurements. However, tide gauges poorly sample the global oceans, and can also be affected by vertical land motions unrelated to climate-driven sea-level variations. Satellite measurements over the last decade have revolutionized our understanding of sea-level change [4]. When combined with the tide gauge record, as well as the record of ocean warming from in situ temperature measurements, a better understanding of the amount of sea-level change and its causes is beginning to emerge.

2. Tide-gauge observations of sea-level change

Prior to the early 1990s, tide gauges provide us with the primary dataset for measuring sea-level change. While some tide gauge records extend back 100 years or more, most of the records are less than 50 years in length. Because the tide gauges so poorly sample the oceans in a geographic sense, long records must be used so that decadal variability caused by the poor sampling can be averaged out. Douglas [12] and Peltier [39] found that when records longer than 50 years are used, and the selected tide gauges are far from tectonically active regions, a rate of sea-level rise of 1.84 ± 0.35 mm yr^{-1} is obtained for the 20$^{\text{th}}$ century (after correcting for vertical motion of the crust due to glacial isostatic adjustment, GIA, in response to last deglaciation). This is somewhat larger than the pre-industrial (prior to 1850) rate of sea-level change determined from ocean sediments [29], which is approximately 1 mm yr^{-1}. Most recent estimates of past few decades sea-level rise confirm Douglas [12] and Peltier [39] values. Based on 177 tide gauges divided into 13 regions, Holgate and Woodworth [15] find a rate of 1.7 ± 0.4 mm yr^{-1} for the period 1950–2000, while Church et al. [8] propose a value of 1.8 ± 0.3 mm yr^{-1} over the same period by applying a reconstruction method that combines information on spatial variability from satellite altimetry and temporal change from tide gauges. No significant acceleration of sea-level rise has been detected in the tide-gauge data, although recently, extending back in time the reconstructed sea-level time series, Church and White [7] find a small acceleration of 1.3 ± 0.5 mm yr^{-1} per century for the period 1870–2000.

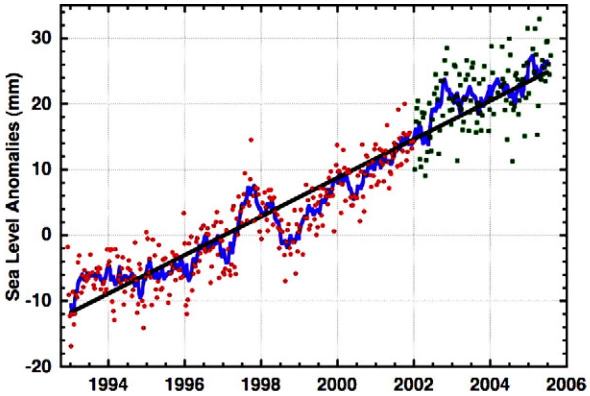

Fig. 1. Sea-level curve from TOPEX/Poseidon and Jason-1 satellite altimetry (updated from [21]). Dots are raw data (red for TOPEX/Poseidon and green for Jason-1). The blue curve is the 60-day smoothed sea level. The solid black line is the best fitting slope.

Fig. 1. Courbe d'évolution du niveau moyen global de la mer d'après les observations des satellites altimétriques TOPEX/Poseidon et Jason-1 (d'après [21]). Les points (rouges pour TOPEX/Poseidon, verts pour Jason-1) correspondent aux estimations brutes tous les 10 jours. La courbe bleue représente un lissage sur 60 jours. La droite noire est la pente calculée par la méthode des moindres carrés.

3. Sea-level change in the Satellite era

The era of precision satellite sea-level measurements began in 1992 with the launch of TOPEX/Poseidon (T/P). In 2001, the Jason-1 satellite was launched to continue the T/P time series, and we now have a 13-year time series of precision sea-level change measurements. The groundtrack of these satellites repeats every 10 days, providing global (±66° latitude) maps of sea-level change with this temporal sampling. When averaged globally, these maps provide 10-day estimates of global mean sea level with an accuracy of roughly 4–5 mm [21]. Over the last 13 years, observations of changes in these estimates have shown a rise in global mean sea level of 3.1 ± 0.4 mm yr^{-1}, after taking into account a GIA correction (of -0.3 mm yr^{-1}) due to the small deformation of oceans basins since last deglaciation [4,21] (Fig. 1). The error estimate is dominated by errors in the calibration of the onboard instruments. These errors are determined from differences of tide gauge and altimeter sea level [33].

Clearly, a change in the rate of sea-level change has been observed during the satellite era. However, it is unknown if this change in the rate will be sustained during the coming years, or if it is shorter-term phenomena

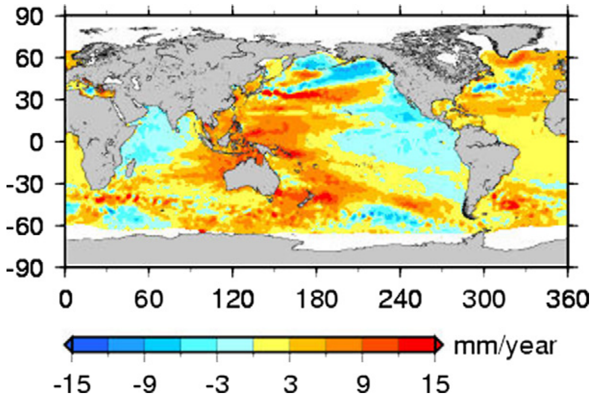

Fig. 2. Geographical distribution of linear sea-level trends computed over 1993–2003 from TOPEX/Poseidon satellite altimetry (updated from [4]).

Fig. 2. Distribution géographique des vitesses de variations du niveau de la mer mesurées par TOPEX/Poseidon entre 1993 et 2003 (d'après [4]).

associated with decadal variability. Owing to the quasi global coverage of satellite altimetry, is it also possible to map the geographical distribution of sea-level change during the satellite era (Fig. 2). While regional variability in coastal areas had been reported from tide gauges [11,20], the global coverage of satellite altimetry shows that in open oceans too, sea-level change is non-uniform. For the last 13 years, some regions, in particular the western Pacific, exhibit rates of sea-level rise up to 5 times the global mean. In other regions (e.g., the eastern Pacific) sea level has been dropping during that period. The geographical pattern seen in Fig. 2 is dominated by the signature of the 1997–1998 ENSO (El Niño-Southern Oscillation) event (e.g., [37]).

4. Causes of the observed sea-level change

Long-term changes in global mean sea level can be caused by a variety of phenomena, but the major contributions arise from changes in ocean temperature (thermal expansion), changes in the volume of ice in mountain glaciers, Greenland and Antarctica, and changes in the amount of water stored in terrestrial reservoirs. Our knowledge of the magnitude of each of these contributions varies considerably. In addition, we have much better knowledge of these contributions during the satellite era than over the last century.

4.1. Ocean-temperature changes

Information on changes in thermal expansion (also called steric sea level) comes mainly from observations of ocean temperature versus depth made from ships at sea. Over the last 50 years, these observations indicate that the global ocean has warmed significantly, although not uniformly [22]. In terms of global mean, ocean thermal expansion has contributed to $\sim$0.4 mm yr^{-1} over the past 50 years [2,16], i.e., by about 25% of the observed rate of sea-level rise. It is worth mentioning that the rate of steric sea level is not constant in time and display considerable interannual/decadal variability. During the satellite era, this rate has accelerated to between 1.2 mm yr^{-1} [2,16] and 1.6–1.8 mm yr^{-1} [24, 25,51]. It has been suggested that part ($\sim$0.5 mm yr^{-1}) of the last decade steric sea-level increase – compared to the previous decades – may be due to recovery to previous state after the transient ocean cooling produced by the volcanic eruption of Mt. Pinataubo in 1991 [9]. While there is a significant acceleration in the rate of sea-level change due to thermal expansion during the last decade, clearly thermal expansion cannot explain all of the change observed by satellite altimetry over the same time period. For both periods (last 50 years and last decade), $\sim$1.5 mm yr^{-1} of the observed sea-level rise cannot be explained by thermal expansion, thus is caused by ocean mass increase due to land ice melt and terrestrial waters [23,30].

Like observed sea-level trends, thermal expansion trends are not spatially uniform. This is illustrated in Fig. 3, which shows the spatial patterns of thermal expansion trends for two periods, 1955–2003 and 1993–2003 (from Ref. [24], using ocean temperature data from [16]). First we can note that for both periods, thermal expansion displays considerable regional variability, a result of non-uniform change in ocean heat content [22]. In addition, when comparing the two maps of Fig. 3, we note that the spatial patterns for the shorter period differ greatly from those of the longer period. Like the global mean thermal expansion, the spatial patterns are subject to decadal variability, partly related to ENSO, PDO (Pacific Decadal Oscillation), and NAO (North Atlantic Oscillation) [24].

4.2. Land ice-mass change

4.2.1. Mountain glaciers

In situ observations of the mountain glaciers are sparse – only a small fraction of the world's glaciers are actively monitored. However, when observations of these glaciers are extrapolated globally, they show a contribution to sea-level change of 0.5 mm yr^{-1} over the past four decades, and 0.8 ± 0.35 mm yr^{-1} over the period 1993–2003 [13], although the errors on these estimates could be quite large. Independent observations of the glaciers appear to support these conclusions [1].

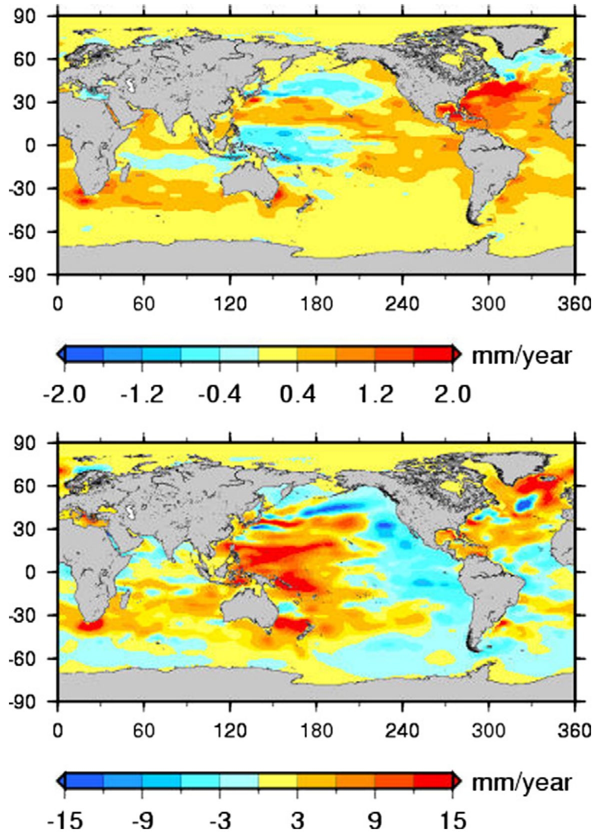

Fig. 3. Spatial patterns in thermal expansion trends for 1955–2003 (upper panel) and 1993–2003 (lower panel) (from [24]).

Fig. 3. Distribution géographique des tendances de l'expansion thermique pour 1955–2003 (en haut) et 1993–2003 (en bas) (d'après [24]).

4.2.2. Greenland and Antarctica

The contributions to 20th century sea-level change from Greenland and Antarctica ice-mass change are almost unknown. This is in contrast with the last decade during which remote sensing observations have provided, for the first time, direct observations of the Greenland and Antarctica mass balance. Greenland ice-sheet elevation changes have been estimated during the 1990s from repeated airborne laser altimetry measurements. Comparison between two surveys held in 1996–1997 and 2002–2003 indicates that on average Greenland is loosing mass, especially in near coastal regions, through both surface melting and glacier discharge. This corresponds to a small positive contribution to sea level of 0.10–0.20 $\mathrm{mm\,yr^{-1}}$ over this time span [18,19,43]. In high-elevation regions of central Greenland, previous remote sensing observations as well as mass budget techniques have reported near balance (e.g., [45,46]), although another study based on satellite radar altimetry suggests an elevation increase in the Greenland interior during 1992–2003 [17]. From 10.5 years of ERS-1/2 satellite altimetry measurements, Zwally et al. [52] find ice-mass increase in central Greenland while thinning is reported at the Greenland margins, leading to near balance. These results contrast with those of Rignot and Kanagaratnam [42], based on satellite radar interferometry, who report widespread glacier acceleration since 1996, with ice volume loss over 1996–2005 corresponding to $+0.23\ \mathrm{mm\,yr^{-1}}$ sea-level rise in 1996 and $0.57\ \mathrm{mm\,yr^{-1}}$ in 2005.

Over West Antarctica, recent laser airborne and radar satellite altimetry, as well as radar interferometry surveys, have reported accelerated ice mass loss in the Amundsen Sea sector during the recent years, corresponding to $0.16\ \mathrm{mm\,yr^{-1}}$ sea-level rise [41,47]. In contrast, radar altimetry measurements over East Antarctica from the ERS-1/2 satellites indicate elevation increase, between 1992 and 2003 [10], corresponding to an average mass gain and associated sea-level drop of $0.12\ \mathrm{mm\,yr^{-1}}$. The Zwally et al. [52] study also reports West Antarctica mass loss and slight ice mass increase in East Antarctica. These results suggest that the Antarctic ice sheet as a whole is in near balance, thus contributes little to sea level. However, as for Greenland, great uncertainty remains, primarily due to the lack of complete coverage by remote sensing surveys.

Since 2002, space gravimetry from the GRACE mission provides a new tool for precisely measuring spatio-temporal changes in liquid- and solid-water mass inside the surface fluid envelopes (e.g., [44,50]), including the ice sheets [6,28,40,48,49]. Compared to satellite and airborne altimetry, which measures ice elevation and hence needs to be corrected for ice compaction, GRACE directly measures the total mass change of the ice sheets. Moreover, GRACE gives nearly complete coverage of high-latitude regions, up to 89°N/S. However, GRACE is also sensitive to solid-Earth mass change, in particular to GIA, thus needs to be corrected for that effect. Over Greenland, recent GRACE results confirm altimetry results, i.e., net ice mass loss. Over Antarctica, GRACE observations suggest mass loss on average over the past 2–3 years. These results however should be considered as still preliminary considering the very short time span of GRACE observations and the significant contamination of GIA.

From the above discussion, we consider as plausible, a range of 0.2–0.4 $\mathrm{mm\,yr^{-1}}$ for the total contribution of Greenland and Antarctica to sea level for the last decade. Accounting for the glaciers contribution, the total land ice contribution of observed sea-level rise (mostly due to mountain glaciers) amounts to 1–1.2 $\mathrm{mm\,yr^{-1}}$ over that period. The combination

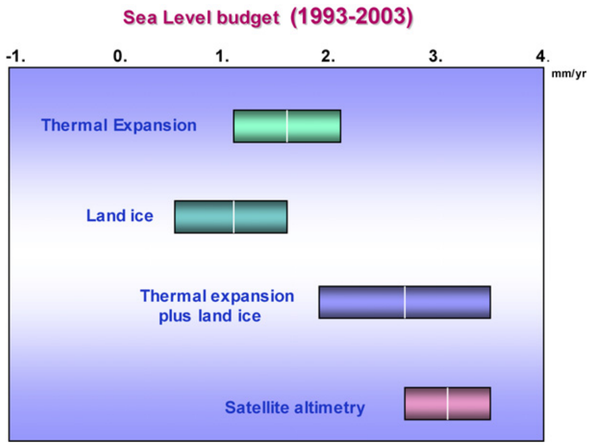

Fig. 4. Sea-level budget for the 1990s; comparison between observations and climatic contributions.

Fig. 4. Schéma de bilan du niveau de la mer pour la période 1993–2003 ; comparaison entre observations et contributions climatiques.

of thermal expansion (assuming an average value of 1.6 mm yr^{-1}) and land ice melt over the last decade indicates a total contribution of $\sim$2.7 mm yr^{-1}. Thus about 0.4 mm yr^{-1} still needs to be explained to close the sea-level budget. A sketch of the sea-level budget for the 1990s is presented in Fig. 4. Uncertainties are 2σ errors.

Constraints from Earth orientation measurements seemed to constrain the land ice contributions to sea level to be quite small, but a recent improvement to the Earth's rotation theory [34] now allows a 1-mm yr^{-1} contribution from land ice, while still satisfying constraints from ancient eclipse records, drift in the rotation pole, and changes in the rotation rate [35]. This recent development appears to resolve the longstanding 'sea-level enigma' [36], which required a large land ice contribution to resolve the difference between 20^{th}-century sea-level change as observed by tide gauges (1.8 mm yr^{-1}) and from ocean temperature measurements (0.4 mm yr^{-1}).

4.3. *Terrestrial water contribution*

Of course there could be other contributions to sea-level change that could help close the sea-level budget. The largest potential contribution to sea-level change not yet accounted for is change in land-water storage due to natural climate variability and human activities (anthropogenic changes in the amount of water stored in soils, reservoirs and aquifers result from dam building, underground water mining, irrigation, urbanization, deforestation, etc.). Model-based estimates of land-water storage change caused by natural climate variability suggest no long-term contribution to sea level although interannual/decadal fluctuations may be significant [31, 38]. Former estimates of changes in the amount of water stored in terrestrial reservoirs caused by human activities suggested a negative contribution to sea-level rise as large as -0.8 mm yr^{-1} [14]. Recent revised estimates suggest near-cancellation between negative contribution due to dam building and positive contribution due to underground water extraction (D. Sahagian and B. Chao, personal communication; [32]). However, these anthropogenic factors remain highly uncertain due to the lack of global in situ observations. As discussed above, the difference between observed sea-level rise over the last decade and thermal expansion plus land ice contributions would constrain the total terrestrial water contribution to $\sim$0.4 mm yr^{-1}. Interestingly, a recent estimate of land-water storage change based on GRACE suggests a contribution of $\sim$0.35 mm yr^{-1} over the last three years [3].

5. New observations of sea-level change

Several new satellite technologies promise to help resolve the uncertainties in the contribution of land ice and terrestrial waters to sea-level change. The Gravity Recovery and Climate Experiment (GRACE) has provided precise estimates of changes in the Earth's gravity field since its launch in 2002. Recent studies [5,26] have shown that GRACE can precisely measure the seasonal and interannual water mass contribution to mean sea-level change via changes in global mean ocean mass. In addition, when combined with satellite altimetry, GRACE observations over the oceans provide an indirect estimate of thermal expansion [26]. We have seen that GRACE has also been used to directly measure changes in the ice mass in Greenland and Antarctica [6, 28,40,48,49]. Although the time series is short, GRACE estimates from each of the ice sheets appear to be in agreement with other remote sensing results. Another very promising application of GRACE is the direct determination of the land-water contribution (due to both natural climate variability and anthropogenic effects) to sea-level change. So far this is the least well-known factor affecting sea-level change.

The launch of ICESat in 2003 brought a new tool to sea-level studies through globally distributed laser altimeter measurements. Instruments problems have restricted ICESat to an intermittent observation schedule, however early estimates of ice-height change [27] suggest ICESat could eventually provide important observations of ice volume change.

6. Discussion

Our understanding of sea-level change has improved considerably over the last decade. Satellite measurements show that the rate of sea-level rise has accelerated when compared to 20th-century tide-gauge measurements, though it is unknown if this increase in the rate will be maintained. For the last decade, about 50% of the current rise is due to thermal expansion. While there is recent evidence of large contributions to sea-level rise from mountain glaciers, a significant contribution from other sources (polar ice sheets and terrestrial water reservoirs) is needed to close the difference between the altimeter observations and the ocean temperature measurements. Recent direct remote sensing observations of the polar ice sheets allow us to almost close the sea-level budget for the last decade. The latter results are still uncertain however, and thus future efforts should be focused on improving mass balance of the polar ice sheets, especially since the Greenland and Antarctica represent the large source of potential future sea-level change (7 and 60 m, respectively), as well as the anthropogenic land water component, at present poorly known.

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