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Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993–2007

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[1] Based on a careful selection of tide gauges records from the Global Sea Level Observing System network, we investigate whether coastal mean sea level is rising faster than the global mean derived from satellite altimetry over the January 1993–December 2007 time span. Over this 15-year time span, mean coastal rate of sea level rise is found to be +3.3 ± 0.5 mm/yr, in good agreement with the altimetry-derived rate of +3.4 ± 0.1 mm/yr. Tests indicate that the trends are statistically significant, hence coastal sea level does not rise faster than the global mean. Although trends agree well, tide gauges-based mean sea level exhibits much larger interannual variability than altimetry-based global mean. Interannual variability in coastal sea level appears related to the regional variability in sea level rates reported by satellite altimetry. When global mean sea level is considered (as allowed by satellite altimetry coverage), interannual variability is largely smoothed out. **Citation:** Prandi, P., A. Cazenave, and M. Becker (2009), Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993–2007, *Geophys. Res. Lett.*, *36*, L05602, doi:10.1029/2008GL036564.

1. Introduction

[2] Sea level variations over the past decades have been essentially estimated from tide gauge records [e.g., *Holgate and Woodworth*, 2004; *Holgate*, 2007; *Jevrejeva et al.*, 2006, 2008] or from sea level reconstructions that combine tide gauge data with 2-dimensional information for representing the regional variability [e.g., *Church et al.*, 2004]. While tide gauges are of great value to estimate historical sea level change, they only reflect coastal sea level. It has been suggested by *Holgate and Woodworth* [2004] that coastal mean sea level is rising faster than the global mean, a result of major societal and economic implication in the context of current global warming. Using a dataset of 177 tide gauges, these authors computed a coastal mean sea level rate ~+4 mm/yr over January 1993–December 2002, a value significantly larger than the global mean rate (of +3.1 mm/yr, Glacial Isostatic Adjustment –GIA- applied) based on satellite altimetry over the same time span [e.g., *Cazenave and Nerem*, 2004]. However satellite altimetry, available since early 1990s, has revealed important regional variability in sea level rates [e.g., *Lombard et al.*, 2005; *Bindoff et al.*, 2007], with rates up to 3 times the global mean in some areas. Thus a coastal mean sea level rate different from the global mean is to be expected. If so, this may have considerable implications for both past and future sea level. For example, if the ~+1.7 mm/yr rate of coastal sea level rise reported by tide gauges for the 20th century were significantly larger than the global mean value [e.g., *Church et al.*, 2004; *Holgate*, 2007; *Jevrejeva et al.*, 2006, 2008], then the ~3 mm/yr global mean rate measured by satellite altimetry since the early 1990s would represent a significant acceleration compared to the previous decades. For the future, global mean sea level projections from climate models may underestimate mean sea level rise in coastal regions, implying even larger negative impacts than previously thought. However, regional variability in sea level trends as reported by satellite altimetry is subject to large interannual/decadal fluctuations linked to ENSO (El Nino Southern Oscillation), NAO (North Atlantic Oscillation) and PDO (Pacific Decadal Oscillation) [e.g., *Lombard et al.*, 2005; *Bindoff et al.*, 2007]. Thus one may wonder whether Holgate and Woodworth's result, based on just 10 years of data, is not biased by the inherent coastal interannual variability. In this study we perform a new comparison between coastal mean sea level based on tide gauges and almost global mean derived from satellite altimetry over a 15-year time span (1993–2007).

2. Data Analysis

2.1. Tide Gauges

[3] We use monthly tide gauges records from January 1993 through December 2007 (hereafter noted as 1993–2007) from the University of Hawaii Sea Level Center (UHSLC) Fast Mode Delivery data base (data available from the web at: ilikai.soest.hawaii.edu/uhslc/woce.html). The UHSLC monthly data set contains 228 records from the GLOSS (Global Sea Level Observing System) tide gauge network [*Intergovernmental Oceanography Commission*, 1997]. The data base is up-to-date and therefore allows the study period to be extended until the end of 2007. The data undergo a first quality check at UHSLC when computing monthly means from the raw data. As sub annual variability is of no interest here, we remove seasonal signal from each record. This is performed through a least squares fit of annual and semi-annual sinusoids. We also correct the tide gauges data for the inverse barometer effect (i.e., the response of sea level to atmospheric perturbations) using surface pressure grids from the NCEP (National Centers for Environmental Prediction) reanalysis [*Kalnay et al.*, 1996]. The pressure grids are available as monthly means on a 2.5 degree grid. We assign to each tide gauge the sea level pressure value of the nearest grid point.

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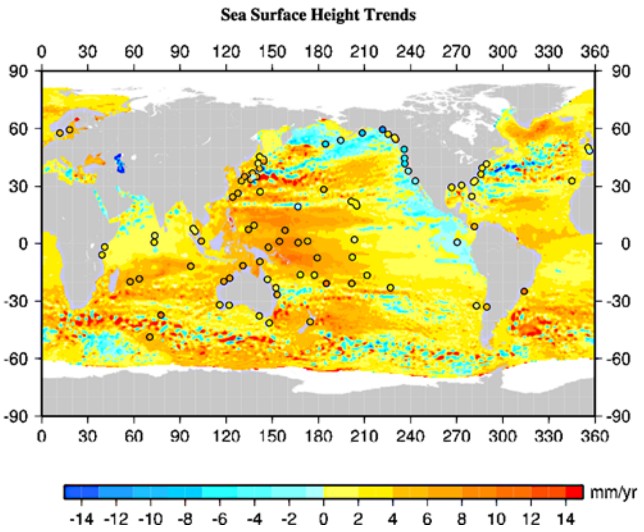

Figure 1. Comparison between tide gauges and altimeter sea level trends over the 1993–2007 period. Colors inside the 91 black open circles represent tide gauges trends, using the same color scale as for satellite altimetry trends. Units: mm/yr.

[4] One problem when using tide gauges records is that they are referenced to local datum. As it is not possible to link local datum together, we cannot directly average the tide gauge records to obtain a mean sea level time series. To overcome the problem of data referencing, previous studies computed overlapping decadal mean sea level rates for each record [*Holgate and Woodworth*, 2004; *Jevrejeva et al.*, 2006; *Holgate*, 2007]. Because of the relatively short time span (15 years) considered in this study, we cannot use this method here. Thus we subtracted to each tide gauge record its mean value computed over the complete time span (1993–2007). This process is equivalent to referencing all tide gauges records into a common unknown reference frame, assuming that all records have the same length (see below). This allows calculating a mean sea level at coastal tide gauges over the whole 1993–2007 period. In the following, this coastal mean sea level is noted CMSL.

[5] Tide gauges records are sensitive to vertical crustal motions, thus only provide relative sea level measurements with respect to the Earth's crust. These motions result from a variety of phenomena: glacial isostatic adjustment of the Earth's crust in response to last deglaciation, tectonic and volcanic deformations, ground subsidence associated with sediment loading (e.g., in large river deltas), water pumping and oil extraction. Such motions are poorly known and there is no global model to account for all of them. Only a few tide gauge sites are monitored by GPS precise positioning techniques [e.g., *Woppelmann et al.*, 2007]. The only process that can be taken into account at all tide gauge sites is GIA. We applied this GIA correction to each tide gauge time series using the ICE-5G VM4 model [*Peltier*, 2004].

2.2. Tide Gauge Records Selection Process

[6] In the UHSLC data base, tide gauge records lengths are not uniform: start and end dates, and time series lengths vary from one tide gauge to another. The first step of the data selection process was to reject all time series without 80% completeness over the 180 months period considered in this study. Applying this criterion leads to a subset of 123 tide gauge records, with all time series having nearly the same length. Therefore no important bias is expected to affect the global mean when we remove the mean of each time series. Among these 123 time series, we select another set of 71 tide gauges (hereafter called reference set), previously checked for quality. In order to augment the reference data set, we analyzed co-variability between nearby tide gauges records. Considering a correlation length of 1000 km and a correlation coefficient >0.5 with respect to the reference records led to reintroduce 18 additional sites. Finally we added manually two time series with high mutual correlation while rejected by the previous test due to lack of tide gauges in the region in the reference set. This process resulted in 20 new sites, hence a total of 91 high-quality tide gauges records. Their location is shown in Figure 1 (open circles). This final set of tide gauges, while smaller than in other studies [*Chambers et al.*, 2002; *Church and White*, 2006; *Jevrejeva et al.*, 2006, 2008], contains only high quality time series, homogeneous in length. As seen in Figure 1, tide gauge coverage is good in the Pacific and Indian oceans, but rather poor in the southern Atlantic Ocean, with only one tide gauge in this region and none along the Atlantic coast of Africa. There is no over sampling of regions that have numerous long and high quality tide gauges records such as Europe and the north-western Atlantic coast.

2.3. Satellite Altimetry Data

[7] The satellite altimetry data are taken directly from Aviso website (www.aviso.oceanobs.com), Centre National d'Etudes Spatiales, France. For the global mean sea level, we use the merged Geophysical Data Records products (based on Topex/Poseidon data between January 1993 and October 2002, a combination of Topex/Poseidon and Jason-1 data between October 2002 and November 2005 and Jason-1 data since then). All classical geophysical and environmental corrections are applied, including the inverted barometer effect (see www.aviso.oceanobs.com for details; see also M. Ablain et al. (A new assessment of global mean sea level from altimeters highlights a reduction of global slope from 2005 to 2008 in agreement with in-situ measurements, submitted to *Ocean Sciences*, 2008)). The altimetry-based global mean sea level −hereafter denoted as GMSL- is corrected for the GIA effect (trend of −0.3 mm/yr [*Peltier*, 2004]). We also used $^1/_4$° gridded sea level data at weekly interval based on multi satellites altimetry data (www.aviso.oceanobs.com).

3. Results

[8] In Figure 1 are presented spatial patterns of the altimetry-derived sea level trends computed over 1993–2007 (from the $^1/_4$° grids). These patterns are now well known and highly correlated to thermal expansion trend patterns [*Lombard et al.*, 2005; *Bindoff et al.*, 2007]. We also computed sea level trends at the 91 tide gauge sites (using the UHSLC data). These are shown in Figure 1 inside circles indicating the tide gauge positions, with the same color scale as for altimetry trends. We can see that tide

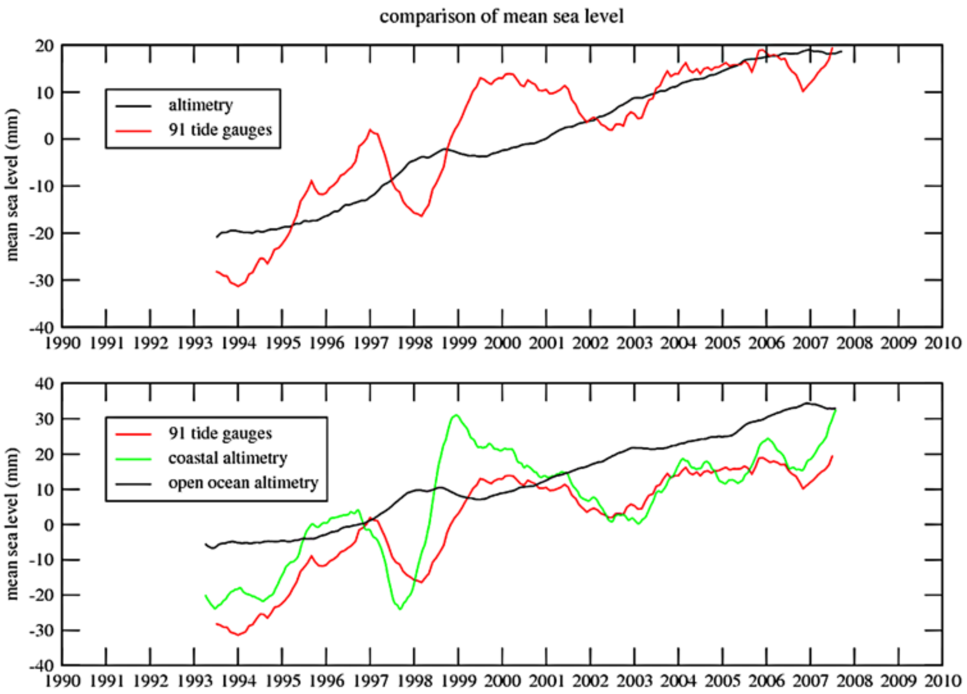

Figure 2. (top) Global mean sea level derived from satellite altimetry (black curve) and averaged at 91 tide gauges sites over 1993–2007 (red curve). Units: mm. (bottom) Coastal mean sea level calculated from tide gauges (red curve), compared with coastal altimetry mean sea level using a 200 km wide coast definition (green curve) and open ocean altimetry mean sea level (black curve). Unit: mm. A 12- month running average filter was applied to all curves shown in Figure 2.

gauge trends agree well with altimetry trends at all sites. Root mean squared (rms) differences between the tide gauge and local altimetry-based trends are <2 mm/yr. Considering that in some regions, trend magnitude can reach up to 15 mm/yr, such a rms difference is acceptable. Moreover altimetry trends are based on gridded data not exactly coinciding with the tide gauge sites. Nevertheless, we cannot exclude contamination from vertical crustal motions at some tide gauges sites [e.g., *Nerem and Mitchum*, 2002], in spite of the drastic tide gauge selection performed here. Figure 2 (top) compares over the 1993–2007 time span, altimetry-based GMSL (GIA correction applied) and CMSL based on averaging the 91 tide gauge records (corrections applied as indicated above). In Figure 2, CMSL is based on the arithmetic mean of all 91 records. We also performed regional grouping before averaging to see the influence of regions covered by many tide gauges (such as northwest Atlantic, northeast and northwest Pacific). Only minor difference was found between the two CMSL curves and in the following we use the arithmetic mean.

[9] The CMSL trend over 1993–2007 calculated from the set of 91 tide gauges is +3.3 ± 0.5 mm/yr. A value of +3.4 ± 0.1 mm/yr, is obtained for the GMSL trend. The quoted errors are revised standard errors (95% level of confidence) based on the method proposed by *Santer et al.* [2000] (see below). Note that for the altimetry-based GMSL trend, error budget analyses by *Beckley et al.* [2007] and Ablain et al. (submitted manuscript, 2008) considering all sources of errors affecting the altimetric system, lead to possible uncertainty in the range 0.3–0.4 mm/yr. Comparing CMSL and GMSL trends over the 1993–2007 time span suggests that mean sea level at the coast does not rise faster than global average. However, as the CMSL curve shows important interannual variability, unlike the GMSL curve, the issue of statistical significance of the CMSL trend needs to be addressed. It is also of interest to check whether the length of the record influences the estimated trend. These two issues are treated together below. Successive CMSL trend estimates are computed over varying time spans, starting with the 1993–2000 time span (year 2000 included), then adding one year to the previous time span, up to 2007. We further assess the trend significance. The t-test applied to the ratio of the CMSL trend to its standard error leads to a critical value strictly above 2 (threshold of statistical significance, considering the n-2 degrees of freedom; n being the number of monthly time samples), for all ending dates from 2000 to 2007. Therefore, CMSL trends are statistically significant at the 95% level of confidence. However as shown by *Santer et al.* [2000], classical tests of trend significance may underestimate the standard error if the detrended time series are not statistically independent. These authors propose an improved method that accounts for the temporal autocorrelation of the detrended time series: it defines an effective sample size n_e (< n) based on the lag-1 autocorrelation coefficient, r_1 [see *Santer et al.*, 2000, equation (6)]. By substituting the effective sample size n_e for n in the trend standard error equation, one obtains a new standard error that is more realistic. Table 1 gathers for the eight time spans (ending dates from 2000 to 2007) the original and effective monthly sample size, trend value, original and new standard errors. The t-test applied to the ratio of CMSL trend to new standard error ranges from 6 to 8, i.e., well above the threshold of ~2. In Table 1 are also presented similar results for GMSL. From Table 1, we note

Table 1. CMSL and GMSL Trends Computed Over Different Time Spans[a]

Time Span of Analysis	CMSL Effective Original Sample Size (in Months)	CMSL Effective Sample Size (in Months)	GMSL Effective Sample Size (in Months)	CMSL Trend and Standard Error (mm/yr) (in Bracket: Revised Error)	GMSL Trend and Standard Error (mm/yr) (in Bracket: Revised Error)
1993–2000	96	38	18	5.8 ± 0.8 (1.3)	3.5 ± 0.13 (0.34)
1993–2001	108	46	21	5.46 ± 0.64 (1.0)	3.45 ± 0.10 (0.26)
1993–2002	120	45	25	4.42 ± 0.56 (0.95)	3.44 ± 0.09 (0.21)
1993–2003	132	54	28	4.07 ± 0.49 (0.79)	3.46 ± 0.07 (0.17)
1993–2004	144	59	34	3.81 ± 0.42 (0.67)	3.47 ± 0.06 (0.14)
1993–2005	156	66	40	3.73 ± 0.36 (0.57)	3.5 ± 0.05 (0.11)
1993–2006	168	74	43	3.41 ± 0.33 (0.51)	3.47 ± 0.05 (0.10)
1993–2007	180	75	40	3.30 ± 0.29 (0.47)	3.37 ± 0.05 (0.10)

[a] Effective sample size and revised errors are based on *Santer al.*'s [2000] method (see text).

that CMSL and GMSL trends are statistically significant at the 95% level of confidence, whatever the time span considered. But we also note that the length of the time series has considerable effect on the tide gauge trend estimate. For the shorter time spans (1993–2000 up to 1993–2003), coastal mean sea level trends are large (>+4 mm/yr). *Holgate and Woodworth* [2004] obtained a CMSL trend of +4 mm/yr over 1993–2002, in good agreement with the result of Table 1 for the same time span, in spite of a quite different selection of tide gauges. But as shown in Table 1, lengthening the CMSL time series tends to decrease the computed trend (as well as its standard error). While the altimetry-based GMSL trends are almost constant over the eight time spans (see Table 1), CMSL trends asymptotically tend towards the GMSL trend value. This is illustrated in Figure 3. Such a result suggests that on the long-term, coastal sea level may in fact rise at a rate similar to the global mean sea level, in agreement with earlier finding by *Church and White* [2006] who found no difference in coastal and global (reconstructed) sea level rise over the last 50 years.

[10] In order to further investigate the difference in interannual variability between CMSL and GMSL, we calculated coastal mean sea level and open ocean mean sea level, using in both cases the $^{1}/_{4}$° satellite altimetry grids. We extracted a global coastline grid from the satellite altimetry grid using grid points adjacent to the altimeter land mask. Altimetry-based coastal mean sea level was calculated by averaging all grid points within a certain distance from the coastline (area-weighting applied). Open ocean sea level was calculated from all other grid points. Figure 2 (bottom) shows altimetry-based coastal mean sea level, calculated for 200 km-wide coast definition (we also considered 100 km-wide coasts and obtained similar results). For comparison is also shown the CMSL curve based on the 91 tide gauges records. Altimetry-based coastal mean trend amounts to +2.95 ± 0.3 mm/yr over 1993–2007 (classical standard error; GIA correction applied), a value slightly lower than the tide gauge-based CMSL trend over the same time span. Difference in sampling, especially along the Atlantic coastlines and no account for Indian and Pacific ocean islands in altimetry coastal sea level may explain this trend difference. Altimetry-based coastal mean sea level (200 km wide coasts) exhibits large interannual variability, in good agreement with the CMSL time series The signatures of the 1997–1998 and 2002–2004 ENSO events dominate the interannual variability. Variability caused by other phenomena (e.g., storm surges) is also expected in coastal areas. This suggests that the large interannual variability of the tide gauge-based and altimetry- based CMSL reflects local/regional physical features (in particular the regional response of sea level to ENSO events [e.g., *Landerer et al.*, 2008]) that are damped out when worldwide averages are considered.

4. Summary and Conclusions

[11] Global mean sea level, calculated from a set of carefully selected 91 tide gauges records over the January 1993 to December 2007 period exhibits a trend of +3.3 ± 0.5 mm/yr. This value is in good agreement with the rate of sea level rise of +3.4 ± 0.1 mm/yr derived from satellite altimetry over the same period. Over this 15-year time span, we find that CMSL and GMSL trends are statistically significant. However, CMSL displays high interannual variability, in particular linked to ENSO, and likely associated with the regional (spatial) variability in sea level rates revealed by satellite altimetry. This regional interannual variability is smoothed out when global average is considered. The large interannual variability of the tide gauges-based CMSL agrees well with that inferred from satellite altimetry data averaged along worldwide coastlines. Therefore CMSL interannual variability is likely not due to

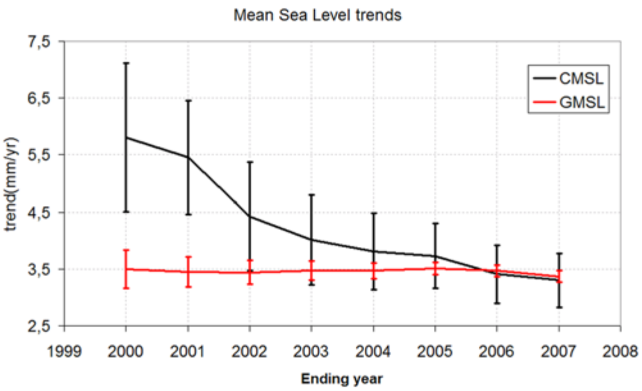

Figure 3. Comparison between mean sea level trends calculated over periods varying from 1993–2000 to 1993–2007, adding one year of data at each time interval; averages at 91 tide gauges sites (black curve) and worldwide averages from satellite altimetry (red curve). Trend error bars for the two curves are revised standard errors based on *Santer et al.*'s [2000] method (see text). Unit: mm/yr.

insufficient sampling by tide gauges but may rather reflect temporal fluctuations in sea level spatial patterns. In smoothing the spatial patterns, GMSL also damps out the interannual variability. This study does not find any significant difference between coastal and global mean sea level rise over the 15-year (1993–2007) time span considered. Thus to the question ‘Is coastal mean sea level rising faster than global mean?’, the answer is likely no. However, because of the large interannual variability in coastal mean sea level, considering shorter CMSL time series (e.g., 10-years) leads to overestimating the rate of sea level rise. Extending the CMSL time series from 10 to 15 years tends to decrease the coastal mean sea level rise and leads to a value similar to the GMSL rate.

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