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Sea Level Rise During Past 40 Years Determined from Satellite and in Situ Observations

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The 3.2 ± 0.2 millimeter per year global mean sea level rise observed by the Topex/Poseidon satellite over 1993–98 is fully explained by thermal expansion of the oceans. For the period 1955–96, sea level rise derived from tide gauge data agrees well with thermal expansion computed at the same locations. However, we find that subsampling the thermosteric sea level at usual tide gauge positions leads to a thermosteric sea level rise twice as large as the "true" global mean. As a possible consequence, the 20th century sea level rise estimated from tide gauge records may have been overestimated.

Coastal tide gauges have provided the main technique by which sea level change has been measured during the past century. For about a decade, sea level has been monitored worldwide by altimeter satellites, in particular by Topex/Poseidon, with global coverage, high spatio-temporal resolution, and direct tie to Earth's center of mass (*1*). The global mean sea level rise observed by Topex/Poseidon amounts to 2.5 ± 0.2 mm/year between January 1993 and December 2000 (*2*). On time scales longer than 1 year, global mean sea level change results from two main causes: (i) volume change due to seawater density change in response to temperature and salinity variations (the two parameters having opposite effects on sea level) and (ii) mass change due to exchange of water with atmosphere and continents, including glaciers and ice sheets, through precipitation, evaporation, river runoff, and ice melting. The recent availability of long time series of global ocean temperatures down to 3000 m, for the period 1945 through 1998 (*3*), has made it possible to quantitatively estimate the thermal contribution to the sea level change observed during the 1990s.

We used the yearly mean temperature data (available for the upper 500 m only) to compute the thermosteric sea level (*4*) and compared it with the yearly averaged sea level derived from Topex/Poseidon (Fig. 1). The thermosteric sea level rise for 1993–98 amounts to 3.1 ± 0.4 mm/year, in agreement with the 3.2 ± 0.2 mm/year rate measured by Topex/Poseidon over the same time span (*5*). The residual sea level (observed minus thermosteric sea level; also shown in Fig. 1) presents a small, not significant, trend of 0.2 ± 0.2 mm/year. Apart from uncertainties in observed and computed sea level rise, the residual trend would reflect unknown contributions from three sources: deep (500 to 3000 m) thermosteric change, water mass addition to the oceans due to exchange with atmosphere and continents, and halosteric (i.e., due to salinity change) variations. The above results suggest that these components contribute negligibly (less than 5%) to the observed sea level rise. The agreement between the Topex/Poseidon-observed and thermosteric sea level trends (*2*, *4*) for 1993–98 is striking, particularly in the tropics and Northern Hemisphere (Fig. 2). The thermosteric trend map reproduces well the Eastern Pacific sea level rise associated with the 1997–98 El Niño–Southern Oscillation (ENSO) event, as well as the Western Indian Ocean rise. Sea level patterns in the equatorial and Northern Atlantic also are well reproduced in shape and magnitude by the thermosteric map. Some discrepancy is observed in the southern oceans, where the positive trends observed by Topex/Poseidon (*6*) are larger than the thermosteric contribution, a likely consequence of sparse temperature coverage in remote southern regions. The quantitative comparison presented here shows that, for recent years, warming of the upper oceans almost fully accounts for the global mean sea level rise observed by Topex/Poseidon. Thus, other climatic contributions to the 1993–98 observed sea level rise, due to water mass exchange with the atmosphere and with continental reservoirs as well as deep ocean (below 500 m) thermal effects and salinity contribution, may globally counterbalance each other.

The third assessment report of the Intergovernmental Panel on Climate Change (IPCC) (*7*) estimates the various factors that have contributed to the 20th century sea level rise. The largest contribution (0.7 mm/year sea level rise) arises from thermal expansion due to warming of the oceans that mainly occurred since the 1950s (*8*). Melting of continental glaciers produces 0.2 to 0.4 mm/year sea level rise (*7*). Estimated Greenland and Antarctica mass imbalance (accounting for a long-term readjustment since Last Glacial Maximum plus a climate-related response) contributes –0.2 to 0.6 mm/year (*7*). The least certain contribution is the change in terrestrial water storage that results partly from human activities, which is in the range of –1.1 to + 0.4 mm/year with a median value of −0.35 mm/year (i.e., corresponding to sea level drop) (*7*). The sum of these contributions ranges from −0.8 to 2.2 mm/year, with a median value of 0.7 mm/year (*7*). Values for the 20th century sea level rise based on tide gauges records, published during the 1990s, are in the range 1 to 2 mm/year (*7*). The most recent global analyses (*9*, *10*), which use the longest tide gauge records available (≥70 years), report a rate of rise closer to 2 mm/year: 1.71 ± 0.55 mm/year (*9*) and 1.84 ± 0.35 mm/year after correcting for postglacial rebound (*10*). The third IPCC report (*7*) adopts a best estimate of 1.5 ± 0.5 mm/year for the observed 20th century sea level rise and notes that the sum of climate-related components is low compared with the observational estimates. In effect, these observed values (1.5 mm/year or 1.8 mm/year) are more than twice as large as the revised estimate of total climate contributions, although there is complete overlap between the range of the sum of contributions (*7*) and the observed range. It would appear that either the climate-related processes causing sea level rise have been underestimated or the sea level rise observed with tide gauges is biased toward values too high. The latter possibility may arise from the fact that tide gauges are located at continents or island coastlines and

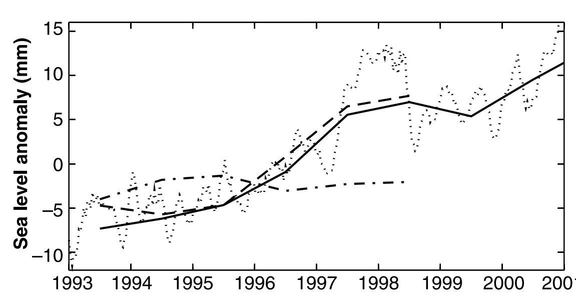

Fig. 1. Global mean sea level curves. Dotted curve, observed at 10-day interval by Topex/Poseidon for 1993–2000. Solid curve, yearly averaged sea level from Topex/Poseidon. Dashed curve, thermosteric component computed from global temperature data (*3*) down to 500-m depths for 1993–98. Dashed-dotted curve, residual (Topex/Poseidon minus thermosteric) sea level.

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hence do not globally sample the spatial variations of the sea level change. The recent availability of global sea temperature data (*3*) can help address the second possibility.

We computed the thermosteric sea level, for the period 1955–96, using the 5-year mean temperature data over the depth range 0 to 3000 m (*3*). The 60°S to 60°N average shows a mean thermosteric trend of 0.50 ± 0.05 mm/year (Fig. 3). To test the agreement between this average and the value that would be calculated by using only data from tide gauge positions, we computed a pseudo "global mean" steric sea level time series by subsampling the global thermosteric sea level grid at locations close to tide gauge sites (*11*), using 25 of the 27 stations selected by Douglas (*9*). The pseudo global mean thermosteric sea level time series, superimposed to the "true" global mean in Fig. 3, is 1.4 ± 0.10 mm/year, a value more than two times as large as the true global mean trend (0.5 ± 0.05 mm/year). Twenty-three out of the 25 sites are located in positive trend regions (Fig. 4). Considering the substantial regional variations in thermosteric trends, it appears clear that these sites fail to correctly sample the global variation and that averaging thermosteric sea level at these sites is not representative of the global mean.

We further checked whether the computed thermosteric sea level rise correctly reproduces the tide gauge–derived sea level rise. For that purpose, we considered tide gauge records from the Permanent Service for Mean Sea Level (PSMSL) (*12*) at the 25 sites. The "average" tide gauge–derived sea level curve over 1955–96, after performing regional grouping (*13*), is shown in Fig. 3. The observed (i.e., tide gauge–derived) mean sea level rise for 1955–96 is 1.6 ± 0.15 mm/year, a value that agrees well with the pseudo global mean thermosteric rise (1.4 ± 0.10 mm/year). The tide gauge–derived sea level curve displays decadal oscillations that are smaller in the thermosteric sea level curve. Inspection of individual tide gauge records indicates that stations of the northeast U.S. coast are largely responsible for the observed decadal variability, which originates from North Atlantic wind forcing (*14*). In our computation, we did not account for the halosteric component because global gridded salinity data are not yet available. Antonov *et al.* (*15*) showed that the halosteric contribution is quite substantial in the subpolar part of the North Atlantic, especially in the Labrador Sea, where it nearly counteracts the thermosteric contribution. However, in terms of global mean, the halosteric sea level rise has not exceeded 0.05 mm/year over the past 40 years (*15*). We checked whether neglect of the haline component when computing the steric sea level at the tide gauge sites would change our results. At each of the 25 stations, we computed difference time series of the tide gauge–derived minus thermosteric sea level and fitted a linear trend to these difference time series. The mean difference trend is 0.25 ± 0.14 mm/year, a value that represents an upper bound of the neglected halosteric and other climatic contributions.

Our study has demonstrated that the global estimate of the thermal expansion component is substantially smaller than the value obtained if the same field is subsampled at the tide gauge positions used to compute the

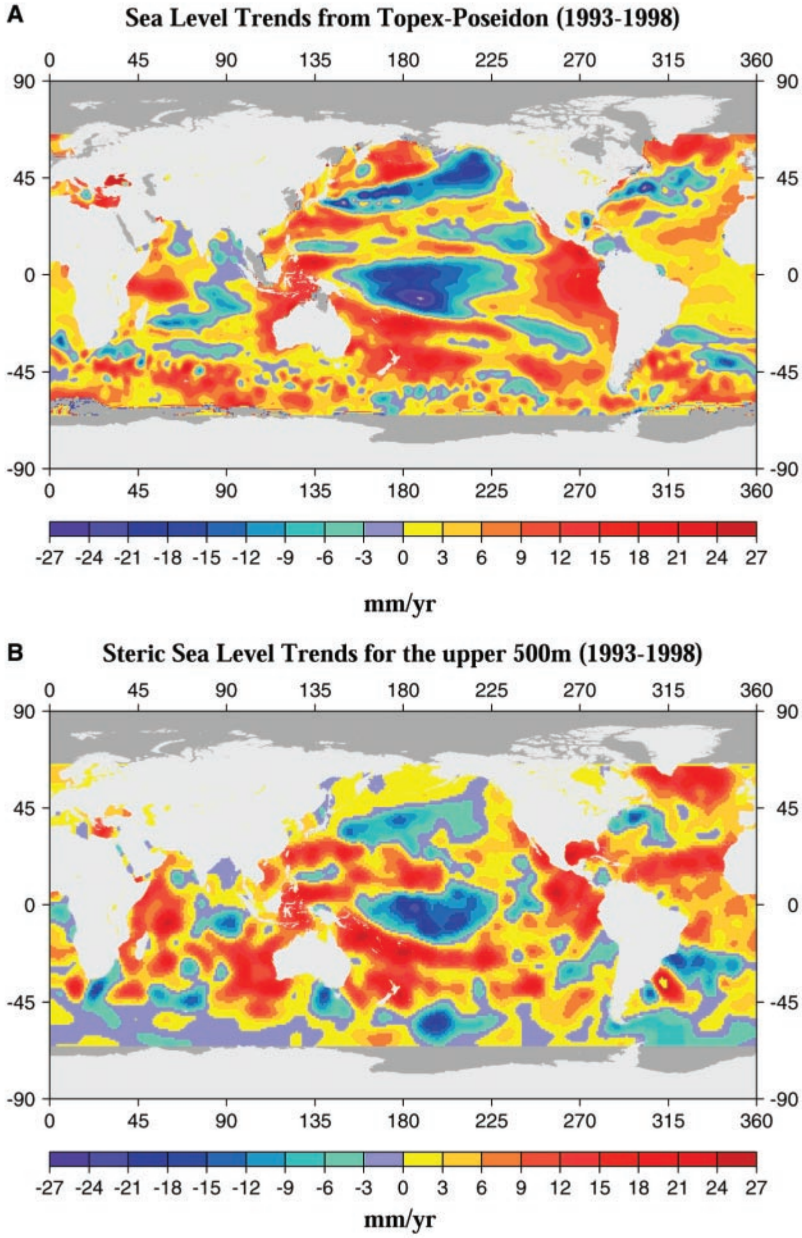

Fig. 2. Map of the geographical distribution of sea level trends over 1993–98 computed from Topex/Poseidon altimetry (**A**) and from the thermosteric sea level data (**B**).

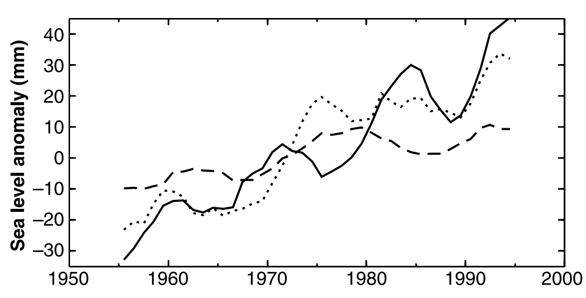

Fig. 3. Mean sea level curves for 1955–96. Dashed curve, global mean thermosteric component computed with data from (*3*) down to 3000-m depths. Dotted curve, pseudo global mean thermosteric sea level computed by subsampling the global data set at the 25 tide gauge sites. Solid curve, observed sea level curve based on the PSMSL records at the 25 tide gauge sites.

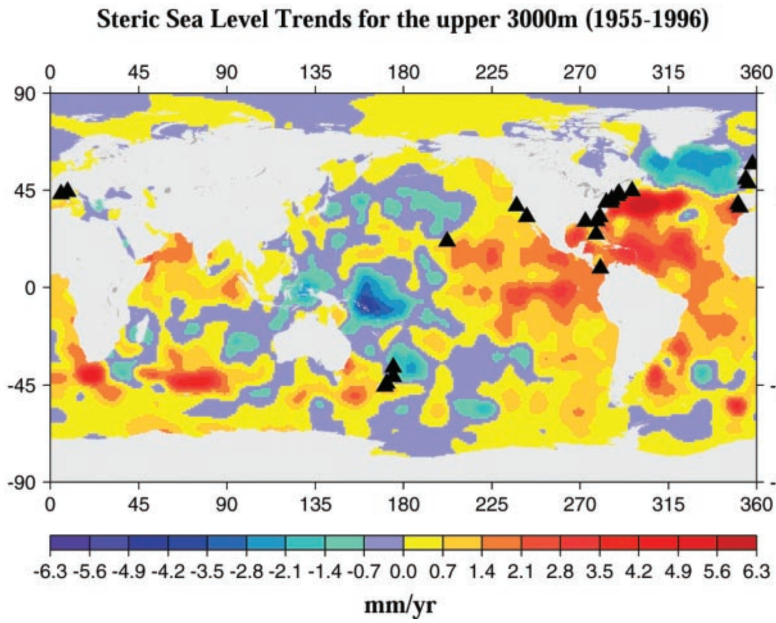

Fig. 4. Map of the geographical distribution of thermosteric sea level trends for 1955–96 computed with temperature data from (*3*) down to 3000-m depths. Black triangles show the locations of the 25 tide gauges.

20th century global mean sea level rise. It is generally assumed that spatial variation of sea level rise is caused by nonuniformity in thermal expansion, other contributions leading rapidly to uniform sea level change. Thus, the reported difference may reflect an overestimate of the sea level rise for the past decades, caused by the uneven distribution of the tide gauges and limited geographical sampling available from historical records. Even though the global tide gauge network has been considerably extended during the 1990s (*16*), recent sea level rise estimates based on the tide gauges still substantially depart from the global mean measured by Topex/Poseidon (*17*). Because of temperature data availability, we limited our analysis to the second half of the 20th century, but it should be noted that the mean sea level rise computed with this 40-year-long tide gauge record agrees well with values based on longer records (*9*, *10*). Thus, our conclusion that the tide gauge–derived sea level rise for the past few decades has been overestimated possibly holds for the whole 20th century. This would reconcile observed sea level rise and estimate of climate-related contributions (on the order of 0.7 mm/year) as reported by the third IPCC assessment report (*7*).

References and Notes

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2. We analyzed Topex-Poseidon altimetry data (merged Geophysical Data Records available from the AVISO/Altimetry data center, Centre National d'Etudes Spatiales, Toulouse, France) from January 1993 through December 2000. Geophysical and instrumental corrections applied to the data are the most recent version provided by AVISO. In addition to the onboard oscillator drift, the 1 mm/year radiometer drift is taken into account up to December 1996. A 7-mm bias is applied to the data beyond February 1999 to account for the vertical offset after the switch to the redundant Topex altimeter (*18*). Otherwise, the data processing is identical to that used in (*6*) and (*19*). For sea level trends computations, two different processing were applied depending on the required representation (global mean sea level trend or geographical distribution of the regional trends). For the former, we averaged the along-track sea level data over each 10-day orbital cycle, applying an equi-area weighting. Only data between 60°S and 60°N are considered because of noisy data at higher latitudes. The mean trend is based on a simple least squares fit to the sea level time series. The associated uncertainty is the formal error based on the scatter of the fit. To estimate regional sea level trends, we interpolated along-track sea level data onto regular 1° by 1° grids. Finally, we low-pass filtered the raw time series at each grid point to remove short-period ($\leq$1 year) signal and fitted a linear trend to the filtered time series through a least squares inversion.
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4. To compute gridded time series of the thermosteric (i.e., due to temperature change) sea level, we first converted the gridded temperature anomalies in terms of density anomalies at each standard level using the classical expression for the equation of state of the ocean (*20*). Then we vertically integrated the density anomalies to compute the thermosteric sea level anomaly. Regional trends were computed through a least squares fit of the thermosteric sea level time series at each grid mesh.
5. Using Topex/Poseidon data over the years 1993 through 1998, Nerem and Mitchum (*21*) found a rate of sea level rise of 2.5 $\pm$ 1.3 mm/year. Their rate uncertainty is based not only on the formal error but also on instrumental drift errors.
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11. Among the 27 sites selected by Douglas (*9*), we did not consider Trieste (North Adriatic Sea) and Buenos Aires (South Atlantic) because of the poor coverage of temperature data at these sites. We performed a series of tests to derive the thermosteric sea level time series at the tide gauge location. We successively considered the three, five, and ten closest grid points to produce spatial averages of the thermosteric sea level, after deleting values larger than three standard deviations. We first averaged the thermosteric sea level data by regions (nine in total) to avoid excessive regional weight when computing the pseudo global mean. When averaging, we applied a cos(latitude) weighting. The corresponding thermosteric sea level time series were found to be very similar, indicating that the averaging procedure is not crucial. To compute the tide gauge–based sea level time series, we also made a series of tests consisting of selecting different locations. We considered the 17 tide gauge sites from (*22*). We also considered a sample of 32 sites that included the 25 sites of the nominal case plus seven island sites in the Western Pacific for which long records of good quality are available. The "observed" sea level curves displayed similar behavior. Computed trends (for the thermosteric and observed sea level curves) did not differ by more than 0.2 mm/year.
12. See www.pol.ac.uk/psmsl.
13. All records were corrected for the inverted barometer response of sea level to atmospheric forcing with pressure data from the National Centers for Environmental Prediction 40-year reanalysis (*23*). The equivalent sea level trend associated with this correction is less than 0.2 mm/year. Land motion due to glacial isostatic adjustment was also corrected for with the ICE-4G VM2 model (*10*).
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17. We used PSMSL data from 209 tide gauges of the GLOSS network (excluding the Mediterranean and Black seas) to compute a pseudo global mean sea level rate of change for 1993–98. Inverted barometer and postglacial rebound corrections were applied. The estimated rate is 5 $\pm$ 1 mm/year, compared with the 3.2 $\pm$ 0.2 mm/year rate based on Topex/Poseidon. A majority of these tide gauges are located in positive trend regions, which causes this higher rate estimate. Anyway, inspection of Fig. 2A shows that the present configuration of continental coastlines and ocean islands simply fails to correctly sample spatial variations of the sea level change.
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24. We thank S. Levitus and his co-workers for having made available their global gridded temperature data set. We also thank J. Antonov for useful discussions on the role of salinity. This work was supported by CNES, CNRS, and the French ministry of research.

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