A 20th century acceleration in global sea-level rise

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[1] Multi-century sea-level records and climate models indicate an acceleration of sea-level rise, but no 20th century acceleration has previously been detected. A reconstruction of global sea level using tide-gauge data from 1950 to 2000 indicates a larger rate of rise after 1993 and other periods of rapid sea-level rise but no significant acceleration over this period. Here, we extend the reconstruction of global mean sea level back to 1870 and find a sea-level rise from January 1870 to December 2004 of 195 mm, a 20th century rate of sea-level rise of 1.7 ± 0.3 mm yr^{-1} and a significant acceleration of sea-level rise of 0.013 ± 0.006 mm yr^{-2}. This acceleration is an important confirmation of climate change simulations which show an acceleration not previously observed. If this acceleration remained constant then the 1990 to 2100 rise would range from 280 to 340 mm, consistent with projections in the IPCC TAR. **Citation:** Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, *33*, L01602, doi:10.1029/2005GL024826.

1. Introduction

[2] Most estimates of 20th century sea-level rise have depended on averaging the rates of rise from the few, long, high-quality tide-gauge records that are available [*Douglas*, 1991, 2001; *Peltier*, 2001]. However, these records contain significant decadal variability, obscuring any acceleration [*Woodworth*, 1990; *Douglas*, 1992]. Even when a global-mean sea level (GMSL) record is known to contain an acceleration (as in numerical models), an acceleration is difficult to detect in an average of a small number of records [*Gregory et al.*, 2001].

[3] The TOPEX/Poseidon (T/P) and Jason-1 satellite altimeters have produced high quality measurements of near global (66°S to 66°N) sea level from 1993. The spatial correlations from this data set, expressed as Empirical Orthogonal (eigen)Functions (EOFs), together with the longer but sparse tide-gauge data set, have been used to produce estimates of reconstructed global sea-level variability [*Chambers et al.*, 2002] and rise [*Church et al.*, 2004] for 1950 to 2000. As these estimates explicitly account for the spatial redistribution of sea level, the temporal variability is at least an order of magnitude lower than that present in individual records. The estimates also allow for the possibility of spatial variability in the rate of sea-level rise [*Nakiboglu and Lambeck*, 1991].

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2. Reconstructing Monthly Sea Levels

[4] We use the same techniques as in our earlier study [*Church et al.*, 2004] of using tide-gauge data to determine the changes in amplitude between consecutive months of a selected number of these EOFs. These techniques were developed to estimate historical values of surface atmospheric pressure and sea surface temperatures [*Kaplan et al.*, 2000; *Rayner et al.*, 2003]. First differences of the tide-gauge data are used because it is not possible to relate all of the separate records to a single vertical datum. The first differences of the EOF amplitudes are integrated backward in time to estimate sea-level fields and hence GMSL each month. A revised scaling of the EOFs results in realistic formal error estimates.

[5] We calculate the EOFs from 12 years (compared with 9 years in our earlier study) of satellite altimeter data (T/P and Jason-1) from January 1993 to December 2004. All standard corrections except the inverse barometer correction are applied, including corrections for the drift of the water-vapour measurements [*Keihm et al.*, 2000; *MacMillan et al.*, 2004] for both T/P and Jason-1 and for the drift of the T/P sea-level measurements [*Mitchum*, 2000]. We map the altimeter data to a 1° × 1° × 1 month grid. We remove the seasonal signal and a linear trend in GMSL, as we will use the EOFs to model variability about the time-varying GMSL. An additional spatially uniform field is included in the reconstruction to represent changes in GMSL. Omitting this field results in a much smaller rate of GMSL rise, inconsistent with tide-gauge data (in the mean and at individual sites) and earlier studies [e.g., *Douglas*, 1991], and results in unrealistically large spatial variability in regional trends as a finite number of EOFs cannot adequately represent a substantial change in mean sea level. Trends from our reconstructed time series agree well with trends from long tide-gauge records. The EOFs provide information on global correlations of sea-level *variability.* There is no assumption that the spatial pattern of sea-level rise for 1993 to 2004 is maintained over a longer period. We have not tried to detect the regional pattern of sea-level rise resulting from the elastic response of the earth to present day contributions from glaciers and ice sheets [*Mitrovica et al.*, 2001].

[6] We use monthly sea-level data downloaded from the Permanent Service for Mean Sea Level (PSMSL [*Woodworth and Player*, 2003]) web site (http://www.pol.ac.uk/psmsl/) in February 2003. Careful selection and editing criteria as given by *Church et al.* [2004] are employed. Where there are multiple records near a single satellite grid point, the changes in height at each time step were averaged. The error estimates of first differences of 50 mm (the solution is not sensitive to the value used) was computed from the rms of the differences between the few sets of nearby (within about 100 km) sea-level records. The impact

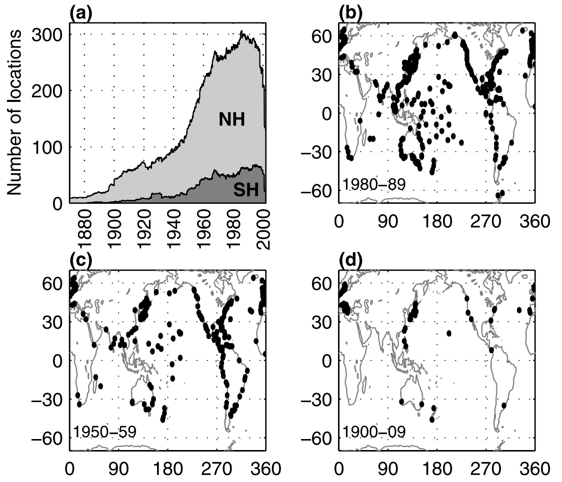

Figure 1. The number and distribution of sea-level records available for the reconstruction. (a) The number of locations with sea-level data. (b), (c) and (d) the distribution of gauges in the 1980s, 1950s and 1900s.

on measured sea level of the ongoing response of the earth to changes in surface loading following the last glacial maximum was removed using the same estimate of glacial isostatic adjustment (GIA) as in our earlier study, as calculated by Mitrovica and colleagues [*Davis and Mitrovica*, 1996; *Milne et al.*, 2001].

[7] As the analysis technique allows us to ingest data from a time-varying array of tide gauges in a consistent way, we can use many more gauges to estimate GMSL than the traditional approach of estimating sea-level rise [*Douglas*, 1991, 1992, 2001; *Peltier*, 2001]. This leads to better spatial coverage and reduced errors in the estimate of GMSL as the few very long records available are clustered in small regions (mostly NW Europe, North America and a few in Australia and New Zealand). The number of sea-level records available for each year is a maximum in the 1980s (Figure 1) but decreases rapidly in the 1990s as a result of late submission of data sets. Running back in time, the number of gauges drops to about 140 in 1950, to just under 50 in 1900, with the majority of gauges in the northern hemisphere. By the 1870s, there are only 10 gauges (none in the southern hemisphere) and by 1860 there are only five gauges available, too few to extend the reconstruction back past 1870. The number of records limits our ability to reconstruct GMSL to January1870 to December 2001. To ensure that we always solve an over-determined problem we use 5 EOFs prior to 1900 and 10 after 1900, but the number of EOFs has virtually no impact on the dominant EOF amplitudes or on GMSL.

3. Global-Mean Sea Level From 1870 to 2004

[8] From the start of the reconstruction in January 1870 to the end of the altimeter data in December 2004 (135 years), the total GMSL rise is 195 mm (Figure 2), an average of 1.44 mm yr^{-1}. For the 20th century, the rise is about 160 mm and the linear least-squares trend is 1.7 ± 0.3 mm yr^{-1} (95% confidence limits). This error includes allowance for the serial correlation of the time series, (four years of data per degree of freedom), uncertainties in GIA corrections (0.09 mm yr^{-1} from the rms difference between GMSL trends calculated using three different GIA models [*Church et al.*, 2004]) and uncertainties in the EOFs (0.1 mm yr^{-1}, see below). For 1950 to 2000, the linear least squares trend is 1.75 mm yr^{-1}, consistent with earlier estimates [*Church et al.*, 2004; *Douglas et al.*, 1991, 2001; *Peltier*, 2001]. The yearly-averaged reconstructed GMSL agrees with the T/P/Jason-1 satellite altimeter data from 1993 to within the error estimates (Figure 2). It also agrees well with an average estimated directly from the tide gauges, but has much smaller error bars.

[9] Fitting a quadratic to the GMSL time series gives an acceleration (twice the quadratic coefficient) of 0.013 ± 0.006 mm yr^{-2} (95%) for 1870 to 2001. The differences between the quadratic and the GMSL time series have an *rms* value of only 7.5 mm (Figure 2b), less than the error estimates for most of the record. For the 20th century alone, the acceleration is smaller at 0.008 ± 0.008 mm yr^{-2} (95%). Another approach, given the clear change of slope at ~1930, is to do linear regressions on the two halves (1870–1935 and 1936–2001) of the record. The slopes are 0.71 ± 0.40 and 1.84 ± 0.19 mm yr^{-1} respectively, implying an acceleration of 0.017 ± 0.007 mm yr^{-2} (95%).

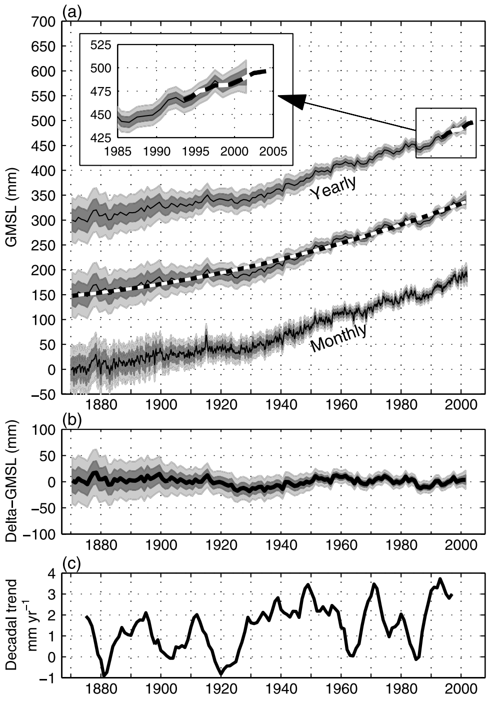

Figure 2. Global mean sea level from the reconstruction for January 1870 to December 2001. (a) The monthly global average, the yearly average with the quadratic fit to the yearly values and the yearly averages with the satellite altimeter data superimposed are offset by 150 mm. The one (dark shading) and two (light shading) standard deviation error estimates are shown. (b) Departures of the GMSL from the quadratic fit to the data. (c) Linear trends in sea level from the reconstruction for overlapping 10 year periods. The trend for each period is plotted at the centre time of the period. The error estimates of GMSL are a minimum of about 5 mm in the 1980s rising to about 22 mm in 1870.

The *rms* residual to the linear fits is lower at 5.8 mm (cf 7.5 mm), consistent with much of the acceleration occurring in the first half of the 20th century rather than a smooth acceleration over the whole period. Recent estimates of regional- and global-MSL constructed using very different techniques are qualitatively similar to ours, including a significant acceleration in the first half of the 20th century (S. A. Jevrejeva et al., Nonlinear trends and multiyear cycles in sea level records, submitted to *Journal of Geophysical Research*, 2005).

[10] While the GIA corrections are essentially constant from 1870 to 2000, it is possible that a temporally varying tide-gauge array may combine with errors in the GIA corrections to give an error in the computed acceleration. Tests, including assuming a 100% error in the GIA, indicate negligible impact on the computed acceleration. Using EOFs obtained from the recent altimeter data is another potential source of error. Tests using EOFs determined from different subsets of the 12 year altimeter record lead to 1-σ uncertainty in GMSL trends of about 0.06 mm yr^{-1} and negligible effects on the estimates of the acceleration. El Nino-Southern Oscillation variability (ENSO, the dominant signal in the low order EOFs) has been present for millennia. However, over time, changes in ENSO patterns could occur and we therefore almost double our uncertainty estimate, assigning a total 1-σ error from uncertainty in EOFs of 0.1 mm yr^{-1}. Note also that any non-stationarity of patterns will also be reflected in the error estimates of GMSL. This conclusion of the relatively minor impact of the assumption of stationarity of EOFs on GMSL trends is consistent with previous work [*Chambers et al.*, 2002; *Church et al.*, 2004] and the application of these techniques to the estimate of sea surface temperature variations [*Rayner et al.*, 2003].

4. Implications and Conclusions

[11] If this acceleration was maintained through the 21st century, sea level in 2100 would be 310 ± 30 mm higher than in 1990, overlapping with the central range of projections in the Intergovernmental Panel on Climate Change Third Assessment Report (IPCC TAR) [*Church et al.*, 2001]. For 1910 to 1990, the acceleration in ocean thermal expansion (only) in these climate models range from 0.005 ± 0.003 mm yr^{-2} to 0.014 ± 0.004 mm yr^{-2} (Table 11.2 of the IPCC TAR), consistent with the present estimates of 0.013 mm yr^{-2} and 0.017 mm yr^{-2} for the 132 year period and the 0.008 mm yr^{-2} for the 20th century.

[12] Between 1930 and 1960, GMSL rises faster than the quadratic curve at a rate of about 2.5 mm yr^{-1} (Figure 2c), following (with about a 20 year lag) the 1910 to 1940 period of more rapid global temperature rise [*Folland et al.*, 2001]. Variability in GMSL trends prior to 1930 are not significant. After 1960, there are minima in the rates of rise in the 1960s and 1980s, each followed by more rapid rates of rise (peaking at over 3 mm yr^{-1}), consistent with *Holgate and Woodworth* [2004]. From 1993, the rates of rise estimated from tide gauge and altimeter data (after correction for GIA effects [*Douglas and Peltier*, 2002]) are about 3 mm yr^{-1} [*Leuliette et al.*, 2004; *Church et al.*, 2004], faster than the quadratic (about 2.3 mm yr^{-1}) at this time. Model simulations and data [*Church et al.*, 2005] show short-term (years to a decade or so) reductions in GMSL following major volcanic eruptions. The post-1960 major volcanic eruptions of Mt. Agung (1963), El Chichon (1982) and Mt Pinatubo (1991) offset about 0.005 mm yr^{-2} of the acceleration that is otherwise present, perhaps explaining why little acceleration has been detected over the second half of the 20th century. The 1930s acceleration occurs during a period of little volcanic activity.

[13] The quadratic implies that the rate of rise was zero in about 1820 when GMSL was about 200 mm below present day values. This level is consistent with estimates from bench marks carved in rock in Tasmania in 1840 [*Hunter et al.*, 2003] and the height of ancient Roman fish tanks [*Lambeck et al.*, 2004], which implies virtually no long-term average change in GMSL from the first century AD to 1800 AD.

[14] The 19th century commencement of the acceleration is consistent with geological data [*Donelly et al.*, 2004] and long tide-gauge records [*Woodworth*, 1990, 1999; *Maul and Martin*, 1993] but this is the first time a post 1870 (and 20th century) acceleration of GMSL has been detected. This acceleration is an important confirmation of climate simulations [*Gregory et al.*, 2001] which show an acceleration not previously detected in observations. Sea-level rise from 20th century climate simulations [*Church et al.*, 2001] is somewhat less than that inferred from observations, perhaps because the acceleration of sea-level rise commenced during the 19th century and by 1870, at the start of our reconstruction, was already rising at a rate of about 0.6 mm yr^{-1}. Both the rate of rise and the observed acceleration should be valuable constraints to test the next round of climate simulations.

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