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Recent global sea level acceleration started over 200 years ago?

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[1] We present a reconstruction of global sea level (GSL) since 1700 calculated from tide gauge records and analyse the evolution of global sea level acceleration during the past 300 years. We provide observational evidence that sea level acceleration up to the present has been about 0.01 mm/yr^2 and appears to have started at the end of the 18th century. Sea level rose by 6 cm during the 19th century and 19 cm in the 20th century. Superimposed on the long-term acceleration are quasi-periodic fluctuations with a period of about 60 years. If the conditions that established the acceleration continue, then sea level will rise 34 cm over the 21st century. Long time constants in oceanic heat content and increased ice sheet melting imply that the latest Intergovernmental Panel on Climate Change (IPCC) estimates of sea level are probably too low. **Citation:** Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth (2008), Recent global sea level acceleration started over 200 years ago?, *Geophys. Res. Lett.*, *35*, L08715, doi:10.1029/2008GL033611.

1. Motivation

[2] Global sea level (GSL) rise and its acceleration are the subjects of an extensive scientific debate. Most of the evidence for global sea level acceleration comes from climate models, providing a wide range of estimates in the Intergovernmental Panel on Climate Change (IPCC) reports: from 0.22 mm/yr^2 in *Intergovernmental Panel on Climate Change* [1995] to 0.014 mm/yr^2 in IPCC 2001 [*Church et al.*, 2001]. The recent IPCC report [*Bindoff et al.*, 2007] suggests a 20th century acceleration of about 0.013 mm/yr^2. Results from analysis of individual long observational records do not present enough evidence for an unambiguous global acceleration. *Douglas* [1992] found weak evidence of 20th Century acceleration in long records (mostly European and North American), but no conclusive evidence of a global acceleration of sea level. *Woodworth* [1990, 1999] suggests a small acceleration between the 19th–20th centuries based on the small numbers of European tide gauges. There are two main problems in the detection of acceleration in observational records: inadequate approaches to overcome interannual and decadal variability in sea level time series and the lack of globally distributed long term tide gauge records [*Douglas*, 1992; *Woodworth*, 1990, 1999]. *Douglas* [1992] investigated the role of record length by computing the trend and acceleration for all sea level records longer than 10 years available from the Permanent Service for Mean Sea Level (www.pol.ac.uk/psmsl [*Woodworth and Player*, 2003]), showing that the decadal variations of sea level dominate the estimate of acceleration for records shorter than about 50 years. Results from *Douglas*'s [1992] study suggested that 50 years is the absolute minimum sea level record length that should be considered in an analysis of global sea level rise or acceleration from tide gauge data alone.

[3] Here we analyse the evolution of global sea level acceleration since 1700 calculated from tide gauge records in order to answer the questions- when did the global sea level acceleration start and how much did it change through the past 300 years. We use a method based on Monte-Carlo-Singular Spectrum Analysis (MC-SSA), [*Moore et al.*, 2005; *Jevrejeva et al.*, 2006] to estimate the time variable trend and its changes over time.

2. Method and Data

[4] The "virtual station" GSL calculated from 1023 tide gauge records [*Jevrejeva et al.*, 2006], optimally solves the sampling problem of station locations. Detailed descriptions of these time series are available from www.pol.ac.uk/psmsl. All data sets were corrected for local datum changes and glacial isostatic adjustment (GIA) of the solid Earth [*Peltier*, 2001]. The reconstruction preserves volcanic signatures [*Grinsted et al.*, 2007] and also has published standard errors [*Jevrejeva et al.*, 2006], available from http://www.pol.ac.uk/psmsl/author_archive/jevrejeva_etal_gsl/.

[5] We extend the record backwards from 1850 using three of the longest (though discontinuous) tide gauge records available: Amsterdam, since 1700 [*Van Veen*, 1945], Liverpool, since 1768 [*Woodworth*, 1999] and Stockholm, since 1774 [*Ekman*, 1988]. We remove the linear part of each record, which contains the land movement component, by comparing each time series with the existing GSL for the period of overlap. In order to estimate the global sea level from these three stations, we assume implicitly that the mean trend from the three records is the same as that globally for the 18th century. And one notes that geological evidence supports relatively stable global sea level over the last 2 millennia [*Lambeck et al.*, 2004]. By far the major source of error when using the three stations as an extended record of GSL is how representative tide gauges from a single ocean basin can be of global sea level; we estimate this error to be ±6 cm from jack knife error estimates when global data are available [*Jevrejeva et al.*, 2006].

[6] We provide a solution for the problem associated with decadal and multi-decadal variability using a method based on the Monte Carlo Singular Spectrum Analysis (MC-SSA). We remove 2–30 year variability, determine the time

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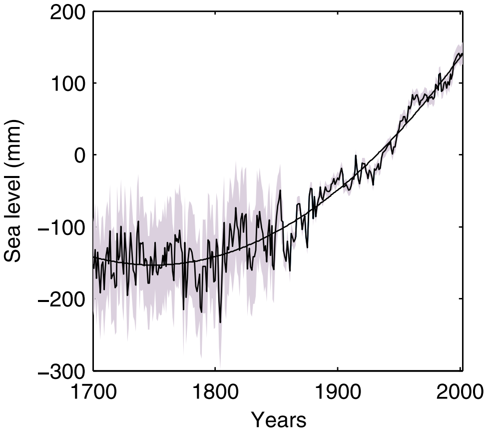

Figure 1. Sea level reconstruction since 1700, the shadow represents the errors of the reconstruction. The fitted curve is a second order polynomial fit.

variable trend and examine temporal variability in acceleration in global sea level during the past 300 years.

3. Results

[7] We first estimate acceleration by the conventional method used in previous studies [*Woodworth*, 1990; *Douglas*, 1992; *Church and White*, 2006], defining the acceleration as the second derivative of sea level with time, measured in mm/yr^2. We calculate an acceleration of 0.01 mm/yr^2 (twice the quadratic coefficient) by fitting a second order polynomial fit to the extended GSL (Figure 1) for the period 1700–2003. The sea level acceleration of 0.01 mm/yr^2 appears to have started at the end of the 18th century, although a significant increase does not occur until much later in the 19th century. Figure 1 strongly suggests that during the last 300 years there have been periods with faster and slower GSL rise, as mentioned in previous studies [*Jevrejeva et al.*, 2006; *Church and White*, 2006; *Woodworth et al.*, 2008]. The fitted curve smooths short term changes of sea level, although it is sufficient to reflect the longer-term changes. Furthermore, we calculate quadratic coefficients using variable windows (from 10 to 290 years), starting from 1700 and sliding the windows year –by -year along the observation period, in order to see the evolution of acceleration depending on the data span and size of the window. Figure 2 reveals that during the past 300 years there are several time periods with positive and negative sea level acceleration, suggesting that a wide spectrum (from 10 to 100 years) of variability influences estimates of sea level acceleration, and this leads to ambiguity in the quadratic fitting of the GSL depending on the time period selected. This motivated us to use an alternative approach. To challenge the existence of acceleration in sea level we apply a method based on MC-SSA [*Moore et al.*, 2005; *Jevrejeva et al.*, 2006] to estimate the time variable trend in global sea level and its changes over time. The main advantage of the method is that we remove 2–30 year variability from the time series, which is the main difficulty for robust acceleration estimation [*Douglas*, 1992]. In addition, the instantaneous rate of the time variable trend is not very sensitive to the length of time series.

[8] The time variable trend (Figure 3, top), detected by the method based on the MC-SSA with a 30-year window (variability <30 years has been removed), provides improved fitting for the GSL compared with the second order polynomial curve (Figure 1). Figure 3 (bottom) shows the evolution of the rate of GSL change, indicating several time periods of faster and slower sea level rise associated with a 60–70 year variability. The fastest sea level rise, estimated from the time variable trend with decadal variability removed, during the past 300 years was observed between 1920–1950 with maximum of 2.5 mm/yr. Figure 4 presents the 20th century time variable GSL trend, calculated with 10-year window, which shows more variability than in Figure 3. GSL rise during 1992–2002 is 3.4 mm/yr, which is good agreement with estimates of sea level rise during the period 1993–2003 from TOPEX/Poseidon satellite altimeter measurements (3.1 mm/yr) [*Bindoff et al.*, 2007], providing an indication of the large contribution from decadal variability in estimation of sea level rise during short time periods.

[9] The evolution of the time dependent trend (Figure 3) shows that dramatic changes in the rate of sea level rise occurred since the 1780s. The calculated acceleration of 0.01 mm/yr^2 using the 300 year long GSL accounts for 6 cm sea level rise in the 19th century, about 19 cm during the 20th century and will contribute 34 cm sea level rise during the 21st century. This estimate assumes that the conditions that produce the present day evolution of sea level will continue into the future–though the acceleration will depend on the actual rate of temperature increase in the 21st Century.

4. Discussion

[10] Utilization of time variable trends provides valuable information about the evolution of sea level rise since 1700, identifying the periods with faster and slower sea level rise. Figure 3 provides observational evidence of continuous increase in the rate of sea level rise during the past 300 years masked by the substantial influence of low-frequency variability, raising the question of the role of low-frequency variability in trend and acceleration determination.

[11] The pattern of 60–65 years periodicity of acceleration/deceleration for the pre-industrial 18th–19th centuries (Figure 3) suggests a natural source for the long-term

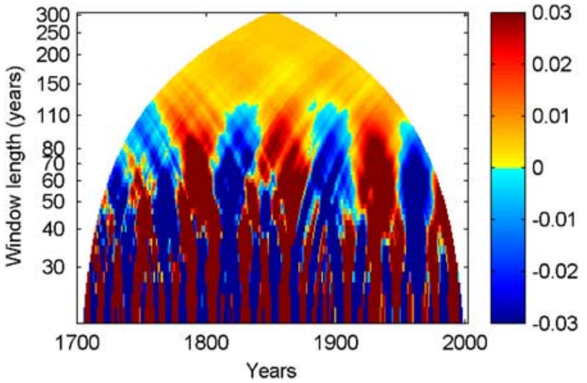

Figure 2. Acceleration (mm/yr^2) calculated using moving windows (10–290 years).

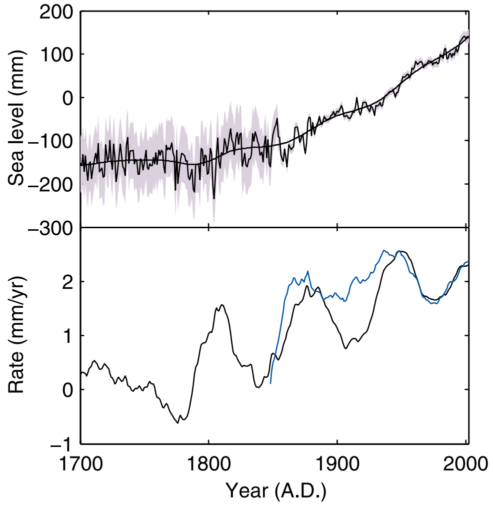

Figure 3. (top) Time series of yearly global sea level and time variable trend detected by method based on MC-SSA with 30year windows, grey shading represents (top) the standard errors. (bottom) The evolution of the rate of the trend (black line) since 1700. Blue line corresponds to the rate of North East Atlantic regional sea level rise since 1850.

variability in sea level. The multi-decadal variability in global sea level for the past 300 years shows the same pattern as previously found in the climate system [*Delworth and Mann*, 2000], including a 60–70 years variability in sea surface temperature (SST) and sea level pressure (SLP). Similar 60-year cycles exist in early instrumental European records of air temperature (1761–1980) and longer paleo proxies from different locations around the world [*Shabalova and Weber*, 1998, 1999], suggesting a global pattern of 60-year variability. A global pattern of 60-year variability is supported by comparison of the GSL and North East Atlantic variability (Figure 3), where a similar pattern of variability is seen, though with differences in amplitude and timing of prior to 1950, which are suggestive of an Atlantic driving mechanism. This may be related to an underlying variability in the thermohaline circulation [*Delworth and Mann*, 2000], perhaps through advection of density anomalies or combinations of gyre and overturning advection [*Dijkstra and Ghil*, 2005]. However, direct observational evidence on these long cycles in thermohaline circulation is very limited and modelling using coupled Global Circulation Models (GCMs) show rather ill-defined power on these timescales [*Knight et al.*, 2005].

[12] The fastest sea level rise during the 20th century was between 1920–50 and appears to be a combination of peaking of the 60–65 years cycle with a period of low volcanic activity [*Jevrejeva et al.*, 2006; *Church and White*, 2006]. Moreover, estimates of the melting glacier contribution to sea level is 4.5 cm for the period 1900–2000 with the largest input of 2.5 cm during 1910–1950 [*Oerlemans et al.*, 2007], supporting an increasing role of the mass component in sea level rise over the thermosteric component, and provides an additional explanation of fastest sea level rise during the first half of the 20th century. *Miller and Douglas* [2007] also propose a possible mechanism whereby large scale pressure changes associated with Northern Annular Mode could lead to the ocean circulation spin-up on long-term scales and contribute to sea level rise during 1920–50.

5. Conclusion

[13] A reconstruction of global sea level since 1700 has been made. Results from the analysis of a 300 year long global sea level using two different methods provide evidence that global sea level acceleration up to the present has been about 0.01 mm/yr^2 and appears to have started at the end of the 18th century. The time variable trend in 300 years of global sea level suggests that there are periods of slow and fast sea level rise associated with decadal variability, which has been previously reported by several authors [*Douglas*, 1992; *Woodworth*, 1990; *Church and White*, 2006]. However, we provide evidence that the main contribution to the evolution of the sea level acceleration is associated with multi-decadal variability, which is superimposed on a background sea level acceleration. We show that sea level rose by 28 cm during 1700–2000; simple extrapolation leads to a 34 cm rise between 1990 and 2090. The lowest temperature rise (1.8°C) IPCC [*Meehl et al.*, 2007] use is for the B1 scenario, which is 3 times larger than the increase in temperature observed during the 20th century. The IPCC sea level projection for the B1 scenario is 0.18–0.38 m. Our simple extrapolation gives 0.34 m. The mean sea level rise for B1, B2 and A1T is below our estimate. However, oceanic thermal inertia and rising Greenland melt rates imply that even if projected temperatures rise more slowly than the IPCC scenarios suggest, sea level will very likely rise faster than the IPCC projections [*Meehl et al.*, 2007].

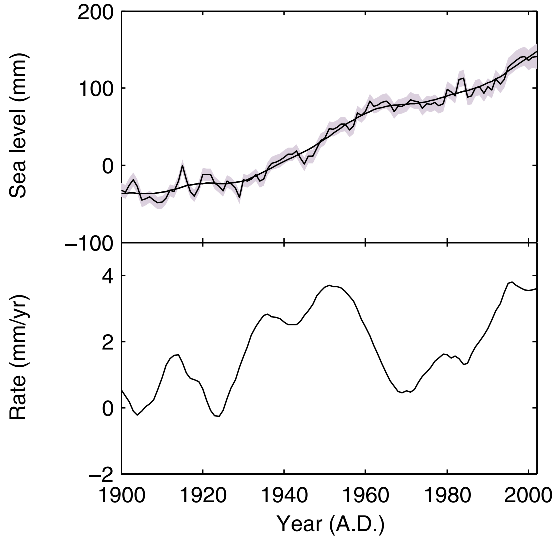

Figure 4. Time series of 20th century global sea level and time variable trend detected by the method based on MC-SSA with 10-year windows. The rate of GSL rise during the period 1993–2002 is 3.4 mm/yr, which is in good agreement with estimates of sea level rise during the period 1993–2003 from TOPEX/Poseidon satellite altimeter measurements (3.1 mm/yr).

[14] **Acknowledgments.** Some of our software includes code originally written by E. Breitenberger of the University of Alaska adapted from the freeware SSA-MTM Toolkit: http://www.atmos.ucla.edu/tcd/ssa. Financial support for J. Moore and A. Grinsted came from the Academy of Finland. We are grateful to anonymous reviewers for helpful comments.

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