GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L20706, doi:10.1029/2009GL040216, 2009

Anthropogenic forcing dominates sea level rise since 1850

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Received 23 July 2009; revised 7 September 2009; accepted 23 September 2009; published 28 October 2009.

[1] The rate of sea level rise and its causes are topics of active debate. Here we use a delayed response statistical model to attribute the past 1000 years of sea level variability to various natural (volcanic and solar radiative) and anthropogenic (greenhouse gases and aerosols) forcings. We show that until 1800 the main drivers of sea level change are volcanic and solar radiative forcings. For the past 200 years sea level rise is mostly associated with anthropogenic factors. Only 4 ± 1.5 cm (25% of total sea level rise) during the 20th century is attributed to natural forcings, the remaining 14 ± 1.5 cm are due to a rapid increase in CO_2 and other greenhouse gases. **Citation:** Jevrejeva, S., A. Grinsted, and J. C. Moore (2009), Anthropogenic forcing dominates sea level rise since 1850, *Geophys. Res. Lett.*, *36*, L20706, doi:10.1029/2009GL040216.

1. Motivation

[2] Controversy and uncertainty cloud discussion of how fast sea level is rising, and why. The latest Intergovernmental Panel on Climate Change (IPCC) report suggests that since 1950 there is evidence for anthropogenic impact on both the main contributors of sea level rise: thermal expansion of ocean water (the thermosteric contribution), and melting of glacier ice (the ocean mass increase part) [*Hegerl et al.*, 2007]. *Crowley et al.* [2003] estimated the ocean heat content changes during the last millennium with a climate model driven by natural and anthropogenic forcings and concluded that most of the 20th century ocean heat content increase was due to the contribution from greenhouse gases. Latest results from modeling [*Gregory et al.*, 2006] and studies of ocean heat content [*Woodworth et al.*, 2004] suggest that anthropogenic forcing contributed ¼ to ½ of the thermosteric sea level rise during the second half of the 20th century. However, the relative contribution of thermal expansion and ice melting to sea level rise during the past millennium (or even the past 100 years) are uncertain. Estimates vary widely, from roughly equal roles for thermal expansion and ice melting during the past 10 years [*Bindoff et al.*, 2007] to a dominant effect of ice melting for the past 50 years [*Miller and Douglas*, 2004; *Jevrejeva et al.*, 2008b] or a leading contribution from ocean thermal expansion since 1960 [*Domingues et al.*, 2008]. In addition, uncertainties associated with ice sheet mass balance [*Bindoff et al.*, 2007] and the fact that the observational sea level budget is not yet closed [*Gregory et al.*, 2006], make it difficult to quantify the anthropogenic contribution to global sea level rise prior to 1950.

[3] In this study, instead of modeling individual components of sea level rise separately, we use a statistical model to evaluate the role of various natural (volcanic and solar radiative) and anthropogenic (greenhouse gases and aerosols) forcings in sea level variability for the past 1000 years.

[4] Here we consider sea level as an integrated indicator of climate variability, reflecting an accommodation of the climate system to changes in the dynamics and thermodynamics of the atmosphere, ocean and cryosphere. We apply a statistical inverse model [*Grinsted et al.*, 2009], constrained by the global sea level record from tide gauges [*Jevrejeva et al.*, 2006], and driven by various forcing time series from the latest IPCC report [*Jansen et al.*, 2007] to reproduce sea level histories over the past millennium.

2. Description of the Model and Forcings

[5] In contrast to previous studies where statistical models have been used to establish a semi-empirical link between sea level rise and global temperature changes using either an infinite response time [*Rahmstorf*, 2007], or by determining a system response time [*Grinsted et al.*, 2009], we relate the changes in global sea level to natural and anthropogenic forcings. We assume that sea level rise is caused primarily by changes in global ice volume and global ocean heat content, both of which will react to changes in forcing with some response time. The fundamental driver is global mean radiative forcing (W/m^2) previously used in the IPCC AR4 WG1 report [*Jansen et al.*, 2007]. This varies due to: (a) volcanic activity; (b) solar irradiance variations, both of which occur naturally; and (c) other forcings which are predominantly anthropogenic and have various components. Three of the four anthropogenic forcings include greenhouse gases and tropospheric sulphate aerosols (Table 1). Data are available from http://www.ncdc.noaa.gov/paleo/pubs/ipcc2007/fig613.html). Global radiative forcings with inherited uncertainties from the four independent estimates of forcing provide a plausible range of uncertainty for input to the inverse modeling, and consistent output would hence suggest that confidence in our attribution results.

[6] We modified a statistical model previously used to produce 2000- year long reconstructions of sea level and projections of sea level for the 21st century [*Grinsted et al.*, 2009]. We assume that there is an equilibrium sea level (S_{eq}) for a given mean global radiative forcing (F). The relationship between S_{eq} and F must be non-linear for large changes in sea level such as those that occur on glacial-interglacial timescales, however, we can do a linearization that is valid for the Late Holocene climate:

$$S_{eq} = aF + b \quad (1)$$

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0094-8276/09/2009GL040216$05.00

Table 1. Name of Experiments, Forcings and References to the Original Source

Experiment Name	Forcings	References
'cbk_2003'	Solar, volcanic, greenhouse gases, aerosols	*Crowley et al.* [2003]
'gsz2003'	Solar, volcanic, greenhouse gases,	*González-Rouco et al.* [2003]
'grt_2005'	Solar, volcanic, greenhouse gases, aerosols	*Goosse et al.* [2005]
'tbc_2003'	Solar, volcanic, greenhouse gases, aerosols, orbital, land use, ozone	*Tett et al.* [2007]

where a is the sensitivity of sea level to a forcing (F) change and b is a constant.

[7] Changes in sea level are caused largely by a reaction to global ice volume and global ocean heat content and are driven by the mean global radiative forcing, which we model with a single characteristic response time (τ). We therefore assume that sea level will approach S_{eq} as follows

$$\frac{\partial S}{\partial t} = \left(S_{eq} - S\right)/\tau \tag{2}$$

In the real world each individual contributor (thermal expansion of the ocean, melting of glaciers and melting of ice sheets in Antarctica and Greenland) is associated with its own response time largely depending on the state of the climate system [*Grinsted et al.*, 2009]. Limiting the use of equation (2) to the late Holocene, which is dominated by sea level rise, we presume a single response time. *Grinsted et al.* [2009] showed that using any single response time between zero and infinity does not greatly affect the simulated sea level curve, over relatively short periods such as discussed in this paper (as will also be seen considering the similar results from the different experiments here), as the other parameters in the model are tend to compensate for changes imposed on any single parameter. Hence the model will not be effected by the assumption of single response time for the ocean thermal expansion and ice melting processes. We integrate equation (2) to give sea level (S) over time using a history of F and knowledge of the initial sea level at the start of integration (S_0).

[8] We use a 2 000 000 member ensemble Monte Carlo inversion [*Mosegaard and Tarantola*, 2002; *Grinsted et al.*, 2009], calibrated by the 300 year long sea level reconstruction based on tide gauge records, to determine the probability density functions of the unknown parameters a, b, τ, S_0 [*Grinsted et al.*, 2009]. Use of a Monte Carlo inversion ensures that our statistical model is consistent with the long term picture of sea level response to the forcing [*Mosegaard and Tarantola*, 2002]. Monte Carlo inversion takes a random walk in the parameters space sampling the space according to the likelihood density. The likelihood density function is defined so that the parameter set with the highest likelihood minimizes the misfit when taking the autocorrelation of errors into account. From the Monte Carlo ensemble of parameter values we derive confidence intervals [*Grinsted et al.*, 2009]. Uncertainties are accounted for completely through the definition of the likelihood density function and the Monte Carlo inversion algorithms guarantee that regions of the parameter space with high likelihood will be sampled with a high density and regions with low likelihood will be sampled less densely - from that large sample of parameter sets we calculate the confidence intervals.

[9] We use the full covariance matrix, C expressing the spatial and time dependence of errors in the complete tide gauge data set which is a much more accurate and rich representation than simply reducing the 'effective degrees of freedom' based on e.g. the properties of a red noise process, or by doing an Empirical Orthogonal Function (EOF) analysis or fitting a reduced auto-regressive model. *Grinsted et al.* [2009] show that evaluation of the C matrix is critical to ensure that the data are not over-fitted due to the very high and time varying autocorrelation structure of the uncertainties.

[10] We performed four experiments, named in the same way as time series in the IPCC AR4 WG1 report [*Jansen et al.*, 2007], with forcings from four different models (Table 1). The difference in modeled sea level during the early part of the simulation for the various experiments is predominantly associated with different estimates of volcanic forcing. There is close agreement on the timing of volcanic eruptions (Figure 1b, for clarity only the post 1860 data are shown), but large uncertainties in the magnitude of individual volcanic eruptions, which lead to slightly different estimates for the influence of volcanism on sea level reconstructions over long periods. For the large volcanic forcing to yield consistency with observed sea level rise data, the response time must be longer (Figure 1a). However, as shown on Figure 2, there is a reasonable agreement between all four experiments for the early period of reconstruction. For the period since 1800 the modeled sea level is almost identical for all four experiments and in excellent agreement with available observations [*Jevrejeva et al.*, 2008a]. In our study, observations are represented by a 300 year long global sea level reconstruction based on tide gauge observations [*Jevrejeva et al.*, 2008a]. The reconstruction is calculated from 1023 tide gauge records since the 19th century [*Jevrejeva et al.*, 2006], and is extended backwards from 1850 using three of the longest (though discontinuous) tide gauge records available: Amsterdam, since 1700; Liverpool, since 1768; and Stockholm, since 1774, [*Jevrejeva et al.*, 2008a]. The limited number of long term tide gauge data during the 18th century and the first half of the 19th century is reflected in the year-by-year errors [*Jevrejeva et al.*, 2006, 2008a].

3. Results

[11] We compare the evolution of global sea level over the past 1000 years in four experiments: 'cbk_2003', 'gsz2003', 'tbc_2006', 'grt_2005' (Table 1). Figure 3a demonstrates that model simulations driven by the mean global radiative forcings are in reasonable agreement with patterns of sea level variability based on independent proxy temperature reconstructions [*Grinsted et al.*, 2009]. Our model is able to reproduce the observed sea level rise over the past 200 years (Figures 2 and 3a), and considering the uncertainties of observed sea level for the period 1700–1800 [*Jevrejeva et al.*, 2008a], the misfit around 1750–1800 is tolerable.

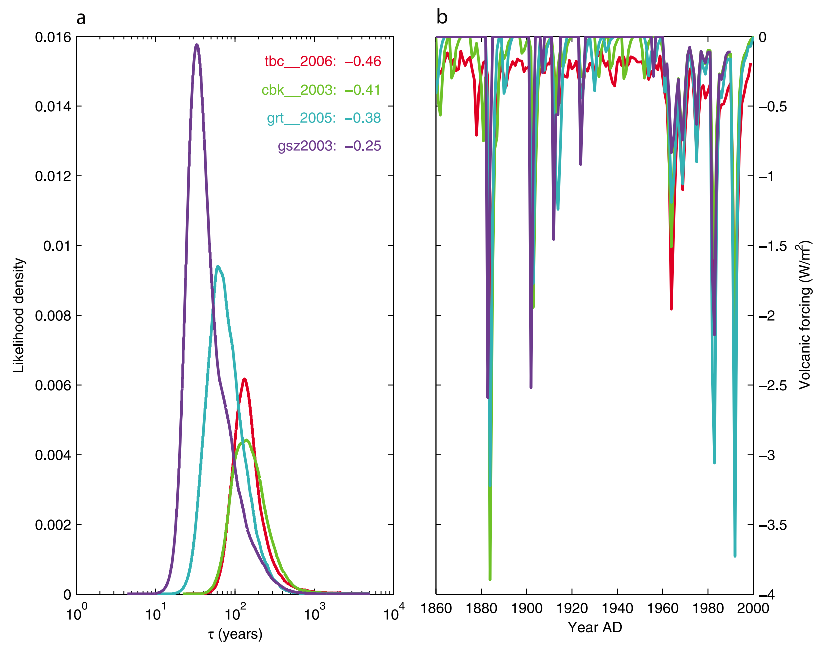

Figure 1. (a) Probability density function estimates of response time (τ), from equation (2), calculated from 2000000 Monte Carlo runs for each experiment, numbers on the right side of the panel correspond to average volcanic forcing since 1860 in W/m^2 for each experiment. (b) Volcanic forcing since 1860 from four experiments (colors are the same as in Figure 1a).

[12] All experiments provide evidence that until about 1800 the main drivers of sea level change are natural; volcanic and solar radiative forcings. Figures 3b and 3c show results of the sea level simulations for the 'cbk-2003' experiment. The long-lasting effects of volcanic eruptions since 1880 has acted to offset a large fraction of the sea level rise due to changes in ocean heat content resulting in a substantial reduction (4–5 cm) of thermosteric sea level

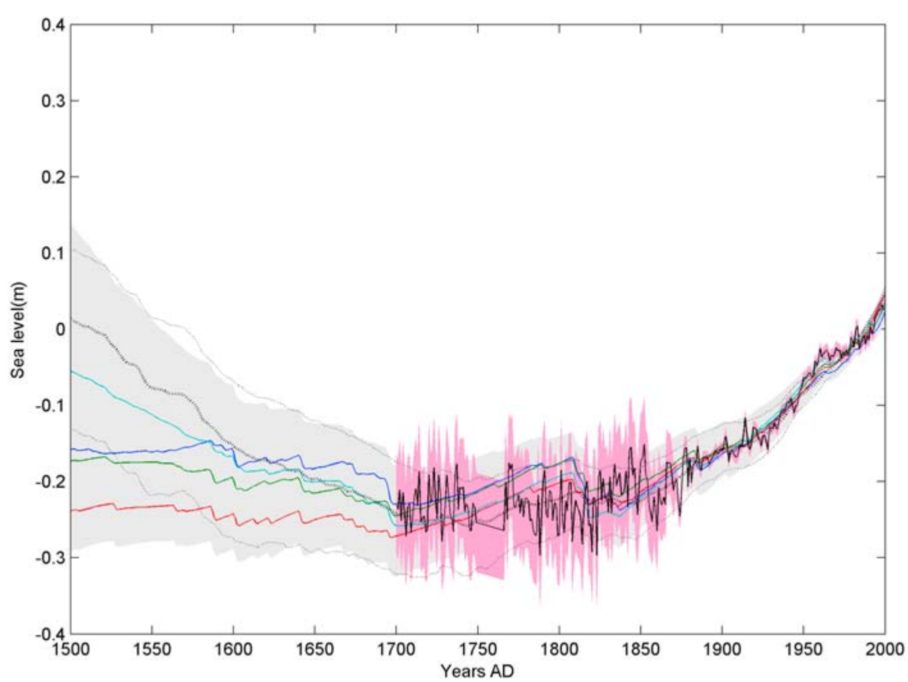

Figure 2. Sea level simulated in this study since AD1500 using mean global radiative forcing from four experiments ('cbk_2003'- blue; 'gsz2003'- red; 'grt_2005'- dark green; 'tbc_2003'- light green). Grey shadow bands represents the 5 and 95% confidence intervals calculated for the four experiments. Black thick dashed line is an independent sea level reconstruction based on the proxy temperature reconstructions [*Grinsted et al.*, 2009], black thin dashed lines are the 5 and 95% confidence intervals. The black solid line is sea level from tide gauge stations, pink shadow represents the 5 and 95% confidence intervals for sea level calculated from observations [*Jevrejeva et al.*, 2008a].

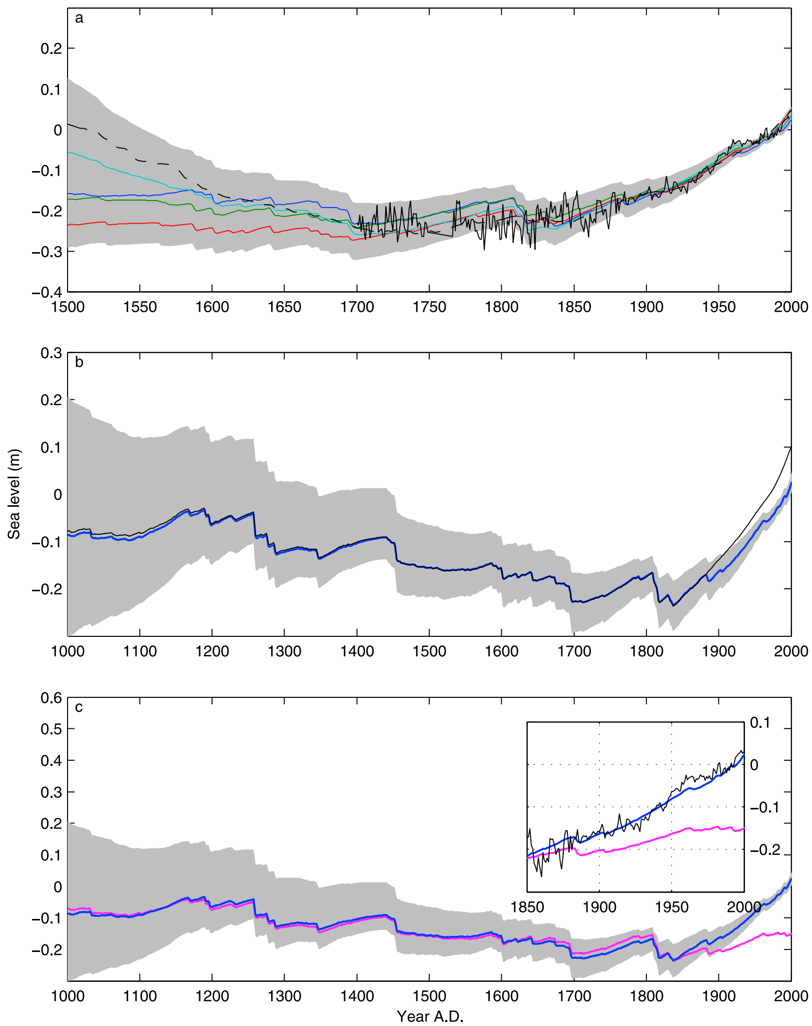

Figure 3. (a) Sea level since AD1500 using mean global radiative forcing from four experiments ('cbk_2003'- blue; 'gsz2003'- red; 'grt_2005'- dark green; 'tbc_2003'- light green). Grey shadow bands represent the 5 and 95% confidence intervals calculated for the four experiments. Black dashed line is an independent sea level reconstruction based on the proxy temperature reconstructions [*Grinsted et al.*, 2009]. The black solid line is observed sea level from tide gauge records. (b) The impact of volcanic forcing since AD1000 illustrated by the results from experiment 'cbk_2003' (solid blue line) with its the 5 and 95% confidence intervals calculated (grey band), the thin black line is simulated sea level excluding volcanic forcing since 1880, suggesting 20th century sea level is about 7 cm lower due to eruptions. (c) Solid blue line and grey shadow are the same as on the previous plot (forcings from 'cbk_2003' experiment). The magenta line is simulated sea level since AD1000 with natural forcings (volcanic and solar irradiance) only. The inset zooms in on the period of significant anthropogenic contribution to sea level rise during the past 150 years, the black line in the inset represents observed tide gauge sea level [*Jevrejeva et al.*, 2008a].

during the 20th century; this has been previously reported from climate model simulations [*Gleckler et al.*, 2006]. In our model simulations we find that if no volcanic eruptions had occurred since 1880, then 20th century global sea level would have been 7 cm higher (Figure 3b). It is possible that volcanic eruptions could have masked a contribution from greenhouse gases (mainly from land use change) since as early as 1700. However, results are inconclusive due to large error bars in observed sea level and sparse global coverage of sea level measurements prior to 1800.

[13] Anthropogenic forcing has been the dominant factor (with a contribution of more than 70%) in sea level rise (Figure 3c, inset) since 1900, and has been the main driving force (from 50–70%) of sea level rise since 1850. This finding is robust in all our experiments. Only 4 cm (with a lower limit of 1 cm and an upper limit of 7 cm) during the 20th century can be attributed to natural climate variability, the remainder, 14 cm (with a lower limit of 11 cm and an upper limit of 17 cm) is due to the rapid increase in anthropogenic forcing.

4. Conclusion

[14] We have used a statistical model driven by a range of forcing time series to reconstruct the history of sea levels during the past 1000 years. The model uses a single response time for the sea level response to climate change which is a simplification, in reality ice sheets probably have different response times than small glaciers or ocean heat content, but the simplification makes little difference over

the timescales we discuss here. Sea level has been within about 20 cm of its present level over the last millennium and been mostly driven by natural forcings. Volcanic forcing made a considerable contribution to the lowering of sea level since the 18th century and furthermore reduced the impact of increasing greenhouse gas concentrations and slight increases in solar irradiation during the past 200 years. Since 1850 sea level rise and its dramatic acceleration is associated with the rapid increase of CO_2 and other greenhouse gases.

[15] **Acknowledgments.** We are grateful to Mark Siddall and an anonymous reviewer for constructive criticisms helped to improve an earlier draft of this manuscript. We would like to acknowledge Judith Wolf for helpful comments.

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