Critique of the methods employed to project global sea level rise from global temperature (*extra materials*)

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Here we present further materials in support of our critique (S12, see also S14) to the models employed by Vermeer and Rahmstorf (S13). Computer codes to reproduce the results presented here form part of this supporting information and are documented at the end of this document.

Table S1 presents a comparison between parameter estimates obtained either using the implicit or explicit form of the models employed in ref S13. Parameter estimates were quite similar (but not equal) to those presented in ref S13, although the explicit formulation (optimal in the least squares sense) provided a better fit to the training data. Then these estimates were employed to update sea level projections for the 21st century (Table S2) using IPCC AR4 climate model temperature projections (S7). Projections based on the explicit formulation (models **S2** and **S4** in Table S1) were quite similar between them and with respect to results presented in ref S13, so the inclusion of temperature dependence does not seem to play a significant role when the model presented in ref S11 (model **S1**) is fitted using its explicit form. Table S3 further illustrates this point, and also shows the direct contribution of the different terms included in each model to sea level rise during the training (1880-2100) and the projection (2000-2100) period. As stated in the main text, the effect of both cumulated temperature and temperature is to reduce sea level rise during the period with observations, while the role of cumulated temperatures is inverted in the projections. The reason behind this is the changing correlation structure in the terms considered by the models between the observational period and the 21st century (Table S4). This is further illustrated in Table S4 and in Figs. S1–S4, which confront among them the data involved in model fitting. Finally, Figs. S5 and S6 present sea level projections based on the explicit formulation of the models.

Table S1. Parameter estimates based on Vermeer and Rahmstorf methods (ref. S13) and on a multiple regression of the explicit form of their models.

Model contrasted to the data	Parameter estimates						
	H_0	$-aT_0$	a	T_0	b	R^2_{adj}	RSS_{Obs}
$dH/dt = a(T - T_0)$ [**S1**]	17.55	0.1972	0.4377	-0.4505	——	0.8812	53.71
$H_t = H_0 + a\sum_0^t T_i - aT_0(t - t_0)$ [**S2**]	-398.2	0.2026	0.5084	-0.3986	——	0.9966	45.83
$dH/dt = a(T - T_0) + b\ dT/dt$ [**S3**]	17.72	0.2318	0.5608	-0.4133	-4.912	0.9815	31.66
$H_t = H_0 + a\sum_0^t T_i - aT_0(t - t_0) + b(T_t - T_{t_0})$ [**S4**]	-468.7	0.2392	0.5902	-0.4053	-6.149	0.9998	32.06

Models were fitted to Church and White global sea level (H) reconstruction (S3,S4) using NASA GIStemp surface temperature (T) analysis (S6). Chao et al. (S2) artificial reservoir adjustment was applied to sea level data. Both time series were smoothed using the methods described in ref S9, and binned in 15 year intervals before model fitting. Estimates are presented for each parameter included in the different models. The last two columns present the adjusted coefficient of determination (R^2_{adj}) for the regression in which parameter estimates are based, and the residual mean square (RSS_{Obs}) for model based projections of sea level rise between 1880 and 2000 (observed, annual sea level data was employed to assess the projections). Vermeer and Rahmstorf used models **[S1]** and **[S3]**, and we reproduced their methods in refs. S11 and S13 to obtain the values presented here. Model **[S1]** was fitted using linear regression, whereas to fit model **[S3]**, Vermeer and Rahmstorf combined an iterative procedure to find $\lambda = a/b$ (precision ± 0.005) and linear regression. In both models **[S1]** and **[S3]**, the constant of integration was adjusted to attain sea level zero in 1990 (e.g. $H_0 = \hat{H}_{1990}$). Models **[S2]** and **[S4]** were fitted using multiple linear regression for an illustrative purpose. Note that multiple linear regression provides better parameter estimates and better or similar projections in terms of goodness of fit; curiously, model **[S3]** provides a slightly better fit to observed data.

Table S2. Sea level ranges projected for year 2100 based on temperatures projected for different IPCC AR4 scenarios.

Scenario	Projected sea level range, cm above 1990			
	R2007 implicit (model **[S1]**)	R2007 explicit (model **[S2]**)	VR2009 implicit (model **[S3]**)	VR2009 explicit (model **[S4]**)
B1	91 (78, 101)	103 (88, 114)	104 (89, 115)	107 (92, 118)
A1T	109 (93, 122)	124 (105, 139)	125 (107, 139)	128 (110, 142)
B2	102 (87, 114)	116 (99, 129)	115 (98, 127)	117 (100, 130)
A1B	111 (95, 123)	126 (107, 140)	124 (105, 138)	127 (108, 140)
A2	114 (97, 127)	130 (110, 144)	124 (106, 138)	126 (108, 139)
A1FI	131 (112, 147)	150 (127, 167)	143 (122, 160)	146 (124, 162)

Projections were based on parameter estimates presented in Table S1 using temperatures derived from IPCC AR4 climate model output from 19 models, three different implementations of carbon cycle feedbacks and six SRES scenarios (S7). Figures represent the mean and the first and third quartiles (within brackets). R2007 refers to the model presented in ref. S11, while VR2009 to the dual model presented in ref S13 (see Table S1 for the formulation of different models and details on how the parameters were estimated). Figures S5 and S6 present another summary of the projections based on models **[S3]** and **[S4]**.

Table S3. Contribution of each term included in the models proposed by Vermeer and Rahmstorf to explain observed sea level rise (1880-2000) and to projections of future sea level rise based on IPCC AR4 temperature projections (2000-2100).

	Period	Contribution to sea level rise, cm			Sea level increase, cm
		$a\sum_0^t T_i$	$-aT_0(t-t_0)$	$b(T_t - T_{t_0})$	
Model **[S2]**	1880–2000	-3.16	24.3	——	21
	2000–2100	100 (80, 115)	20.3	——	121 (100, 135)
Model **[S4]**	1880–2000	-3.67	28.7	-4.04	21
	2000–2100	117 (93, 134)	23.9	-18.1 (-21.7, -13.1)	122 (103, 137)

Projections were based on parameter estimates presented in Table S1, using temperature time series (NASA GISTemp and IPCC AR4 [see Table S2], respectively). For the period 2000–2100, we present the mean (first and third quartiles within brackets) derived from all scenarios and models simulations.

Table S4. Correlation between the terms included in the different models during the training (*upper diagonal*) and the projection (*lower diagonal*) period.

	H	t	dH/dt	dT/dt	T	$\sum_0^t T_i$
H	——	0.971, 0.974, **0.976**	0.103, 0.873, **0.894**	0.033, 0.611, **0.640**	0.840, 0.942, **0.952**	-0.494, -0.478, **-0.450**
t		——	0.148, 0.878, **0.903**	0.045, 0.621, **0.636**	0.839, 0.935, **0.949**	-0.675, -0.661, **-0.631**
dH/dt			——	0.204, 0.393, **0.420**	0.113, 0.936, **0.948**	-0.091, -0.479, **-0.474**
dT/dt		0.115 (-0.569, 0.620)		——	-0.220, 0.631, **0.672**	-0.040, -0.352, **-0.298**
T		0.993 (0.989, 0.997)		0.115 (-0.521, 0.572)	——	-0.443, -0.464, **-0.458**
$\sum_0^t T_i$		0.977 (0.969, 0.984)		-0.024 (-0.686, 0.435)	0.974 (0.967, 0.984)	——

The values are Pearson product moment correlations. In the upper diagonal, the triplets correspond to Pearson product moment correlations between (i) observed, (ii) smoothed, and (iii) binned and smoothed (in boldface; this was the data employed to fit the models) variables. In the lower diagonal, the correlations were estimated using the climate model output from IPCC AR4 (see Table S2), and entries represent the mean (first and third quartiles within brackets) of the correlation found in the 342 simulations employed in projections. Figures S1–S4 further illustrate the relationship between variables.

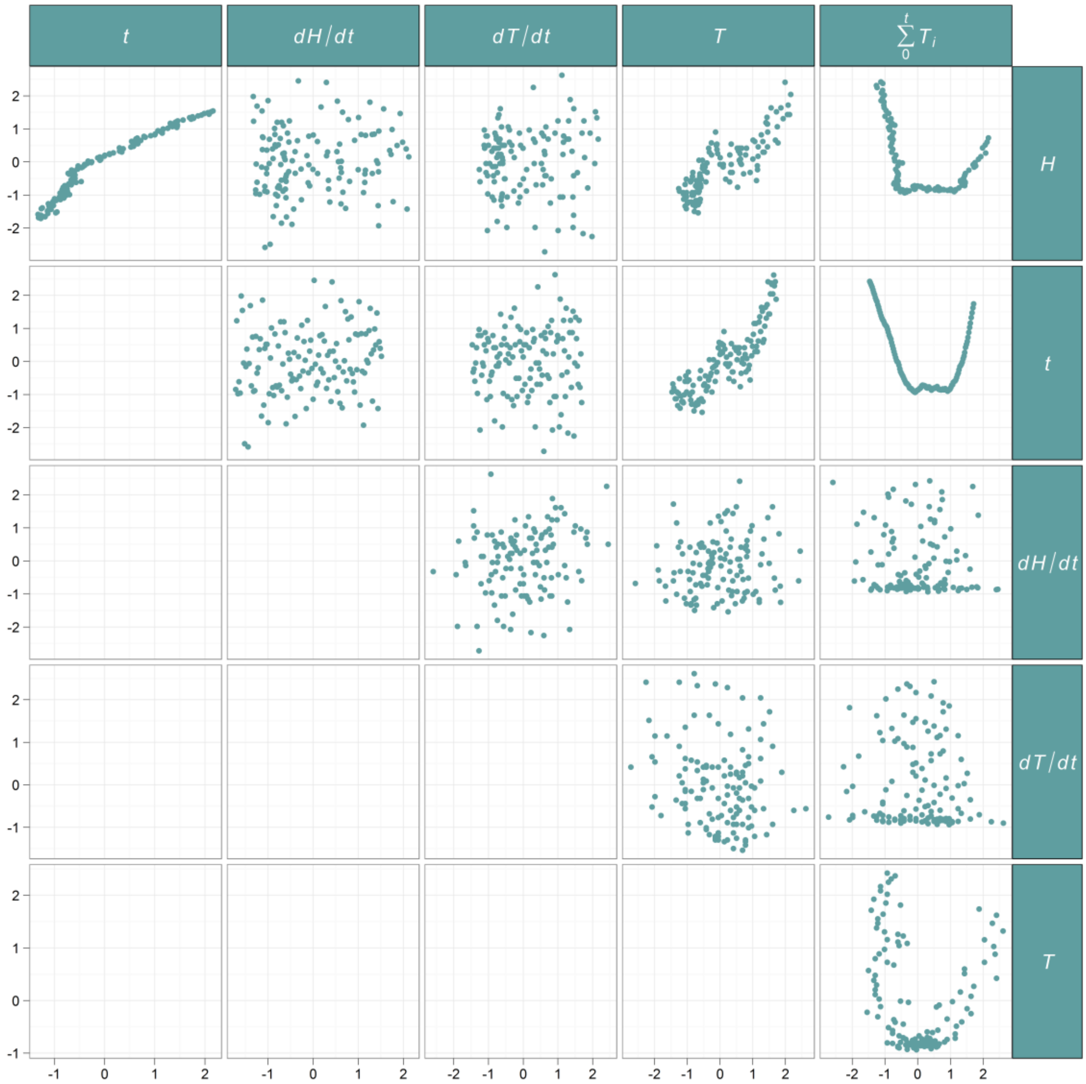

Fig. S1. Scatter plot matrix of the observed, raw data. All the variables were standardized to mean zero and standard deviation one. The panels confront all the possible pairs of variables (labels for x and y axes on the top and lateral strips). See Table S1 for data sources.

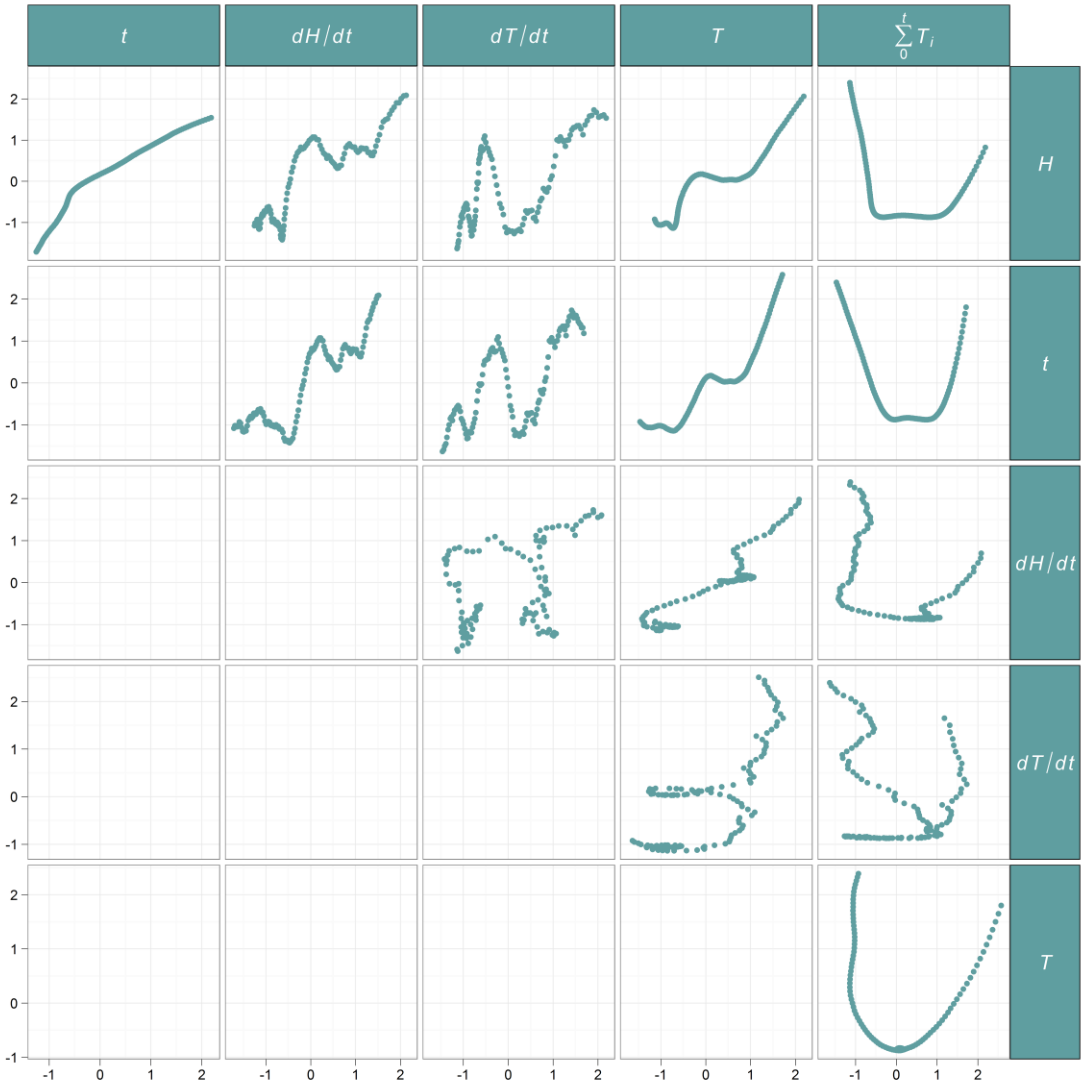

Fig. S2. Scatter plot matrix of the smoothed data. The figure is equivalent to Fig. S1, although the data has been smoothed using Singular Spectrum Analysis (embedding dimension, 15 years) using the procedures described in ref S9. All the variables were standardized to mean zero and standard deviation one. The panels confront all the possible pairs of variables (labels for x and y axes on the top and lateral strips). See Table S1 for data sources.

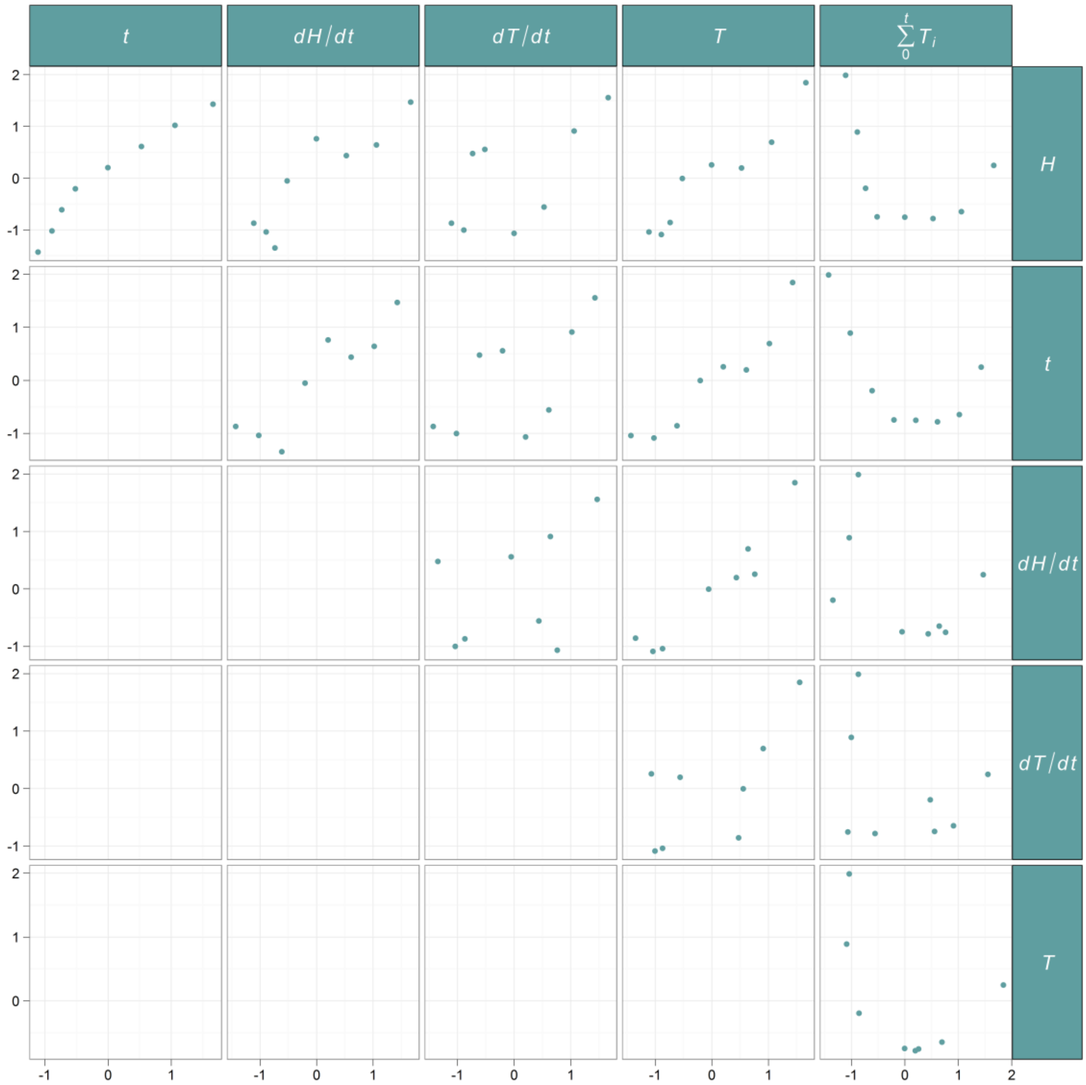

Fig. S3. Scatter plot matrix of the smoothed and binned data. The figure is equivalent to Figs. S1 and S2, although the data has been smoothed using Singular Spectrum Analysis (embedding dimension, 15 years) using the procedures described in ref S9 and binned in 15 year intervals. All the variables were standardized to mean zero and standard deviation one. The panels confront all the possible pairs of variables (labels for x and y axes on the top and lateral strips). See Table S1 for data sources.

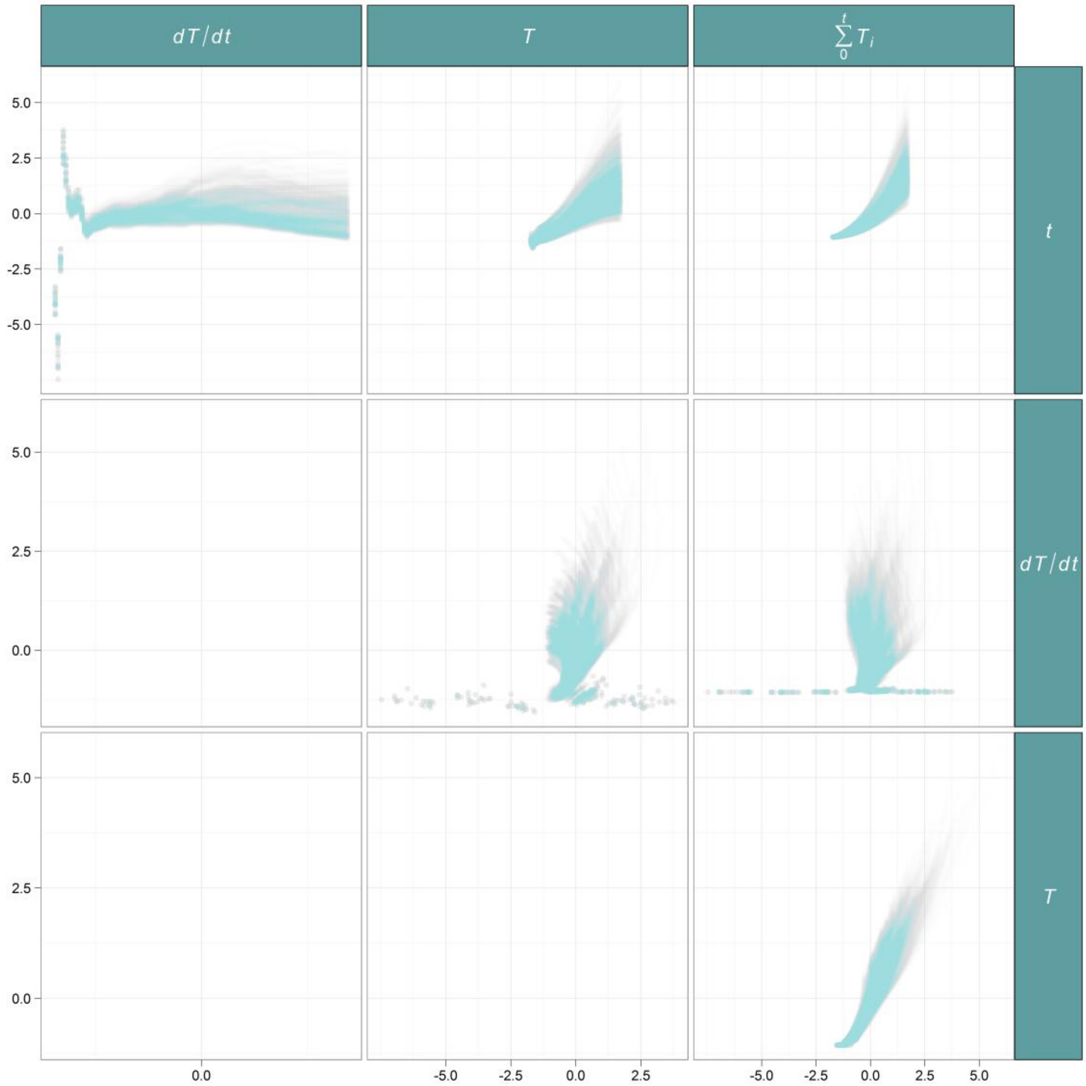

Fig. S4. Scatter plot matrix of the data employed to project future sea level rise, that is, IPCC AR4 model simulations. All the variables were standardized to mean zero and standard deviation one. To improve the visualization of the distribution of the data, alpha blending was applied to tune the transparency of each point. In this way, regions with solid color correspond to the overlap of at least 100 points. The panels confront all the possible pairs of variables (labels for x and y axes on the top and lateral strips). See Table S2 for data sources.

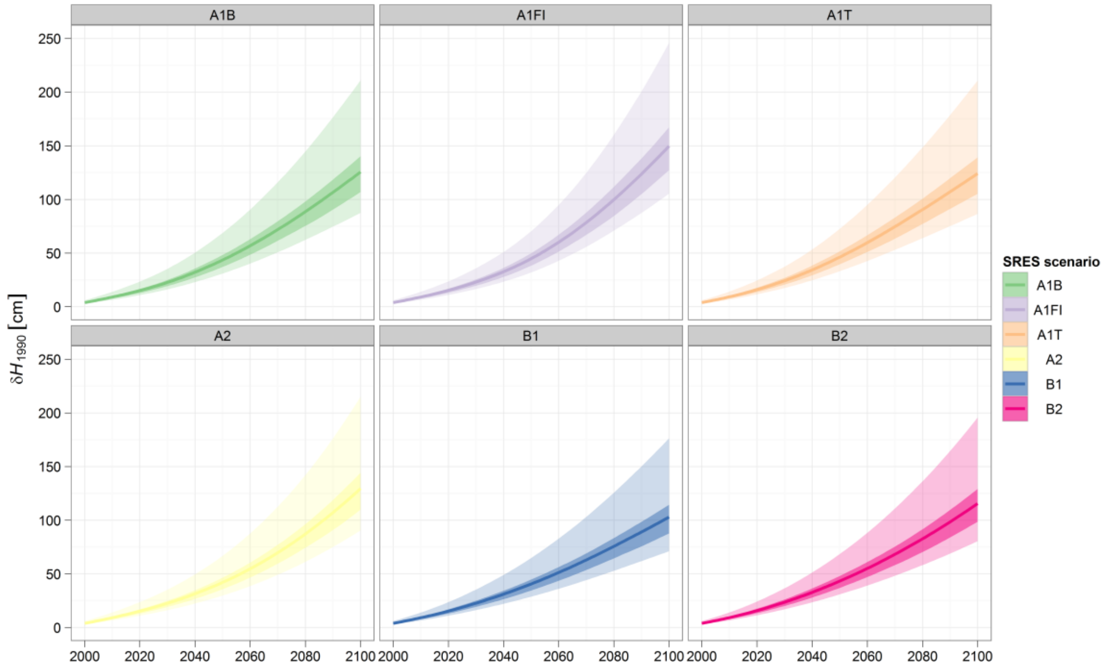

Fig. S5. Sea level projections based on equation **[S2]** (see Table S2). The lines correspond to the mean of several predictions; the inner, darker envelope is based on the first and third quartile of the distribution of simulated sea levels for each year, and the outer, lighter ribbon covers the range of the projections.

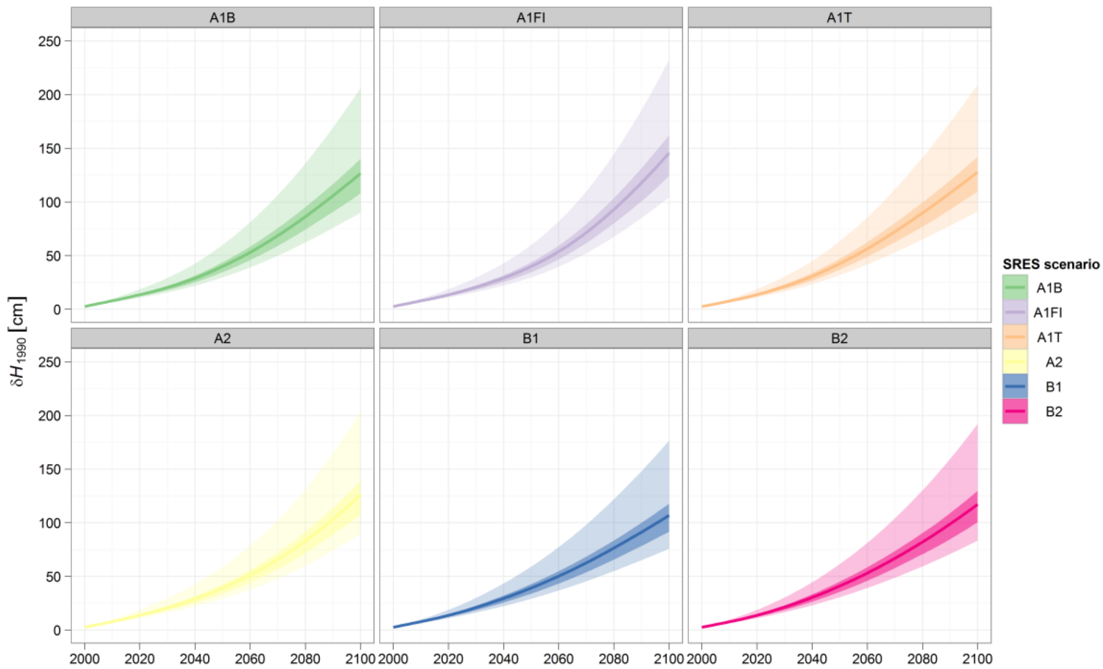

Fig. S6. Sea level projections based on equation **[S4]** (see Table S2). The lines correspond to the mean of several predictions; the inner, darker envelope is based on the first and third quartile of the distribution of simulated sea levels for each year, and the outer, lighter ribbon covers the range of the projections.

Computer codes and data

In order to ease replication of the results presented here, and following the example of Vermeer and Rahmstorf, the Supporting Information includes the computer codes and data files needed. All the calculations and figures were produced in *R* (S10), so in order to run the code, this should be installed in your computer (the program is freely available at www.R-project.org). Apart from the basic *R* installation, some extra packages were employed and their installation is required, including: *gridExtra* (S1), *ggplot2* (S17), *digest* (S5), *reshape* (S15), *plyr* (S16) and *proto* (S8). Once *R* and the extra packages are installed, set the working directory to the folder containing the codes and data (e.g. command 'setwd'). The codes can be run by executing the command 'source' on the file 'sealevelTA.r'. Data was converted from Matlab®, as gently provided by Vermeer and Rahmstorf (S13) to a format more suitable to *R*, so the content of each data file is documented in the following boxes.

sealevel.txt

Raw, smoothed and smoothed and binned observed global sea level and temperature.

t	time in years
H	global mean sea level, expressed in cm. Data comes from Church and White (S4) reconstruction (see also ref S3); data is available at the Permanent Service for Mean Sea Level (PMSL) website, hosted at the Proudman Oceanographic Laboratory; see: www.pol.ac.uk/psmsl/author_archive/church_white/ Chao et al (S2) reservoir correction has been applied, and following Vermeer and Rahmstorf (S13), the smoothed (see variable type) level at 1990 has been subtracted
dH	rate of sea level change, in cm yr^{-1}, estimated by finite differences of *H* values
T	global mean temperature, expressed as anomalies computed relative to 1951-1980 in Celsius degrees. The dataset is produced and updated at NASA Goddard Institute for Space Studies (GISTEMP, see for instance ref S6), and it is available at http://data.giss.nasa.gov/gistemp . The website provides also detailed information and references.
dT	rate of temperature change, in Celsius degrees by year, estimated by finite differences of *T* values.
cT	cumulated sum of temperature anomalies, in Celsius degrees, calculated using T values from 1880, the first year considered in the analysis
type	categorical variable indicating for each record whether it correspond to 'Observed', 'Smoothed' or 'Binned' data. 'Observed' data correspond nearly to raw data, while 'Smoothed' data was derived using Singular Spectrum Analysis, using the procedures and code described in ref S9 (see also, www.glaciology.net/software/ssatrend-m. Note that the mean, smoothed sea level for 1990 was substracted from both the 'Observed' and 'Smoothed' series. 'Binned' data refers to averages taken using a 15 year window over 'Smoothed' data for each variable.

ipccAR4_scenarios.txt

Temperature projections from IPCC AR4 (see Chapter 10 in ref S7)

t	time in years (1990-2100)
model	categorical variable coding each of the 19 climate models considered
scenario	categorical variable coding the IPCC AR4 scenario to which temperature projections correspond. Six SRES scenarios were considered: 'A1B', 'A1FI', 'A1T', 'A2', 'B1', and 'B2'.
ccycle	categorical variable coding the type of carbon cycle feedbacks assumed; it has three levels: 'low', 'default' and 'high'.
dT	rate of temperature change, in Celsius degrees by year, estimated by finite differences of *T* values.
T	temperature increments projected by each model adjusted to GISTEMP series of temperature anomalies (e.g. same mean between 1880 and 1920).
cT	cumulated sum of temperature anomalies, in Celsius degrees, calculated using *T* values from 1880, the first year considered in the analysis (e.g. -9.9145512, the *cT* value in 1990 calculated from smoothed GIStemp data, was added to the IPCC series of projected increments).

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