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Predictability of twentieth century sea-level rise from past data

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Abstract
The prediction of global sea-level rise is one of the major challenges of climate science. While process-based models are still being improved to capture the complexity of the processes involved, semi-empirical models, exploiting the observed connection between global-mean sea level and global temperature and calibrated with data, have been developed as a complementary approach. Here we investigate whether twentieth century sea-level rise could have been predicted with such models given a knowledge of twentieth century global temperature increase. We find that either proxy or early tide gauge data do not hold enough information to constrain the model parameters well. However, in combination, the use of proxy and tide gauge sea-level data up to 1900 AD allows a good prediction of twentieth century sea-level rise, despite this rise being well outside the rates experienced in previous centuries during the calibration period of the model. The 90% confidence range for the linear twentieth century rise predicted by the semi-empirical model is 13–30 cm, whereas the observed interval (using two tide gauge data sets) is 14–26 cm.

Keywords: climate change, sea-level rise, model validation, projections

1. Introduction

Sea-level rise is a complex process involving contributions from thermal expansion of ocean water, the melting of glaciers and ice sheets as well as changes in land water storage [1]. Modelling sea-level rise 'bottom-up' thus involves modelling the response of thousands of mountain glaciers to climatic warming, as well as local ocean warming and subsequent loss of buttressing ice shelves together with the flow response of the adjacent ice sheet. This involves many uncertainties, including even about how much glacier ice exists on Earth [2]. Regarding the 'big gorillas', the ice sheets in Greenland and Antarctica, fundamental processes are only beginning to be understood, like the important effect of albedo changes on surface melt [3] or the feedback of snow-fall rates on calving rates [4]. Aside of process understanding also boundary conditions like for example basal friction remain hard to observe [5] and ice sheet models do not reproduce the accelerating mass loss of recent decades [6–8]. The IPCC in its most recent central estimates projected a net negative contribution of these ice sheets to sea level over the coming hundred years for all emissions scenarios unless scaled-up ice sheet discharge is included (see figure 10.33 in [9]). Given the immense complexities, it is not surprising that sea-level projections are not yet robust. For the past decades these models underestimated the observed sea-level rise [10], although progress was made [11].

While process-based models are still being improved, semi-empirical models have been proposed as a complementary approach [12, 13, 15, 14, 17, 16, 18] and have shown their ability to reproduce sea-level evolution over the last millennium and the modern tide gauge record with useful accuracy, leading to projections that are robust against different choices of input data and statistical approach [16]. These semi-empirical models assume a simple, physically plausible connection between global-mean sea level and global-mean temperature [12–14, 16, 15] or radiative forcing [17, 18], with a few parameters that can be calibrated using observational data. A critical issue for projections is, however, whether these models have a demonstrable predictive skill outside the range for which they have been calibrated. Here we test this by attempting to project twentieth century sea-level rise, both for the whole century and the period since 1961, using previously published semi-empirical models.

2. Semi-empirical sea-level predictions

Two sea-level data sets are suited (and have been used) for calibrating semi-empirical models with pre-1900 data: the tide gauge data set of Jevrejeva *et al* [19] covering the period 1700–2002 AD (henceforth JE08) and the proxy data set of Kemp *et al* [12] covering 100 BC to 2000 AD (henceforth KE11). The proxy data are from one location only, but as discussed in detail in Kemp *et al* [12], they are expected to represent the global sea-level evolution to within ±10 cm, which still provides a useful constraint due to the long time period covered. For global-mean temperature over land and ocean, we use the only available long proxy data set from Mann *et al* [20] covering 500–2006 AD (other data sets to our knowledge only cover the northern hemisphere or exclusively land areas). As we will show, best results are obtained when constraining the semi-empirical model using both the tide gauge and the proxy data. However, as intermediate steps to study the sensitivity of the approach, we first show the model performance using either only tide gauge or only proxy data.

2.1. Calibration on tide gauge data

We start with the calibration on the JE08 data and remove non-climatic factors (i.e. reservoir storage [21] and groundwater extraction [22]), as discussed in detail in [16]. Over the twentieth century, reservoir storage has lowered sea level by 30 mm and groundwater extraction has raised it by 13 mm, according to these estimates, so that removing these effects raises twentieth century sea level by less than 2 cm. The model equation used is the 'dual model' [13]:

$$\frac{\mathrm{d}}{\mathrm{d}t}H(t) = a\,(T(t) - T_0) + b\frac{\mathrm{d}}{\mathrm{d}t}T(t) \qquad (1)$$

where H is sea level, T is global temperature and T_0 is a baseline temperature at which sea level is stable. The parameter a is the crucial sea-level sensitivity to temperature, while b describes short-term (i.e. up to a few decades) sea-level variability. The model parameters a, b and T_0 are determined through a general least-squares fit of the integral of (1) as described in [16], except that the calibration period is now restricted from 1700 up to different times ranging between 1860 and 1960, with the remaining sea-level evolution being predicted. The integration constant H_0, which simply describes a vertical offset of the sea-level curve, was chosen so that the simulation matches with the data mean over the period 1700–1800 AD.

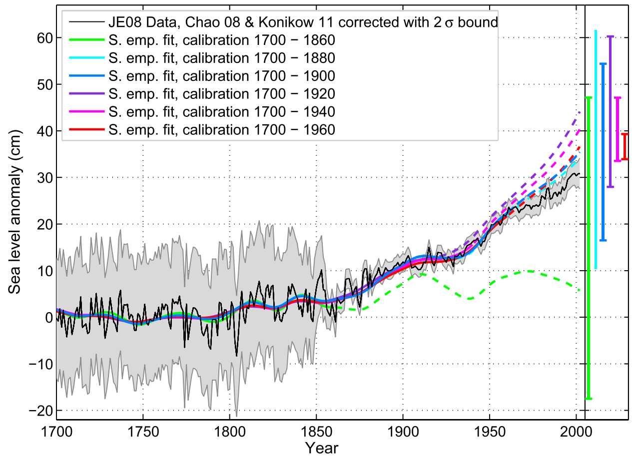

Figure 1. Sea-level projections based on the Jevrejeva *et al* tide gauge data [19]. The different colours denote different calibration periods of the model (1700 until 1860, 1880, . . . , 1960). The parameter a was constrained to be $\geqslant$0. The bars on the right hand side give the 90% confidence of the forecast, starting from the last year of calibration onwards. The JE08 data [19], used for calibration, was adjusted for ground water pumping [22] and reservoir storage [21].

The result is shown in figures 1 and 2. While using calibration data up to 1860 is insufficient to constrain the model, useful predictions are obtained with calibrations up to 1880 or later. In all cases the uncertainty ranges of model and tide gauge data overlap, although only just for calibrations until 1940 and 1960. This is reflected in the convergence of the parameter estimates as the calibration period gets longer (figure 2). As figure 1 shows, the model systematically overpredicts sea-level rise by 11–70% when calibrated up to 1880 or later. We assume this is linked to the steep increase of sea level in the JE08 data until 1960 and lesser increase afterwards, a feature weaker in other data [25].

When calibrated for 1700–1900 AD, the model predicts a twentieth century rise ranging between 5 and 41 cm with a best estimate of 23 cm (figure 1), while the observed linear twentieth century rise in the JE08 data (with the land water adjustment) is 16–26 cm (table 1). Despite of its large uncertainty, the best estimate of the prediction lies well within the observational range although the sea level during the calibration period varies only little. The model even correctly predicts the period of flat sea level from 1900 to 1930 and the subsequent decades of steep rise from 1930; only after 1970 does it start to deviate a few centimetres from the tide gauge data.

2.2. Calibration on proxy data

Next we turn to the proxy data. The KE11 data have been used with a modified model equation (rather than (1)) in the literature [12, 16], which reflects their longer timescale. On

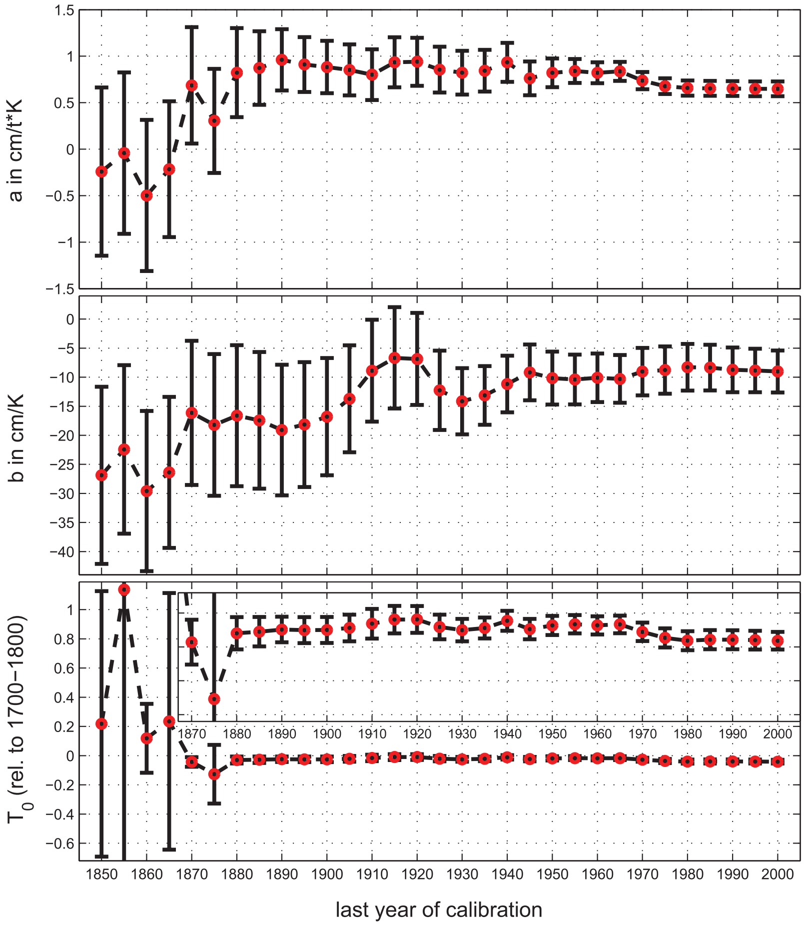

Figure 2. Parameter dependency on calibration period. The parameters a, b and T_0 from (1) with 1 σ error shown over the last year of calibration, on the JE08 data, starting 1700. The inset in the lower panel expands the vertical scale.

Table 1. Comparison of the rates of sea-level rise 1901–2000 AD. Proxy (KE11 [12]) and tide gauge (JE08 [19]) data sets have been used for the semi-empirical forecasts as described in the text (see figures 1 and 3). KE11 and JE08 denotes the merged data set from figure 4. The rates are calculated as linear trends.

	Data source	Calib. period	Rate (mm yr^{-1})	90% confidence
S.e. fit	KE11 and JE08	1000–1900	2	[1.3–3.0]
	KE11	1000–1900	1	[0.5–1.8]
	JE08	1700–1900	2.5	[0.9–4.1]
Data	JE08	X	2.1	[1.6–2.6]
	CW11	X	1.7	[1.4–2.1]

one hand, short-term variability (for example due to the ocean mixed layer response [13]) is not resolved by the proxy data, so the second term in (1) is superfluous and dropped. On the other hand, besides a 'perpetual' sea-level rise possibly due to the multi-millennial timescale of large ice sheets and glacial isostatic adjustment, a multi-century timescale τ of the sea-level response to climate needs to be explicitly resolved. As discussed in [14] as well as in subsequent papers [12, 15], sea level will respond to a step-function warming by initially starting to rise at a certain rate proportional to the magnitude of the warming, followed by an asymptotic approach to a new, higher equilibrium sea level. This asymptotic approach can be approximated by a rate of rise that decays exponentially on a timescale τ. This leads to the model equation

$$\frac{\mathrm{d}}{\mathrm{d}t}H(t) = a_1(T(t) - T_{00}) + a_2(T(t) - T_0(t)),$$

$$\text{with } \frac{\mathrm{d}}{\mathrm{d}t}T_0(t) = \frac{(T(t) - T_0(t))}{\tau}. \quad (2)$$

The parameters a_1, a_2, τ, T_{00} and the initial condition T_0 (t_0) are determined from the data by a Bayesian approach, as described in [12, 16] except of course for the reduced calibration period and a different set of *a priori* distributions (see appendix).

As discussed more in previous publications [12, 16], the proxy data from before 1000 AD are not used, because during this time interval the relatively warm temperatures of the Mann *et al* reconstruction [20] are incompatible with the

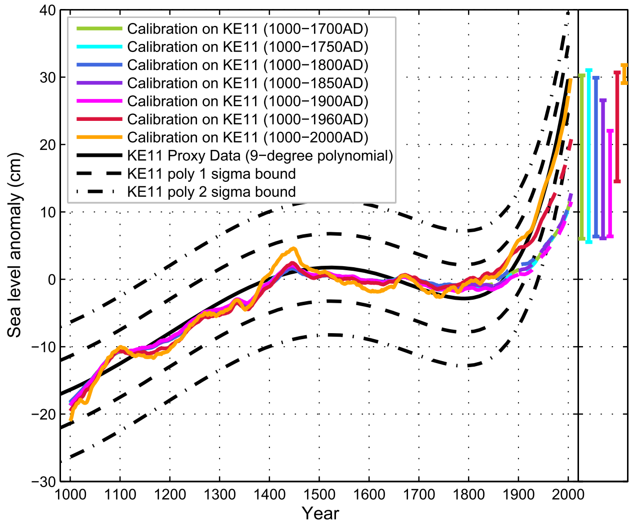

Figure 3. Sea-level projections based on the Kemp *et al* proxy data, plotted relative to the mean 1400–1800 AD. Experiments with varying calibration periods are marked with different colour. The solid, coloured lines represent the calibration period, the dashed lines show the forecast from the end of the calibration period until 2006. The bars on the right give the 90% confidence level of the forecast for the different experiments. In black we see a 9-degree polynomial fitted to the KE11 data with 1 and 2 σ confidence [12].

stable sea level found in the Kemp *et al* reconstruction [12]. As analysed in [16] there are two possible explanations for this discrepancy: either the model or the data might be wrong. As for the model it is important to note that any simple, physically plausible model relating sea-level changes to temperature changes would fail in a case like this where sea level is constant while temperature exhibits a clear step of around 0.2 °C. Other temperature proxy series do not show this step, and as shown in [12], temperatures only 0.2 °C cooler before 1100 AD—well within the uncertainties of [20]—would remove the discrepancy. This is an illustration of how tight the connection between temperature and sea level assumed in the model is, which cannot accommodate any kind of data by simple parameter adjustment.

For calibration up to the year 1900 AD, the linear twentieth century rise is predicted as 5–18 cm and is thus lower than the observed rise but overlapping with the observed range, which is 14–26 cm in the tide gauge data (table 1). This is not an effect of the broad prior distributions used, which work well as we can see when calibrating the model with data until 2000 AD. The underestimation of sea level is probably due to the low time resolution of these data, which do not clearly resolve the phase of sea-level rise between 1860 and 1900 which provides a calibration target in the JE08 data. We conclude that the pre-1900 proxy data alone are not sufficient to provide good predictions.

2.3. Calibration on combined tide gauge and proxy data

However, in practice these proxy data have not been used alone in modelling but only in combination with tide gauge data, to extend these back in time: the twentieth century parameter fit has been used as a prior constraint on the model in previous publications [12], before the proxy data were added as an additional constraint. This has shown that the proxy data, thanks to the long time interval of stable sea level covered by them, are mostly useful in constraining T_0 more tightly than the shorter tide gauge data could [16]. Following these previous applications of the proxy data, we now also test a combination of the KE11 proxy data (used from 1000–1700 AD) with the JE08 tide gauge data (used from 1700–1900 AD) for calibrating the model, using (2). The two data sets were combined by matching the average sea level over the period of overlap, 1700–1900 AD, and the merged data set was used to constrain the model parameters with a Bayesian approach (see appendix).

Figure 4 shows the twentieth century prediction which results from calibrating the model with this merged data set (dashed blue line) as compared to the JE08 observational data. With this approach, the forecast of total twentieth century rise is indeed improved as compared to that using the JE08 data alone (figure 1); it is in very good agreement with measurements. Note that the forecast rate of rise is about three times as large as that in any previous century during the calibration period; this is relevant since projections for the next three centuries have recently been published in which rates of rise likewise exceed the calibration period by up to a factor of three [24]. However, the variations on shorter timescales are not so well resolved due to the absence of the b-term in (2). Table 1 summarizes our three forecasts for the period 1900–2000 AD based on pre-1900 sea-level data and compares them to observational estimates.

3. Comparison with IPCC hindcast

Finally, we apply the semi-empirical projection approach to the time period 1961–2003 AD, which was the subject of detailed analysis in the last IPCC report [9]. To this end, we use the JE08 and KE11 data sets as well as a third one from Church and White [25] (which starts in 1880, henceforth CW11) up to 1960 for calibration, and predict sea level up to 2003. Equation (1) was used for the instrumental data (JE08 and CW11), and (2) again with the proxy data. For the CW11 data the GISS global temperature data were used for calibration and forecasting whereas for KE11 and JE08 the above proxy temperatures [20] were used, because they cover a longer time span. The results are summarized in table 2 and compared to the IPCC model hindcast for the same period [9]. Note that the IPCC did not hindcast the ice sheet contribution to sea level but included this (+0.19[−0.24–0.62] mm yr^{-1}) from observational data in their ‘model-based’ estimate ([9, table 9.2.])—presumably the rate would have been lower otherwise, since the ice sheet models used by the IPCC show a negative ice sheet response to climatic warming (i.e., a lowering of sea level), as mentioned earlier.

We find that the forecast using the CW11 and KE11 data is in very good agreement with the data, while the one using the JE08 data overestimates the rise, as we found in section 2.1 above. This is not due to the additional data coverage over

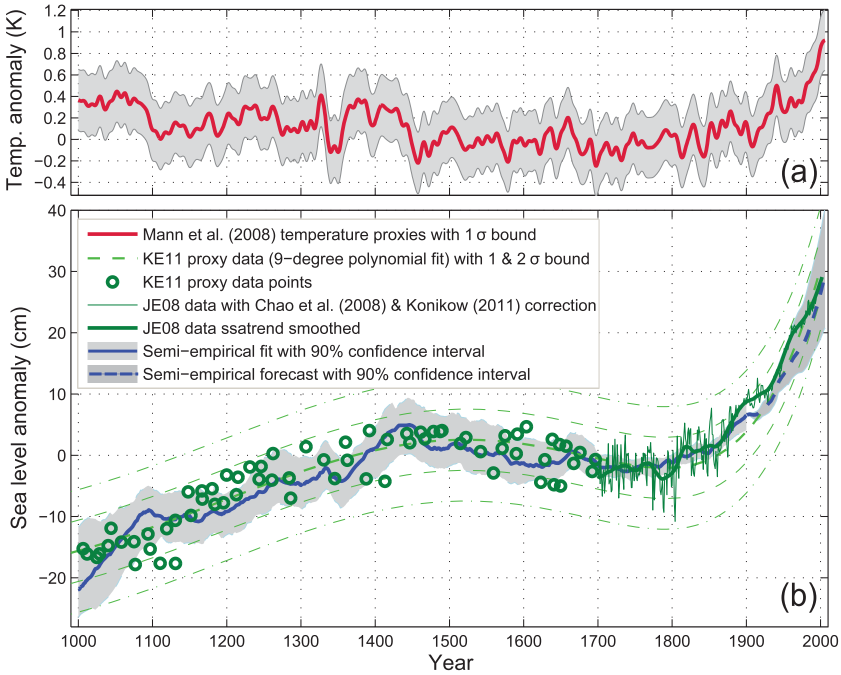

Figure 4. (a) Mann *et al* [20] temperature proxy data with 1 σ error used for calibration and forecasting. (b) Semi-empirical fit to a combination of proxy [12] and tide gauge data [19] until 1900 and forecast for the last century. A Bayesian update was performed as described in the text. The resulting fit is shown as a solid blue line with grey 90% confidence. The dashed blue line gives the forecast for the last century, again with 90% confidence. Overlayed we see the data points of the KE11 proxies until 1700 as well as a 9-degree polynomial fit to the full set of KE11 proxies with 1 and 2 σ errors. Plotted in green from 1700 AD onwards is the JE08 tide gauge data and for the sake of clarity a SSA (singular spectrum analysis [23]) smoothed version with 15-year half-width of the filter. The tide gauges are corrected for reservoir storage [21] and ground water pumping [22].

Table 2. Comparison of the rates of sea-level rise 1961–2003 AD. Proxy (KE11 [12]) and instrumental (JE08 [19], CW11 [25]) data sets have been used for the semi-empirical forecasts as described in the text (see figures 1 and 3). The rates are calculated as linear trends. The IPCC hindcast can be found in [9, table 9.2.].

	Data source	Calib. period	Rate (mm yr^{-1})	90% confidence
S.e. fit	KE11	1000–1960	2.1	[0.8–4.1]
	JE08	1700–1960	3.5	[2.8–4.1]
	CW11	1880–1960	2.0	[1.9–2.3]
IPCC	'ALL'	X	1.2	[0.7–1.7]
Data	JE08	X	2.0	[1.2–2.9]
	CW11	X	2.2	[1.7–2.6]

1700–1880 AD but rather due to the rapid rise right up to 1960 in these data, which happens to coincide with the end of the calibration period and which is not found to this extent in the CW11 data. We assume the CW11 data are more accurate in this respect due to their better global averaging procedure, which reduces the spurious decadal noise related to spatial under-sampling by the tide gauges [16]. As acknowledged by the IPCC, model-based estimates underestimated the observed rise despite the added ice sheet component.

4. Conclusion

In summary, we find that the previously published semi-empirical models show acceptable predictive skill, even for sea level and rates of rise well outside those found in the calibration period. The bias and confidence range depend on the calibration period and the data to calibrate the model with as well as the sea-level data to compare it with. For the twentieth century sea-level rise we found that using pre-1900 tide gauge or proxy data alone is insufficient to calibrate the model. When using both the proxy and tide gauge data up to 1900 AD, a correct forecast with useful confidence interval is obtained for the twentieth century sea-level rise—the 90% confidence range for the linear twentieth century rise predicted is 13–30 cm, whereas the observed interval (using two tide gauge data sets) is 14–26 cm. Calibration up to 1960 gives good results for sea-level evolution during 1961–2003 AD when the Church and White (2011) tide gauge data [25] or the proxy data [12] are used, but not using the JE08 data [19].

Our results add credence to projections of the future with semi-empirical models. To our knowledge, sea-level projections of similar quality for the twentieth century with process-based models have not yet been published. A demonstrated predictive skill is an important prerequisite for making future sea-level projections with models, regardless whether they are semi-empirical or process based.

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Appendix. Methods

The Bayesian formalism for the analysis of the proxy (KE11) and the merged proxy tide gauge (KE11 and JE08) data set was used the following way [12, 24]:

$$P(\theta|x) = \frac{P(x|\theta)}{P(x)} P(\theta) = \mathcal{L}_x(\theta)\ P(\theta) \quad \text{(A.1)}$$

$$\mathcal{L}_x(\theta) = \exp(-\tfrac{1}{2}\, r'\, \Sigma^{-1}\, r) \quad \text{(A.2)}$$

and $$\theta = [a_1, a_2, b, \tau, H_0, \langle \tilde{T}_0 \rangle, T_0(1000), T(t)] \quad \text{(A.3)}$$

where $P(\theta)$ are the prior probabilities for the parameters θ and $\mathcal{L}_x$ denotes the likelihood distribution for the calculated sea level depending on the covariance matrix of the observations Σ and the residuals of data and simulation r. As shown in table A.1 we applied broader and uniform *a priori* distributions on the parameters θ listed in table S3 of the supporting information of [12]. The parameter b, controlling short time variations in sea level which are not resolved in our data, is superfluous and was dropped.

The integration constant H_0 accounting for the vertical offset was chosen so that the data and the fit match over the period of relatively constant sea level 1400–1800 AD in contrast to previous studies where H_0 was considered a model parameter. A sensitivity test showed indeed that the difference in forecast and error for different H_0 priors is only small. So is the difference of simulations with different *a priori* τ distributions as long as $\tau \neq \infty$.

For the analysis of the proxy data the covariance matrix Σ is taken to be a diagonal matrix consisting of the observational errors since the covariance structure is unknown. When analysing the merged KE11 and JE08 data set we use the diagonal matrix for the KE11 part of the data until 1700 AD and from there on the covariance matrix reported in [15].

Table A.1. The *a priori* distributions $P(\theta)$ for the Bayes update of (2). The distributions of the temperature and τ are chosen as in the supplementary table S3 of [12]. $U[\alpha, \beta]$ denotes a uniform distribution between α and β, $U_{\mathrm{Sum}}[\alpha_{\mathrm{sum}}, \beta_{\mathrm{sum}}]$ is the pyramid shaped sum of two uniform distributions U_1 and U_2 with $\alpha_{\mathrm{sum}} = \alpha_1 + \alpha_2$ and $\beta_{\mathrm{sum}} = \beta_1 + \beta_2$. The brackets $\langle\ \rangle$ stand for the mean over the given period.

Parameter	Prior distribution
a_1	$U[0, 1]$ cm yr^{-1} K^{-1}
a_2	$U[0, 1]$ cm yr^{-1} K^{-1}
$a = a_1 + a_2$	$U_{\mathrm{sum}}[0, 2]$ cm yr^{-1} K^{-1}
b	0
$\langle \tilde{T}_0 (\mathrm{recent}) \rangle$	$\langle T(1400 - 1800\ \mathrm{AD}) \rangle + U[-0.3, 0.3]$ K
T_0 (1000 AD)	$\langle T(1000 - 1100\ \mathrm{AD}) \rangle + U[-0.3, 0.3]$ K
τ	$400 \times \exp(U[-2, 2])$ yr

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