Some Pitfalls of the Semiempirical Method Used to Project Sea Level

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ABSTRACT

Three variants of the semiempirical method for sea level projection are considered. They differ in assuming that the response of sea level to temperature forcing is equilibrium, inertial, or a combination of the two. All variants produce a successful regression of the temperature and sea level data, albeit with controlling parameters that differ among the cases. The related response times vary considerably, with a realistic value (~50 yr) obtained only if both the equilibrium and the inertial dynamics are taken into account. A comparison of sea levels projected by using the three variants shows that the time series are similar through the middle of the twenty-first century but they radically diverge by the end of the twenty-third century. This result is interpreted with the aid of the underlying transfer functions. It suggests that one should be cautious when using the semiempirical method to project sea level beyond the twenty-first century.

1. Introduction

Sea level rise is one of the most worrisome consequences of expected climate change, and it has therefore attracted considerable attention from researchers (e.g., Stocker et al. 2014). In projecting sea level change during the next century and beyond, two dynamic methods are commonly used. The process-based method addresses the contribution of thermal expansion to sea level rise by using coupled atmosphere–ocean models and allows for the contribution of land-ice mass changes by using sea level models combined with some empirical relationships. The semiempirical method does not distinguish between the two contributions to sea level change, but it reproduces the response of total sea level to temperature increase via a set of physically motivated relationships and relies on available data to determine the controlling parameters.

At first sight, the existence of two independent methods would appear to be advantageous, because it may enable sea level researchers to address unanswered questions with both methods. However, an overview of recent literature reveals that the two methods are a bone of contention, primarily because semiempirical projections presently tend to exceed process-based projections even if uncertainties are taken into account. Some researchers favor the results obtained by the semiempirical method (Rahmstorf et al. 2012; Bittermann et al. 2013), and a larger group prefers the outcome of the process-based method (Church et al. 2013; Stocker et al. 2014). A smaller group of investigators advocate a reconciliation of the two methods (Moore et al. 2013; Orlić and Pasarić 2013), which would enable the projections to be issued with more confidence than if based on a single method.

We believe that the gap between the two methods could be narrowed considerably if the assumptions and procedures on which they rest are analyzed in detail. As is well known, the process-based method has considerable difficulties with the ice sheets, especially when it comes to calving and migration of grounding line, and with the hundreds of thousands of glaciers approached via a small sample (Moore et al. 2013). The semiempirical method has its own shortcomings. Previously, researchers have examined the method's sensitivity to the data used to determine the inherent parameters (Rahmstorf et al. 2012), the spread of the temperature projections (Guttorp et al. 2014), and the way the varying water storage on land is taken into account (Orlić and Pasarić 2013). Here, we concentrate on the dynamics underlying three variants of the semiempirical method. It is shown that the projections obtained by the

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method are sensitive to whether the response of sea level to temperature forcing is assumed to be purely equilibrium, purely inertial, or some combination of the two.

2. Data

Because this paper is not focused on the sensitivity of the semiempirical method to the data used in calibration, a single pair of time series of temperature and sea level is selected for the analysis. The global mean temperatures are those produced by the Goddard Institute for Space Studies (Hansen et al. 2001, with updates), whereas global mean sea levels are reconstructions prepared by Church and White (2011). Both time series extend over the 1880–2009 interval. From both time series, the interannual and decadal variability is removed by computing nonlinear trend lines with an embedding period of 15 years (Moore et al. 2005).

The temperature projection is the one prepared by the Intergovernmental Panel on Climate Change under the RCP4.5 scenario for an interval extending to the year 2300 (Stocker et al. 2014). With the aim of concentrating on dynamic issues, no attention is paid to the spread of projections under this scenario; neither is any paid to the other scenarios. However, to illustrate the possible importance of multidecadal variability, another projection is considered alongside the original one by simply continuing the 60-yr oscillation that was detected in the 1880–2009 interval. Whereas such a procedure does not result in a true projection of multidecadal variability, it enables an order-of-magnitude estimate of the influence of the variability.

No attempt is made to allow for a change of ocean mass related to water storage on land between the years 1880 and 2009. The findings on the process differ widely: some authors concentrate on water impoundment in artificial reservoirs (Chao et al. 2008), while other authors find that the impoundment was roughly compensated by groundwater depletion over the past century (Konikow 2011; Wada et al. 2012), and there are some indications that extraction of groundwater was more important than dam retention (Pokhrel et al. 2012) without, however, being widely accepted (Konikow 2013). As previously shown, the relative strength of the two contributions has far-reaching consequences for the application of semiempirical method. The dominance of dam retention means that during the past century, sea level rise has been smaller than would be implied by the temperature rise; when dams are taken into account, the estimates of future sea level rise are higher. The prevalence of groundwater depletion has the opposite effect. The present analysis of sea level data without correcting for the terrestrial-water effect implies that all numerical values pertain to the case when the effect is minimal. However, it is not expected that this assumption will adversely influence our other findings, and especially not those on the importance of the dynamic relationship between temperature and sea level.

3. Three variants of the semiempirical method

In all variants of the semiempirical method, the departure of the global mean sea level from the related baseline level ($\zeta = Z - Z_0$) is related to the difference between the global mean temperature and the corresponding baseline temperature ($\tau = T - T_0$). The oldest variant, called variant A here, is based on the linear relationship

$$E\zeta = \tau\,, \tag{1}$$

where E is the equilibrium coefficient. The variant was originally proposed by Gornitz et al. (1982), who applied it to the smoothed temperature and sea level data available at the time and also allowed for a possible time lag between the two time series. When the relationship is used in its original form to perform regression analysis of our time series (Fig. 1a), $E = 4.7°\mathrm{C\,m^{-1}}$ is obtained with a high determination coefficient. In this case, the response of sea level to temperature forcing is instantaneous (i.e., the response time equals zero).

The next variant, called variant B according to our nomenclature, rests on the rate of change of a global sea level anomaly related to the global temperature anomaly:

$$I\frac{d\zeta}{dt} = \tau\,, \tag{2}$$

where I is the inertia coefficient. This relationship was proposed by Rahmstorf (2007), who applied it to a dataset somewhat shorter than the one presently employed. Our regression analysis yields $I = 588°\mathrm{C\,yr\,m^{-1}}$, again with a high determination coefficient (Fig. 1b). In this case, the response of sea level to temperature forcing is very slow and the response time is infinite.

The third variant, which we call variant C, allows for both the equilibrium and the inertial response of sea level to temperature forcing:

$$I\frac{d\zeta}{dt} + E\zeta = \tau\,. \tag{3}$$

The two responses were considered by Grinsted et al. (2010) by separately taking into account the equilibrium sea level corresponding to temperature forcing ($Z_e = aT + b$, where Z_e is the equilibrium sea level whereas a and b are

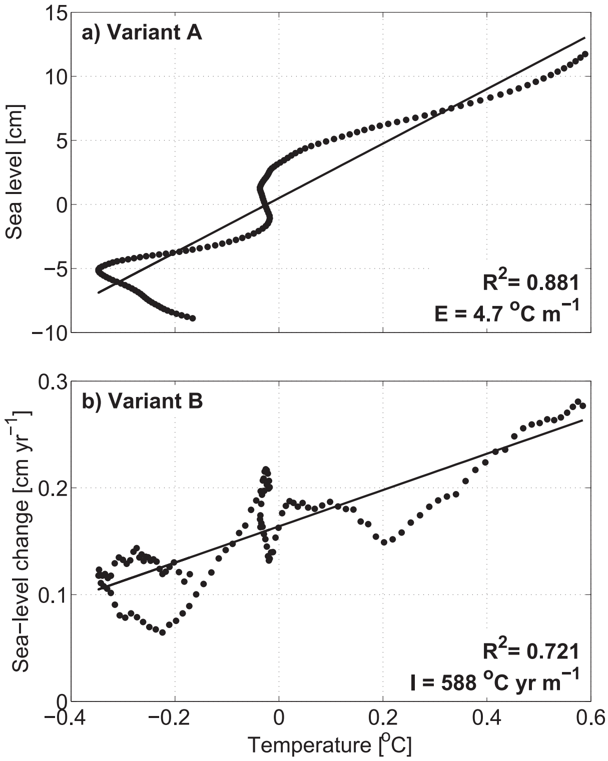

FIG. 1. Regression of (a) sea level on temperature (variant A of the semiempirical method) and (b) sea level change on temperature (variant B of the semiempirical method) over the 1880–2009 interval. In both cases, the fitting parameter and the determination coefficient are indicated.

some constants) and the real sea level adjustment to the equilibrium value [$dZ/dt = (Z_e - Z)/\delta$, where δ is the response time]. The present, closed form of relationship between temperature and sea level anomalies was proposed by Orlić and Pasarić (2013), and it implies $a = 1/E$, $b = Z_0 - T_0/E$, and $\delta = I/E$. In the latter paper, the two parameters involved were determined following a three-step procedure. First, an exponential function and a cosine were fitted to the temperature time series. Next, Eq. (3) was solved with such a forcing to determine how sea level depends on time. Finally, the resulting analytical expression for sea level, consisting of two exponential functions and a cosine, was fitted to the sea level time series. The procedure, when applied to the present dataset, gives $E = 2.3°\mathrm{C\,m^{-1}}$ and $I = 95°\mathrm{C\,yr\,m^{-1}}$ with the determination coefficient equal to 0.939.

Incidentally, the two parameters appearing in Eq. (3) could be obtained in a more straightforward way by performing a two-to-one regression analysis as suggested by the equation. This approach results in $E = 3.1°\mathrm{C\,m^{-1}}$ and $I = 161°\mathrm{C\,yr\,m^{-1}}$ with a determination coefficient of 0.923. The agreement of these values with those obtained by solving Eq. (3) is good.

A distinctive quality of the variant C is that it allows for a response time that may fall anywhere between zero and infinity (being equal to I/E). According to our two estimates of the equilibrium and inertia coefficients, the response time amounts to 41–52 yr. These values are similar to independent estimates of the response time of the upper-ocean thermosteric sea level (Marčelja 2010) and of the response time of alpine glaciers (Raper and Braithwaite 2009). Because upper-ocean expansion and melting of glaciers were found to be the main contributors to sea level rise during an interval for which the necessary data are available (Church et al. 2011), the agreement of response times lends support to variant C of the semiempirical method.

Additional support comes from an estimation of the depth to which the heat-content change mostly extended over the sea level measurement interval, which equals $S/(\alpha E)$ with S denoting the share of thermal expansion in the total sea level rise and α standing for the thermal expansion coefficient. With $S \approx 1/3$ (Gregory et al. 2013), $\alpha \approx 2.5 \times 10^{-4}\,°\mathrm{C}^{-1}$, and $E = 2.3$–$3.1°\mathrm{C\,m^{-1}}$ as given above, the depths are found to range between 430 and 580 m. It is encouraging that these depths are close to the values resulting from the heat-content measurements over the second half of the twentieth century (Domingues et al. 2008).

Besides these three variants of the semiempirical method, often used is the one proposed by Vermeer and Rahmstorf (2009). However, it belongs to a different class and will be only briefly addressed in the concluding section of the present paper.

4. Results and discussion

The three variants of the semiempirical method are compared in Fig. 2. The figure shows temperatures measured since the year 1880 and projected until the year 2300, both with and without multidecadal variability, followed by a comparison of sea levels obtained by numerically solving the equations corresponding to variants A and C, and finally a comparison of sea levels representing the numerical solution of the equations related to variants B and C. It is obvious from the figure that the variant-A values become progressively smaller than the variant-C projections over the next three centuries. On the other hand, the variant-B values are smaller than the variant-C projections at the end of the twenty-first century and considerably surpass the variant-C values by the end of the twenty-third century. It is interesting that for the end of the present century, the largest projections are provided by variant C, relatively small values are implied by variant B, and even smaller values result from application of variant A. By

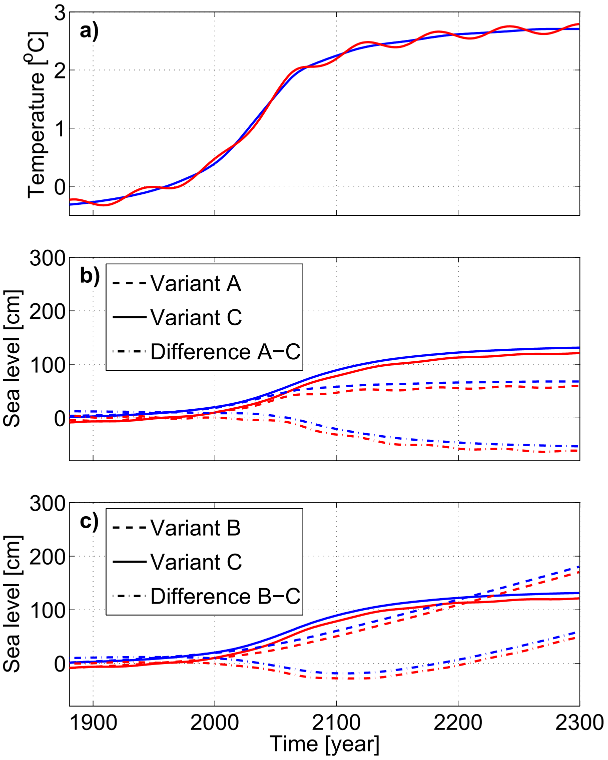

FIG. 2. Temperature and sea level time series with the multidecadal variability included (red) and excluded (blue). (a) Temperatures are observations prior to the year 2009 and projections under the RCP4.5 scenario after that year. Sea levels and their differences are computed (b) by applying variants A and C of the semiempirical method and (c) by using variants B and C of the semiempirical method. Sea level time series with and without multidecadal variability are slightly offset to make them discernible.

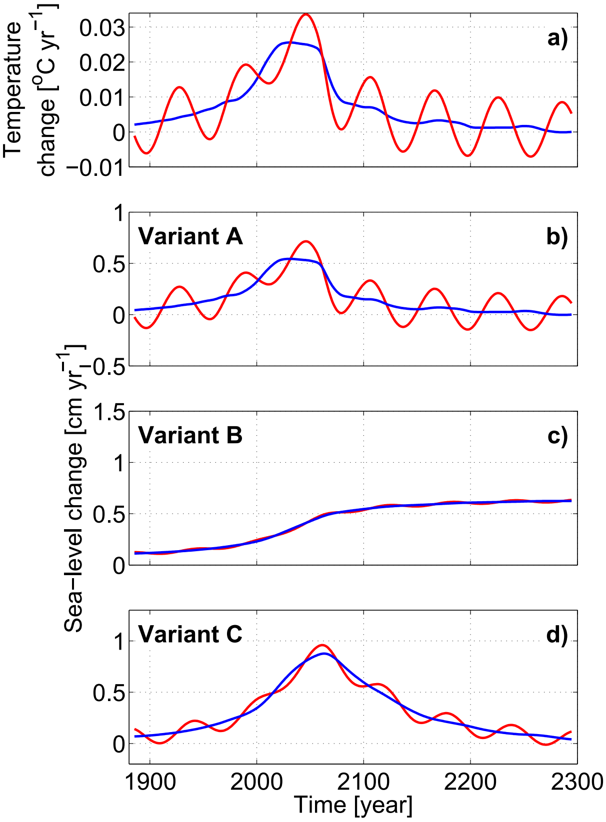

FIG. 3. Time series of (a) temperature trends, and of (b)–(d) sea level trends computed by applying variants A, B, and C, respectively, of the semiempirical method. The multidecadal variability is included (red) and excluded (blue). The trends are obtained by linear regression against time in overlapping 11-yr windows, with value of the trend plotted at the center of the window.

the end of the twenty-third century, the three projections differ radically.

Multidecadal variability, which is visible in temperature, is imperceptible in sea level (Fig. 2). The variability, however, is well documented by Fig. 3, which shows trends of temperature and of sea level computed in three different ways. The temperature increase was maximal in the 1920s and 1980s and minimal in between. These changes agree with those detected by other researchers (e.g., Smith 2013); in particular, the present deceleration following the late-twentieth-century maximum is related to what has become known as the global warming hiatus.

The relationship between sea level trends and temperature trends depends on which semiempirical method is used (Fig. 3). The multidecadal variability of sea level trends is greatest and closely follows the corresponding temperature-trend variability under variant A; it is smallest and lags behind the forcing by a quarter of a period (~15 yr) if variant B is used; and it is characterized by amplitudes and phases falling somewhere between the two extreme cases according to variant C. The variability of sea level trends resulting from the application of the last variant agrees best with the variability observed over the past century (Ray and Douglas 2011; Hay et al. 2015), regarding both the amplitudes (approximately 0.1 cm yr^{-1}) and phases (maximal trends in 1940s and 2000s). The present maximum corresponds to trends provided by satellite altimeter measurements, albeit with an amount somewhat surpassing the observations due to the smoothing of transition from observed to projected temperatures.

Whereas variant A of the semiempirical method relies on the equilibrium response of sea level to temperature forcing at all frequencies, and variant B assumes that the response is inertial everywhere, variant C with a response time of approximately 50 years implies that the response is near inertial at the multidecadal period and close to equilibrium at the longer periods. Therefore, the variant-C prediction of sea level depends on previous temperatures at the multidecadal frequency and on concurrent temperatures at lower frequencies. It may then be expected that the global warming hiatus will be reflected in a small sea level acceleration over the next decade or two (Fig. 3d) unless the average temperatures increase more than projected under the RCP4.5 scenario.

To interpret these findings, it is useful to consider transfer functions corresponding to the three variants of the semiempirical method. As is well known (e.g., Glisson 1985), the relationship between the input to and the output from a linear systems is completely determined by amplitude gain (Γ) and phase shift (Φ). It is straightforward to show that for variant C these functions are given by

$$\Gamma(\sigma) = \frac{1}{\sqrt{E^2 + I^2\sigma^2}}, \quad \Phi(\sigma) = \arctan\left(\frac{I\sigma}{E}\right), \qquad (4)$$

where σ is the angular frequency. The corresponding functions for the other two variants are easily obtained from Eq. (4) by neglecting the inertial effect ($I = 0$) in the case of variant A and by neglecting the equilibrium effect ($E = 0$) in the case of variant B. The three pairs of transfer functions thus determined are illustrated in Fig. 4 for the equilibrium and inertia coefficients calculated by rounding off the values given in the third section. It is obvious that the variant-C amplitude gain is larger (smaller) than the variant-A (variant-B) gain at low frequencies and is smaller (larger) than the variant-A (variant-B) gain at high frequencies. As for the phase shift, there is agreement between variants A and C at low frequencies and between variants B and C at high frequencies.

These transfer functions elucidate the previously documented differences between the time series. In particular, they explain the divergence of projections extending beyond the twenty-first century, when the temperature curve levels out and when, consequently, the dynamics are dominated by low frequencies: the variant-A projections then undershoot the variant-C values, whereas the variant-B projections surpass them. Moreover, for a multidecadal period (~60 yr), the transfer functions imply the largest sea level amplitudes for variant A, somewhat smaller amplitudes for variant C, and still smaller amplitudes for variant B—again in agreement with the results obtained in the time domain.

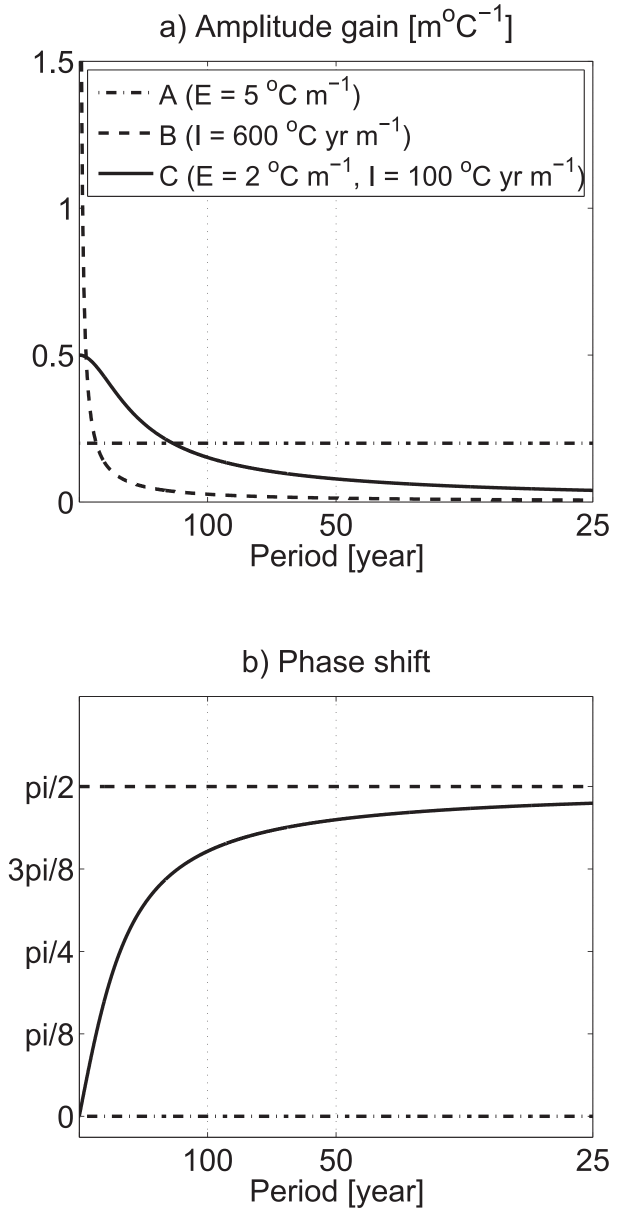

FIG. 4. (a) Amplitude gain and (b) phase shift related to variants A, B, and C of the semiempirical method. Numerical values of the parameters used to depict the transfer functions are indicated in the legend.

It is of some interest to consider why the three variants of the semiempirical method could not be distinguished by the goodness of the data fitting they imply. While it is true that the obtained determination coefficient is highest for variant C, somewhat lower for variant A, and yet lower for variant B, the differences are too small to be decisive. The finding may easily be interpreted by looking at Eqs. (1)–(3) and by taking into account the fact that the temperature and sea level variability over the past century were dominated by the same exponential rise (Orlić and Pasarić 2013). Because the derivative of an exponential function equals the exponential function, the temperature rise could be balanced by the sea level rise, by the change of sea level rise, or by a combination of the two. The controlling parameters, however, differ between the three cases, with the variant-A equilibrium coefficient surpassing the corresponding variant-C value and the variant-B inertia coefficient surpassing its variant-C counterpart. This explains why it is not possible to give preference to one of the three variants by considering solely the data fitting procedure and why the three variants differ not only in the underlying dynamics but also in the numerical values of parameters that were determined from the data.

5. Conclusions

Three variants of the semiempirical method, relying on three different relationships between the global mean temperature and the global mean sea level, are considered. It is shown that all variants produce a successful regression of the temperature and sea level data, albeit with the controlling parameters that differ among the three cases. What sharply distinguishes the cases is the time of response of sea level to temperature forcing. It is close to the response time of approximately 50 years that was independently obtained for seawater expansion and melting of glaciers, the two processes that dominated sea level rise over the past century, only when both the equilibrium and the inertial dynamics are taken into account. A comparison of time series projected in three different ways shows that they stay close until the middle of the twenty-first century and that they radically diverge by the end of the twenty-third century. The finding is interpreted with the aid of the underlying transfer functions, which show that at low frequencies the purely equilibrium effect tends to support small sea levels but the purely inertial effect allows sea level to rise infinitely; the combined equilibrium and inertial effects maintain sea at a moderate level. This strongly suggests that one should be cautious when using the semiempirical method to project sea level beyond the twenty-first century. The fact that a variant of the semiempirical method successfully reproduces sea level measurements characterized by a specific spectral content does not guarantee that the variant will be useful when preparing projections under the forcing having different spectral characteristics.

A common feature of the three variants of the semiempirical method considered here is that each of them is characterized by a single response time, with a value that depends on the variant employed. Yet, it may be expected that at least two response times are needed to adequately represent all temperature-related processes that contribute to sea level rise: thermal expansion of upper ocean and melting of alpine glaciers with the response time of $O(10\text{–}100\,\mathrm{yr})$ and thermal expansion of deep ocean and melting of Greenland and Antarctica with a response time of $O(1000\text{–}10\,000\,\mathrm{yr})$.

A variant of the semiempirical method allowing for two response times was proposed by Vermeer and Rahmstorf (2009), with one response time assumed to equal zero and the other allowed to extend to infinity. By using subscript 1 to mark fast processes and subscript 2 to indicate slow processes, it may be written:

$$E_1\zeta_1 = \tau, \quad I_2\frac{d\zeta_2}{dt} = \tau, \tag{5a}$$

and these two equations, with $\zeta = \zeta_1 + \zeta_2$, lead to

$$\frac{d\zeta}{dt} = \frac{1}{I_2}\tau + \frac{1}{E_1}\frac{d\tau}{dt}, \tag{5b}$$

which is the original equation used by Vermeer and Rahmstorf (with their constants a and b equaling $1/I_2$ and $1/E_1$, respectively). Whereas the first of underlying response times is obviously too small, the other may be acceptable bearing in mind the relative shortness of the projection interval when compared with the response time of the entire ocean and that of ice sheets. The equilibrium coefficient obtained by Vermeer and Rahmstorf (E_1) equals $-20°\mathrm{C\,m^{-1}}$ whereas their inertia coefficient (I_2) is found to amount to $178°\mathrm{C\,yr\,m^{-1}}$. The equilibrium coefficient is obviously off the mark, with its value departing from all previous estimates and its sign implying that a temperature increase brings about contraction of seawater and/or build-up of glaciers. As for the inertia coefficient, which in this case is related to the way the deep ocean and ice sheets respond to the temperature variability, it appears that no independent estimates of its value are available in the literature and that therefore no comparison is possible. The transfer functions related to the Vermeer and Rahmstorf variant point to the inertial dynamics at low frequencies and to the equilibrium dynamics at high frequencies. The projections obtained by applying the variant could be acceptable if the future sea level rise is dominated by the contribution of deep layers of the ocean and of Greenland and Antarctica, providing that the related inertia coefficient is well defined by the available sea level measurements and/or proxy data. It is obvious, however, that this variant of the semiempirical method warrants further scrutiny.

The semiempirical method could be further improved by allowing for more than two response times, each corresponding to one of the contributions to sea level change. A first step in that direction was taken by Winkelmann and Levermann (2013), who have determined transfer functions, related to the upper-ocean thermal expansion, the melting of Greenland, and the melting of Antarctica, on the basis of modeling of the three processes. To make the approach truly independent from the process-based one, the transfer functions would have to be determined from the data rather than from the modeling results. The time series needed presently appear to be too short for the purpose (e.g., Church et al. 2011), but their extension over the coming decades could make the method feasible.

To summarize, some of the presently used variants of the semiempirical method rely on dynamics that fit the past but may not be adequate for the future, whereas the others rest on the dynamics that may be expected to prevail in the future but do not realistically reproduce the past. In the former cases the controlling parameters may be insufficient, and in the latter cases they may be wrong. It therefore appears that the immediate problem is to apply dynamics that would be adequate for both the past and the future and, in particular, to determine a larger number of necessary parameters from the available data. The next step would be to consider changes of the parameters related primarily to the changing ice-sheet dynamics. These tasks seem quite demanding. However, the prospect of creating a credible complement to the process-based method of projecting sea level would justify the effort.

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