Storch, H.v.; Zorita, E.; Gonzalez-Rouco, F.:

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In: Ocean Dynamics (2008) Springer

DOI: 10.1007/s10236-008-0142-9

Ocean Dynamics manuscript No.
(will be inserted by the editor)

Relationship between global mean sea-level and global mean temperature and heat-flux in a climate simulation of the past millennium

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Received: date / Accepted: date

Abstract The possibility of using global mean near-surface temperature, its rate of change, or the global mean ocean heat-flux as predictors to statistically estimate global mean sea-level is explored in the context of a long climate simulation of the past millennium with the climate model ECHO-G. Some of these semi-empirical relationships have recently been proposed to by-pass the difficulty of estimating future sea-level changes based on simulations with coarse-resolution climate models. It is found that, in this simulation, a simple linear relationship between mean temperature and the rate of change of sea-level does not exist. A regression parameter linking both variables, and estimated in sliding 120-year windows varies widely along the simulation and in some periods even attains negative values. Better empirical predictors for the rate-of-change of sea level are the ocean heat-flux and the rate-of-change of mean temperature.

Keywords global sea-level · temperature · last millennium, climate simulation

1 Introduction

The physical mechanisms that cause global sea-level variations at decadal timescales mainly comprise the changes in water density due to changes in water temperature and salinity, and the increase of ocean water mass due to melting of land glaciers and polar ice caps. Estimations of future global sea-level rise brought about by increasing concentrations of atmospheric greenhouse gases of anthropogenic origin are based on simulations with coarse-resolution global climate models, which include a representation of the most important components of the climate system, the atmosphere, the ocean and the cryosphere. The coarse horizontal resolution of current climate models, roughly 200x200 km, imposes some limitations on the skill of future projections

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of global sea-level rise. Some of processes that modulate the heat flux into the ocean, such as convection, may not be adequately represented in ocean models. Also, land-locked glaciers, with extensions of a few kilometers often located in areas of complex topography are only very crudely represented in the soil sub-models, which operate at a resolution that usually matches the resolution of the atmospheric models. A further complication stems from the ice dynamics in the polar ice sheets and its response to an increased heat flux in the future. This dynamics, far from being a simple heat-uptake from the atmosphere, may be modulated by the presence of ice-craks, melt water flow within the ice and ice sliding over the bedrock that support the ice caps. Due to these reasons the Fourth Assessment report of the Intergovernmental Panel on Climate Change (Meehl et al. 2007) included estimations of future projections of sea-level rise with wide uncertainty ranges and it was very cautious about the question of the magnitude of the sea-level rise component due to the melting of the polar ice caps.

However, decisions makers require information about the possible range of sea-level rise that include all possible components for long-term planning with a time horizon of 100 years or longer. To fulfil this need, and partially by-pass the uncertainties associated to the representation of the above processes in climate models, semi-empirical methods have been proposed to to estimate future global mean sea level rise based on the global mean temperature change simulated by climate models. Recently, Rahmstorf (2007), hereafter R07, proposed a linear relationship between the rate of global mean sea-level rise $\frac{dH}{dt}$ to the global mean near-surface air-temperature deviations. This relationship is calibrated with observed data, thus incorporating more realistically and in a condensed manner all known and unknown mechanisms modulating the global sea-level height. As it is generally assumed that climate models are much more skilful in simulating future changes of the global mean temperature, such a empirical relationship would perhaps allow for more realistically estimations of future sea-level rise and of their uncertainties.

As any empirical-statistical relationships, it is assumed that the same physical mechanisms operating in the present climate will operate in the future, even when the predictors and the predictand will attain values outside the range observed in the calibration range. It is, of course, not possible to test the validity of this assumption in the future. One strategy is to test the semi-empirical methods in the virtual reality produced in simulations with state-of-the-art climate models. This line of research has also been exploited before to test the skill of statistical methods of proxy-based reconstructions of past climates (see e.g. Lee et al., 2008). Following this strategy we test in this paper several hypothesis concerning the relationship between global mean sea-level and other thermal surface variables in a long climate simulation of the past millennium with the climate model ECHO-G driven by estimations of past greenhouse gas, volcanic, and solar forcing. The rationale of using this simulation is to test whether the statical relationships are stable in time in a climate that may not deviate very strongly from the present one.

2 Semi-empirical models linking global mean sea-level and global mean surface thermal variables

The method proposed in R07 relates the rate of change of sea-level height H with the global mean temperature deviations from a from a reference level $T - T0$:

$$\frac{dH}{dt} \sim a(T - T0) \quad (1)$$

The coefficient a is estimated from the observational record of the past 120 years (1880-2000) by ordinary least squares. Once estimated, the statistical model (1) can be applied to any projection of future global temperature change simulated by a climate model, and assuming that the linear relationship would still hold in the future, an estimation of global mean sea-level rise can be obtained. The justification for the conceptual model (1) is based on the argument according to which sea-level in a stationary state, after forced by a sudden temperature change, will adjust exponentially to a new stationary state (see Fig 1 in Rahmstorf 2007). This adjustment would follow a decay-type function $g(t - t_0)$ with a typical timescale of the order of several hundred years, reflecting the time required by a heat pulse to reach the deeper ocean layers and the time needed by land-ice to melt. The initial rate of the sea-level adjustment $\frac{dg}{dt}$ would be proportional to the magnitude of the sudden temperature change, from which the the linear relationship between T and rate of sea-level rise follows. The semi-empirical method embodied in R07 has been subject to some criticism on statistical grounds(Schmith et al., 2007). One important caveat is the non-stationary, or near non-stationary, character of the timeseries of global mean near-surface temperature and global mean sea-level. Clear trends are obviously present in both timeseries, which jeopardize the application of standard methods for the estimation of the regression parameter a based on ordinary least-squares. When the input data used to estimate a linear relationship can be represented by auto-regressive processes with a high degree of autocorrelation or even are the outcome of non-stationary (so called integrated) processes, other methods such as co-integration analysis have to be applied to ascertain whether a linear relationship exists and, in that case, to estimate the regression parameter (see e.g. Kaufmann and Stern, 2002 for the application of co-integration analysis in a climate research context). Otherwise the estimation of the parameter a might be biased and therefore not applicable to periods outside the period used to calibrate the statistical model.

From the physical point of view, the statistical model (1) may not appear completely straightforward. Global mean temperature does not change stepwise from one stationary state to another, but follows a continuous and smooth evolution T(t). Still in the framework of R07, rather than being caused by the instantaneous deviations of the global mean temperature, global sea-level at a certain time t will be more accurately described by the mathematical convolution of the two functions: the temperature at all times previous to time t T(t'-Δt) and the corresponding adjustment function g(Δt). Also, ignoring for the moment the non-linear dependence of the thermal expansion of sea-water with water temperature, the contribution of the thermal expansion to the rate of sea-level change $\frac{dH_{te}}{dt}$ would not be directly linearly related to the water temperature - and therefore not to the near-surface air-temperature either- but to the global mean heat-flux into the ocean F:

$$\frac{dH_{te}}{dt} \sim F \quad (2)$$

Equation (2) should hold exactly, without any time lag, if the thermal expansion of seawater were independent of temperature. For model (1) to hold , at least approximately, a linear relationship between the heat flux F and the near-surface air-temperature should exist, which does not seem directly obvious in view of the complexity of the ocean processes that modulate the heat-uptake by the ocean.

Other plausible model for the thermal expansion component of sea-level would be simply to assume a proportionality between deviations of the global mean sea-level and deviations of the global mean near-surface temperature. This would stem from (2) by assuming that the latter is a proxy for the 3-dimensional average of ocean temperature:

$$H_{te} \sim T \tag{3}$$

From this statistical model, a relationship between the rates of change of global mean sea-level and of near-surface temperature can be also proposed:

$$\frac{dH_{te}}{dt} \sim \frac{dT}{dt} \tag{4}$$

It is not easy to test which one of these statistical models may be more valid in the real world. Timeseries of estimations of global sea-level based on satellite measurements start only in 1993 (Cazenave and Nerem, 2004) and the estimations of global mean sea-level based on tide-gauges are burdened by the relatively sparse sampling in the first half of the 20th century. An alternative strategy is to test these statistical models in the virtual reality produced by simulations with global climate models. In these virtual, physically consistent, realities all data are known perfectly and the complete chain of reasoning leading to a semi-empirical estimation of sea-level rise - i. e. calibration of the statistical model in an pseudo-observational period, application to future climate-change scenario projections and comparison with the simulated sea-level - can be emulated and the skill of the statistical model evaluated. This test is, of course, too optimistic, since in the real world the temperature and sea-level data are affected by sampling and measuring uncertainties which are absent in the model data. Rahmstorf (2007) tested the statistical model (1) with data from a climate simulations with the model of intermediate complexity CLIMBER (Montoya et al., 2005) in the period 1880-2100 under the SRES emission scenario A1F1 (Meehl et al., 2007). The model CLIMBER does not represent the contribution of land-ice melting, so that only the statistical relationships between the thermal expansion component and the global mean temperature could be tested. The statistical model (1) delivered reasonable estimations of global mean sea-level until about 2070, producing an overestimation of the global sea-level from there onwards. In year 2100 the semi-empirically estimated global-sea level rise was about 30% higher that the sea-level rise actually simulated by CLIMBER.

3 Climate model and simulation

This study analyses a simulation with the coupled atmosphere-ocean General Circulation Model ECHO-G, consisting of the atmospheric model ECHAM4 (horizontal resolution approx. $3.75\ ^\circ \times 3.75^\circ$) and the oceanic component HOPE-G (Legutke and Voss, 1999). The ocean model has a horizontal resolution of $2.8^\circ \times 2.8^\circ$ with a increasingly finer resolution in the tropical regions towards the equator, where it is $0.5^\circ \times 0.5^\circ$. The ocean model has 19 levels in the vertical. A version of the ECHO-G model, slightly modified to include the effect of anthropogenic aerosols in the 20th century, has been included in the simulations for the Fourth Assessment Report of the IPCC (Meehl et al., 2007). The simulation analysed here covers the period 1000-1990 and was driven by the estimations of past external forcing until 1990 (solar variations, greenhouse trace-gas concentrations and volcanic activity). No anthropogenic aerosols or ozone changes were considered (González-Rouco et al., 2006). The external forcings were derived from the values provided by Crowley (2000). The variations in solar irradiance, implemented in the simulation as a single annual value independent of spectral band, were estimated from concentrations of ^{10}Be in ice-cores and re-scaled to units of watts/m^2 so that the difference in solar irradiance between the mean of 1960-1990 and that of 1680-1710 (the Late Maunder Minimum) was 0.3 %. The volcanic forcing was taken also from the estimations provided by Crowley (2000) and translated to an annual and global (season and latitude independent) effective changes in the solar constant in the simulation. The concentrations of CO_2 and CH_4, to drive the model were taken from ice-core-based estimations (Etheridge et al., 1996; Etheridge et al., 1998). The simulation used here is not the one presented in previous papers, e.g. (von Storch et al., 2004). This former simulation may present some initial drift in the first 2-3 centuries due to initial conditions extracted from a present-day control run that could have been possibly too warm and not in equilibriums with the external forcing in year 1000 (Osborn et al, 2006). The present simulation was started from the initial conditions extracted from year 1700 AD. in the previous simulation (von Storch et., 2004).

4 Model sea-level data

The model ECHO-G does not represent changes in the volume of land-ice or polar ice caps. Therefore, long-term changes in global mean sea-level are very approximately due to changes in the density of the water column, ignoring possible storage of water in the atmosphere. The density of the water column was computed from the simulated in-situ modelled temperature and salinity according to the standard UNESCO formula for sea-water (Fofonoff and Millard, 1983). The resulting 2-dimensional sea-level field was globally averaged taking into account the diminishing size with latitude of the model grid cells. The statistical model used by Rahmstorf (2007) (equation 1 here) uses estimated non-linear trends of the global mean sea-level and global mean temperature. These trends were calculated in R07 by the application of Singular Spectrum Analysis (Allen and Smith 1996), a statistical technique related to Principal Components Analysis, with an embedding dimension of 15 years. The output of Singular Spectrum Analysis is a smoothed version of the original timeseries, whereby the filter characteristics are derived from the input data. The same method, with the same embedding dimension, was applied here to the ECHO-G data.

5 Results

The non-linear trends of the model global mean thermosteric sea-level and global mean temperature are displayed in Figure 1a. In the following, model sea-level will refer only to the thermosteric component, as explained in the previous section.

Both series show maximum values at the beginning and at the end of the simulation, which straddle three centuries - roughly between 1500 and 1800- when both global means of temperature and sea-level were lower than the long-term average. The simulation of the global mean temperature agrees well with other simulation of the same period with the Climate System Model CSM (Zorita et al., 2007). No other published data of modelled global mean sea-level can be used to compare with the ECHO-G results. However, the simulated evolution of global ocean heat content is quite similar

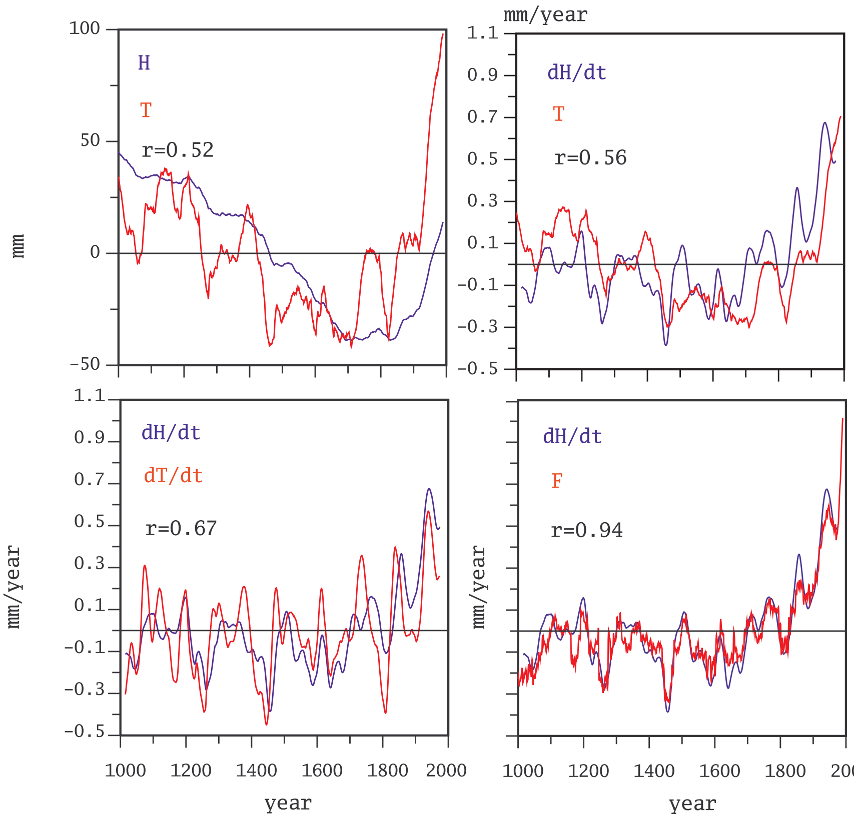

Fig. 1 Time series derived from the simulation with the model ECHO-G in the past millennium related to global mean near-surface temperature T and global mean thermosteric sea-level H_{te}, total heat-flux into the ocean F and the time derivatives of T_{te} and H. The predictands H and $\frac{dH}{dt}$ are shown with their physical units as simulated by the model ECHO-G, the other predictor variables are rescaled to have the same variance as the corresponding predictand.

to the one obtained by Crowley (2003) in a simulation with an energy-balance model. (Fig 2). The global mean-sea level simulated by ECHO-G shows an increase in the last 200 years of the simulation of about 70 mm and a linear trend in the period 1955-1995 of 0.42 ± 0.06 mm/year, which agrees quite well with estimation of the observed thermosteric contribution to global sea-level rise in the same period (0.40± 0.09 mm/year, Antonov et al., 2005).

Figure 1 additionally shows paired time series from the ECHO-G simulation that form the basis of the linear statistical models presented in the previous section. The skill of each model along the whole simulation is assessed by the correlation between the respective predictor and predictand timeseries, indicated also within each of the panels in figure 1. As expected on physical reasoning the best match is found between the ocean heat-flux and the rate of sea-level change (r=0.94). The match is not perfect because of the non-linear dependence of the thermal expansion coefficient of seawater with temperature. Also, there exists no time lag between both variables. Next in terms of skill is the statistical relationship between the rate of change of temperature and

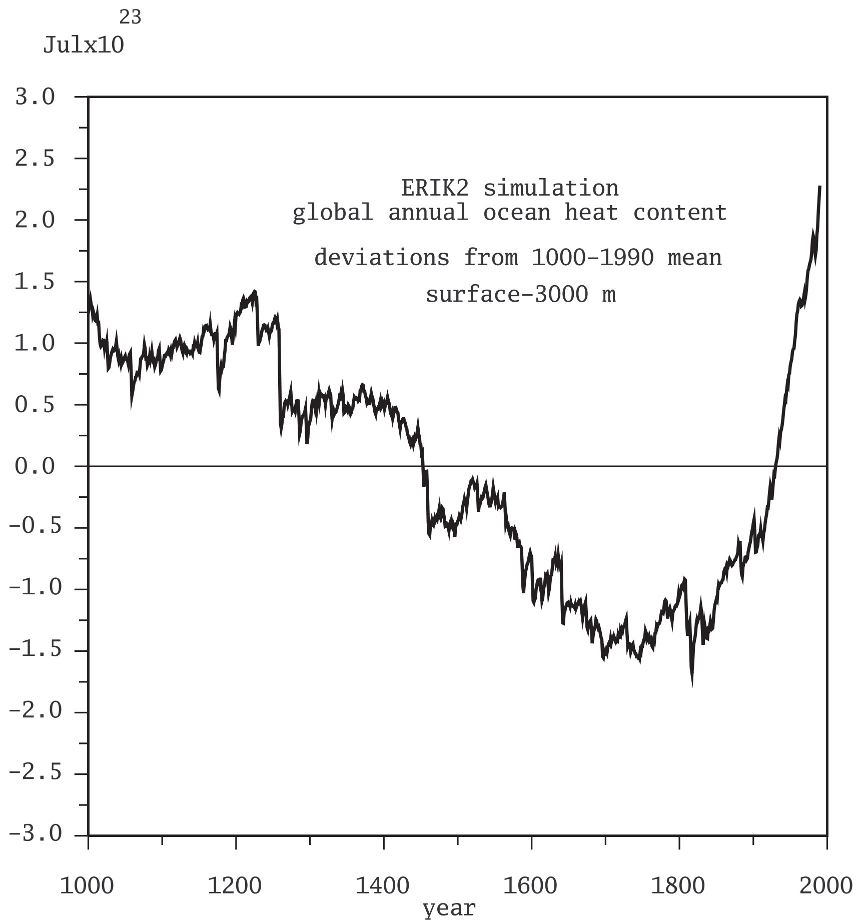

Fig. 2 Simulated evolution of the ocean heat content in the ECHO-G simulation in the past millennium. This figure should be compared with that simulated with an energy balance model (Crowley et al., 2003; their figure 3). The sharp drops in heat content around 1260 and 1820 are caused be the large volcanic eruptions.

the rate of change of sea-level (r=0.67). This illustrates probably that the the ocean-heat flux is more closely connected to the rate of change of near-surface air temperature than to the temperature deviations themselves. This can be also expected from physical reasoning. The third statistical model in terms of skill is the one using global mean air temperature as predictor and the rate of sea-level change as predictand (r=0.56). This is the model proposed by Rahmstorf (2007). Both time series agree on multicentennial timescales, but they show discrepancies at centennial and multidecadal timescales. This can be problematic because in practice the statistical model (1) is calibrated with observational data in the observational period at these timescales. Thus, the apparent agreement in a short calibration period may not be stable in time. This will be investigated further in the following sections. Lastly, the worst statistical model is the one based on global mean temperature as predictor and global mean sea-level as predictand (r=0.52). It is noteworthy that, as all series are highly autocorrelated, a test for significance for these correlations is not straightforward. The lag-1 autocorrelation for all these series is close to 0.99. Taking as null-hypothesis that the timeseries are the result of an autoregressive process of order 1 with a 1-lag autocorrelation of 0.99, the 95% significance level estimated by Monte Carlo realizations is 0.46.

The practical application of the statistical model embodied in the R07 model (equation 1), will be now analysed in more detail. The process of estimating the regression parameter a will be emulated in the virtual reality of the ECHO-G simulation, recalling that in the model only the thermosteric contribution is represented. As the simulation ends in year 1990, the pseudo-observational period for calibration is 1880-1990, instead of 1880-2000 as in the real observations. In the period 1880-1990 the least-mean-square error estimation of a yields a value of 0.57 mm/year per Kelvin, that amounts to about one third of the value estimated by Rahmstorf (2007) in the simulation with the CLIMBER model (also considering only the thermosteric contribution). The estimation of the uncertainty bounds for this central value of a is not straightforward, as both timeseries, predictor and predictand are strongly autocorrelated (lag-1 autocorrelation of 0.99 for both). The residuals of the regression also display a high degree of positive autocorrelation with a very low Durbin-Watson statistic of 0.002. This indicates that the conditions to apply a standard least-square-error estimator of the regression coefficients are not fulfilled and that probably the linear model (1) linking both variables is not correct.

As mentioned in the introduction, it seems plausible that a potential relationship between global mean temperature and the rate of change of global mean sea-level could be lagged in time. This aspect can be also easily tested in the ECHO-G simulation, as shown in Figure 3, by inspecting the lag-correlation function between these two variables. The correlation attains its maximum value when the global mean temperature is leading by about 25 years, which seems reasonable from a physical point of view. The observational timeseries would be too short to test whether this lag is realistic, but it would be an interesting parameter to compare in other long climate simulations, once they become available.

The question arises as to whether the estimation of the regression parameter in model (1) is stable in time. The value of the regression parameter a has been estimated in running segments of 120 years length along the simulations. The resulting timeseries together with its histogram are displayed in figure 4. The possible values for the regression parameter cover a wide range and they even show non-negligible probability of being negative.

6 Conclusions

Several simple linear models linking global mean sea-level, global mean temperature, their rate of change and the heat-flux into the ocean have been tested in a long simulation of the past millennium with the climate model ECHO-G. These relationships could be potentially used to estimate semi-empirically the future sea-level change based on the temperature changes simulated by climate models driven by different scenarios of emissions of greenhouse gases. This type of tests performed in the virtual reality produced by climate models cannot prove whether a certain hypothesis, in this case the different statistical relationships, hold in the real world as well, but they can falsify

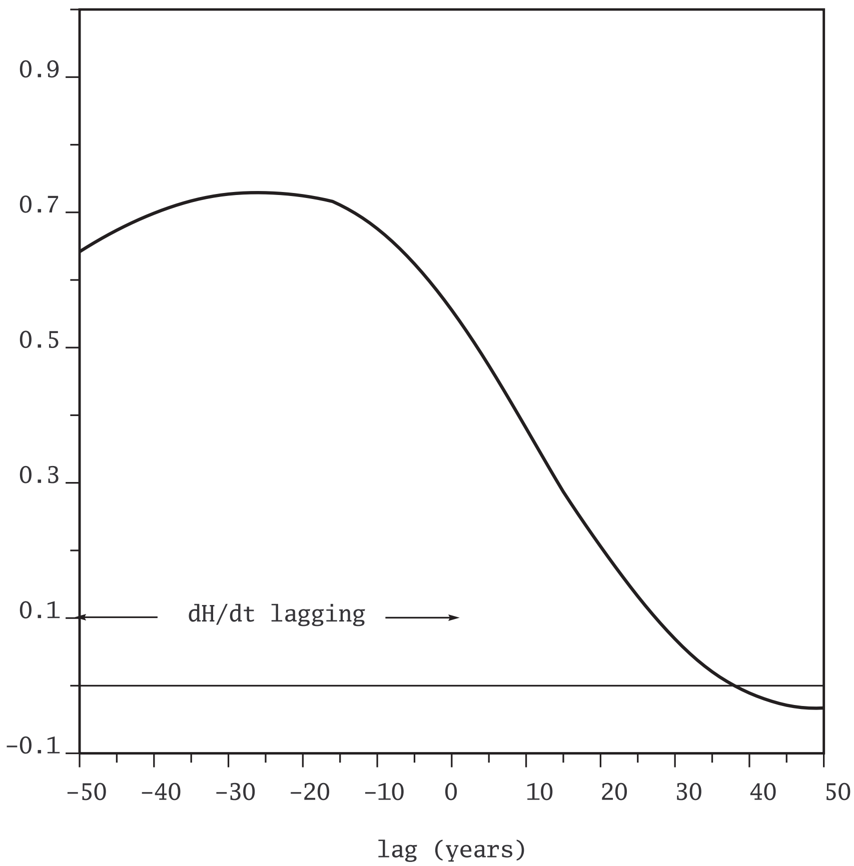

Fig. 3 Lag-correlation function between global mean near-surface air temperature and rate-of-change of global mean sea-level in the millennium simulation with the model ECHO-G

a particular hypothesis: if it is not fulfilled in a simple virtual reality, it will probably also fail in a more complex real world.

The sea-level simulated by the model ECHO-G, for instance, only contains the contribution of the thermal expansion of the water column, and disregards other contributions that are present in the real world as the melting of land ice. However, it seems plausible to assume that the existence of several and unrelated physical processes that link temperature and sea-level would hinder their description by a simple statistical linear model. In this sense, the conditions provided by the climate model to test any statistical relationship will be too optimistic.

Even in these conditions, it has been found that the best statistical model of the four explored here is the one that uses the ocean heat-flux as predictor. Unfortunately, the ocean heat-flux is a variable that is difficult to estimate in the real world, and of which long timeseries simply do not exist. Therefore, this close relationship is not useful to estimate semi-empirically future sea-level changes. Other purported linear link (Rahmstorf, 2007) between global mean temperature and the rate of change of global

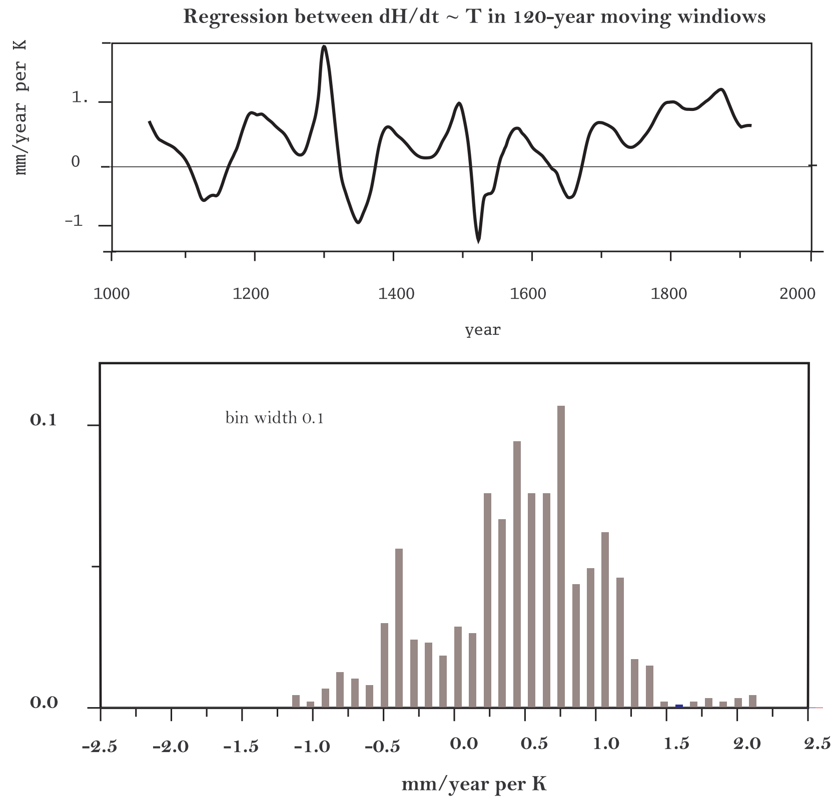

Fig. 4 Upper panel: regression coefficient between global mean near-surface air temperature and global mean sea-level rate of change (thermoesteric component) in gliding windows of 120 years in the ECHO-G simulation of the past millennium. Lower panel: histogram.

mean sea-level has turned to be not reliable in the context of this climate simulation. Nevertheless, it could represent a starting point to explore other variables that could show more potential as predictors for mean sea-level, for instance the rate of change of mean temperature. Due to the limited length of the observational record, and the strong linear trends of all these variables in the observational period, it seems however compulsory to submit any simple statistical model to a careful test with simulated data, ideally stemming from long climate simulations performed with several different models.

Acknowledgements F. G-R was partially funded by the Spanish Ministerio de Educación y Ciencia through grant REN-2002-04584-CLI.

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