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A simple, physically motivated model of sea-level contributions from the Greenland ice sheet in response to temperature changes

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A B S T R A C T

Sea level could rise by several meters over the next centuries. The Greenland ice sheet could be an important contributor to future sea-level rise, because of its large volume and its high sensitivity to surface air temperature increases. Frameworks for the integrated climate risk management often require fast, simplified treatments of sea-level rise, in particular for estimating the risks associated with low probabilities but potentially high impacts. State-of-the-art ice sheet models provide important insights, but are often computationally too demanding to evaluate tail-area risks. Here we present SIMPLE, a physically motivated model of the Greenland ice sheet in response to temperature changes. SIMPLE can skillfully reproduce the results from a three-dimensional ice sheet model and outperforms existing simple models, after similar calibration. We anticipate that SIMPLE will be calibrated to other ice sheet models and can provide a fast approximation (emulator) for such models in studies that require many model evaluations.

1. Introduction

The response of the Greenland ice sheet (GIS) to anthropogenic climate change is an important, but deeply uncertain factor determining future sea-level change (Meehl et al., 2007; Church et al., 2013; Moore et al., 2013, 2010; Applegate and Keller, 2015). Total melting of the GIS would lead to an increase in global mean sea level of approximately 7.4 m (Bamber et al., 2013). The time needed for complete melting of the GIS is, however, deeply uncertain. The lowest published estimate of the time required for total loss of the GIS is 300 yr (Lenton et al., 2008), but most likely this time scale strongly depends on the magnitude of the temperature forcing (Applegate et al., 2015; Robinson et al., 2012). Some have argued that geo-engineering can help the ice sheets to regrow (Moore et al., 2010; Irvine et al., 2012). Yet, regrowth of the GIS may be considerably slower than the melting (Applegate et al., 2015; Applegate and Keller, 2015). Anticipating future sea-level rise requires a careful consideration of the relevant sources of uncertainty (e.g. Lempert et al., 2012).

Many applications require fast treatments of sea-level rise, including Integrated Assessment Models (IAMs; e.g. Nordhaus, 2008) and decision support frameworks such as (Many Objective) Robust Decision Making (RDM, MORDM; Lempert et al., 2003; Hall et al., 2012; Hadka et al., 2015). IAMs represent the coupled economic-climate system, which could be strongly affected by sea-level rise (e.g. Yohe and Schlesinger, 1998). RDM identifies decisions that produce good outcomes over a wide range of potential futures. Integrated assessments of the risks and strategies associated with climate change and sea-level rise often require many (10^3–10^6) model runs (e.g. McInerney et al., 2011; Lempert et al., 2012), although integrated assessment can also refer to a more adaptive process actively involving stakeholders (Jakeman and Letcher, 2003).

The integrated assessments of local risks and adaptation strategies require treatments that resolve the different components of sea-level rise separately (Slangen et al., 2012), because the individual components may have quite different time scales. For example, small glaciers respond to temperature increases with a characteristic time scale of decades (Oerlemans, 2005), whereas the Greenland ice sheet has a time scale that can vary over two orders of magnitude depending on the forcing temperature (Applegate et al., 2015). Moreover, the different components of sea-level rise have very different ‘fingerprints’ (distinct spatial patterns of the response; see Mitrovica et al., 2011). In particular, large mass losses from an ice sheet cause near field sea-level fall (e.g. Vermeersen and Sabadini, 1999; Mitrovica et al., 2009), even though the global mean sea level rises.

Three-dimensional models of the Greenland ice sheet capture

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many of the relevant feedbacks in the ice sheet system, but can often be too computationally expensive to include in integrated assessments. Ice sheet models track the change in mass of the ice sheet during each time step as a function of mass gain due to snowfall and mass loss due to melting and calving. The treatments of ice flow used in ice sheet models fall along a continuum (Kirchner et al., 2011) from the shallow ice approximation (e.g. SICOPOLIS Greve, 1997) to full-Stokes treatments (e.g. Elmer/Ice; Seddik et al., 2012), with hybrid models (e.g. Pollard and DeConto, 2012) falling in between. Full-Stokes models include all the stress components acting within the ice body, but have high computational costs, and their projections still include uncertainties due to imperfectly-known model input parameters, processes, and boundary conditions (Moore et al., 2013; Applegate et al., 2015).

The high number of runs required for the integrated assessment of climate risks is typically computationally infeasible using the state-of-the-art three-dimensional ice sheet models. And, even with simpler one-dimensional models (e.g. GLISTEN, Haqq-Misra et al. (2012)) this task may prove too computationally demanding (Fig. 1). In response, there is an active area of research that develops simpler, faster approximations of the complex systems (e.g. Oerlemans, 2003). Other approaches to reduce the computational burden include the reduction of the climatological input (e.g. Bakker et al., 2011) or the strategic subsetting of the relevant scenarios (e.g. Ntegeka et al., 2014; van den Hurk et al., 2014).

Simplified treatments of the Greenland ice sheet include emulators (simple models of complex model output) of simulations with the state-of-the-art ice-sheet models. For example, Meehl et al. (2007; see also Irvine et al. (2012)). emulated the rate of mass loss from the GIS as a second-order polynomial function of temperature, whereas Bindschadler et al. (2013) used a linear combination of different forcings. These approaches are useful for interpolating the results from complex model simulations. They neglect, however, the dependence of the change rate to ice volume and are therefore less suited to project large changes.

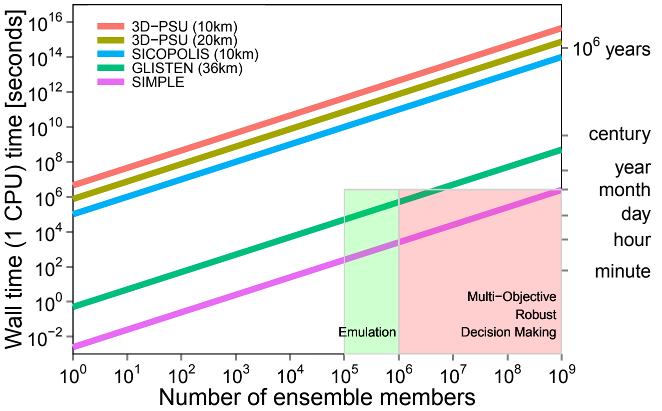

Fig. 1. Approximate estimates of the computing time required for various numbers of model runs using a hierarchy of models (colored lines), assuming that only one processor is available to perform the calculations. Computing times for 125,000-yr simulations are shown because ice sheet models must be 'spun up' over at least this much time for every unique parameter combination (Rogozhina et al., 2011; Applegate et al., 2012; Haqq-Misra et al., 2012). The colored boxes mark the zones that achieve the minimum number of simulations required for Integrated Assessment studies (>10^5, green; e.g McInerney et al. (2011)) and for Multi-Objective Robust Decision Making (MORDM) (>10^6, red; Kasprzyk et al. (2013); Singh et al. (2015)) within a computation time of one month. Three-dimensional ice sheet models such as the PSU-3D ice sheet model (Pollard and DeConto, 2012), which includes 'hybrid' ice dynamics, and SICOPOLIS (Greve, 1997), which is a Shallow-Ice Approximation model, are clearly too computationally expensive to achieve these numbers of simulations in a reasonable time. One-dimensional models such as GLISTEN (Haqq-Misra et al., 2012) may be more appropriate for IAM studies from a computational perspective; however, SIMPLE, which we describe here, is about two orders of magnitude faster than GLISTEN. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Semi-empirical models may be better suited to guide a probabilistic assessment of potential large changes. Semi-empirical models are simple, but mechanistically motivated models of which the complexity is balanced to the availability of observational data to calibrate the model (Moore et al., 2013, e.g.). Recently, Applegate et al. (2015) proposed a semi-empirical model that addresses both the ice sheet's potential sensitivity to ice volume changes and to temperature. The model expands on the delayed linear concept (e.g. used for global sea-level projections by Grinsted et al., 2010), in which the ice volume V [m sle (meter sea-level equivalent)] is assumed to change exponentially towards a temperature-dependent equilibrium volume $V_{eq} = f(T)$ with a temperature-dependent timescale $\tau = g(T)$. A similar concept has been applied in the latest versions of the Integrated Assessment Models DICE and RICE (Dynamic/Regional Integrated model of Climate and the Economy) (Nordhaus, 2010; Nordhaus and Sztorc, 2013).

Here, we introduce a computationally efficient, physically motivated model SIMPLE (Simple Ice-sheet Model for Projecting Large Ensembles). SIMPLE can provide quite fast and arguably skillful emulations of the GIS response as simulated by the shallow ice approximation, three-dimensional ice sheet model SICOPOLIS for a wide range of warming and cooling temperature scenarios (Greenland surface temperatures T between 0 and 12 °C relative to 1976–2005; Applegate and Keller, 2015), while its computational efficiency enables large ensembles (>10^7) within reasonable time, even on a single computer core.

SIMPLE expands on the work of Applegate et al. (2015) and Nordhaus (2010). Rather than an exponential decay towards an equilibrium volume (≥ 0 m sle), SIMPLE assumes that *initially* the ice mass will exponentially decay towards a 'virtual equilibrium' $V_{v.eq}$ that may be lower than zero for high temperatures. The difference between the current volume and 'virtual equilibrium' ($\Delta V_{v.eq} = V - V_{v.eq}$) is interpreted as a measure for the 'imbalance' of the ice sheet that is roughly determined by snow accumulation, melt water runoff and dynamic ice flow. This concept allows the 'imbalance' that drives the ice volume change $\dot{V}$, to increase with temperature, even for temperatures that will (eventually) lead to an ice-free state $V_{eq} \approx 0$.

Section 2 introduces SIMPLE and the GIS simulations used for its development. Subsequently, we assess and compare SIMPLE to other simple representations of the GIS behavior in Section 3. Section 4 discusses SIMPLE.

2. Methods and data

2.1. The SIMPLE model

SIMPLE estimates the ice volume change $\dot{V}$ [m sle/yr] from the volume V [m sle] and annual mean surface temperature at Greenland T [°C] relative to 1976–2005 by applying an exponential decay function

$$\dot{V} = -\frac{1}{\tau}\left(\Delta V_{v.eq}\right). \tag{1}$$

Here, the difference between the ice volume and 'virtual equilibrium' $\Delta V_{v.eq} = V - V_{v.eq}$ parameterizes the imbalance between mass gain due to accumulation and mass loss due to melting and calving. We refer to 'virtual' equilibrium because this measure may be lower than zero for high values (see Fig. 2). We assume that *initially* the ice mass will exponentially decay towards $V_{v.eq}$ (dashed, red line), but for low ice volumes close to zero this relation is obviously not valid.

Both the timescale τ [yr] and the 'virtual equilibrium' $V_{v.eq}$ are linear functions of temperature T,