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Invited review

Current state and future perspectives on coupled ice-sheet – sea-level modelling

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A B S T R A C T

The interaction between ice-sheet growth and retreat and sea-level change has been an established field of research for many years. However, recent advances in numerical modelling have shed new light on the precise interaction of marine ice sheets with the change in near-field sea level, and the related stability of the grounding line position. Studies using fully coupled ice-sheet – sea-level models have shown that accounting for gravitationally self-consistent sea-level change will act to slow down the retreat and advance of marine ice-sheet grounding lines. Moreover, by simultaneously solving the 'sea-level equation' and modelling ice-sheet flow, coupled models provide a global field of relative sea-level change that is consistent with dynamic changes in ice-sheet extent. In this paper we present an overview of recent advances, possible caveats, methodologies and challenges involved in coupled ice-sheet – sea-level modelling. We conclude by presenting a first-order comparison between a suite of relative sea-level data and output from a coupled ice-sheet – sea-level model.

1. Introduction

Global sea-level records, particularly those dating from the Quaternary glacial cycles, provide crucial insight into past ice-sheet change. Interpreting the complex relationship between spatially-variable sea-level change and the growth and decay of the major ice sheets forms the basis of the field of Glacial Isostatic Adjustment (GIA). Traditionally, GIA models have been used to understand the impact of ice-sheet change on global sea level. This study describes recent efforts to understand feedbacks in the opposite direction, namely, the impact of spatially-variable sea-level change on ice-sheet dynamics. Theories relating to the gravitational attraction between the ice sheets and the ocean were first proposed in the late 19th century (e.g. Woodward, 1888, and reference therein), but it was only in the 1970s that gravitational effects began to be accounted for in calculations of global sea-level. Woodward (1888) had demonstrated that the gravitational potential at the outer surface of the Earth would be perturbed due to a change in mass at a point. However, in order to accurately determine the details of the perturbation, and hence calculate how meltwater would be distributed across the ocean, this also required the establishment of viscoelastic Green functions for the radial displacement of the solid Earth (Peltier, 1974) and the perturbation of the gravitational potential (Peltier and Andrews, 1976). This theory was then applied to the problem of global sea-level change by Farrell and Clark (1976), who additionally accounted for mass conservation during the transition from continental loading by ice sheets to meltwater redistribution throughout the ocean.

These studies from the 1970s provided the first statement of the sea-level equation (SLE), which forms the basis of all contemporary GIA models, and accounts for the gravitational attraction of ice sheets on the ocean, as well as the deformation of the Earth due to changes in ice loading and the redistribution of ocean water. From the 1980s to the early 2000s a number of improvements were made to the theory originally laid out by Clark et al. (1978), with the result that GIA models now typically also account for rotational feedback effects and shoreline migration, as well as the inundation of ocean water into regions previously

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covered by marine-grounded ice (e.g. Wu and Peltier, 1984; Peltier, 1994; Kendall et al., 2005).

The SLE is typically solved using the 'pseudo-spectral' approach (e.g. Mitrovica and Peltier, 1991; Mitrovica et al., 1994) for a 1-D spherically symmetric Earth. Calculations are carried out using a particular maximum spherical harmonic degree (e.g. 128, 256 or 512), which defines the spatial resolution of the solution to the SLE. After iteratively solving the SLE, the solution is given by:

$$\Delta S = \Delta N - \Delta U. \quad (1)$$

Here ΔS is relative sea-level (RSL) change, given as the difference between the change in sea-surface height, ΔN, and the deformation of the Earth ΔU. The shape of the sea surface is defined by the shape of the gravitational equipotential surface, or geoid. The deformation of the Earth is usually determined by considering a radially-symmetric Earth model. In addition to defining an Earth model, the history of global ice loading must also be prescribed in order to solve the SLE. Most well-known and widely-used within the field of GIA are the ICE-NG global ice-sheet reconstructions, e.g. ICE-3G (Tushingham and Peltier, 1992), ICE-5G (Peltier, 2004) and more recently ICE-6G_C (Peltier et al., 2015). These global reconstructions were derived via the comparison of GIA model output with a global suite of field data, including RSL data.

A similar data-driven approach has been used to constrain or tune regional ice-sheet reconstructions, e.g. for Fennoscandia (Lambeck et al., 1998), the British Isles (Bradley et al., 2011), Arctic Canada (Simon et al., 2015) and Antarctica (Ivins and James, 2005; Ivins et al., 2013), while some studies have additionally made use of a numerical (3-D) ice-sheet model to determine glaciologically-consistent, climatically-forced changes to the Greenland (Tarasov and Peltier, 2002; Simpson et al., 2009; Lecavalier et al., 2014), North American (Tarasov and Peltier, 2004; Tarasov et al., 2012) and Antarctic (Whitehouse et al., 2012a, b; Briggs et al., 2013) ice sheets.

Solutions to the SLE describe the gravitationally self-consistent change in RSL that would arise due to forcing by the prescribed ice-sheet history. Fig. 1 illustrates in a schematic way how a change in ice-sheet volume will affect RSL. In the absence of self-gravitational effects and solid Earth deformation, a change in ice-sheet volume would result in a uniform change in sea level (Fig. 1b). However, including self-gravitation and solid Earth deformation means that the change in RSL over the globe is non-uniform. For a decrease in ice volume, RSL will fall close to the ice sheet but rise by an amount greater than the global mean at far-field sites (Fig. 1c). As an example, when the ice-sheet is described as a point source, a fall in RSL will be seen up to ~ 2200 km from the ice sheet, and a rise by an amount greater than the mean will be seen at sites more than ~ 6700 km from the ice sheet (e.g. Vermeersen and Sabadini, 1999). This spatial variability in the sea-level response can be used to infer the pattern of past ice-sheet change (e.g. Clark et al., 1978; Peltier, 2004).

Alongside studies that use sea-level records to determine past ice sheet change, the ice-sheet modelling community has also sought to reconstruct changes in global ice volume. Early studies used vertically-averaged models (Oerlemans, 1982; Pollard, 1982), but since the 1990s more sophisticated models have been used to reconstruct changes to specific ice sheets (e.g. Huybrechts, 1990; Deblonde et al., 1992; Ritz et al., 1997; Tarasov and Peltier, 1999; Van de Wal, 1999; Huybrechts, 2002; Tarasov and Peltier, 2003; DeConto and Pollard, 2003; Zweck and Huybrechts, 2005; Philippon et al., 2006; Pollard and DeConto, 2009; Bintanja and Van de Wal, 2008; De Boer et al., 2013; Stuhne and Peltier, 2015). All models referred to above use an approximation of the full Stokes equation of ice flow. Most notably, the shallow ice approximation

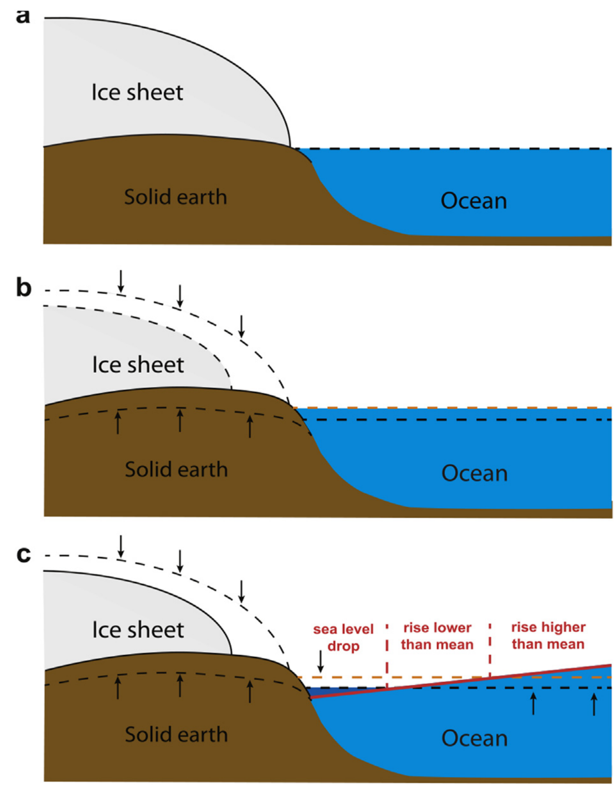

Fig. 1. A schematic representation of the gravitational interaction between ice sheets, the solid Earth and the ocean. a) The initial state of the system: For illustrative purposes we take the initial sea surface to be horizontal. b) A decrease in ice-sheet mass will result in rebound of the solid Earth beneath the ice sheet and an increase in ocean volume. In (b) we show the change in sea level as uniform, but in reality due to self-gravitation effects the sea surface will fall in close proximity to the ice sheet, it will rise by an amount less than the mean at mid-field locations, and it will rise by an amount greater than the mean at far-field locations. The initial sea surface from panel (a) is illustrated in (b) and (c) by the horizontal dashed black line. The horizontal dashed orange line in (b) and (c) represents the sea surface following ice mass loss in the absence of self-gravitation from panel (b). The dark blue area indicates the region of sea-level fall, and the solid red line represents the actual sea surface.

(SIA), which only considers shear stresses, is assumed to govern the flow of grounded ice (Hutter, 1983), while the shallow shelf approximation (SSA), which only considers longitudinal stresses, is assumed to govern the flow of floating ice shelves (Morland, 1987). Although these approximations reduce the computational cost of running an ice-sheet model for long-term paleoclimate simulations, it has been shown that more sophisticated physics are needed to accurately represent grounding-line migration (e.g. Bueler and Brown, 2009; Larour et al., 2012; Cornford et al., 2013), or to reproduce observed lateral gradients in ice velocity (Rignot et al., 2011).

In recent years several studies have emerged that include additional physical mechanisms aimed at improving model representations of grounding-line migration (e.g. Schoof, 2007; Bueler and Brown, 2009; Gladstone et al., 2010; Pollard and DeConto, 2012; Seroussi et al., 2014; Feldmann et al., 2014). When comparing output from these models it is clear that results may diverge significantly for different grounding-line approximations, levels of model complexity, or horizontal resolution (Pattyn et al., 2013; Bindschadler et al., 2013; Pattyn and Durand, 2013; Feldmann et al., 2014). However, so far, uncertainty associated with the grounding-line response to sea-level forcing has not been quantified. Ice flux across the grounding line is strongly dependent