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Atmosphere-driven ice sheet mass loss paced by topography: Insights from modelling the south-western Scandinavian Ice Sheet

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ABSTRACT

Marine-terminating glaciers and ice streams are important controls of ice sheet mass balance. However, understanding of their long-term response to external forcing is limited by relatively short observational records of present-day glaciers and sparse geologic evidence for paleo-glaciers. Here we use a high-resolution ice sheet model with an accurate representation of grounding line dynamics to study the deglaciation of the marine-based south-western Norwegian sector of the Scandinavian Ice Sheet and its sensitivity to ocean and atmosphere forcing. We find that the regional response to a uniform climate change is highly dependent on the local bedrock topography, consistent with ice sheet reconstructions. Our simulations suggest that ocean warming is able to trigger initial retreat in several fjords, but is not sufficient to explain retreat everywhere. Widespread retreat requires additional ice thinning driven by surface melt. Once retreat is triggered, the underlying bedrock topography and fjord width control the rate and extent of retreat, while multi-millennial changes over the course of deglaciation are modulated by surface melt. We suggest that fjord geometry, ice-ocean interactions and grounding line dynamics are vital controls of decadal-to centennial scale ice sheet mass loss. However, we postulate that atmospheric changes are the most important drivers of widespread ice sheet demise, and will likely trump oceanic influence on future ice sheet mass loss and resulting sea level rise over centennial and longer time scales.

1. Introduction

Ice streams and marine-terminating glaciers are capable of rapidly discharging significant amounts of ice into the ocean. Their response to the current climate warming trend remains a major uncertainty in projections of future ice sheet mass loss and sea level rise (Nick et al., 2013; Nowicki et al., 2013; Ritz et al., 2015). Outlet glaciers and ice shelves in Greenland and Antarctica are retreating (e.g. Moon and Joughin, 2008; Murray et al., 2015), accelerating (Moon et al., 2012; Joughin et al., 2014), thinning (Pritchard et al., 2009; Paolo et al., 2015), and weakening (Borstad et al., 2013; Fürst et al., 2016). The bed topography of most major outlet glaciers remains below sea level far inland (Morlighem et al., 2014; Fretwell et al., 2013; An et al., 2017; Millan et al., 2017), making present day glaciers vulnerable to warm ocean waters as grounding lines retreat. Moreover, some beds deepen inland, a configuration associated with a potential marine ice sheet instability (e.g. Weertman, 1974; Feldmann and Levermann, 2015; Golledge et al., 2015). The latter conditions suggest that dynamic mass loss, once triggered, may continue largely decoupled from future changes to external forcing and associated efforts to decrease anthropogenic emissions. For marine margins buttressed by ice shelves, or for glaciers terminating in fjords, it is uncertain to what extent such accelerated mass loss will take place, given the additional support provided by ice shelves and trough walls (Schoof et al., 2017; Haseloff and Sergienko, 2018; Åkesson et al., 2018).

It is unclear for how long accelerated ice discharge can be sustained, and it is therefore crucial to assess the relative importance of the drivers of mass loss over centennial-to millennial-scales. A leading hypothesis explaining contemporary changes to marine terminating glaciers and ice shelves is the intrusion of warm subsurface waters reaching ice shelf drafts and glacier grounding lines (Holland et al., 2008; Straneo and Heimbach, 2013). However,

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reconstructions and model studies are inconclusive with regards to whether high surface melt or ocean-driven dynamic mass loss control long term ice sheet stability and sea level rise (Golledge et al., 2015; Stokes et al., 2016).

Another source of uncertainty is which glaciers are most vulnerable, and whether their responses are non-linear (Reyes et al., 2014; Dutton et al., 2015; Mengel and Levermann, 2014; Mengel et al., 2016). Both empirical ice sheet reconstructions (Mangerud et al., 2013, 2016; Stokes et al., 2014) and modern observations (Moon et al., 2012; Bartholomaus et al., 2016; Felikson et al., 2017) show that responses vary even within regions experiencing similar external forcings. This behaviour, apparently out-of-phase with contemporary climate, complicates interpretation of observations and excludes marine-terminating glaciers as past climate indicators without additional knowledge of site-specific controls.

Our ability to model past ice sheet change provides an important metric to evaluate the accuracy of numerical models used for future predictions. To test the accuracy of these models, geologic evidence can be used. However, sedimentary and geomorphologic data provide only mean rates of change, constrained by dating accuracy. Short-term variations may thus be masked out and interpretations hampered. For example, glacier moraines may be deposited several hundreds or thousand years apart. Cosmogenically dated erratics, though useful to map ice-free surfaces, have uncertainties in the centennial to millennial range (e.g. Briner et al., 2005). These types of evidence provide only snapshots in time. Sedimentary sequences, in contrast, are inherently continuous. Yet, their spatial coverage is sparse; to elucidate whether they represent a regional ice sheet margin or a local anomalous feature requires many samples and extensive field studies.

While certainly having limitations, numerical ice sheet models give a continuous and spatially complete picture, and can resolve ephemeral behaviour. Models can also help disentangle the extent to which external forcing or site-specific factors dominate glacier behaviour. Numerous large-scale, transient simulations of the deglaciation of past ice sheets have been carried out. Studies of the Antarctic (Golledge et al., 2012; Pollard et al., 2015), Greenland (Robinson et al., 2011; Applegate et al., 2012), British-Irish (Hubbard et al., 2009), Laurentide (Marshall et al., 2000; Tarasov et al., 2012), and Eurasian Ice Sheets (Arnold and Sharp, 2002; Kleman et al., 2002; Patton et al., 2017) have all improved our understanding of long-term ice sheet change. However, marine-terminating glaciers, distributed all around the coasts of Greenland, Norway, Svalbard, Patagonia, Alaska, and parts of Antarctica, are often too small to be resolved accurately in such coarsely resolved large-scale ice sheet models. This issue limits model accuracy and our understanding of past behaviour. Many paleo-ice sheet models rely solely on the computationally-efficient Shallow Ice Approximation (Hutter, 1983; Morland, 1984), which is unable to capture interactions between fast-flowing ice streams and the interior ice sheet.

One of the most important physical processes that needs to be correctly captured by models is grounding line dynamics (e.g. Schoof, 2007), for which accurate representation requires spatial scales of ~1 km or better (Vieli and Payne, 2005; Durand et al., 2011; Seroussi et al., 2014; Gagliardini et al., 2016). Currently, computational constraints prevent continental-scale, high-resolution, transient paleo-simulations, i.e. several thousand years and longer at a resolution of ~1 km. Most work to date has therefore been on (i) coarse spatial and long temporal scales; or (ii) fine spatial and short temporal scales.

Flowline models remain an exception, as they can finely track grounding line motion over long time scales. These models have been used to study Antarctic ice streams (Jamieson et al., 2012, 2014), Greenlandic outlet glaciers (Nick et al., 2009, 2013; Vieli and Nick, 2011; Lea et al., 2014; Steiger et al., 2018), as well as idealised glaciers (e.g. Vieli et al., 2001; Nick et al., 2010; Enderlin et al., 2013; Åkesson et al., 2018). While useful to better understand physical processes, including calving dynamics, flowline models are not suitable for complex geometries, nor can they capture interactions between neighbouring drainage basins. These models are also width-averaged by definition, which precludes accurate representation of across-flow topographic features such as local pinning points.

Here, we use an alternative approach to simulate the deglaciation of south-western Norway by applying a high resolution, regional ice sheet model to assess this area's sensitivity to ocean and atmospheric warming. We resolve individual fjords and their interactions, and provide a spatially complete, transient picture from 18 to 11 ka before present (BP). South-western Norway was the marine-based western Norwegian sector of the Scandinavian Ice Sheet and is exceptionally data-rich (e.g. Hughes et al., 2016; Mangerud et al., 2017), yet the ice sheet behaviour has not been studied in a detailed model framework before.

This paper is structured as follows. First, we briefly describe relevant ice sheet changes in south-western Norway over the modelled period 18–11 ka BP (Sect. 2). Details of the ice sheet model and implementation of atmosphere and ocean forcing are given in Sect. 3, followed by a description of experimental design and empirical constraints (Sect. 4). Our results are divided into sensitivity experiments to forcing from the ocean (Sect. 5.2) and the atmosphere (Sect. 5.3), as well as simulations of the deglaciation 18–11 ka BP (Sect. 5.4). We discuss the relative influence of the forcing (Sect. 6.1), topography (Sect. 6.2), as well as model limitations (Sect. 6.3), and finally highlight implications for past and future stability of ice sheets in Sect. 6.4.

2. Deglacial history of south-western Norway

During the Last Glacial Maximum (LGM) c. 21–20 ka BP, the Scandinavian Ice Sheet was connected with the British-Irish Ice Sheet (e.g. Hughes et al., 2016). Subsequently, the major Norwegian Channel Ice Stream was activated in the Norwegian Channel. This ice stream flowed northwards along the west coast of Norway before collapsing 19–18 ka BP (Svendsen et al., 2015; Sejrup et al., 2016). Here we do not model these early phases, instead we examine the triggers and drivers of deglaciation of south-western Norway over the period 18–11 ka BP. Once the Norwegian Channel Ice Stream collapsed, a new stable ice margin roughly parallel with the Norwegian coast was established (Mangerud et al., 2017) (see Fig. 1). Our simulations start from this period, when western Norway resembled present-day Greenland, with marine-terminating glaciers and deeply incised subglacial valleys draining the interior ice sheet (Morlighem et al., 2014, 2017).

Deglaciation of western Norway started around 18 ka BP with the southernmost offshore islands and coastal areas becoming ice-free first (Fig. 2). In contrast, coastal areas farther north remained ice-covered until 15 ka BP, during which time sea surface temperatures (SSTs) remained relatively stable in the Norwegian Sea (Eldevik et al., 2014; Dokken et al., 2015). Widespread retreat in western Norway only occurred after 15 ka BP. The paleoclimate record suggests an asynchronous retreat history across different outlet glaciers, despite similar changes to the maritime climate. Stratigraphic evidence from lakes and bogs, as well as cosmogenically dated erratics, suggest that retreat of the Boknafjorden outlet glacier and Jæren regions (Fig. 2) to the south commenced 17–16 ka (Briner et al., 2014; Svendsen et al., 2015; Lunnan, 2016; Johnsen, 2017; Gump et al., 2017). In contrast, Hardangerfjorden glacier,