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Invited review

Holocene evolution of the western Greenland Ice Sheet: Assessing geophysical ice-sheet models with geological reconstructions of ice-margin change

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ABSTRACT

Geophysical ice-sheet models are used to predict future ice-sheet dimensions and, in turn, these projections help estimate the magnitude of eustatic sea-level rise. Before models can confidently predict ice-sheet behavior, they must be validated by being able to duplicate the geological record of ice-sheet change. Here, we review geological records of Greenland Ice Sheet (GrIS) change, with emphasis on the warmer-than-present middle Holocene, and compare these records to published studies that numerically simulate GrIS behavior through the Holocene. Geological records are concentrated in West and Southwest Greenland, which are also the regions where the GrIS margin likely experienced the greatest distance of inland retreat during the middle Holocene. Several records spanning from Melville Bugt to Jakobshavn Isfjord in western Greenland indicate the GrIS achieved its minimum extent between ~5 and 3 ka, and farther south in the Kangerlussuaq region, new data presented here indicate the ice margin reached its minimum extent between ~4.2 and 1.8 ka. In the Narsarsuaq region in southern Greenland, the GrIS likely achieved its minimum configuration between ~7 and 4 ka. We highlight key similarities and discrepancies between these reconstructions and model results, and finally, we suggest that despite some degree of inland retreat, the West and Southwest GrIS margin remained relatively stable and close to its current position through the Holocene thermal maximum.

1. Introduction

The GrIS is the largest ice mass in the Northern Hemisphere with an estimated 7.36 m sea-level equivalent and is expected to be a key contributor to 21st century sea-level rise (Bamber et al., 2013). The recent Intergovernmental Panel on Climate Change Fifth Assessment Report projects that the GrIS contribution to global mean sea-level rise by AD 2100 will range between 7 and 21 cm with a median value of 12 cm under the RCP8.5 scenario (the strongest forcing scenario; Church et al., 2013), whereas an independent estimate ranges between 4.5 and 66.3 cm, with an average estimate of 22.3 cm over the next 100 years under conditions similar to the RCP8.5 scenario (Bindschadler et al., 2013). Estimates of GrIS-induced sea-level rise such as these are dependent upon numerical geophysical ice-sheet models of varying complexity (e.g. Nowicki et al., 2013), but regardless of complexity, models require some degree of "spin-up" or tuning to test model validity before forward modeling can commence. Within this framework, well-constrained geological records of GrIS change can provide important spatial and temporal benchmarks for which to test numerical ice-sheet models.

Decades of research have resulted in numerous reconstructions of GrIS dimensions through the late Pleistocene (e.g. Weidick, 1968; Ten Brink and Weidick, 1974; Hjort, 1981; van Tatenhove et al., 1996; Bennike and Björck, 2002; Weidick and Bennike, 2007; Larsen et al., 2014). The overwhelming majority of these records are reconstructions of the GrIS when it was larger than today, but there are a number of records providing constraints on a smaller-than-present GrIS (e.g. Weidick et al., 1990). In light of projected 21st century warming, which is likely to be amplified in the Arctic (Miller et al., 2010a; Collins et al., 2013), it is these reconstructions of a smaller-than-present GrIS that are most relevant for accurately predicting the dimensions of the GrIS, and thus estimating its future contribution to global mean sea-level rise.

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Although well-constrained geological records of a smaller-than-present GrIS are critical for predicting the GrIS' future dimensions in a warming world, it is extremely difficult to develop reliable and direct measures of a restricted GrIS. This difficulty arises primarily from the simple fact that following times of a smaller GrIS in the past, re-growth of the GrIS overran and destroyed any evidence on the landscape (e.g. moraines) that would help delimit the configuration of a reduced GrIS. Nonetheless, the dimensions of the GrIS during notable warm periods such as Marine Isotope Stage (MIS) 5e (~128–116 ka; the Last Interglacial) and the exceptionally long MIS 11 interglacial (~424–395 ka) remains a key focus within the paleoclimate community (Carlson et al., 2008; Colville et al., 2011; NEEM Community Members, 2013). Because of the difficulty in deciphering the dimensions of GrIS during past warm periods, indirect geological evidence is often used to infer the past dimensions of the GrIS. For example, reconstructed surface temperatures and ice-sheet elevations from MIS 5e-dated Greenland ice have been used to infer a relatively stable MIS 5e GrIS, and isotopic

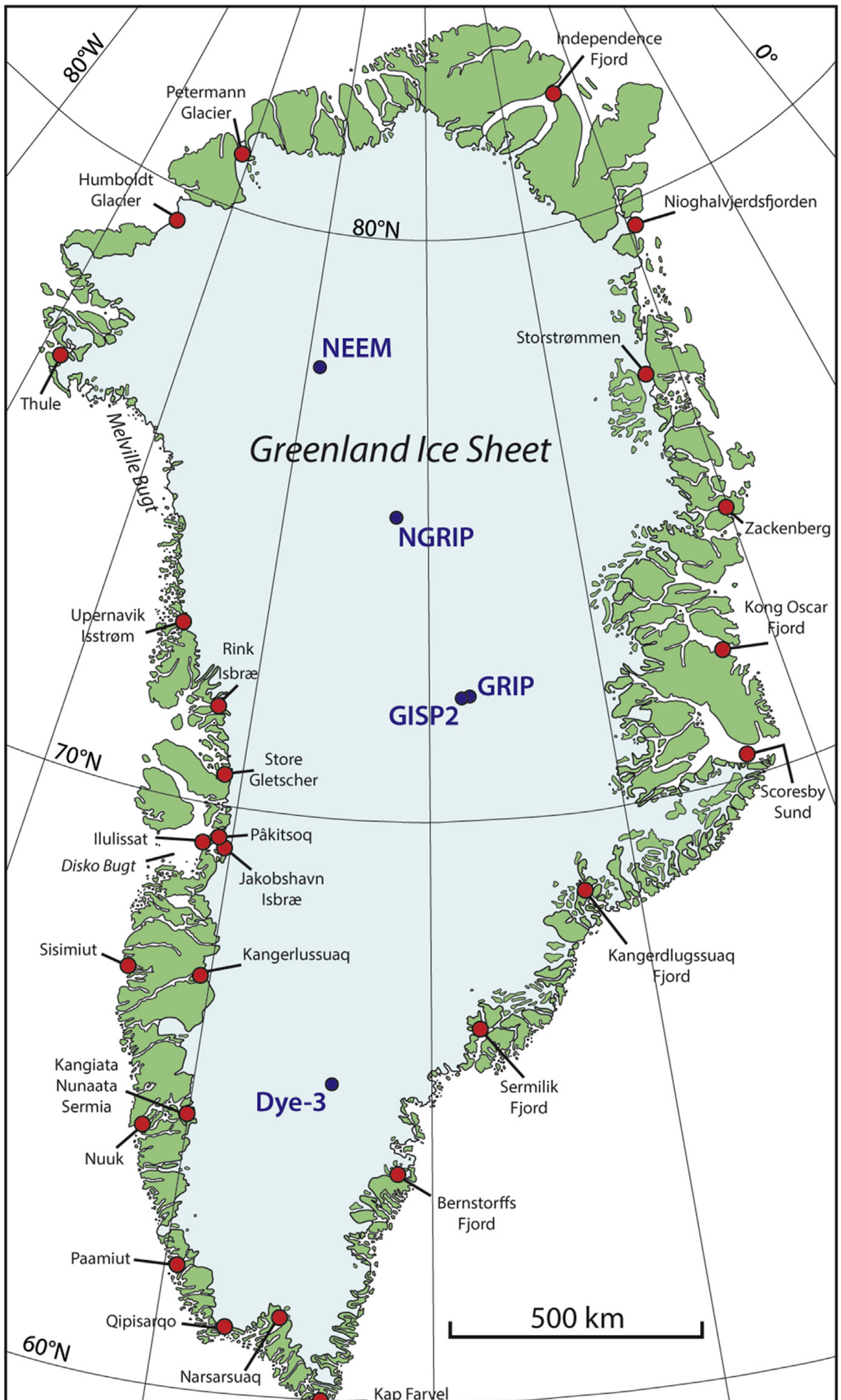

Fig. 1. Map of Greenland with locations discussed in the text.