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Holocene evolution of Hans Tausen Iskappe (Greenland) and implications for the palaeoclimatic evolution of the high Arctic

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ABSTRACT

In this study the Holocene evolution of Hans Tausen Iskappe (Peary Land, North Greenland) is investigated. Constraints on the ice cap evolution are combined with climatic records in a numerical ice flow – surface mass balance (SMB) model to better understand the palaeoenvironmental and climatic evolution of this region. Our simulations suggest that after disconnecting from the Greenland Ice Sheet (GrIS) the ice cap had roughly its present-day size and geometry around 9–8.5 ka BP. During the Holocene Thermal Maximum (HTM) the southern part of the ice cap is modelled to collapse, while the northern part of the ice cap survived this warmer period. The late Holocene regrowth of the ice cap to its maximum Neoglacial extent at the end of the Little Ice Age (LIA) can be reproduced from the temperature reconstruction. The simulations suggest that over the last millennia the local precipitation may have been up to 70–80% higher than at present. By coupling the pre-industrial temperature forcing to a post-LIA warming trend, it is suggested that the warming between the end of the LIA and the period 1961–1990 was between 1 and 2 °C. In all experiments the ice flow model complexity and horizontal resolution have only a minor effect on the long-term evolution of the ice cap. We further conclude that the glacial isostatic adjustment has a significant effect on the modelled Holocene ice cap evolution. This suggests that modelling studies of millennial-scale ice cap evolution should focus on SMB and boundary conditions, rather than on complex ice dynamics.

1. Introduction

Holocene fluctuations of the glaciers and ice caps (GICs) that surround the Greenland ice sheet (GrIS) are poorly understood, as only few measurements exist to constrain their evolution (Kelly and Lowell, 2009). To address this lack of data and to obtain a better insight in the Holocene evolution of Greenlandic GICs, modelling studies are a powerful tool. Such studies improve our understanding of the role of past changes on the present-day evolution of GICs (e.g. Gilbert et al., 2016). They also allow us to constrain palaeoclimatic conditions, by comparing modelled past changes in ice masses with palaoglaciological inferences (e.g. Huybrechts, 1990; Pollard and DeConto, 2009; Steig et al., 2015; Goelzer et al., 2016). Furthermore a better understanding on the evolution of Greenlandic GICs and climatic conditions during the early and mid Holocene, when temperatures were higher than today, is of large interest, as this could provide information about changes to come in the future (cf. Masson-Delmotte et al., 2013). Of particular interest is the influence that a palaeo ice-free ocean may have had on the northern Greenland precipitation. This could provide insights in future precipitation increases following from the projected disappearance of the permanent Arctic ocean sea-ice in the coming decades (Singarayer et al., 2006; Collins et al., 2013; Overland and Wang, 2013).

Despite their importance, to our knowledge, no detailed modelling attempts exist to simulate the Holocene evolution of a local Greenlandic ice cap combining palaeoclimatic and palaeoglaciological constraints. In this study, we aim to solve for this lack of research by simulating the Holocene evolution of Hans Tausen Iskappe (Peary Land, see Fig. 1). A palaeomodelling study on this ice cap offers a number of unique opportunities:

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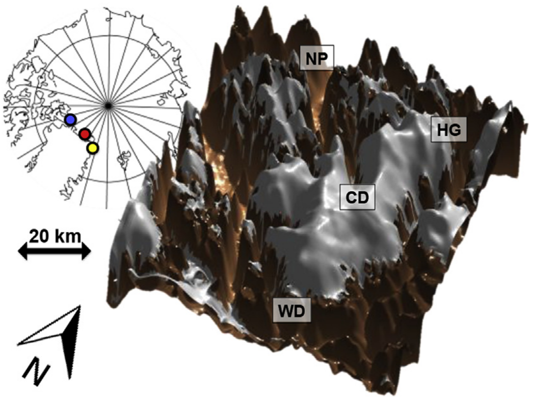

Fig. 1. Present-day geometry of Hans Tausen Iskappe (CD = Central Dome, HG = Hare Glacier, NP = Nord Passet, WD = Wandel Dal) (figure created with TopoZeko toolbox (Zekollari, 2016)). The inset shows the location of Hans Tausen Iskappe (red dot), the Agassiz ice cap (blue dot) and Flade Isblink (yellow dot). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(i) Despite its extreme northern location and remoteness a substantial wealth of field data exists for the present-day Hans Tausen Iskappe (Hammer, 2001). These data were previously used to extensively calibrate and validate a coupled ice flow – surface mass balance (SMB) model (Zekollari et al., 2017). The ice cap dynamics and sensitivity to climatic changes are therefore quite well understood.

(ii) A recently updated palaeotemperature record from the nearby Agassiz ice cap is available, spanning the past 12,000 years (Lecavalier et al., 2017). The proximity of the record is relatively unique. For Holocene palaeoglaciological modelling studies usually records from more distant locations (e.g. NGRIP) need to be used, which can be up to thousands of kilometres away from the site location and situated at a significantly higher elevation (e.g. Flowers et al., 2008).

(iii) There are several constraints on the past ice cap evolution, such as deglaciation dates and information from an ice core that was drilled to the bedrock (Clausen et al., 2001; Hammer et al., 2001; Landvik et al., 2001; Madsen and Thorsteinsson, 2001; Weidick, 2001). Present-day simulations suggest that the ice cap is highly sensitive to changes in climatic conditions, making constraints on its past evolution well suited to constrain past climatic changes.

We start by shortly reviewing the literature on the past evolution of the ice cap and its surroundings (section 2) and then describe the model (section 3) and the experimental setup (section 4). Subsequently the Holocene evolution of the ice cap is modelled (section 5). The implications and uncertainties of this modelling, both from a modelling perspective as from a palaeoclimatic perspective, are discussed in section 6.

2. Past evolution and present-day ice cap geometry

Glacial-geological data suggest that during the Last Glacial Maximum (LGM) the Hans Tausen Iskappe was a semi-independent ice cap, usually referred to as 'North Cap', which was connected to the GrIS (Bennike, 1987; Landvik et al., 2001; Larsen et al., 2010; Jakobsson et al., 2014). At that time it is believed that the GrIS and North Cap had shelf-based ice, which was likely controlled by very thick sea ice that prevented it from breaking up (Larsen et al., 2010; Jakobsson et al., 2014). Palaeorecords suggest that this shelf-based ice began to retreat around ca. 16 ka BP, before eventually breaking up around 10 ka BP in response to higher temperatures and an increased inflow of warm water through the Fram Strait (Larsen et al., 2010). Subsequently the ice margin in Peary Land started retreating (Bennike and Björck, 2002; Nørgaard-Pedersen et al., 2008; Larsen et al., 2010), a bit later than for other northern Greenland coastal areas, where the retreat typically started around 12.5–11.5 cal ka BP (Bennike and Björck, 2002; Funder et al., 2011b). During this retreat several short-lived re-advance episodes of local glaciers may have occurred (Funder et al., 2004; Möller et al., 2010; Larsen et al., 2015), as is also believed to be the case for other Greenlandic GICs (e.g. Ingólfsson et al., 1990).

After its disconnection from the GrIS it is believed that the ice cap had roughly its present-day extent sometime between 9 and 6 ka BP (Landvik et al., 2001). The lower bound (9 ka BP) corresponds to the earliest times when other northern Greenland ice masses reached their present-day position, as was for instance the case at Independence fjord (Bennike, 1987; Bennike and Weidick, 1999). Shells dated up to 8120 cal BP suggest that the area north of the present-day ice cap (Nordpasset, see Fig. 1) deglaciated before this time (Landvik et al., 2001). In the Wandel Dal, south of the present-day ice cap (Fig. 1), records suggest that the disconnection with the GrIS occurred somewhat later, potentially as late as 6 ka BP (Landvik et al., 2001).

The mass loss over Hans Tausen Iskappe persisted for several millennia, and in the mid-Holocene the ice cap was smaller than at present. Palaeorecords suggest that the ice cap may have (partly) disappeared (Madsen and Thorsteinsson, 2001). Crystal size analyses from an ice core drilled to the bed at the present-day Central Dome of Hans Tausen Iskappe (Madsen and Thorsteinsson, 2001) have been interpreted as indicating that the ice cap disappeared. The oldest ice was estimated to be 3.5 to 4.0 ka old and simple temperature calculations show that bottom temperatures were never near the melting point (Madsen and Thorsteinsson, 2001), meaning that the ice core should contain a preserved section since the time that the location was covered by the ice cap. Over the last millennia the ice cap grew and terminal moraines suggest that the maximum Neoglacial extent occurred at the end of the LIA, around 1900 AD (Landvik et al., 2001; Weidick, 2001). This is in line with most other GICs in Greenland (Kelly and Lowell, 2009; Balascio et al., 2015; Schweinsberg et al., 2017). During the first part of the 20th century the ice cap margin slightly retreated (Davies and Krinsley, 1962). The latter half of the 20th century was characterized by slower recession (limited to tens of meters), stand-still or even slight readvances (Weidick, 2001). The present-day ice cap volume is around 770 km^3 and locally the ice thickness reaches up to 600 m (Starzer and Reeh, 2001) (see Fig. 2 and Zekollari et al. (2017) for a more detailed account). It covers a higher-lying northern plateau (typically at 800–1100 m a.s.l.) and a lower-lying southern plateau (600–900 m a.s.l.). Except for a few neighbouring small ice masses (<300 km^2) (Weidick, 2001), at present the Hans Tausen Iskappe is the world's northernmost ice cap.

3. Ice flow – surface mass balance model

The Holocene evolution of the ice cap is simulated with a 3-D coupled ice flow –SMB model that was tuned and validated with present-day observations (Zekollari et al., 2017). The ice flow is calculated from a 3-D higher-order (HO) thermo-mechanical model (Fürst et al., 2011; Zekollari et al., 2013, 2014; Zekollari and Huybrechts, 2015) that is run at a 250-m horizontal resolution, with 21 vertical layers. The internal deformation is described through Nye's generalisation of Glen's flow law (Glen, 1955; Nye, 1957). A full 3-D calculation of the ice temperature is performed, accounting for diffusion, advection and basal heating (cf. Huybrechts, 1996). Surface temperatures are derived from the