Simulating the extent and depth of spring snow cover for medieval settlements in Iceland and Greenland

Laura E.L. Comeau [a,1], Richard T. Streeter [b,*], Christian K. Madsen [c]

[a] School of Geosciences, University of Edinburgh, United Kingdom
[b] School of Geography and Sustainable Development, University of St Andrews, United Kingdom
[c] Greenland National Museum and Archives, Greenland

ARTICLE INFO

ABSTRACT

Medieval settlements in Iceland and Greenland were vulnerable to changes in spring (April-June) snow cover duration and depth. These would have adversely affected the viability of their pastoral farming systems, but the impact would have been spatially variable. We use a physical-based model of snow distribution and melt to model spring snow cover and depth at a scale relevant to human activities across four sites: southern and northern Iceland, and inner and middle fjord sites in South Greenland, using both present day and simulated climate data from the HadCM3 GCM-model. Our climate scenarios cover the period CE 1000–1500, encompassing a climate shift to cooler conditions. We find that under average present climate conditions the inner fjord site in Greenland has similar spring snow conditions to sites in Iceland, but that the middle fjord site has notably greater snow cover, and as climate cools spring snow cover at this site becomes extensive (>60 days). The largest increase in snow cover duration between current average climate conditions and the coolest climate scenarios (47 days increase) is experienced at our Iceland sites. Inner and middle fjord sites in Greenland diverge in terms of snow cover under all scenarios, a potential driver of the growing importance of marine wild resources and the end of the Norse Greenland settlement.

1. Introduction

An understanding of the impact of past climate change on societies is important in order to inform our adaptation to future climatic change (Jackson et al., 2018a). As a result, there has been a renewed interest in the impact of past climate change on societies and their responses (Büntgen et al., 2011; White, 2014), although care needs to be taken to avoid simplistic interpretations of the relationship between climate and societal responses (Coombes and Barber, 2005; Butzer, 2012). Our understanding of human responses to climate has been aided by increases in the quantity and quality of palaeoclimatic data available (e.g. Mann et al., 2009). These records show that climate in the late-Holocene has been far from stable. However, frequently these records are of insufficient spatial or temporal resolution for understanding human-climate interactions. An additional problem is that climate reconstructions are rarely re-cast into terms relevant to human societies (Caseldine and Turney, 2010). Where this has been done, new insights into the consequences of climate change and the drivers of transformation in

settlements are possible (e.g. Bocinsky and Kohler, 2014; d'Aploim Guedes et al., 2016). In the sub-Arctic and Arctic regions variability in snow distribution and duration has a wide-ranging influence on human eco-dynamics and is a potential driver of transformative change. Here we examine the impact of climate change at a scale comparable to the societies that experienced it (at spatial scales of tens of metres and temporal scales of days) by quantifying spring snow cover changes across settlements in Iceland and Greenland.

Iceland was settled around CE 870 and southwestern Greenland around CE 985 (Vésteinsson and McGovern, 2012; Arneborg et al., 2012a). They were settled by people of predominately Scandinavian heritage, although in the case of Iceland there was a notable proportion who originated from the British Isles (Hartman et al., 2017). Both areas were largely dependent on pastoral farming, with the incorporation of fodder production for winter animal feed. In Iceland this was supplemented with some intermittent and localised cereal cultivation (Karlsson, 2000) – in contrast there is little evidence for any successful cereal cultivation in Greenland (Schofield et al., 2013). In Greenland there was

---

varying (but generally increasing) degrees of dependence on wild marine resources such as seals, and a community based network was key to subsistence and survival (Arneborg et al., 2012b, McGovern, 1985; Ogilvie et al., 2009; Dugmore et al., 2005; Dugmore et al., 2012; Jackson et al., 2018b). By CE 1500 the Norse settlement in Greenland had ceased to exist, but in Iceland settlement persisted. The marginality of agriculture in Greenland and Iceland meant that settlements were vulnerable to even minor climatic shifts. Climatic deterioration has been implicated in the end of Norse settlements in Greenland (Dansgaard et al., 1975; Barlow et al., 1997; Patterson et al., 2010; Dugmore et al., 2012). In Iceland bad weather caused widespread famine and hardship on numerous occasions but never seriously threatened the viability of the settlement (Karlsson, 2000).

Long-term variations in climate are driven by changes in insolation, but climatic change at any one location is moderated by local and regional factors. North Atlantic palaeoclimate records show centennial and millennial variability which likely reflect changes in ocean and atmosphere circulation, local and global volcanism and solar variability. The two most significant climate events in the North Atlantic in the past 2000 years were the Medieval Climate Anomaly (MCA: Trouet et al., 2009) and the Little Ice Age (LIA: Ogilvie and Jonsson, 2001). These were complex multi century events occurring across wide regions, and it is therefore difficult to give precise dates for their start and end, and much debate remains about the utility of the terms MCA and LIA generally (e.g. see Ogilvie, 2010). Here we consider the earlier part of our study period (up to CE 1300) as having generally warmer conditions, more typical of the MCA, and that from CE 1300 onwards conditions became generally cooler. An CE 1300 start date for the onset of LIA-type conditions is earlier than some definitions (White, 2014), but one supported by local paleoenvironmental evidence.

Lake sediments in Iceland suggest that the LIA had some of the coldest conditions of the Holocene (Geirsdóttir et al., 2009; Larsen et al., 2011; Geirsdottir et al., 2013). In addition to declining terrestrial temperatures there was a significant (although still variable on decadal scales) increase in sea ice around the north coast of Iceland from CE 1300 (Masseé et al., 2008; Ogilvie, 1984). A study from the west of Iceland using chironomids found that prior to CE 1300 temperatures were relatively warm, the period from CE 1310 to CE 1500 s was variable with cold episodes and there was a consistently colder period from CE 1560–1810 (Holmes et al., 2016). Evidence from Greenland shows a broadly similar pattern of cooling from CE 1300 onwards (Crowley and Lowery, 2000; Christiansen and Ljungqvist, 2012). A chironomid based record of summer temperatures from Lake Igaliku, which is located within our study area, suggests a notable cool period over CE 1280–1460 (Millet et al., 2014). Marine sediment cores from near the Norse Greenland Eastern settlement indicate limited sea ice and calm conditions prior to CE 1300, followed by sea ice within the fjords becoming more frequent from CE 1300 to CE 1500 (Jensson et al., 2004). Although these regional and century scale climate changes are well documented we have a very limited understanding of changes in snow cover in areas of settlement as a result of LIA cooling in Iceland or Greenland. Regional climate changes were experienced by people at much smaller scale, that of yearly changes in local weather and variation across the settled landscape. Previous studies have re-cast regional climate records into scales and terms relevant to societies (e.g. simulating the impact of LIA cooling but on biomass productivity in Iceland, Thomson and Simpson, 2007) – here we do this with snow cover for settlements in Iceland and Greenland.

Changes in temperature and precipitation affect the timing of the first snow, depth of snow cover, and the timing of the spring melt. In the Norse North Atlantic, where on the whole societies were dependent on pastoral agriculture, annual variability in snow cover can be linked to fluctuations in the production of food resources on which these societies depended. The distribution and persistence of snow has an inverse relationship to the length of the growing season, and a direct influence on the availability of winter grazing, winter livestock loss, neonatal

mortality rates, hydrology, wildlife and travel across the landscape (Luce et al., 1998; Kohler et al., 2006; Rixen et al., 2008; Masden, 2008). Reconstructions of the Norse seasonal round note the concentration of activity in the late spring and summer months. These are the busiest of the Norse calendar, with homefield activity including the main stock being led out to graze the homefields, fertilizing soils as soon as frost has left the ground, milking activities and birthing of calves, lambs and kids, as well as communal hunting of mass-migrating seal species (McGovern, 1985; Jackson et al., 2018b). In the late spring months, winter fodder and food storage resources are at their lowest, and activities such as provisional gathering of food, moving livestock to pastures free of snow (and in Greenland, sealing in the coastal region) are, therefore, key for survival to fill the resource gap. Snow cover in these important spring months is likely to have been a key factor in Norse human eco-dynamics, and during the LIA snow cover variability is likely to have been a critical limiting factor on livestock numbers, pastoral productivity and mobility. For these reasons, we focus on spring (April-June) snow cover.

Here we address the need for climate reconstructions relevant to human experience and adaptation. We employ a modelling approach to understand the impact of LIA cooling on spring snow cover depth and duration at sites of Norse habitation in Iceland and Greenland. The settlements in Greenland were abandoned towards the end of the 14th century whereas those in Iceland persisted through to the present. This contrast allows us to consider how changes in snow cover may have contributed to this difference in outcomes. We show a) the differences in spring snow cover within and between sites in Iceland and Greenland under the range of recent climate conditions and, b) the differences in spring snow cover experienced within and between sites over the likely range of climate conditions experienced in CE 1000–1500.

2. Materials and methods

High-resolution records of snow cover beyond a few decades do not exist for our study area, or more generally. Therefore numerical models are one of the few ways in which to understand and simulate temporal and spatial variations in snow cover as a result of climate change. We use field measurements and weather station data to calibrate an existing snow model for sites in Iceland and Greenland, and then simulate spring snow cover for a range of different climate scenarios.

2.1. Study areas

We simulate snow cover at two sites in Iceland and two sites in the Eastern Settlement of Greenland (Fig. 1a). All sites cover an area of 6.4 X 6.4 km (~41 km^2). This size was chosen as it encompasses farm homesteads, most shieling and grazing areas and a large proportion of the farm watershed. Sites were selected to cover a wide range of climatic conditions within Iceland and Greenland (Table 1, Fig. 2) and encompass areas of archaeological interest.

In Greenland we selected two study sites in the Norse Eastern Settlement, where we have good knowledge of the sites and a fairly robust chronology: One area (Greenland inner fjord) is centered on farm Ø47 at the head of the Igaliku fjord, the site of the medieval Episcopal farm of Garðar, which is richly documented through archaeological and paleoenvironmental investigations (Bruun, 1895; Buckland et al., 2009; Krogh, 1974; Massa et al., 2012; McGovern, 1992; Nørlund, 1929; Ogilvie, 1984; Panagiotakopulu et al., 2012). Ø47/ Garðar is the largest and richest of all known Norse farms in Greenland, located in a subarctic inner fjord environment that is amongst the most favourable and fertile in Greenland, as evidenced also by having the longest reestablished farming community in Greenland, present day Igaliku. The other study area (Greenland middle fjord) is centered on Ø78 in the Vatnahverfi (Tasikuluulik), which was initially a large church farm, but appears to have contracted somewhat after ca. CE 1300 (Madsen, 2014). Ø78 is surrounded by smaller (tenant) farms, of which one (Ø78a) has seen both archaeological and paeloenvironmental investigations suggesting
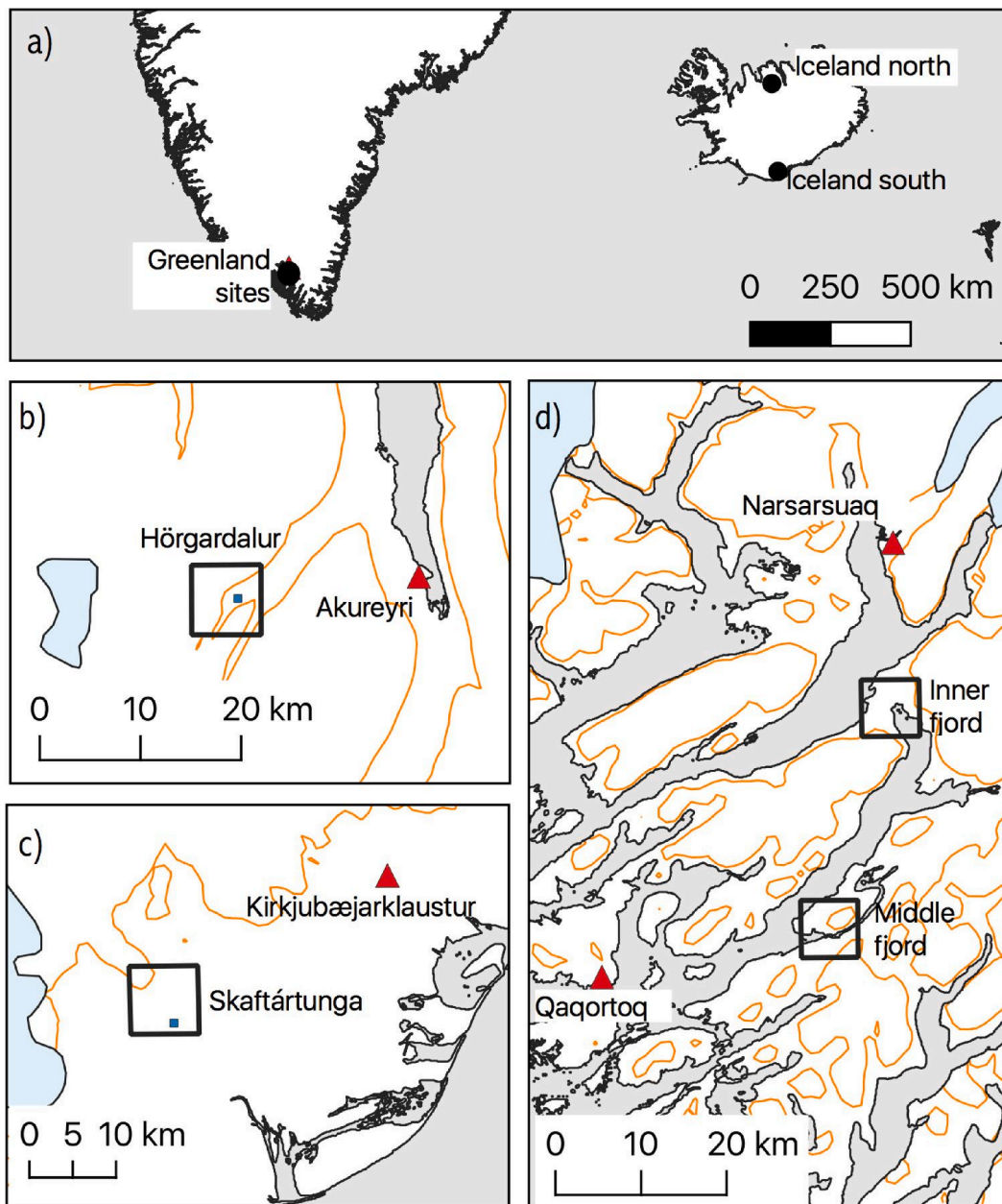
Fig. 1. Areas of snow simulation. Panel b shows the Iceland north site, panel c shows the Iceland south site. Panel d shows the Greenland sites. Black lines outline the areas of simulation. Red triangles show long-term meteorological stations, blue squares location of our meteorological measurements (Iceland sites). Orange line represents the 300 m asl contour and blue shaded areas are glacial ice.

Table 1
Selected climate data (1961 onwards) for meteorological stations nearest the study sites.

Site name	Iceland south	Iceland north	Greenland inner fjord	Greenland middle fjord
Meteorological Station	Kirkjubæjarklauster	Akureyri	Narasarsuaq	Qaqortoq
Years of data used	1961–2013	1961–2014	1961–2008	1961–2010
Mean annual precipitation (mm)	1645	490	874	1242

it was abandoned just before the time of Ø78′s contraction (Ledger et al., 2014a; Schofield et al., 2013; Vebæk, 1943; Ledger et al., 2014b; Madsen, 2014). The overall signs of 13th century decline of Norse settlement and farming in the area of Ø78 correspond well with the areas sub-arctic middle fjord environmental setting. It experiences higher overall precipitation and has cooler summer temperatures highly influenced by the presence/absence of drift ice in the fjord, resulting in poorer vegetation.

In contrast, the inner fjord area of Ø47 was characterized by a more continental environment with overall less precipitation, warmer summers and colder winters (Table 1, Fig. 2b). The inner and middle fjord environments - as exemplified by our study sites - sustained the vast majority of Norse farms in Greenland. By comparison, the outer fjord area was thinly populated.

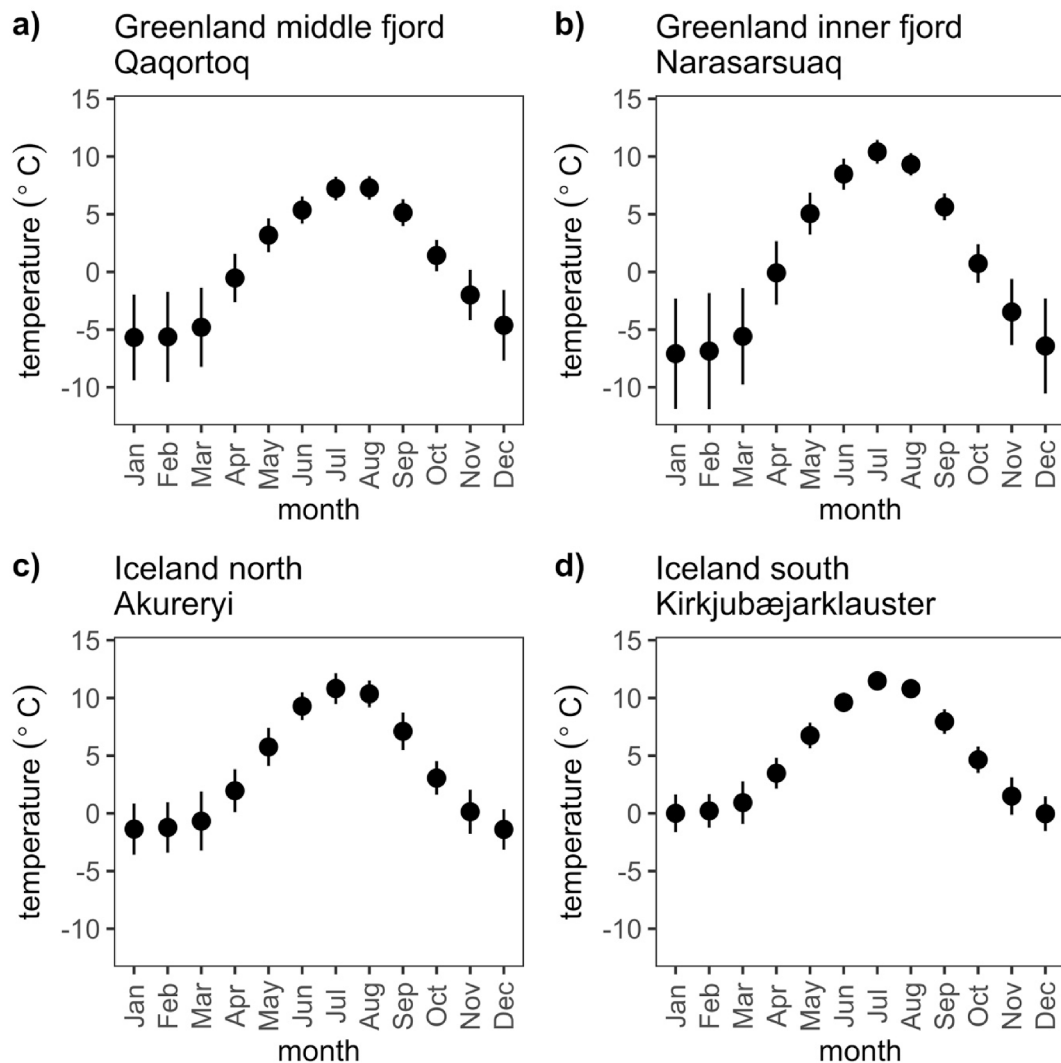In Iceland we selected two study sites. The first site (Iceland south) is

Fig. 2. Monthly temperatures at the nearest meteorological station to each of our study sites. Mean and one standard deviation are shown.

within the area known as Skaftártunga (Fig. 1c). This is one of the mildest and wettest areas in Iceland (Table 1, Fig. 2d). This area has been occupied continuously from the earliest period of settlement, with Landnám farms (farms established in the initial phase of settlement) located within the modelled areas. Studies of landscape change demonstrate that the area experienced extensive soil erosion immediately after settlement, implying a period of extensive vegetation change (Streeter et al., 2012; Streeter and Dugmore, 2013; 2014). They also show a second period of enhanced erosion during the LIA. The second Iceland study site (Iceland north) is in the valley of Hörgardalur in north-central Iceland (Fig. 1b). Here winters are cool/cold and total precipitation is relatively low (Table 1, Fig. 2c). Archaeological work in this area has revealed a complex history of changing settlement patterns and different types of settlement (Harrison, 2014). There is a high level of local relief and settlements are concentrated along the valley bottom.

2.2. Model description

We use a high-resolution numerical snow distribution and energy balance melt model, known as JIM (Essery et al., 2013) to simulate snow accumulation, distribution and melt across our study sites. The Liston wind model (Liston et al., 2007) is used to calculate a wind field according to the topography and surface roughness (influenced by vegetation height) from point wind speed and wind direction input data. Snow is subsequently blown across the landscape by suspension in the

air and saltation across the ground surface according to the wind field, and some is lost through sublimation. As a result of blowing snow, snow cover is highly heterogeneous at mesoscales (100 m to 10 km) and microscales (1 m to 100 m), depending on elevation, relief features, terrain variables such as slope and aspect and vegetation cover (Pomeroy and Gray, 1995). Snow melt is quantified as a residual in the heat balance, with the energy budget from the snowpack calculated from input meteorological data.

The input meteorological variables required for the model are: incoming short.

wave radiation; incoming long wave radiation; rainfall rate; snowfall rate; air temperature; relative humidity; wind speed; wind direction and air pressure. The energy balance melt model can be run separately at a point with hourly meteorological input data for a given time period, outputting snow depth and Snow Water Equivalent (SWE) at specified temporal intervals (with an hourly minimum). To distribute the point meteorological data across the landscape, temperature and precipitation lapse rates within the model reduce the temperature and increase the precipitation with elevation. The distributed model output is in the format of gridded snow depth and SWE at the spatial resolution of the digital elevation model (DEM).

2.3. Secondary data

A DEM of 25 m resolution was used (Kjaer et al., 2012 for Greenland,

and Íslands, 2014 for Iceland). Vegetation height data at a 25 m resolution are not available for the time period under consideration, so vegetation heights were inferred from recent Landsat images (Table S1). A Normalised Differential Vegetation Index (NDVI) is calculated from each Landsat image using the widely used NDVI formula (e.g. Pettorelli et al., 2005). A direct relationship between NDVI values and vegetation height was assumed (Roettger, 2007), and vegetation height thresholds were based on field observations in Greenland and in Iceland (Table S2). In Iceland it was not possible based on NDVI alone to separate fertilised fields and areas of shrub cover. In this case fertilized fields were manually identified using aerial imagery and assigned a vegetation height of 0.1 m. Past vegetation cover may have been different from the present cover; we explore the implications of this in Section 4.3. Areas of sea and glacial outwash plains were masked in the model. Current meteorological data (Fig. 2) was obtained from the nearest meteorological stations with long-term records of key variables (Fig. 1b, c and d, showing locations of stations relative to study area, Table 1).

The observed meteorological data required for input to the snow model were available from the Danish Meteorological Institution and Icelandic Meteorological Office/from our site met stations as measured observations, with the exception of longwave and shortwave radiation. This was calculated according to the method described in Liston and Elder (2006) using the following data: wind speed, cloud cover, snow precipitation, rain precipitation, relative humidity, maximum air temperature, minimum air temperature and air pressure, site elevation and latitude.

2.4. Model calibration

The numerical snow model is calibrated and validated at sites and in time periods when snow data measurements and input model data are available. Model calibration and verification took the form of a visual comparison of modelled snow cover and actual snow cover on the same date from Landsat images (Greenland and Iceland sites, Table S3), comparison of distributed modelled snow depth and snow water equivalent (SWE) with field measurements across the study areas (Iceland sites) and comparison of point modelled snow depth with long term (30-year) records of measured snow depth at meteorological stations (Greenland sites). For a full description of the calibration process see Comeau, (2013).

Snow depth and SWE measurements were made at 10 m intervals along transects at locations in and near the Iceland sites in early March 2014 (Table S4). A total of 456 measurements of snow depth within Skaftártunga were made, with 320 measurements of snow depth made in Hörgárdalur. SWE was calculated from density measurements made using a snow tube at 100 m spacings and where snow depth was > 10 cm.

2.5. Modelling past meteorological data

Of critical importance is the selection of appropriate climatic scenarios. Snow cover is sensitive to changes in temperature and precipitation so both need to be considered. We are interested in climate extremes, therefore regional synthesis of palaeoclimatic proxies are not appropriate due to the smoothing involved and the difficulty they have representing short-term volcanic perturbations (Mann et al., 2012; Stoffel et al., 2015), and the fact many of them are based on dendrochronological datasets, which are absent from Iceland and Greenland (Mann et al., 2009; Christiansen and Ljungqvist, 2012). An additional issue is that many climate proxies record some aspect of summer temperatures (e.g. temperatures reconstructed from chironomids), which do not necessarily correlate with spring temperatures. For these reasons, we used simulated climate data as the input to the snow model.

A global circulation model (GCM) named HadCM3 has been used to simulate climate data from CE 1000 to present with a spatial resolution of 2.5° latitude and 3.75° longitude and daily temporal resolution

(Schurer et al., 2013). This climate model presents a higher spatial and temporal resolution dataset than the proxy records, with climate variables that translate into snow model inputs and a range of climate that includes extreme events. The HadCM3 model is widely used to understand past climate changes and has performed well in GCM model comparisons (Stott et al., 2000; Reichler and Kim, 2008). We only use one of the available GCM models in this study — it is likely that downscaling other available GCM models using the same methods would add new insights. One GCM cell covers the Greenland sites and another the Iceland sites. The HadCM3 model has been run with several forcings scenarios to understand the impact of different forcing variables. Here we used the all forcings scenario HadCM3 dataset because this is expected to best reflect the past climate.

The data is corrected for each study area by applying monthly delta correction factors calculated from a comparison of current (approx. 1960-present) local meteorological station and GCM data for each climate variable; temperature, wind speed, relative humidity, air pressure, radiation, and total precipitation. The GCM outputs included all the meteorological variables required for the snow model (except wind direction) and monthly delta correction factors were calculated by dividing the measured mean monthly meteorological variable by the GCM mean monthly meteorological variable, for example, mean measured January temperature divided by the GCM mean January temperature. For precipitation, the delta factors were calculated by comparing the mean monthly sum. The delta factors were then applied (by multiplication) to the simulated GCM daily data from CE 1000 to present to produce meteorological data from CE 1000 corrected to each study area. Additionally, at the Iceland sites a weather station logged conditions within the Iceland simulation areas during the collection of snow measurements (Fig. 1b-c) for 63 h at the southern site and 30 h at north site, allowing site specific calibration of weather station records.

Before using the corrected GCM meteorological data as input to the snow model, the GCM corrected daily data were compared with the local meteorological station data to check that the corrected GCM data sufficiently captures the daily variability of the meteorological variables. Corrected GCM temperature, air pressure and radiation data closely match the measured daily and monthly data from local meteorological stations at each study area. However, the corrected daily GCM precipitation, relative humidity and wind speed data failed to capture accurately the variability observed in the measured daily data. Precipitation is a key input variable for the snow model, therefore it was decided that current measured precipitation data (from records dating between 1960 and 2010) would be used as input to the snow model as proxies for past conditions. The range of current measured spring sum precipitation is very similar to the range of GCM CE 1000–1500 spring sum precipitation at each site, therefore we consider current precipitation measurements as suitable as representative of the range of precipitation experienced during the MCA and LIA. Relative humidity is closely linked to precipitation and therefore current measured relative humidity data was also used. In this way, the precipitation and relatively humidity input to the snow model reflects the range of monthly and annual precipitation conditions simulated by the GCM for CE 1000 – 1500 at each site yet also captures the daily variability observed at local meteorological stations. Precipitation was defined as rain or snow according to a threshold air temperature of 2 °C (pers.comm., Richard Essery; John Pomeroy).

Similarly, current measured wind speed is used as a proxy for past conditions and wind direction is not available from the GCM so present day data from the local meteorological stations were used with the assumption that the wind speed and predominant direction have not changed from CE 1000 to present day. The model distributes the wind direction according to the local topography so it is further localised within the model (Liston et al., 2007). Shortwave and longwave radiation and temperature are downscaled to hourly data using the latitude of the site and a sine curve and linear interpolation method (Waichler and Wigmosta, 2002).

Temperature is another key input variable for the snow model, and

the range of current measure spring temperature is narrower than the range of GCM CE 1000–1500 spring temperature at each site. To simulate the CE 1000–1500 climate, therefore, it is considered appropriate to use present day precipitation, relative humidity, wind speed and wind direction and air pressure but adjustments should be made to temperature, radiation and the division of total precipitation into rainfall and snowfall based on the air temperature threshold of 2 °C to reflect climate differences between present day and CE 1000–1500.

Overall, for this study the GCM and observed meteorological data provided the variables that were required. We acknowledge that such variables are often not available, and in such cases an alternative method would be to apply a temperature index based snow melt model which requires much simpler inputs (air temperature), and can be calibrated to perform well (e.g. Hock, 2003). Temperature index based models assume an empirical relationship between air temperature and melt rate and are commonly used due to the wide availability of air temperature data, which is also relatively easily interpolated and forecasted, and for their computational simplicity.

2.6. Scenario selection

We modelled snow cover over the entire hydrological year to simulate both snowpack development and melt, however in our results we focus on the snow cover over the months April-June. Observations of Landsat images for our sites indicated that low elevation areas started to become free of snow cover in April, and all elevations were generally snow free by the end of June. Typically, snow depth reaches its maximum in March. Snow cover over April-June therefore reflects a combination of the persistence of the winter snow pack, and spring snowfall events.

The GCM is not designed to replicate any specific day, and rather than assessing the accuracy of the GCM data in a specific year we seek to illustrate the range of snow cover conditions experienced in each study site from CE 1000–1500 (encompassing both the warmer, earlier part of this period and the later, cooler conditions of the LIA). We do this by generating five scenarios which are used as input climates for the snow model (Table 2). In this instance, the best and worst conditions were defined as minimum and maximum extent and duration of spring (April-June) snow cover, respectively. We recognise that 'best' and 'worst' are subjective terms, and that increasing levels of snow cover may not be detrimental to pastoral farming systems under all circumstances. However, we use these terms because they make clear the most likely impact of changing levels of snow cover on the productivity of pastoral farming systems. This is explored in section 4.1. The snow model was initially run using observed meteorological data as input for the duration of available data at each site (approx 1960 to present, Table 1). The five maximum and five minimum hydrological years (September-August) of snow cover were identified from the model outputs of mean monthly spring snow depth and extent across each site to illustrate the range of worst and best snow cover conditions experienced in the present day climate. Average present climate conditions are also represented in the analysis and were selected as years in which both the spring snow sum and spring mean temperature were within 10 years of their respective median values. Our study sites likely experienced greater extremes of temperature in the MCA and into the LIA than present conditions. To understand the impact of these extremes on our study areas, we use the snow model to simulate scenarios of the worst and best snow cover conditions experienced between CE 1000–1500.

The scenarios are generated by applying monthly temperature delta adjustment factors to the 1960-present worst and best five year snow cover scenarios. The delta monthly factors are calculated from the comparison of the mean monthly spring (April-June) temperatures to those of the five lowest and five highest spring temperature years in the GCM CE 1000–1500 record at each site (using the site corrected GCM data see Section 2.4). Shortwave and longwave radiation is then recalculated using the adjusted temperature based on the method described

Table 2
Climate scenarios used in the model.

Scenario Name	Source data	Criteria
Worst GCM	GCM CE 1000–1500 (site corrected) spring temperatures and associated snowfall	Apply monthly temperature adjustment factors to the 1961-present worst observed scenario and re-define snowfall according to the adjusted temperature using the 2 °C air temperature threshold. The delta adjustment factors are calculated from the monthly mean of the five lowest spring temperature years in CE 1000–1500 GCM simulation.
Worst observed *	Observed meteorological data (approx. 1961-present)	Mean temperature and precipitation conditions of the five simulated maximum years of spring snow depth and extent.
Average observed *	Observed meteorological data (approx. 1961-present)	Years where spring snow sum depth and spring temperature are both within 10 years of the median.
Best observed *	Observed meteorological data (approx. 1961-present)	Mean temperature and precipitation conditions of the five simulated minimum years of spring snow depth and extent.
Best GCM	GCM CE 1000–1500 (site corrected) spring temperatures and associated snowfall	Applying monthly temperature adjustment factors to the 1961-present best observed scenario and re-define snowfall according to the adjusted temperature using the 2 °C threshold. The adjustment factor is calculated from the monthly mean of the five highest spring temperature years in the GCM CE 1000–1500 record

* Observed refers to the observed meteorological data that form the inputs to the snow model, the resulting snow cover and depth has not been observed.

in Liston and Elder (2006). Furthermore, the total precipitation in the 1960-present worst and best five year snow scenarios is then split into rain and snow precipitation based on the adjusted temperature using a 2 °C threshold.

In the comparison of snow cover between sites we focused on snow cover below 150 m asl as this ensured consistency between sites, which varied in the range of altitudes the site encompassed. An additional reason for focusing on this altitude is that the majority of Norse farms and their infield and outfield areas were located around this altitude, whereas rangeland grazing areas were more likely to be found at higher altitudes. Infields (enclosed areas for hay cultivation) and outfield areas (uncultivated farmland used for grazing) were critical to Norse pastoralism (Thomson and Simpson, 2006). This is because they provided winter grazing for sheep (Simpson et al., 2004), and were also used to grow fodder crops to feed livestock through the winter months (Amorosi et al., 1998). Therefore variability in spring snow cover at this altitude range would likely have had the greatest impact on the success of pastoral farming at our sites.

2.7. Model output analysis

The model defines a snow day for a single model cell as being when the modelled snow cover is > 10 kg/m^2. It then outputs the total number of snow days per month for each cell. We define snow cover days in the following way. For each monthly output, we selected cells within an altitude band (e.g. all cells between 100 and 150 m asl) and calculated the mean number of snow-days across all these cells. We use this mean value to indicate the snow cover days for that site for a given month.

3. Results

3.1. Temperature and precipitation

Four climate scenarios were generated for each site and compared to the average current (approx 1960-present) conditions. These are shown in Table 3. In average current conditions, mean spring temperatures are cooler and spring sum snowfall is greater at the Greenland sites than the Iceland sites. Greenland middle fjord is coldest (3 °C) with the most snowfall (90 mm water equivalent), and Iceland south is warmest (8 °C) with the least snowfall (17 mm water equivalent). Although Iceland south has the highest precipitation (379 mm), it has the smallest proportion of precipitation falling as snow due to the warmer temperatures. Iceland north has the equal lowest precipitation (89 mm), but has a high proportion falling as snow.

In the worst and best observed (approx. 1960-present) climate conditions, the relative differences between sites is similar to in average conditions, with Greenland middle fjord experiencing the coldest temperatures and greatest snowfall, and Iceland south experiencing the warmest temperatures and lowest snowfall (Table 3). The relative differences between sites is also the same in the warmest GCM climate scenario, when temperatures at all sites were approximately 3 °C warmer than average observed conditions (and 0.5 °C warmer than the best observed current conditions). The spring mean temperature range experienced in the warmest and coldest GCM scenarios is, however, greater at the Iceland sites (+3 °C above average to 7/8 °C below average) compared to Greenland sites (+3 °C above average to 4/5 °C below average), due to the larger difference of the worse GCM scenario from the average in Iceland. This leads to Iceland north experiencing lower temperatures than the Greenland sites in the worst GCM scenario, and Iceland south experiencing greater snowfall (173 mm water equivalent) than Iceland north (70 mm water equivalent) (and similar to Greenland inner fjord at 176 mm water equivalent) due to higher precipitation (Table 3).

3.2. Snow cover duration and depth

In the best current climate conditions and the best CE 1000–1500 climate conditions, spring snow duration is similar across all sites with less than six days snow cover in April and generally snow free conditions in May and June (Figs. 3–7). Average monthly snow depth in April is less

than 3 cm across all sites (Fig. 5). Snow cover is slightly greater in current average climate conditions at the Iceland sites with less than 10 days snow cover in April, and at the Greenland inner fjord site with less than 15 days snow cover in April, and mostly snow free conditions in May and June (Fig. 6). Average monthly snow depth in April is 5 cm at the Iceland sites and 6 cm at Greenland inner fjord site (Fig. 7). However Greenland middle fjord experiences much greater snow cover in current average conditions with 21 days of snow cover in April at an average depth of 23 cm, and 8 days of snow cover in May at an average depth of 7 cm (Figs. 6 and 7).

In the worst current climate conditions spring snow cover duration increases sharply to over 25 days in all locations and there is greater variability between sites. In the worst current climate conditions, the Iceland sites experience 20–25 days snow cover in April at an average depth of ~ 30 cm, less than 5 days snow cover in May at an average depth of 2 cm and very little snow cover in June (Figs. 6 and 7). Iceland south experiences 5 days less spring snow cover than Iceland north. The Greenland sites experience notably longer snow cover, with 24–28 days snow cover in April at an average depth of ~ 50–70 cm, 15–22 days snow cover in May at an average depth of ~ 30–50 cm and also ~ 5 days snow cover in June of less than 10 cm average snow depth (Figs. 6 and 7). There are greater differences between the two Greenland sites; Greenland middle fjord experiences 14 days more spring snow cover than Greenland inner fjord, with seven days more snow cover in May (Figs. 4 and 6). Average monthly snow depth in Greenland middle fjord is ~ 20 cm greater than Greenland inner fjord in April and May. These differences in snow cover in worst current conditions reflect the relative differences in temperature and snowfall between sites.

In the worst CE 1000–1500 climate conditions spring snow cover increases to over 50 days in all locations and is notably greater than in the current worst climate conditions (Figs. 3–7). Iceland sites experience a greater increase in snow cover from current worst climate conditions compared to Greenland sites, with complete snow cover in April at an average depth of ~ 60–80 cm, 20 days snow cover in May at ~ 35–50 cm and approximately five days snow cover in June at less than 10 cm (Figs. 6 and 7). This reflects the greater decrease in temperature from current worst conditions to CE 1000–1500 worst conditions in Iceland compared to Greenland. Greenland inner fjord experiences similar (only 5 days less) snow cover to the Iceland sites, with 24 days snow cover in April at an average depth of 60 cm, 21 days snow cover in May at 46 cm depth and 5 days snow cover in June at 3 cm depth. In the worst climate conditions experienced in CE 1000–1500, Greenland middle fjord experiences the greater snow cover duration with generally total snow cover in April and May, and 11 days snow cover in June. Greenland middle fjord also experiences the greatest snow depths in the worst CE 1000–1500 conditions with an average monthly snow depth of 93 cm in April, 85 cm in May and 21 cm in June, which is 15 cm greater than the Greenland inner fjord and both Iceland sites in June (Figs. 4 and 5).

A notable feature of the results is that spring snow cover is much more variable in worse years than best years. At the Iceland sites, in the best years experienced in current conditions and the best GCM scenario have ~ 7 days less spring snow cover than in average current conditions. In the worst years compared to current average conditions, however, Iceland sites have ~ 18 days more snow cover and ~ 45 days more snow cover in the worst conditions experienced in CE 1000–1500 (Figs. 3 and 4). In Greenland, the best years experienced in current conditions and in CE 1000–1500 have ~ 15 days less snow cover than in current conditions at Greenland inner fjord and ~ 28 days less snow cover at Greenland middle fjord. In the worst years compared to current average conditions, the Greenland sites have ~ 25 days more snow cover in the worst current conditions experienced and ~ 35 days more snow cover in the worst conditions experienced in CE 1000–1500 (Figs. 3 and 4).
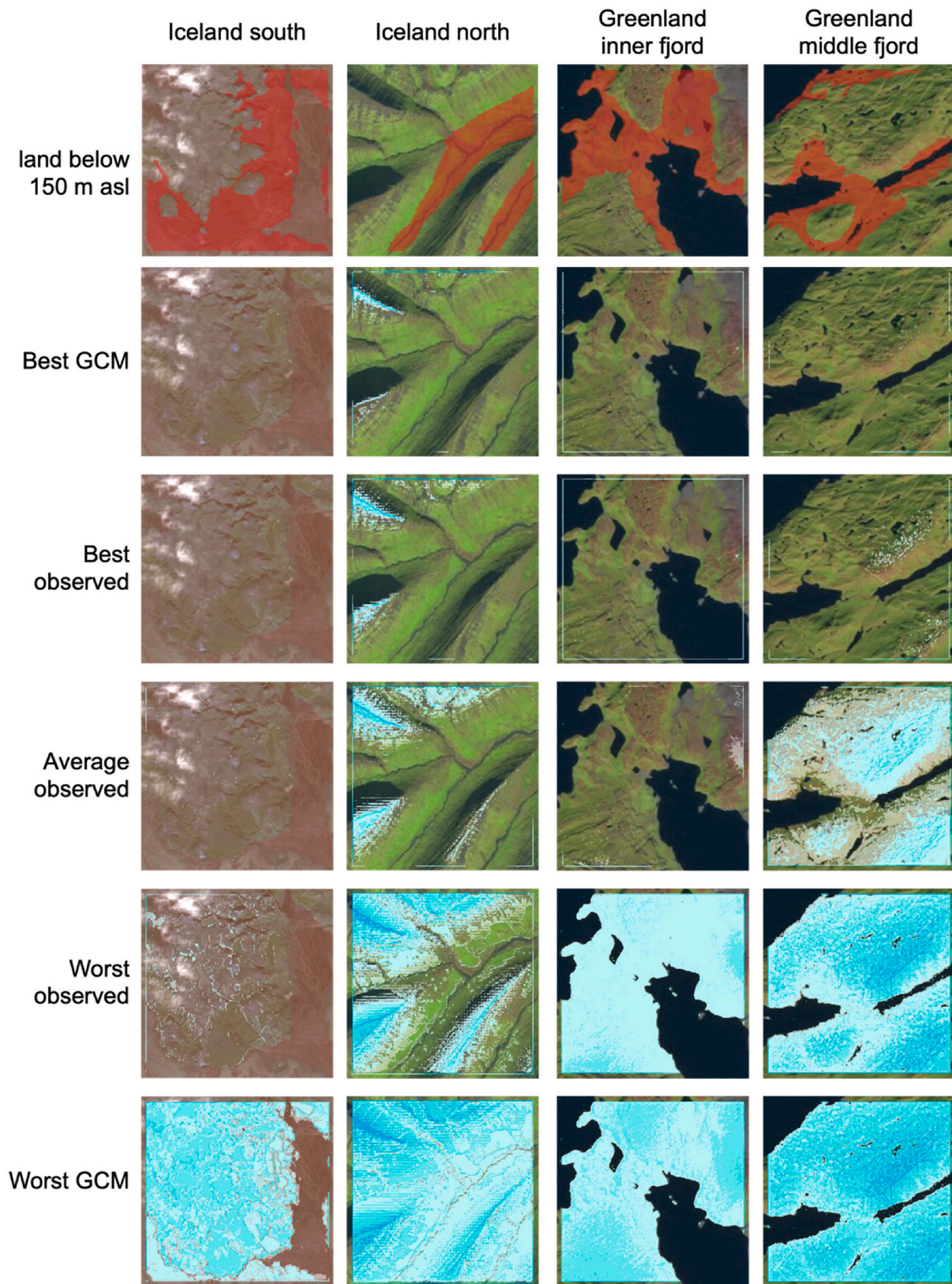
Table 3
Simulated climate conditions at our study sites for five different climate scenarios.

	Worst GCM	Worst observed	Average observed	Best observed	Best GCM
	April-June temperature (mean, °C)				
Iceland south	1	7	8	9	11
Iceland north	−2	5	6	7	9
Greenland inner fjord	0	2	5	6	7
Greenland middle fjord	−1	2	3	4	6
	April-June snowfall (mm water equivalent)				
Iceland south	173	27	17	13	2
Iceland north	70	48	28	16	5
Greenland inner fjord	176	137	58	24	5
Greenland middle fjord	236	183	90	35	15
	April-June precipitation (mm)				
Iceland south	358	358	379	329	329
Iceland north	87	87	89	78	78
Greenland inner fjord	275	275	89	113	113
Greenland middle fjord	332	332	281	139	139

Fig. 3. Model outputs for May at our study sites. Top row shows areas below 150 m asl (shaded area). Subsequent rows show simulated mean monthly snow cover for May under different climate scenarios. Snow cover is shaded blue. Background images from Landsat.
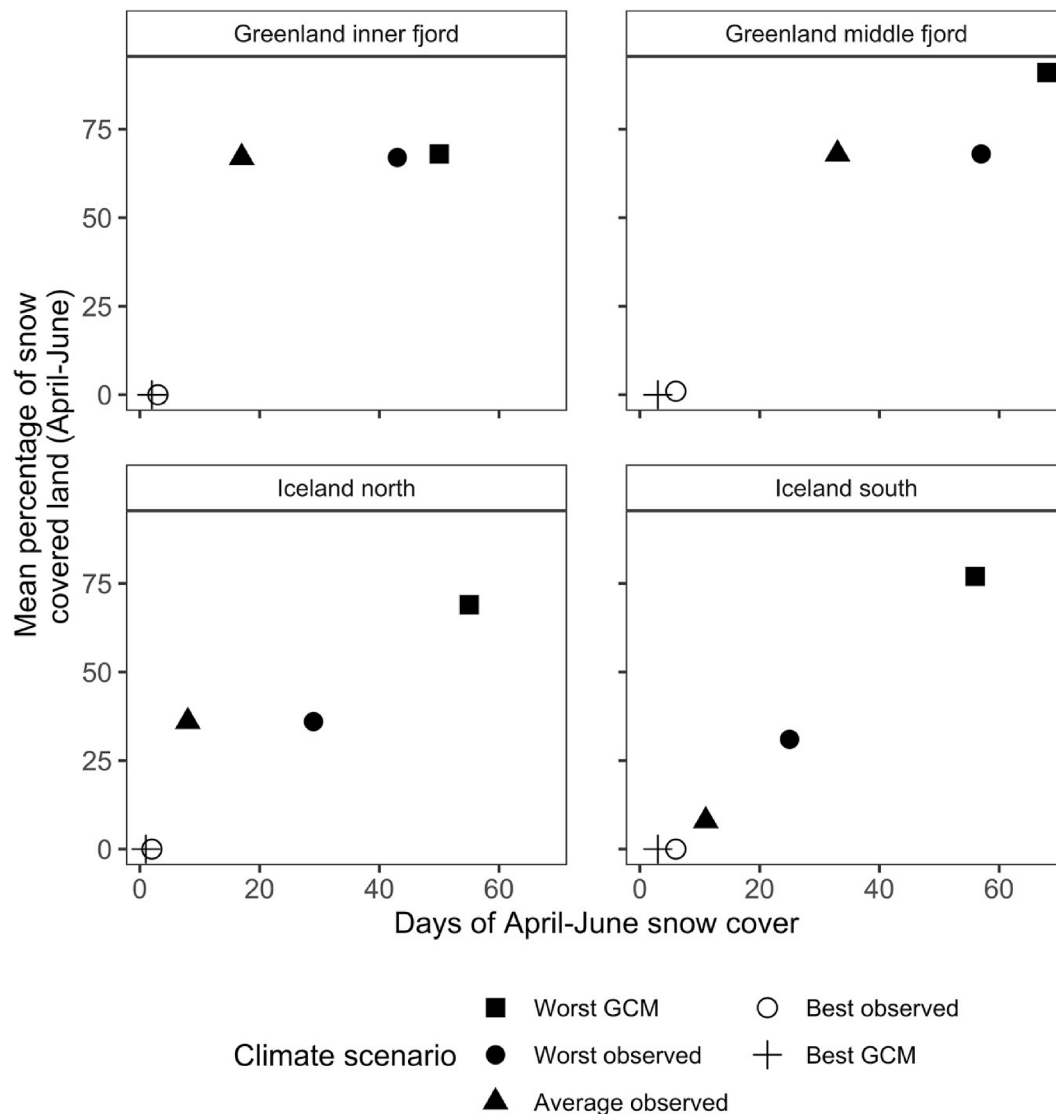
Fig. 4. Number of days with snow cover in April-June (mean of the five output years for each scenario) and mean percentage of land snow covered (below 150 m asl) for study sites.

4. Discussion

4.1. Impact of spring snow cover on pastoral farming

It might be assumed that Greenland sites would experience longer lasting snow cover than sites in Iceland, given that it is colder (Table 1, Fig. 2). That is true of the Greenland middle fjord site, but our model results show that in the cooler climate scenarios spring snow cover is similar (albeit generally lower) in the Iceland sites to the Greenland inner fjord site. This reflects the importance of precipitation as well as temperature in controlling snow cover, with Iceland south recording higher precipitation than the Greenland inner fjord site. It also suggests that, in terms of spring snow cover and pastoral farming, favourable inland sites in Greenland would not have been notably more challenging than many locations in Iceland, where settlement was successful throughout the LIA.

Maintaining a pastoral farming system at the Greenland middle fjord site under worse than average 20th century conditions, such as would have been increasingly frequent from CE 1300 onwards, would have been very challenging. The only ways for farmers past and present to counteract the effects of severe winters is to winter stall and feed their animals, requiring additional fodder production. However, this means

putting additional strain on the low agrarian productivity of the middle and outer fjord settlement areas and therefore increasing fodder production may have been difficult. In the worse current conditions scenario snow cover would have persisted over 70% of the area below 150 m in altitude for about half of the spring (April-June) – the GCM model suggests that at least for some years during the LIA snow cover would have been even more persistent. The impact of this level of spring snow cover can be estimated by using 20th century records of sheep mortality from Inuit farms in the same area as Norse settlements (Madsen, 2014). These records show that in known cold and snowy winters sheep populations frequently decline by 10–20%, and in four instances sheep population declines were > 20% (Masden, 2014). One of the main reasons given for these population declines is prolonged deep snow cover preventing access to vegetation for grazing, particularly during the spring time and especially when coupled with rapid thaw and freeze events that forms an ice crust over the vegetation. Given that the climate data used to construct our present worst climate scenarios largely overlaps in time with the sheep mortality data, it seems probable that similar levels of sheep mortality occurred during the time of the Norse at the Greenland middle fjord site. In these years, and in the even snowier years implied in the GCM scenarios, the levels of sheep mortality must have had significant negative consequences for the viability of pastoral
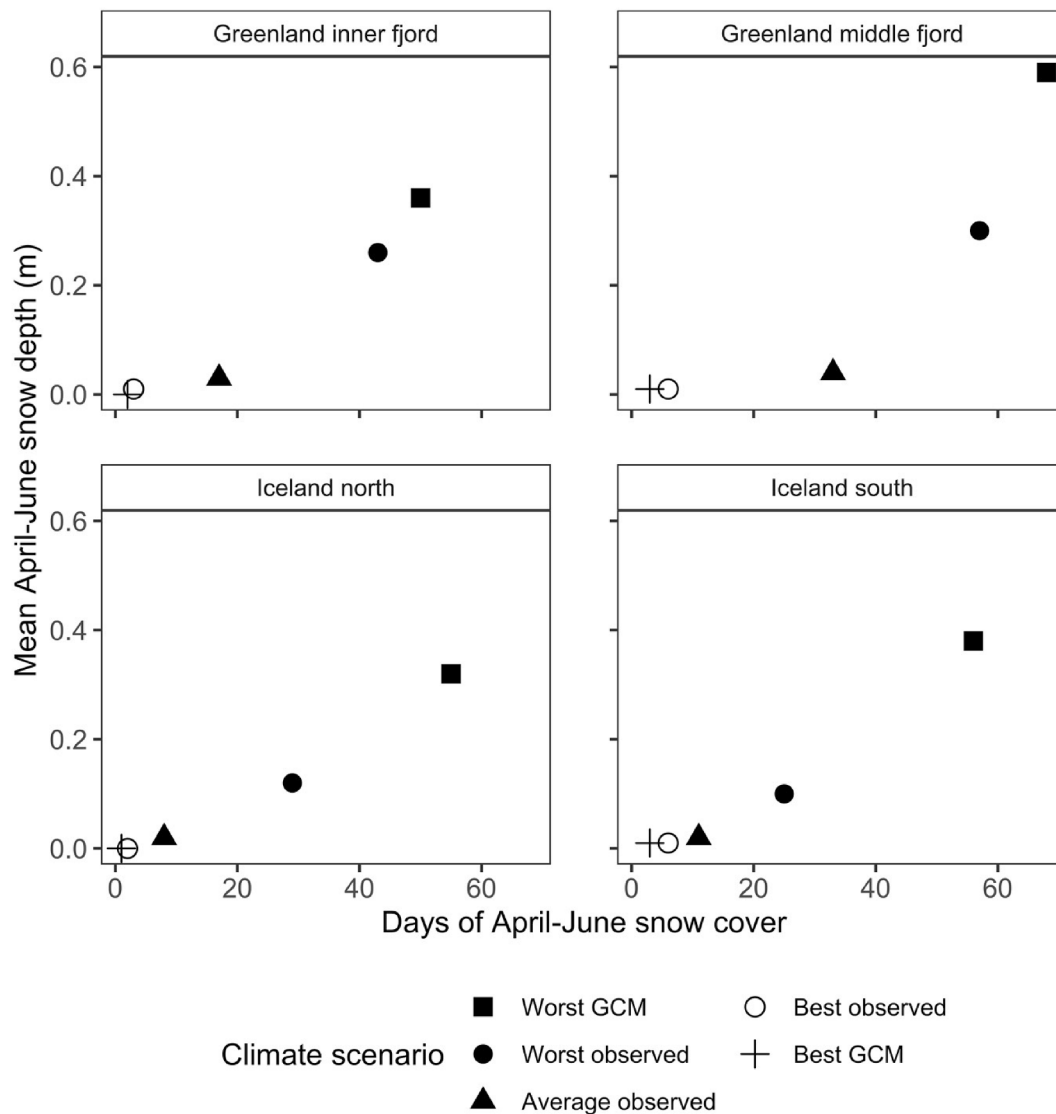
Fig. 5. Mean depth of snow against total number of days of snow cover (mean of the five output years for each scenario) for altitudes between 100 and 150 m asl.

farming at the middle fjord sites, and may have been pushed them towards a greater dependency on marine resources. Outer fjord areas tend to be colder and experience higher precipitation than the sites we consider here – it is likely the spring snow cover would have been even more extensive – and the impacts on seasonal farming larger. However, relatively few settlements were located in the outer fjord areas.

In contrast, years of modest snow cover at the inner fjord areas may have presented farmers with a different challenge in the late summer. Located on generally thin and nutrient poor soils overlying gravelly deposits, agrarian production in the inner fjord areas is vulnerable to prolonged draughts, which pose a frequent seasonal challenge to the present Inuit farmers, and likely affected the Norse as well (Adderley and Simpson, 2006). Upland, shaded snow patches would have provided a steady meltwater runoff to the water catchment areas that fed farms in the lowlands and, in the case of Ø47/Gardar (Krogh, 1974), an extensive water management and -irrigation system that could counteract the effects of draughts on homefield productivity. Evidence of Norse water management systems are rare in the middle to outer fjord environments (Arneborg, 2005), likely reflecting the higher annual precipitation and more prolonged snow cover in these areas.

In Iceland snow cover increased from lower starting levels, and in general snow cover scenarios are not as severe. However, the increase in snow cover from the worst present conditions to the worst GCM

conditions is considerable. These GCM climate scenarios suggest that at times during the LIA spring snow cover was severe (>50 days coverage, compared to ~ 10 days under average current conditions), even in the relatively mild south of Iceland. It seems likely that in these instances the consequences for livestock would have been similar to that observed in the Inuit records from Greenland.

We have considered individual extreme snow years. Yet, the cooling climate in the LIA would have not only changed the magnitude of extremes, but also increased the frequency of years with more extensive snow cover than average current climate conditions. Although individually these years would not have been as catastrophic as the worst snow-cover scenarios suggested by the GCM, if they occurred regularly there may have been a cumulative impact. Sheep mortality data from Inuit farms shows that it takes 2–7 years for free grazing sheep populations to recover to their previous levels after severe population declines (Madsen, 2014), suggesting that if years of extensive spring snow cover happened more frequently than a couple of times a decade, livestock recovery would have been at the least further delayed, and possibly livestock levels could decline below a level at which it was possible to recover from. Volcanically induced periods of climate cooling, for instance after the 1257 CE Samalas eruption (Sigl et al., 2015), may have resulted in more extensive than average snow cover conditions for several years in a row. Assuming this resulted in high levels of
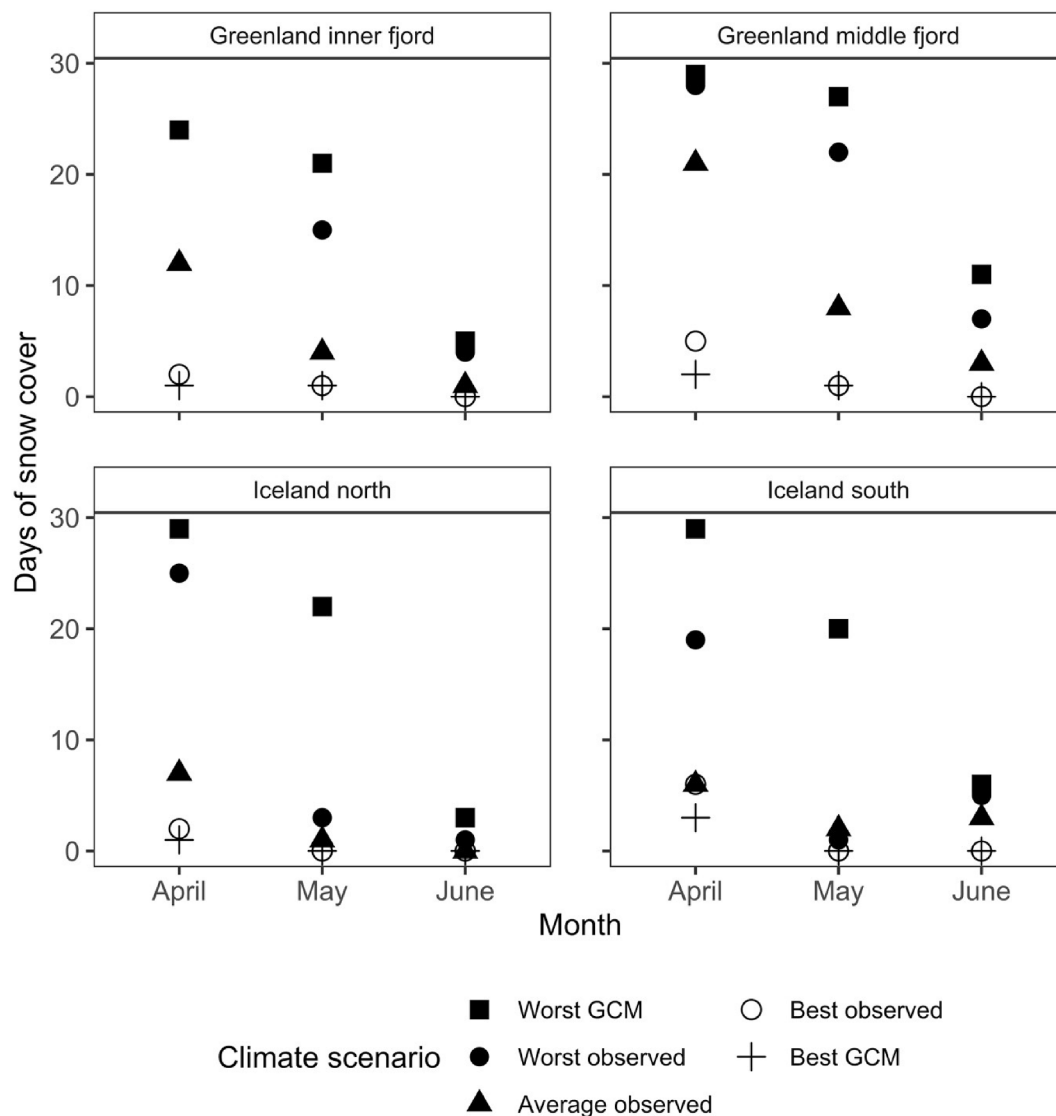
Fig. 6. Number of days of with snow cover (mean of the five output years for each scenario) by month and climate scenario for altitudes between 100 and 150 m asl.

cumulative livestock mortality then the concurrence of several snow winters may have had a significant impact on livestock numbers at our study sites.

4.2. Differences between Greenland and Iceland

A difference between the Iceland and Greenland sites is that, under average-present and cooler-than present-average conditions, the Iceland sites are similar in their levels of snow cover, but the Greenland sites differ in levels, depth and duration of snow cover (e.g. Fig. 7). This may reflect the fact that our Iceland north site is not the snowiest location within Iceland – there are higher altitude farms in the Myvátn region, and the far-north east of Iceland is cooler than our site at Hörgardalur. However, populated areas in Iceland which are notably snowier than Hörgardalur are likely to be limited, and we argue that our Iceland north site is a reasonable approximation for the cooler (but generally drier) north of Iceland. Therefore, in terms of spring snow cover, we would argue that the differences within Iceland were minimal, but significant between our sites in Greenland.

This spatial imbalance in degrees of snow cover during a period of cooling climate could have had wider ramifications in Greenland. It's generally accepted that Greenland had a more communal nature of subsistence provisioning, particularly the communal effort required to

obtain marine resources to fill the spring resource gap (Jackson et al., 2018b). Therefore the impact of snow on individual farms was also likely to have had an impact on the wider settlement. In the unfavourable climate of the 13th century, increasing intensification of the seal hunt could have been a very effective way to respond to the increased snow cover pressures which limited the terrestrial resources (Dugmore et al., 2012). However, the journey to the seal hunting areas would be increasingly risky in the unfavourable weather of the LIA. As has been argued elsewhere, if the population passed below the minimum threshold for communal activities and the maintenance of their provisioning networks (of domesticates, caribou, marine mammals), then the Greenland Norse would have faced a terminal subsistence crisis with increased snow cover limiting land based resources at some locations, population loss limiting marine hunting resources and insufficient alternative resource options for survival (Dugmore et al., 2012; Jackson et al., 2018b).

Although we have found that favourable sites in Greenland were not much more affected by increasing snow cover than in Iceland, we suggest that as a whole the Greenland settlement was more vulnerable to increasing spring snow cover. This is because the severe conditions at the middle and outer fjord sites would have had a wider impact due to the more integrated nature of Greenlandic society, and could certainly have been a key factor in pushing the Norse subsistence economy into
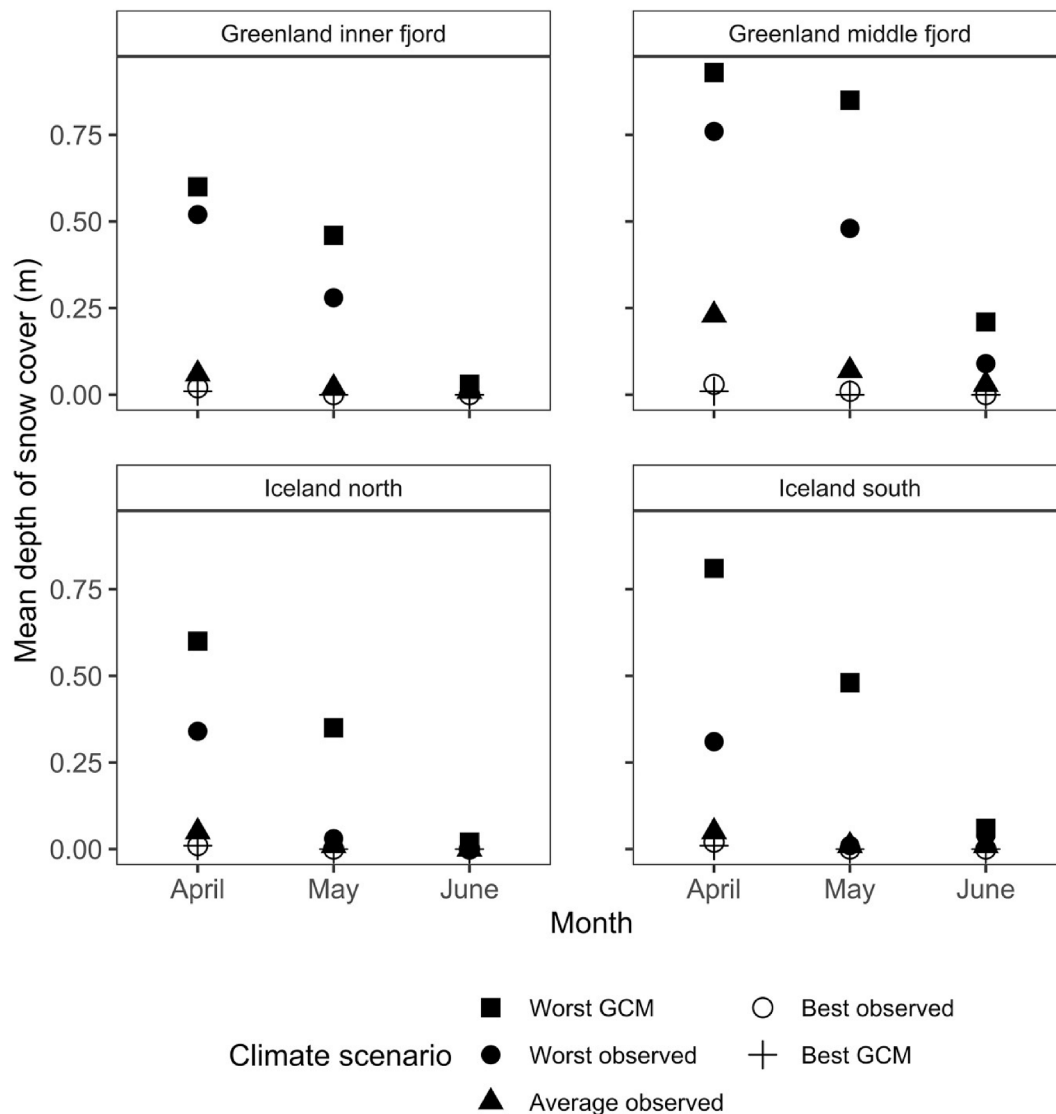
Fig. 7. Mean snow depth by month and climate scenario at altitudes between 100 and 150 m asl.

the marked marine subsistence regime shown in both zooarchaeological assemblages and human remains (McGovern 1985, 1992; Arneborg et al., 2012b, Jackson et al., 2018b).

4.3. The role of vegetation cover

The model is sensitive to vegetation cover because of the role of vegetation in trapping and retaining snow (Pomeroy and Gray, 1990). This emphasizes the importance of understanding the vegetation history at a site. Vegetation cover and height will have changed through time, affecting snow cover. The vegetation cover in both Greenland and Iceland was substantially altered as a result of the Norse settlement (e.g., Lawson et al., 2007; Ledger et al., 2014b).

The present extent of shrubby vegetation cover at the Iceland south site is one reason why snow cover at this site is deeper and longer lasting than might be expected by just looking at the climatic inputs. The large areas of shrub cover on rangeland areas away from farms are a consequence of local reductions in grazing intensity, reflecting an Iceland wide reduction in livestock stocking intensity over the last 40-years (Marteinsdóttir et al., 2017). Across Iceland, palynological evidence suggests that most areas near habitation were substantially clear of extensive shrub or woodland cover by CE 1300, but prior to CE 1300 shrub cover may have been more extensive in the wider landscape

(Streeter et al., 2015; Lawson et al., 2007). At the Iceland south site we suspect current shrub cover is probably more extensive than during most of the last 1,100 years, although we lack local pollen records to test this assumption. If this is the case, snow-cover depth and duration are likely to be slightly overestimated here compared to when the landscapes were covered with a well grazed grass sward.

In Greenland after the arrival of the Norse in CE 1000 there was also a similar change in vegetation to that observed in Iceland, with perhaps more evidence that woodland areas near the farms may have been sustainably managed and/or grazed (Ledger et al. 2014a). In the Vatnahverfi area (encompassing our middle fjord site) post-settlement vegetation change involved a switch from sparsely present to locally absent birch (*Betula pubescens*) woodland cover (Ledger et al., 2014). In other parts of Norse Greenland a general decline in shrub cover was observed (Massa et al., 2012; Edwards et al., 2008; Schofield et al., 2007). A photographic record prior to the mid-20th century renewal of sheep grazing supports the view that shrub cover at our Greenland sites during the Norse settlement was broadly similar to that observed today.

At sites where we lack good local palynological records (e.g. our Iceland south site) the uncertainty in our vegetation cover reconstructions will increase the uncertainty of the snow cover reconstruction. Additional local palynological data - particularly its modelled past extent over the landscape (e.g. using the Multiple Scenario

Approach; Bunting and Middleton, 2009) - would increase our confidence that vegetation cover was correctly represented in the model.

4.4. Implications for interpreting palaeoclimatic models and the past lived experience

Far less attention is given to changing precipitation in the LIA compared to temperature, primarily due to the difficulty of reconstructing it. Yet the findings here emphasise the importance of precipitation in snow cover. For example, in areas with high precipitation, relatively small declines in spring temperatures can rapidly increase the level of snow fall. We see this at our Iceland south site, which under most scenarios has limited snow cover, but under the coolest scenarios sees the largest increase in snow cover of all our sites. Conversely, at the colder sites, relatively small increases in precipitation would lead to large increases in snow cover. If snow cover, as we have argued, is an important variable for the success of these settlements, then changes in precipitation (which is affected in Iceland and Greenland by the strength of the North Atlantic Oscillation) should be given more consideration in discussions of the impact of a changing climate on the Norse settlements. Recent papers have used new methods to reconstruct changes in the North Atlantic Oscillation during the LIA, which may help better constrain precipitation estimates (Ortega et al., 2015).

5. Conclusion

This paper used a physical-based model of snow cover to investigate the range of spring snow cover conditions experienced by Norse settlements at sites in Iceland and Greenland, and discusses the implications of changing snow cover for the sustainability of pastoral farming at these sites.

Levels of snow cover under best current conditions and best GCM scenario are low at all sites. The most marked increase in snow cover across all sites is between worst current conditions and the worst GCM scenario. The worst GCM scenario represents the likely maximum spring snow cover during the period CE 1000–1500. All sites experience snow cover conditions under this scenario that would have represented a major challenge to pastoral farming.

Under cooler climate scenarios there is an increasing divergence between sites. This is most noticeable in the Greenland sites, where the middle fjord site experienced consistently snowier conditions than the inner fjord site, which had similar snow conditions to the Iceland sites. In Iceland settlement persisted, but by CE 1500 the Norse settlement in Greenland had ceased. Community based provisioning in Greenland and increasing reliance on marine resources due to snow cover limiting terrestrial resources meant that the increased snow cover conditions at the Greenland middle and outer fjord sites would have impacted the whole community. Changes in snow cover could have been a potential driver of transformative change contributing to the end of the Norse Greenland settlement.

We illustrate how physical-based models can be used to down-scale regional palaeoclimate reconstructions to the scale of communities, and to re-cast climate variables into climate characteristics that have a direct bearing on the success of subsistence activities, as originally suggested by Caseldine and Turney (2010). This approach can generate new insights into the impact of climate change on past-societies, and in doing so has the potential to aid long term sustainable planning in the face of anticipated future climate change.

CRediT authorship contribution statement

Laura E.L. Comeau: Methodology, Investigation, Formal analysis, Writing – original draft. **Richard T. Streeter:** Investigation, Project administration, Formal analysis, Writing – original draft. **Christian K. Madsen:** Writing – review & editing.

References

Adderly, P.W., Simpson, I.A., 2006. Soils and paleo-climate based evidence for irrigation requirements in Norse Greenland. J. Archaeol. Sci. 33, 1666–1679.

Amorosi, T., Buckland, P.C., Edwards, K.J., Mainland, I., McGovern, T.H., Sadler, J.P., Skidmore, P., 1998. They did not Live by Grass Alone: the Politics and Palaeoecology of Animal Fodder in the North Atlantic Region. Environ. Archaeol. 1 (1), 41–54.

Arneborg J, Lynnerup N and Heinemeier J (2012a). Human Diet and Subsistence Patterns in Norse Greenland AD c.980–AD c.1450: Archaeological Interpretations. *Journal of the North Atlantic*, Special Volume 3 - Greenland Isotope Project: Diet in Norse Greenland AD 1000–AD 1450:119-133.

Arneborg, J., Lynnerup, N., Heinemeier, J., Møhl, J., Rud, N., Sveinbjarnardóttir, Á.E., 2012. Norse Greenland Dietary Economy ca. AD 980-ca. AD 1450: Introduction. J. North Atl., Special 3, 1–39.

Arneborg, J. (2005) Greenland Irrigation Systems on a West Nordic Background. An overview of the evidence of irrigation systems in Norse Greenland c. 980-1450 AD. In: Klapste J (ed.) *Water Management in Medieval Rural Economy, Ruralia V. Památky Acheologické – Supplementum 17*, pp. 237-245.

Barlow, L.K., Sadler, J.P., Ogilvie, A.E.J., Buckland, P.C., Amorosi, T., Ingimundarson, J. H., Skidmore, P., Dugmore, A.J., McGovern, T.H., 1997. Interdisciplinary investigations of the end of the Norse Western Settlement in Greenland. The Holocene. 7 (4), 489–499.

Bocinsky, R.K., Kohler, T.A. (2014) A 2,000-year reconstruction of the rain-fed maize agricultural niche in the US Southwest. *Nature Communications.* 5(1): –12: doi: 10.1038/ncomms6618.

Bruun, D., 1895. Arkæologiske Undersøgelser i Julianehaabs Distrikt. Meddelelser om Grønland 16, 173–461.

Buckland, P.C., Edwards, K.J., Panagiotakopulu, E., Schofield, J.E., 2009. Palaeoecological and historical evidence for manuring and irrigation at Garðar (Igaliku), Norse Eastern Settlement, Greenland. The Holocene 19 (1), 105–116.

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J.O., Herzig, F., Heussner, K.-U., Wanner, H., Luterbacher, J., Esper, J., 2011. 2500 Years of European Climate Variability and Human Susceptibility. Science 331 (6017), 578–582.

Bunting, M.J., Middleton, R., 2009. Equifinality and uncertainty in the interpretation of pollen data: the multiple scenario approach to reconstruction of past vegetation mosaics. The Holocene 19, 799–803. https://doi.org/10.1177/0959683609105304.

Butzer, K.W., 2012. Collapse, environment, and society. Proc. Natl. Acad. Sci. 109 (10), 3632–3639. https://doi.org/10.1073/pnas.1114845109.

Caseldine, C.J., Turney, C., 2010. The bigger picture: towards integrating palaeoclimate and environmental data with a history of societal change. J. Quat. Sci. 25 (1), 88–93. https://doi.org/10.1002/jqs.1337.

Christiansen, B., Ljungqvist, F.C., 2012. The extra-tropical Northern Hemisphere temperature in the last two millennia: reconstructions of low-frequency variability. Clim. Past 8, 765–786.

Comeau, L.E.L. (2013) Snow modelling for understanding human ecodynamics in periods of climate change. Unpublished PhD thesis. The University of Edinburgh. Available at the Edinburgh Research Archive: http://hdl.handle.net/1842/8012.

Coombes, P., Barber, K., 2005. Environmental determinism in holocene research: causality or coincidence? Area 37 (3), 303–311.

Crowley, T.J., Lowery, T.S., 2000. Northern hemisphere temperature reconstruction. Ambio 29, 51–54.

d'Alpoim Guedes, J.A., Crabtree, S.A., Bocinsky, R.K., Kohler, T.A., 2016. Twenty-first century approaches to ancient problems: Climate and society. Proc. Natl. Acad. Sci. 113 (51), 14483–14491.

Dansgaard, W., Johnsen, S.J., Reeh, N., Gundestrup, N., Clausen, H.B., Hammer, C.U., 1975. Climatic changes, Norsemen and modern man. Nature 255 (5503), 24–28.

Dugmore, A.J., Church, M.J., Buckland, P.C., Edwards, K.J., Lawson, I., McGovern, T.H., Panagiotakopulu, E., Simpson, I.A., Skidmore, P., Sveinbjarnardóttir, G., 2005. The

Norse landnám on the North Atlantic islands: An environmental impact assessment. Polar Rec. 41 (1), 21–37.

Dugmore, A.J., McGovern, T.H., Vesteinsson, O., Arneborg, J., Streeter, R., Keller, C., 2012. Cultural adaptation, compounding vulnerabilities and conjunctures in Norse Greenland. Proc. Natl. Acad. Sci. 109 (10), 3658–3663. https://doi.org/10.1073/pnas.1115292109.

Edwards, K.J., Schofield, J.E., Mauquoy, D., 2008. High resolution paleoenvironmental and chronological investigations of Norse landnám at Tasiusaq, Eastern Settlement, Greenland. Quat. Res. 69 (1), 1–15.

Essery, R., Morin, S., Lejeune, Y., B Ménard, C., 2013. A comparison of 1701 snow models using observations from an alpine site. Adv. Water Resour. 55, 131–148.

Geirsdóttir, Á., Miller, G.H., Axford, Y., Sædís Ólafsdóttir, 2009. Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. Quat. Sci. Rev. 28 (21-22), 2107–2118.

Geirsdóttir, Á., Miller, G.H., Larsen, D.J., Ólafsdóttir, S., 2013. Abrupt Holocene climate transitions in the northern north Atlantic region recorded by synchronized lacustrine records in Iceland. Quat. Sci. Rev. 70, 48–62. https://doi.org/10.1016/j.quascirev.2013.03.010.

Harrison, R., 2014. Connecting the land to the sea at Gásir: International Exchange and Long-term Eyjafjörður Ecodynamics in medieval Iceland. In: Harrison, R., Maher, R. (Eds.), Human Ecodynamics in the North Atlantic: A Collaborative Model of Humans and Nature through Space and Time. Lexington Publishers, Lanham, Maryland, pp. 117–136.

Hartman, S., Ogilvie, A.E.J., Ingimundarson, J.H., Dugmore, A.J., Hambrecht, G., McGovern, T., 2017. Medieval Iceland, Greenland, and the New Human Condition: A case study in integrated environmental humanities. Global Planet. Change 156, 123–139.

Hock, R., 2003. Temperature index melt modelling in mountain areas. J. Hydrol. 282 (1–4), 104–115.

Holmes, N., Langdon, P.G., Caseldine, C.J., Wastegård, S., Leng, M.J., Croudace, I.W., Davies, S.M., 2016. Climatic variability during the last millennium in Western Iceland from lake sediment records. The Holocene 26 (5), 756–771.

Íslands, L., 2014. Free Digital Data, Landmælingar Íslands. accessed June 2015,. https://atlas.lmi.is/LmiData/index.php?id=502401439494.

Jackson, R., Arneborg, J., Dugmore, A., Madsen, C., McGovern, T., Smiarowski, K., Streeter, R., 2018b. Disequilibrium, Adaptation, and the Norse Settlement of Greenland. Hum Ecol 46 (5), 665–684.

Jackson, R.C., Dugmore, A.J., Riede, F., 2018a. Rediscovering lessons of adaptation from the past. Global Environ. Change 52, 58–65. https://doi.org/10.1016/j.gloenvcha.2018.05.006.

Jensen, K.G., Kuijerps, A., Koc, N., Heinemeier, J., 2004. Diatom evidence of hydrografhic changes and ice conditions in Igaliku Fjord, South Greenland, during the past 1500 years. The Holocene 14, 152–164.

Karlsson, G., 2000. Iceland's 1000 Years: History of a Marginal Society. Hurst & Company, London.

Kjær, K.H., Khan, S.A., Korsgaard, N.J., Wahr, J., Bamber, J.L., Hurkmans, R., van den Broeke, M., Timm, L.H., Kjeldsen, K.K., Bjørk, A.A., Larsen, N.K., Jørgensen, L.T., Færch-Jensen, A., Willerslev, E., 2012. Aerial Photographs Reveal Late-20th-century dynamic ice loss in northwestern Greenland. Science 337 (6094), 569–573.

Kohler, J., Brandt, O., Johansson, M., Callaghan, T., 2006. A long-term Arctic snow depth record from Abisko, northern Sweden, 1913–2004. Polar Res. 25 (2), 91–113.

Krogh, K.J., 1974. Kunstvanding - hemmeligheden bag Grønlandsbispens hundrede køer. Nationalmuseets Arbejdsmark 1974, 71–81.

Larsen, D.J., Miller, G.H., Geirsdóttir, Á., Thordarson, T., 2011. A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvítárvatn, Iceland. Quat. Sci. Rev. 30 (19-20), 2715–2731.

Lawson, I.T., Gathorne-Hardy, F.J., Church, M.J., Newton, A.J., Edwards, K.J., Dugmore, A.J., Einarsson, A., 2007. Environmental impacts of the Norse settlement: palaeoenvironmental data from Mývatnssveit, northern Iceland. Boreas 36 (1), 1–19.

Ledger, P.M., Edwards, K.J., Schofield, J.E., 2014a. A multiple profile approach to the palynological reconstruction of Norse landscapes in Greenland's Eastern Settlement. Quat. Res. 82 (1), 22–37.

Ledger, P.M., Edwards, K.J., Schofield, E.J. (2014b) Vatnahverfi: A Green and Pleasant land? Palaeoecological Reconstructions of Environmental and Land-use Change. *Journal of Archaeological Research*, Special Volume 6 - In The Footsteeps of Vebæk—Vatnahverfi Studies 2005-2011, 29-46.

Liston, G.E., Elder, K., 2006. A meteorological distribution system for high- resolution terrestrial modelling (MicroMet). J. Hydrometeorol. 7, 217–234.

Liston, G.E., Haehnel, R.B., Sturm, M., Hiemstra, C.A., Berezovskaya, S., Tabler, R.D., 2007. Instruments and methods Simulating complex snow distributions in windy environments using SnowTran-3D. J. Glaciol. 53 (181), 241–256.

Luce, C.H., Tarboton, D.G., Cooley, R.R., 1998. The influence of the spatial distribution of snow on basin-averaged snowmelt. Hydrol. Process. 12 (10–11), 1671–1683.

Madsen, C.K., 2008. 'Far, geder og fold i det norrøne Vatnahverfi'. Tidsskriftet Grønland 1, 4–14.

Madsen, C.K. (2014) *Pastoral Settlement, Farming, and Hierarchy in Norse Vatnahverfi, South Greenland*. University of Copenhagen, Unpublished PhD thesis. 440 pp.

Mann, M.E., Zhang, Z., Rutherford, S., Bradley, R.S., Hughes, M.K., Shindell, D., Ammann, C., Faluvegi, G., Ni, F., 2009. Global signatures and dynamical origins of the little ice age and medieval climate anomaly. Science 326 (5957), 1256–1260.

Mann, M.E., Fuentes, J.D., Rutherford, S., 2012. Underestimation of volcanic cooling in tree-ring-based reconstructions of hemispheric temperatures. Nat. Geosci. 5 (3), 202–205.

Marteinsdóttir, B., Barrio, I.C., Jónsdóttir, I.S., 2017. Assessing the Ecological Impacts of Extensive Sheep Grazing in Iceland. Icel. Agric. Sci. 30, 55–72. https://doi.org/10.16886/IAS.2017.07.

Massa, C., Perren, B.B., Gauthier, É., Bichet, V., Petit, C., Richard, H., 2012. A multiproxy evaluation of Holocene environmental change from Lake Igalíku, South Greenland. J. Paleolimnol. 48 (1), 241–258.

Massé, G., Rowland, S.J., Sicre, M.A., Jacob, J., Jansen, E., Belt, S.T. (2008) Abrupt climate changes for Iceland during the last millennium: Evidence from high resolution sea ice reconstructions. *Earth and Planetary Science Letters* 269(3-4): 565–569: doi:10.1016/j.epsl.2008.03.017.

McGovern, T.H., 1985. Contributions to the Paleoeconomy of Norse Greenland. Acta Archaeologica 54, 73–122.

McGovern, T.H., 1992. Bones, Buildings, and Boundaries: Palaeoeconomic Approaches to Norse Greenland. In: Morris, C.D., Rackham, D.J. (Eds.), Norse and Later Settlement and subsistence in the North Atlantic. Department of Archaeology, University of Glasgow, Glasgow.

Millet, L., Massa, C., Bichet, V., Frossard, V., Belle, S., Gauthier, E., 2014. Anthropogenic versus climatic control in a high-resolution 1500-year chironomid stratigraphy from a southwestern Greenland lake. Quat. Res. 81 (2), 193–202.

Nørlund, P., 1929. Norse ruins at Gardar. The Episcopal Seat of Mediaeval Greenland. Meddelelser om Grønland 76, 7–170.

Ogilvie, A.E.J., 1984. The past climate and sea-ice record from Iceland, Part 1: Data to A. D. 1780. Clim. Change 6 (2), 131–152. https://doi.org/10.1007/BF00144609.

Ogilvie, A.E.J., 2010. Historical climatology, Climatic change, and implications for climate science in the 21st Century. Clim. Change 100, 33–47.

Ogilvie, A.E.J., Jonsson, T., 2001. "Little ice Age" research: A perspective from Iceland. Clim. Change 48, 9–52.

Ogilvie, A.E.J., Wollet, J.M., Smiarowski, K., Arneborg, J., Troelstra, S., Kuijpers, A., Pálsdóttir, A., McGovern, T.H., 2009. Seals and sea ice in medieval greenland. J. N. Atl. 2 (1), 60–80.

Ortega, P., Lehner, F., Swingedouw, D., Masson-Delmotte, V., Raible, C.C., Casado, M., Yiou, P., 2015. A model-tested North Atlantic Oscillation reconstruction for the past millennium. Nature 523 (7558), 71–74.

Panagiotakopulu, E., Greenwood, M.T., Buckland, P.C., 2012. Insect Fossils and irrigation in Medieval Greenland. Geografiska Annaler: Series A, Physical Geography 94 (4), 531–548.

Patterson, W.P., Dietrich, K.A., Holmden, C., Andrews, J.T., 2010. Two millennia of North Atlantic seasonality and implications for Norse colonies. Proc. Natl. Acad. Sci. 107 (12), 5306–5310. https://doi.org/10.1073/pnas.0902522107.

Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.-M., Tucker, C.J., Stenseth, N.C., 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends Ecol. Evol. 20 (9), 503–510.

Pomeroy, J., Gray, D.M. (1995) *Snow accumulation, relocation and management*, NHRI Science Report No.7. Environment Canada, Saskatoon. 144pp.

Pomeroy, J.W., Gray, D.M., 1990. Saltation of snow. Water Resour. Res. 26 (7), 1583–1594.

Reichler, T., Kim, J., 2008. How well do coupled models simulate today's climate? Bull. Am. Meteorol. Soc. 89, 303–311.

Rixen, C., Freppaz, M., Stoeckli, V., Huovinen, C., Huovinen, K., Wipf, S., 2008. Altered snow density and chemistry change soil nitrogen mineralization and plant growth. Arct. Antarct. Alp. Res. 40 (3), 568–575.

Roettger, S. (2007) *NDVI-based Vegetation Rendering*. Paper presented at the Computer Graphics and Imaging CGIM '07, Innsbruck, Austria. Proceedings of the Ninth IASTED International Conference on Computer Graphics and Imaging, Pages 41-45, ACTA Press Anaheim, CA, USA.

Schofield, E.J., Edwards, K.J., Christensen, C., 2007. Environmental impacts around the time of Norse landnám in the Qorlortoq valley, Eastern Settlement, Greenland. J. Archaeol. Sci. 35, 1643–1657.

Schofield, J.E., Edwards, K.J., Erlendsson, E., Ledger, P.M., Svenning, J.-C., 2013. Palynology supports 'Old Norse' introductions to the flora of Greenland. J. Biogeogr. 40 (6), 1119–1130.

Schurer, A.P., Hegerl, G.C., Mann, M.E., Tett, S.F.B., Phipps, S.J., 2013. Separating Forced from Chaotic Climate Variability over the Past Millennium. *J. Climate*. American Meteorological Society 26 (18), 6954–6973. https://doi.org/10.1175/JCLI-D-12-00826.1.

Sigl, M., Winstrup, M., McConnell, J.R., Welten, K.C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C., Maselli, O.J., Mekhaldi, F., Mulvaney, R., Muscheler, R., Pasteris, D.R., Pilcher, J.R., Salzer, M., Schüpbach, S., Steffensen, J.P., Vinther, B.M., Woodruff, T. E., 2015. Timing and climate forcing of volcanic eruptions for the past 2,500 years. Nature 523 (7562), 543–549.

Simpson, I.A., Gudmundsson, G., Thomson, A.M., Cluett, J., 2004. Assessing the role of winter grazing in historic land degradation, Myvatnssveit, northeast Iceland. *Geoarchaeology-an*. International Journal 19 (5), 471–502. https://doi.org/10.1002/gea.20006.

Stoffel, M., Khodri, M., Corona, C., Guillet, S., Poulain, V., Bekki, S., Guiot, J., Luckman, B.H., Oppenheimer, C., Lebas, N., Beniston, M., Masson-Delmotte, V., 2015. Estimates of volcanic-induced cooling in the Northern Hemisphere over the past 1,500 years. Nat. Geosci. 8 (10), 784–788.

Stott, P.A., Tett, S.F.B., Jones, G.S., Allen, M.R., Mitchell, J.F.B., Jenkins, G.J., 2000. External Control of 20th Century Temperature by Natural and Anthropogenic Forcings. Science 290 (5499), 2133–2137.

Streeter, R., Dugmore, A.J., Vésteinsson, O., 2012. Plague and landscape resilience in premodern Iceland. Proc. Natl. Acad. Sci. U.S.A 109 (10), 3664–3669.

Streeter, R.T., Dugmore, A.J., 2013. Reconstructing late-Holocene environmental change in Iceland using high-resolution tephrochronology. Holocene 23 (2), 197–207.

Streeter, R., Dugmore, A., 2014. Late-Holocene land surface change in a coupled social–ecological system, southern Iceland: a cross-scale tephrochronology

approach. Quat. Sci. Rev. 86, 99–114. https://doi.org/10.1016/j.quascirev.2013.12.016.

Streeter, R., Dugmore, A.J., Lawson, I.T., Erlendsson, E., Edwards, K.J., 2015. The onset of the palaeoanthropocene in Iceland: Changes in complex natural systems. The Holocene 25 (10), 1662–1675. https://doi.org/10.1177/0959683615594468.

Thomson, A.M., Simpson, I.A., 2006. A grazing model for simulating the impact of historical land management decisions in sensitive landscapes: Model design and validation. Environ. Modell. Software 21 (8), 1096–1113. https://doi.org/10.1016/j.envsoft.2005.05.008.

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., Frank, D.C., 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. Science 324 (5923), 78–80.

Vebæk, C.L., 1943. Inland farms in the Norse East Settlement. Meddelelser om Grønland 90, 1–120.

Vésteinsson, O., McGovern, T.H., 2012. The peopling of Iceland. *Nor. Archaeol. Rev.* Routledge 45 (2), 206–218. https://doi.org/10.1080/00293652.2012.721792.

Waichler, S.R., Wigmosta, M.S., 2002. Development of hourly meteorological values from daily data and significance to hydrological modelling at H.J. Andrews experimental forest. J. Hydrometeorol. 4, 251–263.

White, S., 2014. The real little ice age. *J. Interdiscip. Hist.,* XLIV 3, 327–352.

Further reading

Schofield, J.E., Edwards, K.J., 2011. Grazing impacts and woodland management in Eriksfjord: Betula, coprophilous fungi and the Norse settlement of Greenland. Vegetation History and Archaeobotany. 20 (3), 181–197.