Late Holocene climatic Forcing of Geomorphic Activity in the Faroe Islands

Seinholosena veðurlagið elvdi til jarðformandi virksemi í Føroyum

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Úrtak

Veðurlagið í Føroyum er óstøðugt.Tí ber til at skráseta, nær og hvussu ógvisligar seinholosenar veðurlagsbroytingar eru, sum endurspegla broytingar í termohalinu ringrásini. Hædd millum 250-450 m yvir sjóvarmálanum er nútíðar lágmarkið fyri periglasialum virksemi; tað svarar til ein árligan miðallufttemperatur upp á 5-3,5°C. Oman fyri hesa hæddina eru virkin periglasial drøg vanlig, og gróðurin lítil. Periglasiala økið røkkur til hægsta hálendi (mesta hædd er 882 m yvir sjóvarmálanum). Veðurlagið í Føroyum seint í 20. øld er merkt av sera nógvari vætu og nógvum vindi heldur enn av ógvisligum kulda. Nútíðar træmarkið er nær sjóvarmálanum, og í dag er tann møguliga ósamanhangandi permafrosthæddin 300-500 m oman fyri tey hægstu fjøllini. Á sama hátt man tann møguliga glasiatiónshæddin í dag bert vera 150-250 m oman fyri tey hægstu fjøllini. Meðan køld millumbil vóru í teirri lítlu ístíðini, kann tað lægra markið fyri periglasialum virksemi bráðfeingis hava nærkað seg sjóvarmálanum, samstundis sum permafrost fór at taka seg upp her og har í hálendinum, og tá vóru nøkur støð á teimum hægstu fjøllunum óivað nær endurglasiatión.

Abstract

The location of the Faroe Islands in a climatically uniquely sensitive part of the North Atlantic region provides opportunities to register timing and severity of late Holocene climatic changes reflecting variations in thermohaline circulation. An altitudinal range of 250-450 m a.s.l. represents the modern lower limit for periglacial activity, corresponding to a mean annual air temperature of 5-3.5°C. Above this range, active periglacial features are widespread and plant growth restricted. The periglacial zone extends to the top of the highlands (maximum altitude 882 m a.s.l.). The late 20th century climate in the Faroe Islands is characterised by extreme humidity and strong winds, rather than extreme cold. The present treeline is close to sea level, and the potential present discontinuous permafrost level is situated 300-500 m above the highest mountains. Likewise, the modern potential glaciation level is presumably situated only 150-250 m above the highest mountains. During cold intervals of the Little Ice Age the lower limit for periglacial activity may temporarily have approached sea level, simultaneous with incipient establishment of sporadic permafrost in the highlands, and a number of sites in the highest mountains then were presumably close to reglaciation.

Introduction

Analysis of meteorological land and marine temperatures indicate that the planet surface has heated about 0.5°C since the late 19th century (Jones and Briffa, 1992). The observed warming, however, has not been equal everywhere, nor equal throughout the seasons. Some of the greatest warming has occurred over continental areas of the Northern Hemisphere, while other regions, especially oceanic, have cooled. Research on global climate change indicates that, in general, land surfaces will heat or cool more rapidly than oceans and that temperature variations within especially high-latitudinal regions will be pronounced (Houghton *et al.*, 1996), mainly due to the operation of various, interrelated climatic feedback mechanisms (Kellogg, 1973).

Instrumentally recorded surface temperature observations indicate the North Atlantic region including Greenland and Iceland to have cooled significantly in the latter half of the 20th century (Jones and Briffa, 1992; Houghton *et al.*, 1996), which makes this an important area for global change research, past and present. Oceanic circulation in the North Atlantic plays a major role in determining poleward energy transfer in the northern hemisphere, and is thought to be a key factor regulating global climate change (e.g., Ruddiman and McIntyre, 1981; Broecker *et al.*, 1985; Rind *et al.*, 1986; Bard *et al.*, 1987; Broecker and Denton, 1990; Lehman and Keigwin, 1992; Koç *et al.*, 1993; Bigg, 1996; Björck *et al.*, 1996; Rasmussen *et al.*, 1997).

Within the North Atlantic region the Faroe Islands are situated in a uniquely sensitive part of the North Atlantic Ocean for registering the timing and severity of late Quaternary climatic changes (Humlum *et al.*, 1996; Humlum, 1998). Warm and saline Atlantic surface water presently flows around the Faroe Islands into the Norwegian and Greenland Seas, where evaporation and cooling during winter produces a gradually higher water density. This dense water then overturns, probably in very localised regions up to a few tens of kilometres in diameter, resulting in deep convection (Bigg, 1996). The sinking cold water represents a major constituent of North Atlantic Deep Water, part of the global thermohaline circulation, and is considered of global importance (Broecker, 1991). In comparatively warm periods, when generally strong, or northward-displaced, circulation occurs in the atmosphere and ocean, the Faroe Islands lie continually in the main arm of the North Atlantic Drift. In colder periods, when the North Atlantic Drift weakens or its main branch takes a more southerly position, a tongue of polar water from the East Iceland branch of the East Greenland Current approaches the Faroe Islands from the northwest. As a consequence, the Faroe Islands are well placed to register terrestrial geomorphic imprints of any large amplitude shifts of the water current boundary in the North Atlantic, both past and present.

Topography and geology

The Faroe Islands have a total area of 1397 km^2 and are situated between 61°20'N – 62°24'N and 6°15'W and 7°41'W. The highlands rise gradually from about 400-600 m a.s.l. in the southern part of the islands to almost 900 m a.s.l. in the northern and northeastern areas (Fig. 1). The average altitude is about 300 m a.s.l. The northeastern part of the Faroe Islands is dominated by alpine topography, while rolling highland plateaus delimited by steep headwalls characterise the remaining regions. The bedrock is Tertiary-age plateau basalts, about 50-60 million years old, gently dip-

Fig. 1. Slættaratindur (882 m a.s.l.), highest mountain in the Faroe Islands, seen from NE. The snow-filled upper part of the large cirque valley east of the summit is called Gívrabotnur. Northern Eysturoy. May 1995.
Mynd 1. Slættaratindur (882 m), hægsta fjall í Føroyum, sæð úr landnyrðingi. Tann kavaklæddi ovari parturin av botninum eystur úr tindinum eitur Gívrabotnur. Norðureysturoy. Mai 1995.

ping eastward, having a total thickness of at least 5,200 m (Rasmussen and Noe-Nygaard, 1970; Berthelsen *et al.*, 1984). Since termination of Tertiary volcanic activity, coastal erosion has gradually reduced the area of the islands, simultaneous with their slow sinking into the crust due to cooling and isostatic effects. The humid and warm Tertiary climate caused strong chemical erosion, by which a low relief (100-200 m) rolling landscape evolved during the late Tertiary (Humlum, 1996).

Late Weichselian and Holocene environment

The fluctuating Quaternary climate has left significant cold-climate geomorphic imprints such as glacial trough valleys, cirques and glacially abraded bedrock surfaces in the Tertiary landscape. Regional mapping of glacial striae indicates that several local ice caps accumulated in the Faroes in the Weichselian, covering the landscape up to about 700 m a.s.l. in the north-central part of the islands, and extending beyond the present coastline onto the surrounding shelf (Jørgensen and Ras-

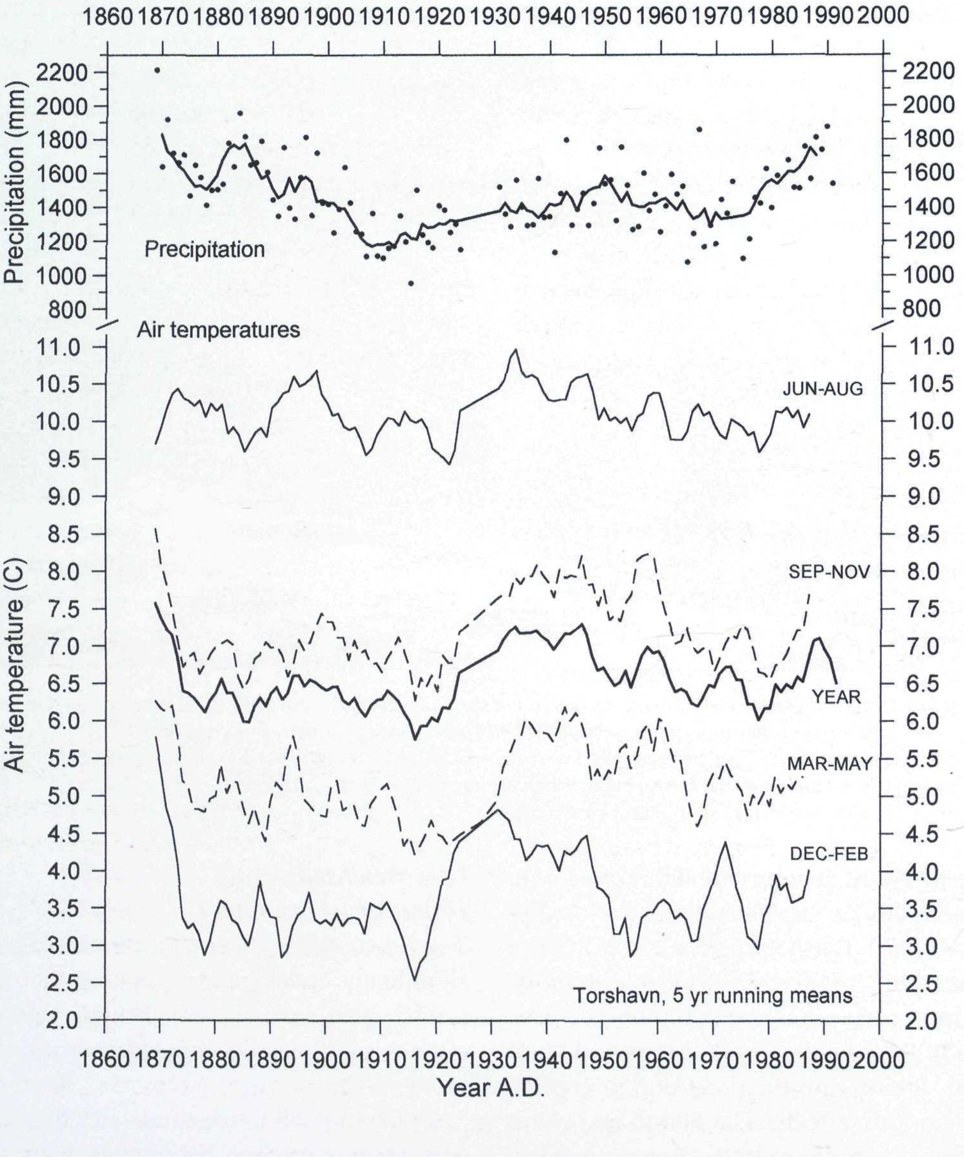

Fig. 2. Precipitation (mm water equivalent) and air temperatures (annual and seasonal) in Tórshavn AD 1867-1995. Dots represent the individual annual value, while the continuous lines indicate the 5 yr. running mean. Sources: Danish Meteorological Institute.

Mynd 2. Avfall (svarar til mm av vatni) og lufttemperaturur (árligur og árstíðar-) í Tórshavn 1867-1995. Prikkar standa fyri teimum einstøku árligu virðunum, meðan tær óbrotnu linjurnar vísa miðalvirðini 5 ár upp í slag. Kelda: Dansk Meteorologisk Institut.

mussen, 1986). Assuming a postglacial eustatic sea level rise of about 125-130 m (Pirazzoli, 1996), the mean regional maximum Weichselian ice thickness can not have exceeded 350-400 m, as there are no late Weichselian or Holocene-age raised beaches on the Faroe Islands (Humlum *et al.*, 1996).

Little is known about the late Weichselian deglaciation of the Faroe Islands. Most investigations note a conspicuous lack of recessional or readvance moraine systems; only dead-ice features and ancient medial moraine accumulations have been described from certain major valleys on Streymoy (Sugden and John, 1976); Jørgensen and Rasmussen, 1986). However, a series of rather small, but distinctive, moraine ridges relating to a final valley and cirque glaciation was recently described by Humlum *et al.* (1996). By comparing with reconstructed Loch Lomond equilibrium line altitudes from Scotland, a tentative Younger Dryas age was suggested for these moraine systems. Proper dating of the moraines has not yet been successful, and when the Faroe Islands became ice-free in the late Weichselian is therefore still unknown. The oldest relevant ^{14}C date, obtained from a lake-bottom core near Tórshavn, gives an age of 9,660±150 BP (^{14}C-years; Jóhansen, 1975; 1985). There is no indication of any Holocene reglaciation in the Faroe Islands (Humlum *et al.*, 1996), and probably, the islands have been exposed to cold, non-glacial (periglacial) conditions for the last 10000-15000 years.

The early Holocene (Preboreal 10000-9000 ^{14}C-yrs BP) climate on the Faroe Islands was arctic-subarctic with the arrival of plant species such as *Betula nana* (Jóhansen, 1985). In Boreal times (9000-8000 ^{14}C-yrs BP) the climate changed towards more oceanic conditions, with disappearance of *Betula nana*. Plant species such as *Juniperus* and *Salix* expanded, covering the lowlands, together with tall-herb vegetation and grass heaths. The Atlantic period (8000-5000 ^{14}C-yrs BP) was wet, with evidence of strong leaching of soils. Peat began to accumulate, especially on high grounds. From the onset of the Subboreal (5000-2500 ^{14}C-yrs BP), climate became cooler and wetter leading to widespread peat formation and decreasing frequency of *Juniperus* and *Salix*. Subatlantic time (2500-0 ^{14}C-yrs BP) brought the arrival of man in possibly two phases, AD 600-700 and AD 800-900, most likely monks from Ireland and the Vikings, respectively, although researchers do not entirely agree on this issue (Mortensen, 1994; Haywood, 1995). The Subatlantic period was punctuated by the so-called Little Ice Age (roughly AD 1300-1900).

With the exception of few, isolated stands of *Betula pubescens* (dated to about 4300 BP, Jóhansen, 1989), there have been no natural forests on the Faroe Islands during the Holocene, and the predominant vegetation is of the heath type. In particular grass heaths are widespread (Tuhkanen, 1987), and give the islands their characteristic green summer appearance. The grazing of sheep (about 70000) may have converted areas originally covered by dwarf-shrub heaths into grass heaths (Gimingham, 1964).

Climate during the instrumental period

Meteorological observations were initiated in Tórshavn AD 1867 by the Danish Meteorological Institute, and the complete temperature data series obtained is summarised in Figure 2, showing the mean annual air temperature (MAAT) as well as seasonal values. In general, interannual temperature variations in Tórshavn since AD 1867 are seen to be substantial (1-2°C) for the winter season, December-February, and smaller (0.1-0.3°C) for the summer season, June-August. The spring (March-May) and the autumn (September-November) both display medium year-to-year variations (0.2-0.8°C). Most of the registered interannual variation in MAAT is derived from winter temperature variations, and comparatively little is derived from summer temperature variations.

The oldest observations (AD 1867-72) indicate a substantial cooling, even though summer temperatures then were on the rise, leading up to a cold period lasting about 45 years, characterised by MAAT ranging from 6 to 6.5 °C. This period represents the last cold interval of the Little Ice Age (LIA), and was terminated by a marked warming from AD 1920 to 1930, clearly reflected in the MAAT, but primarily affecting the winter season (Fig. 2). Since then, air temperatures in Tórshavn have shown a gradual falling trend. To illustrate this, the Tórshavn AD 1931-60 MAAT was 7.0°C, but only 6.5°C AD 1961-90, and in the late 20th century the Tórshavn climate is again approaching the cold character experienced AD 1872-1920. One may wonder if the Little Ice Age really ended AD 1920 in the Faroe Islands? Smaller variations of ±0.5°C with 10-15 yr periods are superimposed upon this overall climatic evolution. These variations presumably reflect contemporary variations in water temperature and intensity of the North Atlantic Drift such as documented by Hansen and Meincke (1984). The North Atlantic Drift presently flows around the Faroe Islands with a typical velocity of 0.1-0.3 ms^{-1} and a mean SST of 8°C (Hansen, 1996). In the absence of the North Atlantic Drift, considering the latitude, winter air temperatures would probably be at least 6-7°C lower than at present (Søgaard, 1996).

Precipitation in Tórshavn also varied significantly during the instrumental period (Fig. 2). The mean annual precipitation for the whole period is 1471 mm water equivalent (w.e.), but the annual precipitation has varied significantly from about 900 to 2200 mm w.e. through a number of periods of varying length, very much different from contemporary variations of both MAAT and seasonal temperatures. As an example, the first half of the final Little Ice Age cold interval was characterised by rather wet conditions, while the latter half was comparatively dry. Also the temperature maxima around AD 1930 were associated with dry conditions, while especially the late 20th century climate has been characterised by comparatively high precipitation. It appears noteworthy that the marked rise in MAAT AD 1920-30 is not reflected by variations in the annual precipitation.

Projections of sea-level rise due to anticipated modern greenhouse warming often involves the assumption that increased wa-

Fig. 3. *Active small-scale sorted stripes at 460 m a.s.l., southern Borðoy. The stripes measures 10-20 cm across, and the sorting is shallow (5-10 cm). The terrain slopes about 10 degrees. May 1995.*
Mynd 3. Virknar smáar sundurskildar rípur 460 m yvir sjóvarmálanum sunnarlaga í Borðoy. Rípurnar eru 10-20 m tvørvegis, og tær eru grunnar (5-10 cm). Lendið hellir um 10 stig. Mai 1995.

ter vapour pressure will enhance snow accumulation in cold regions of ice sheets, thereby partially offsetting the increased ablation of low-latitude and low-altitude glaciers (Houghton *et al.*, 1996). During the instrumental period in Tórshavn other parameters such as the overall atmospheric circulation as well as oceanographic conditions, rather than air temperature appear to be the primary control on precipitation in the SE North Atlantic region. Precipitation varies according to a different scheme than can be explained in purely thermodynamic terms, most likely because of regional changes in storm tracks. This kind of meteorological complexity was demonstrated as early as in the AD 1970s for Canada by Bowling (1974).

Modern climate

The modern climate of the Faroe Islands is strongly maritime in character, windy, humid and changeable, reflecting proximity to the sea and the moderating influence of

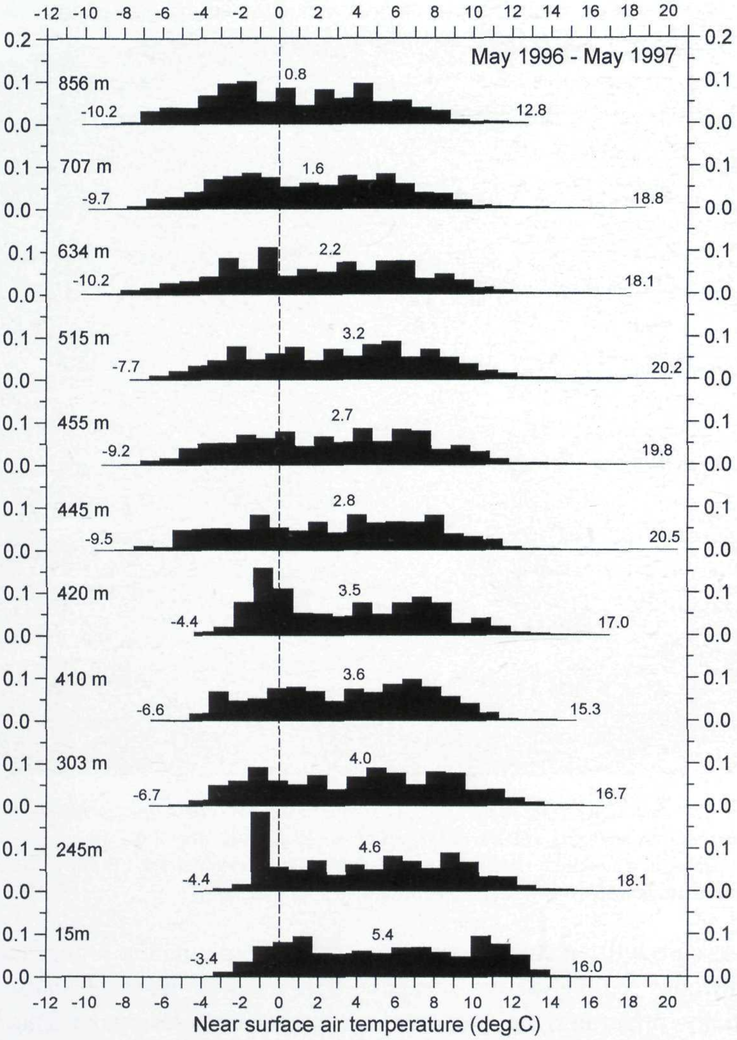

Fig. 4. Range and frequency distribution of air temperatures from May 1996 to May 1997 at different altitudes above sea level in the Slættaratindur massif, northern Eysturoy. For each site the minimum, mean and maximum temperature (°C) are indicated, as are the observational site altitudes (m a.s.l.). The vertical stippled line indicates 0°C. Frequency (0-1) is shown along the vertical axis. The site at 856 m a.s.l. is represented by the summit of the mountain Gráfelli, likewise northern Eysturoy.

Mynd 4. Økis- og títtleikabýti av lufttemperaturi frá mai 1996 til mai 1997 í ymiskum hæddum á rygginum á Slættaratindi í norðara parti av Eysturoynni. Á hvørjum stað verður lágmarks-, miðal- og hámarkstemperaturin (°C) vístur, eins og hæddin (yvir sjóvarmálanum) á kanningarstøðunum eisini verður víst. Tann loddrætta prikkalinjan vísir 0°C. Títtleikin (0-1) sæst á uppásini. Staðið, ið er 856 m yvir sjóvarmálanum, er fjallið Gráfelli, sum eisini er í norðara parti av Eysturoy.

the North Atlantic Drift. Rapid variations in weather (often within few hours) are characteristic of the present Faroese climate. In Tórshavn, close to sea level, the MAAT is 6.5°C (AD 1961-1990), with year-to-year variations of 0.5-1.5°C. August is the warmest month with 10.5°C and January the coldest with 3.2°C. The annual mean precipitation is less than 900 mm w.e. in the west (Mykines), increasing to almost 2,800 mm w.e. in the mountainous northern and eastern part of the islands (Hansen, 1990; Søgaard, 1996). As an average, precipitation is registered in Tórshavn on 3 out of 4 days. Fog is common and relative humidity is high throughout the year. The dominant wind direction is from the W, SW and S. In many places, however, the topography causes a local air flow pattern. The average wind speed is high, 7.2 m/s (AD 1961-1995; data obtained by the Danish Meteorological Institute) at exposed Akraberg, southern Suðuroy, and has shown an increasing trend since the early AD 1970s, for the time being with a culmination AD 1989 to 1993. During this five-year period the average wind speed at Akraberg was no less than 10.5 m/s. In the classical Köppen system (Köppen, 1918), the Faroe Islands fall within the type Cfc, a moist, temperate climate with cool summers. This, however, only applies for altitudes close to sea level.

Knowledge on the mountain climate of the Faroe Islands is poor as most meteorological stations are located at low altitudes. Above 200-300 m a.s.l. the widespread occurrence of small-scale patterned ground phenomena (Fig. 3), solifluction features and deflation surfaces, suggests a mountain climate characterised by extreme humidity and strong winds rather than extreme cold (Christiansen, 1988; Humlum and Christiansen, in press). Adopting a standard vertical lapse rate of about 0.0065°Cm^{-1}, the modern mean winter air temperature in the highlands is expected to lie between -3°C and 0°C, with mean annual temperatures in the range of 1°C to 4°C (Hansen, 1990).

In the northern hemisphere the principal premise for distinguishing the Arctic zone is frequently treelessness, so that all areas lying north of the treeline are regarded as part of the Arctic zone or tundra (Tuhkanen, 1987). In low-relief regions the 'treeline' may take the form of a 50-100 km wide zone (French, 1996), while in high-relief areas this boundary is well-defined, approximately coinciding with a mean air temperature of 10°C for the warmest month. On the Faroe Islands the warmest month is slightly above 10°C at sea level, and the modern treeline is located 0-100 m above sea level, so from this point of view the major part of the Faroese landscape is clearly within the Arctic or periglacial domain.

Late 20th century mountain climate

In 1995 a limited meteorological programme was begun in the highest mountain massif in the Faroe Islands, the Slættaratindur region, northern Eysturoy, to obtain information on the effect of altitude, topographic shadow, aspect and distance from the sea (Humlum and Christiansen, in press). From May 1995 to May 1996 five daily measurements were carried out at

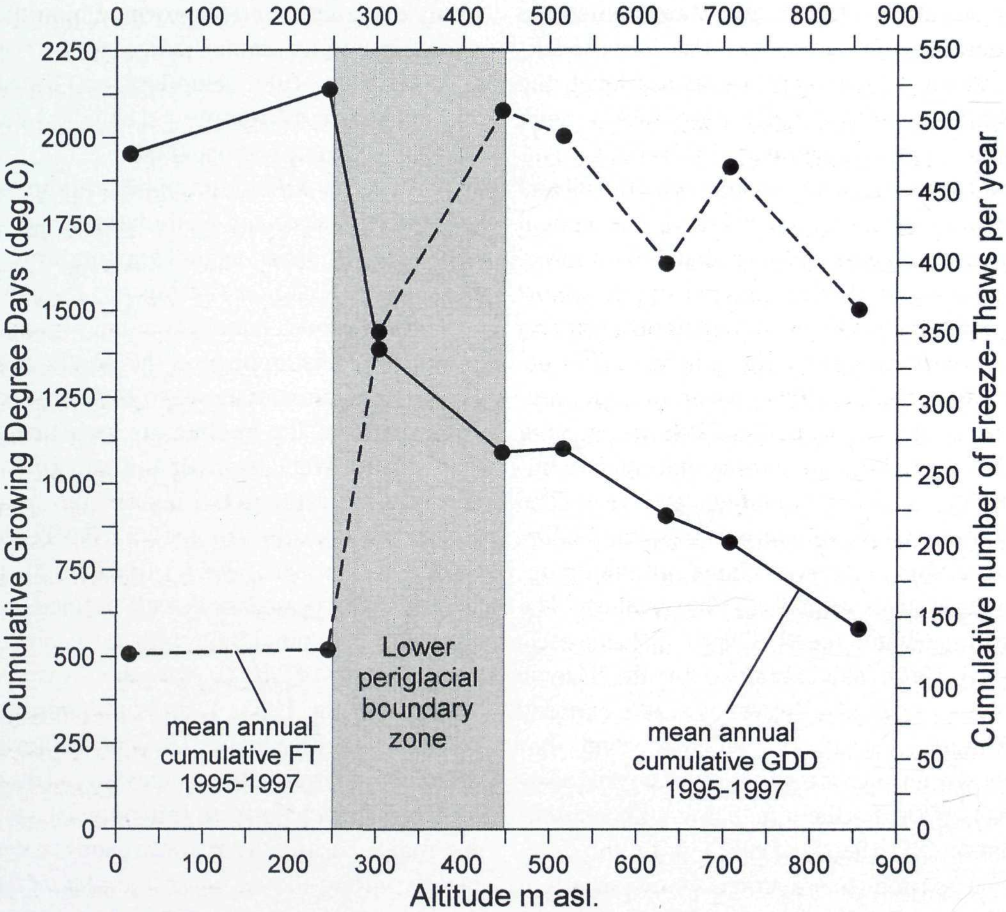

Fig. 5. Altitudinal distribution of the mean annual cumulative number of growing degree days (GDD, left scale) and the mean annual cumulative number of freeze-thaws (FT, right scale) May 1995 – May 1997 in the Slættaratindur massif, northern Eysturoy. The lower periglacial boundary zone is shown by grey shading.
Mynd 5. Hæddarbýti av tí árliga kumulativa miðaltalinum á døgum, tá ið temperaturin hækkar (GDD=growing degree days, vinstri stigi), og tað árliga kumulativa miðaltalið á tíðarskeiðum, tá ið tað frystir og síðani toyar (FT = freeze-thaws, høgri stigi), frá mai 1995 til mai 1997 á rygginum á Slættaratindi í norðara parti av Eysturoy. Tað lægra periglasiala marknaøkið verður víst við gráari skuggalegging

each observational site, while 12 daily measurements were obtained from May 1996 to June 1998.

The effect of altitude on the mean air temperatures and the absolute temperature range is illustrated by Fig. 4, based on data registered from May 1996 to May 1997. The oceanic influence is obvious at all altitudes; summers are cool and winters mild. The typical annual range of daily mean temperatures is about 15°C. The calculated annual vertical lapse rate varies from $0.0065°Cm^{-1}$ to $0.0055°Cm^{-1}$. At the summit of the highest mountains the annual near-surface mean air temperature is only slightly above 0°C. Permafrost is consequently presently absent in the Faroe Islands, but would presumably only require a limited temperature lowering to form in the highlands, as will be further discussed below.

The altitudinal distribution of the mean annual cumulative frequency of freeze-thaws events (FT) and Growing Degree Days (GDD) is shown in Fig. 5 (1995-97). Before calculating GDD and FT, all data were normalised to a daily observation frequency of 24 (Molau and Mølgaard, 1996). GDD is a substitute for plant growth conditions, and equals the number of degree days above 5°C (Maxwell, 1992; Molau and Mølgaard, 1996). Usually GDD shows a good correlation with plant growth, except in regions where lack of precipitation limits growth (Zoltai, 1988). GDDs have relevance within a geomorphic context, since the presence or absence of a plant cover can control the development of small-scale patterned ground (Ballantyne, 1996). The FT parameter equals the number of daily temperature transitions across 0°C. A high FT presumably indicates conditions suitable for recurrent needle ice growth and decay at the ground surface, and associated geomorphic effects such as soil creep.

The mean annual number of FTs increases significantly from about 120 to more than 400 across the altitudinal range from 250 to 450 m a.s.l., parallel with a likewise marked decrease in the mean annual number of GDD from more than 2000 to less than 1100 (Fig. 5). This altitudinal range is identical to the modern lower limit of active, small-scale patterned ground on the Faroe Islands (Humlum and Christiansen, in press), and thereby delimits the lower boundary for the late 20th century periglacial (arctic) zone.

Snow survival in the highlands

In an early description of the Faroe Islands written about AD 1680 (Descriptio Færoarum) the following (translated) general information on 17th century snow survival in the Faroes is found (Resen, 1972, p.17): 'Snow lies without interruption on the high mountains and never melts, but are forming overhanging cornices along the highest summits and headwalls. This frequently leads to the death of many sheeps walking on these snow drifts, when they melt and suddenly avalanches down'. Clearly, perennial snow accumulations were widespread in the Faroes during certain cold intervals of the Little Ice Age, in contrast to late 20th century conditions, where snow with several years of interruption survives the summer in a few sheltered sites only.

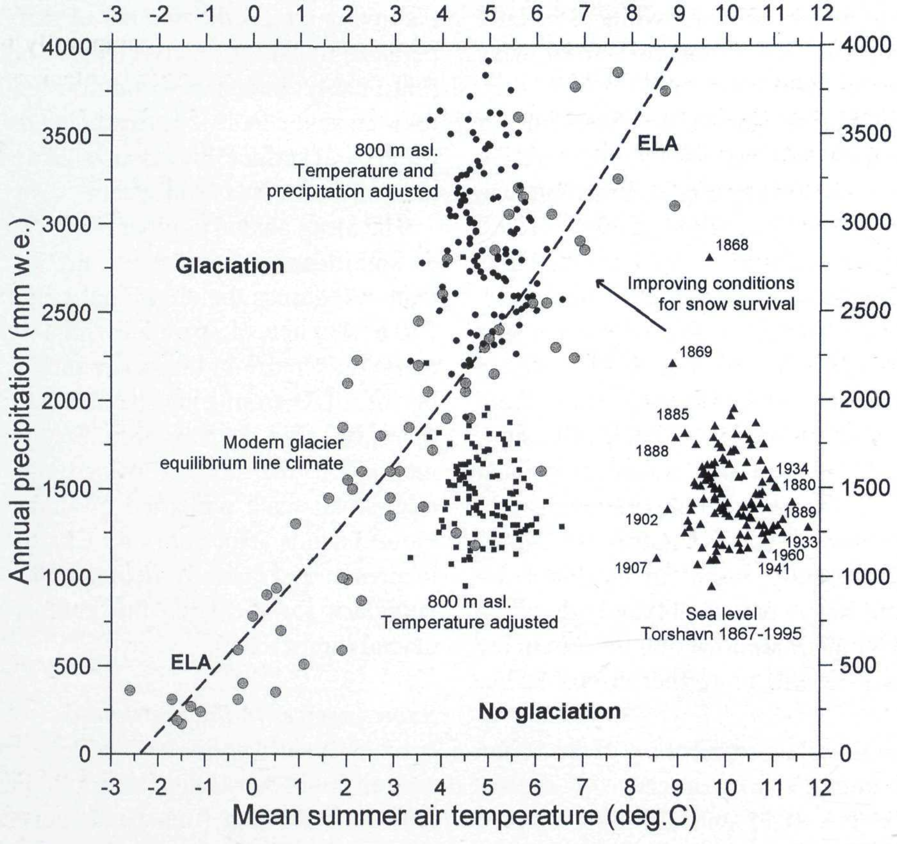

Fig. 6. Scatter diagram showing Tórshavn mean summer air temperature versus annual precipitation AD 1867-1995 (filled triangles), and a plot of meteorological data obtained at the equilibrium line of modern glaciers (grey circles; data from Ohmura et al., 1992), together with a polynomial fit (broken line) indicating the approximate climatic position of the equilibrium line (ELA). This line divides the diagram in two parts, representing glaciation and no glaciation, respectively. Six Tórshavn years (AD) signalling especially favourable conditions for snow survival and six especially bad years is indicated. The filled squares represent the Tórshavn sea-level observations transformed to an altitude of 800 m a.s.l., assuming a standard vertical lapse rate of 0.0065°Cm^{-1}. The filled circles represent a further adjustment for an altitudinal precipitation increase of 10% per 100 m. Discussion in text.

Mynd 6. Breiðslustrikumynd, sum vísir miðallufttemperaturin um summarið í Tórshavn mótvegis árligum avfalli 1867-1995 (fyltir tríkantar) og eina farmynd av veðurfrøðiligum upplýsingum, sum eru útvegaðar við javnváglinjuna á jøklum í okkara tíð (gráir sirklar; upplýsingar frá Ohmura o.fl., 1992), saman við einum fleirliðaðum máti (brotin linja), sum á leið vísir veðurlagsstøðuna við javnváglinjuna (ELA = equilibrium line). Henda linjan brýtur strikumyndina í tveir partar, sum sýna ávikavist glasiatión og onga glasiatión. Eisini vísir myndin seks ár (e.Kr.) í Tórshavn, sum boða frá, at líkindini eru serliga góð til at kavi verður liggjandi, og somuleiðis seks ár, har hesi líkindi eru serliga vánalig. Teir fyltu fýrkantarnir sýna kanningarúrslitini í Tórshavn ájavnt við sjóvarmálan umroknað til 800 m yvir sjóvarmálanum við teirri fyritreyt, at lutfallið fyri tað loddrætta frávirkið í miðal er 0,0065°Cm^{-1}. Teir fyltu sirklarnir sýna enn eina tillaging av avfalsvøkstrinum upp á 10% fyri hvørjar 100 m í hædd. Viðgerð í tekstinum.

Assuming the meteorological Tórshavn observations to be roughly representative for regional conditions within the Faroe Islands, these data might provide a basis for an attempt to evaluate the likelihood of periodical late Holocene perennial snow survival and associated geomorphic effects in the highlands. Figure 6 shows a plot of the mean summer (June-August) air temperature versus the annual precipitation for all Tórshavn data (filled triangles), together with analogue meteorological data representing conditions at the equilibrium line at various modern glaciers world-wide (grey circles), where mass balance measurements are being carried out, using data from Ohmura *et al.* (1992). From a geomorphic point of view, glacier equilibrium lines are important as any incipient glaciation, in general, requires the existence of an equilibrium line at the terrain surface. The rate of cold-climate bedrock weathering is also known to reach a maximum for altitudes near the ELA, wherefore this represents a geomorphic zone of high importance for understanding long-term, high-relief landscape evolution (Humlum, unpubl.).

Average annual accumulation on a glacier approximates closely to the annual precipitation at the equilibrium line, while ablation is most usefully predicted by the mean summer air temperature (Sutherland, 1984). As is seen from Figure 6, there is a close, non-linear, empirical relationship between precipitation and the mean summer air temperature at the equilibrium line (Ohmura *et al.*, 1992). This positive correlation between glacier mass-balance input (accumulation) and summer air temperature (a substitute for ablation) is known to apply both spatially and temporally within many regions with modern glaciers (see, e.g., Oerlemans, 1982; Sutherland, 1984, Muszynski and Birchfield, 1985; Bromwich, 1988; Fortuin and Oerlemans, 1990).

The variation of the AD 1867-1995 Tórshavn meteorological observations signals a considerable spread of associated mass balance characteristics for Faroese snow accumulations during the instrumental period (Fig. 6). Some of the best years as seen from a positive mass balance point of view (reflecting good possibilities for snow survival) are represented by AD 1868, 1869, 1885, 1888, 1902 and 1907, while especially bad years are represented by AD 1880, 1889, 1933, 1934, 1941 and 1960. From Fig. 2 is seen that the years with good regional conditions for survival of snow in general are coinciding with cold summers, but that a number of even colder summers in the early AD 1920s are not represented within this group owing to low annual precipitation. Likewise, the years signalling poor regional possibilities for survival of snow are generally associated with warm summers, even though some years with hot summers are not represented due to high annual precipitation. In particular the period AD 1930-47 appears to have provided extraordinary bad conditions for snow survival in the Faroese highlands.

Figure 6 also illustrates an attempt to estimate climatic conditions in the Faroese highlands (800 m a.s.l.) during the instrumental period. By assuming a mean annual vertical lapse rate of 0.0065°Cm^{-1}, the temperature adjusted plot (squares) in Fig. 6

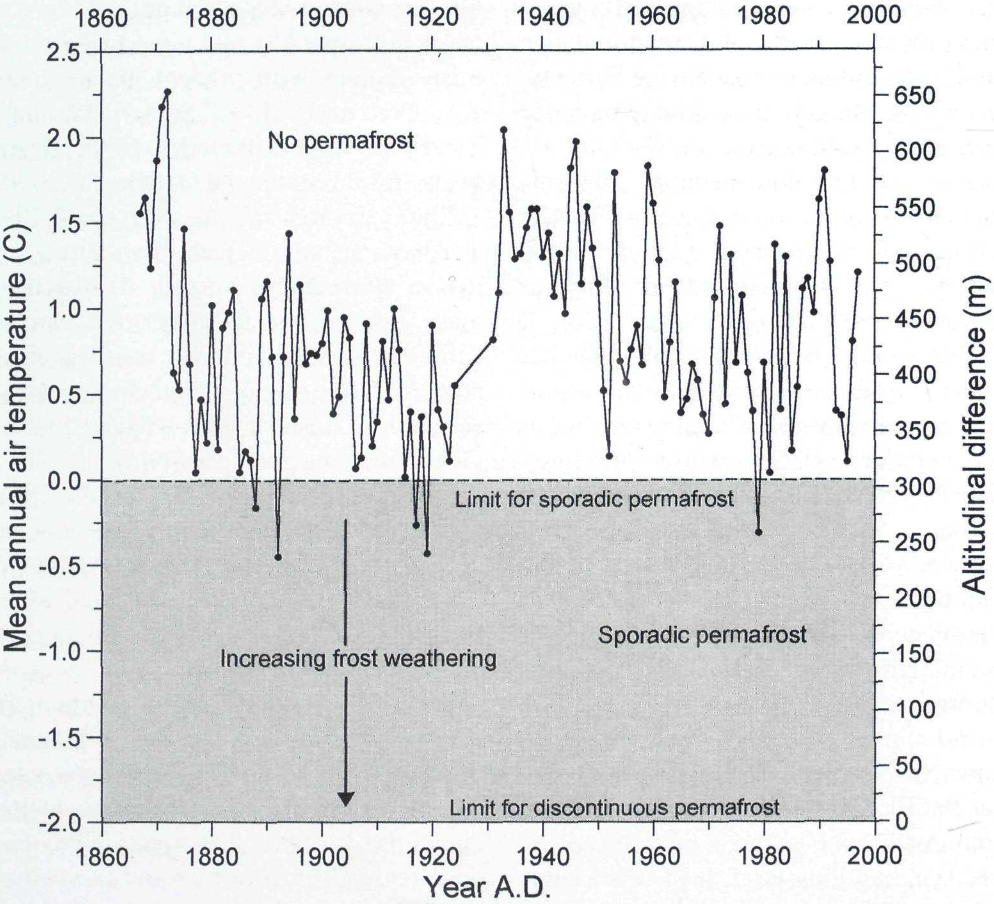

Fig. 7. Estimated mean annual air temperature (MAAT) at the summit of Slættaratindur (882 m a.s.l.) AD 1867-1995, using sea-level observations from Tórshavn and assuming a standard vertical lapse rate of 0.0065°Cm-1. The right scale (m) indicates the vertical distance between the summit of Slættaratindur (indicated by the temperature graph) and the empirical altitude for discontinuous permafrost (-2°C MAAT). Discussion in text.

Mynd 7. Mettur árligur lufttemperaturur í miðal (MAAT = mean annual air temperature) ovast á Slættaratindi (882 m yvir sjóvarmálanum) 1867-1995; kanningarúrslit ájavnt við sjóvarmálan í Tórshavn er brúkt, og fyritreytin er, at lutfalstalið fyri tað loddrætta frávirkið í miðal er 0,0065 °Cm^{-1}. Tann høgi stigin (m) vísir ta loddrøttu fjarstøðuna millum toppin á Slættaratindi (sæst á temperaturfarmyndini) og sannroynda hædd á ósamanhangandi permafrosti (-2 °C MAAT). Viðgerð í tekstinum.

was obtained. This simple transformation brings the point agglomeration close to the empirical position for modern ELA's, suggesting that climatic conditions in the highlands during cold intervals of the Little Ice Age were rather close to those of glaciation. However, also precipitation varies with altitude due to orographic effects, and usually increases by 10-20% per 100 m altitude (Søgaard, 1996). If a conservative precipitation adjustment of only 10% per 100 m is introduced in the above analysis, most of the fully transformed annual data (filled circles) plot very close to the empirical ELA-zone or even within the zone of glaciation. By this, a number of sites within the highest mountains in the Faroe Islands with little doubt experienced a positive snow mass balance in certain years during cold intervals of the Little Ice Age, and from a glaciological point of view were on the brink of glaciation. One obvious candidate for incipient glaciation is Givrabotnur on the eastern side of Slættaratindur (Fig. 1), where snow is known to have survived several summers during the latter part of the 20th century. There is, however, no geomorphic indication of any Holocene reglaciation in the Faroes (Humlum *et al.*, 1996), and the number of consecutive years with positive mass balance during the Little Ice Age was probably too small. Presumably, an uninterrupted row of at least 15-25 years with positive mass balance is required to accumulate an ice body thick enough to generate significant internal deformation.

Permafrost in the highlands ?

Permafrost most likely was absent in the Faroe Islands since the Younger Dryas (since 11500 cal. years BP; Humlum, 1998), although the highest mountains presently only are 300-500 m below the theoretical level for discontinuous permafrost (Humlum and Christiansen, in press). Considering empirical knowledge, sporadic permafrost may be met with from a MAAT of about 0°C, discontinuous permafrost from about -2°C, while continuous permafrost usually requires a MAAT below -6.5°C (see, e.g., French, 1996).

The meteorological observations from Tórshavn have been used to estimate the temperature conditions during the instrumental period at the summit of Slættaratindur (882 m a.s.l.), the highest mountain in the Faroe Islands (Fig. 7). The estimated average MAAT for Slættaratindur AD 1867-1995 is only slightly above freezing, about 0.8°C, assuming a standard vertical lapse rate of 0.0065°Cm-1, corresponding rather well to actual measurements (Fig. 4) at the summit of neighbouring Gráfelli (856 m a.s.l.). However, significant variations are seen to have occurred during the instrumental period. Especially during the final cold interval of the Little Ice Age the summit MAAT apparently was below 0°C for several years (AD 1888, 1892, 1917, 1919), and apparently this was also the case for a single year in the latter half of the 20th century (AD 1979). Several other years plot close to 0°C. During years like these, a number of high summits in the Faroes probably were close to the establishment of sporadic permafrost, especially at wind exposed sites without thick snow cover (Harris, 1986). From Fig. 7 is also seen that a MAAT lowering of only 2-3°C, compared to modern conditions, presumably is enough to establish meteorological conditions for widespread discontinuous permafrost in the Faroese highlands. As the weathering rate of bedrock tends to increase as MAAT is lowered and areas of permafrost is being established (Humlum, 1992; unpubl.), there is empirical reason to expect an increased production rate of talus in the highest Faroese mountains during years with particular low MAAT. By this, the vertical distance from the summit of Slættaratindur to the theoretical level for discontinuous permafrost (Fig. 7) represents an inverse proxy for the expected rock-fall intensity.

The periglacial environment

Our investigations on the Faroese terrestrial environment indicate a strong coupling between the distribution of modern geomorphic processes, topography and mountain climate. Adopting a geomorphic approach, the present periglacial boundary is typically located within a range from 250 to 450 m a.s.l., corresponding to a MAAT of 3.5-5°C; above this altitude vegetation is sparse and periglacial activity widespread. Across this range patterned ground and sorted stripes become frequent, and impart a clear periglacial appearance to the landscape. This important geomorphic boundary closely corresponds to that proposed by Williams (1961) as a means of delimiting the periglacial environment. It is hypothesised that especially the number of growing degree days and frequency of freeze-thaw events (Fig. 5) represent important controls on the lower limit for modern periglacial activity. A third control is presumably that of wind exposure. At some very wind exposed sites the modern lower periglacial boundary may be as low as 100-200 m a.s.l.

In short, the late 20th century periglacial environment in the Faroe Islands is characterised by extreme humidity and strong winds, rather than extreme cold. The present treeline is close to sea level, the lower periglacial boundary is at about 250-400 m a.s.l., and the potential discontinuous permafrost level is situated 300-500 m above the highest mountains (Fig. 7). Likewise, the present potential glaciation level is presumably situated only 150-250 m above the highest mountains.

During the LIA, assuming a periodical MAAT lowering of 2-3°C in the Faroe Islands, as documented by historical sources (Lamb, 1989), the periglacial boundary may have shortly approached sea level in exposed regions. Within this context the historical documentation of LIA periods with extensive loss of sheep due to lack of grazing may be significant (Madsen, 1990). This occurred several times during the LIA and as late as AD 1888, when polar ice extended south on both sides of the Faroe Islands (Lamb, 1977; 1985). Especially the winters AD 1694-95 and 1716-17 are known as very hard (West, 1985). During the last of these winters as many as two-thirds of all sheeps were killed, especially due to recurrent late spring snow. Also fishery was very bad at that time, and the Faroe Islands suffered an economic disaster

(West, 1985). Also the following winter AD 1717-18 was very cold, and many of the cattle died that winter. Lamb (1982) concludes that the ocean surface temperature between Iceland and the Faroe Island AD 1690-1699 was probably 5°C lower than today (see also Ogilvie, 1992), and in AD 1695 cod were sparse even as far south as the Shetland Islands, suggesting a significant extension of polar water below 2°C (Grove, 1988). In this period, the periglacial environment in the Faroe Islands probably extended almost to sea level, and certain exposed localities may shortly have approached the climatic conditions for initiation of either glaciation or permafrost (Figs. 6 and 7).

Grass is the main crop grown in the Faroe Islands. The yield of grass depends very much on the air temperature during both the growing season and the previous winter (Grove, 1988). Cool summers restrict grass growth, but cold winters are even more effective in restricting growth (Bergthórsson, 1985). Hard frost in late winter usually kills the grass, as does prolonged snow cover; especially if there is repeated melting and freezing. During the late 20th century, cold winters are almost invariably associated a high frequency of strong, northerly winds with associated, numerous snow showers. From this empirical basis it may be suggested that also cold intervals of the LIA such as AD 1872-1920 were characterised by a high frequency of northerly winter winds, leading to significant snow drifting from slopes with northerly aspect, thereby exposing vegetation (grass) in these areas to the full effect of low air temperatures. Most likely, extensive areas with dominant grass vegetation were killed at such events, especially on slopes with northerly exposure, which subsequently became exposed to soil erosion by winds, drifting snow, rain, needle ice action and solifluction (Humlum and Christiansen, in press). This scenario is supported by the widespread occurrence of late Holocene eolian deposits on slopes with southerly exposure (Christiansen, 1998), and the likewise universal evidence of deflation effects caused by northerly winds (Humlum and Christiansen, in press). Also historical reports on recurrent LIA snow avalanches on slopes with southerly aspect (Madsen, 1990) suggest a LIA winter wind régime characterised by frequent northerly winds. We have found no geomorphic evidence suggesting that the grazing of sheep is the prime cause for past and present soil erosion in the Faroe Islands; this is basically a normal geomorphic phenomenon controlled by the prevailing climate.

The Faroese landscape and climatic change

The present very sensitive position of the Faroese landscape within a climatological context is highlighted by diagrams such as Figs. 6 and 7. Due to their limited size, the islands are not liable to produce any significant climatic feed-back effects, such as caused by variations in mean snow cover. They are located in the middle of the North Atlantic drift, and therefore represent a highly suitable location for registering regional North Atlantic climatic variations. Based on an inventory of spatial, temporal and seasonal 20th century global temperature variations, Jones and Briffa (1992) concluded that oceanic regions of the world vary more coherently than terrestrial regions, and that data obtained from oceanic regions therefore are likely to be more indicative of any global change than observations obtained from other regions.

As demonstrated by Briffa and Jones (1993), summer season air temperatures are the most atypical of all the various seasonal averages, especially in the Northern Hemisphere, where most of the global surface warming observed since the middle of the 19th century has occurred in winter, spring and autumn, but only little in summer. Inferring climate change on the basis of observations biased toward summer conditions is therefore questionable regardless of spatial scale, and winter responsive data, in general, represent a much more powerful source of information. Therefore, in an overall global change context, the occurrence of geomorphic cold-climate phenomena such as those discussed above should be considered with special interest, because they are controlled mainly by winter season climate. In short, winter-sensitive geomorphic phenomena in oceanic land areas such as the Faroe Islands are therefore expected to yield extraordinarily important information on climate change, past as well as present.

Conclusions

The Faroe Islands is close to the 20th century southern limit for the northern hemisphere polar periglacial zone. According to the treeline, the modern periglacial environment on the Faroe Islands extends almost to sea level. The occurrence of active periglacial features such as patterned ground and sorted stripes, however, suggest the modern lower periglacial boundary to be located within a range from 250 to 450 m a.s.l. This altitudinal range is controlled by temperatures as well as exposure to wind and insolation. Above the periglacial boundary the vegetation rapidly becomes patchy and periglacial activity widespread. The modern limit of periglacial activity on the Faroe Islands corresponds to a MAAT of about 3.5-5°C.

From a geomorphological point of view the land areas above the periglacial boundary (about 50% of the total land area) represent a typical cold-climate, arctic environment. The present MAAT is only slightly above 0°C at the highest mountains on the Faroe Islands, but the modern potential discontinuous permafrost level is most likely situated 300-500 m higher. During cold intervals of the LIA the lower limit for periglacial activity may temporarily have approached sea level, contemporary with beginning establishment of sporadic permafrost in the highlands. Presumably, a few sites in the highest mountains were then close to reglaciation. By this, the present Faroese landscape is highly sensitive towards any climatic change; a situation which is enhanced by the location in a uniquely sensitive region of the North Atlantic Ocean for registering Holocene climatic changes, as is documented by proxy data, historical records and modern observations on climate and geomorphic processes.

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