1 INTRODUCTION

Northern Hemisphere periglacial terrain near the southern (warm) limit is at risk of losing its periglacial character over the next 50–100 years, as indicated by projections of climate change from Global Circulation Models (GCMs) (Houghton et al. 2001). The Faroe Islands (62° N) in the North Atlantic lie within this potentially zone of change. Motivated by the importance of estimating the impact of projected climate change on periglacial environments, we have reconstructed Faroese air temperatures from the years 1867–2002, over elevations of 0–850 m a.s.l., using the long term (AD 1867–2002) Tórshavn meteorological station record and recent (1995–2002) records from four stations located from sea level up to 850 m a.s.l. Late 20th century temperatures and the altitudinal FDD, TDD and GDD distributions do not suggest modern permafrost at the Faroe Islands, but the highest mountains presumably are close to permafrost conditions. Since about 1930, a cooling trend has prevailed, culminating around 1980, followed by a slight warming trend. Widespread shallow sorting producing small-scale sorted circles and stripes occur in the highlands where shallow seasonal freezing reach 10–20 cm. The mountains have a continuous winter snow cover from December to April.

2 STUDY AREA

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, 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 North Atlantic 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 (the Gulf Stream). 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 north. As a consequence, the Faroe Islands are well placed to register periglacial imprints of any large amplitude shifts in North Atlantic oceanic variations, both past and present.

The Faroe Islands are characterised by alpine topography due to Quaternary glaciations. There is no tree vegetation, except where planted in few sheltered locations below 100 m a.s.l. At sea level the warmest month is near 10°C and sorted ground phenomena are widespread above 200–300 m a.s.l. (Humlum and Christiansen, 1998a). Most of the Faroese landscape is therefore within the periglacial zone and is exposed to Arctic conditions.

By representing a series of modern periglacial environments ranging from marginal close to sea level to full periglacial in the highlands, the modern Faroese landscape may provide useful information regarding the climatic constraints on the North Atlantic periglacial environment.

Meteorological observations were initiated in Tórshavn in AD 1867 (Brandt, 1994). The data series...
document the final part of the Little Ice Age (LIA) and its termination shortly after 1920, as indicated by a temperature increase (Fig. 1). The transition was mainly signalled by higher winter temperatures and only to a lesser degree by other seasonal temperatures. After 1940 the mean annual air temperature (MAAT) gradually decreased to typical LIA values until around 1980, again mainly caused by changes in winter temperatures. Since then, a slight warming has occurred. From a temperature point of view, the LIA thus more or less still continues on the Faroe Islands, and was only shortly interrupted by a relatively warm period 1925–1940. There is no clear evidence for an association between MAAT and annual precipitation in the Faroe Islands during the observational period (r-squared: 0.12), and precipitation is presumably also controlled by local factors such as wind direction and orographic effects.

Until recently all Faroese meteorological stations were located close to sea level with only a few stations operating at higher altitudes (up to 282 m a.s.l.). The establishment of a mountain meteorological station in the year 2000, however, suggested a position of the low arctic boundary at only 200 m a.s.l. (Christiansen and Mortensen, 2002). This altitude corresponds to a mean annual air temperature (MAAT) of 5.0 to 3.5°C, depending upon exposure to the prevailing wind (Humlum and Christiansen, 1998).

In the present paper new 1995–2002 data series of air- and ground temperatures, supplemented by automatic digital snow cover observations are used to improve the description of the modern Faroese periglacial environment and to analyse the magnitude and significance of interannual variations. The data are further used to reconstruct MAAT for different altitudes back to the final parts of the LIA.

3 AIR TEMPERATURES

In the highest mountain massif, Slettaratindur (50 km NNE of Tórshavn), air temperatures at different altitudes have been recorded since 1995. Temperatures were measured using miniature single channel Tinytalk (1995–1997) and TinyTag (1997–2002) data loggers with external sensors located 10 cm above the terrain surface in small stone cairns, protecting the sensors from sheep, people and direct solar radiation and exposing them to efficient ventilation. Presumably the recorded temperatures are slightly higher than if recorded at standard height, 2 m above ground. Data recording intervals were 5 hours May 1995–1996, 2 hours May 1996–1999 and 1 hour since May 1999. The accuracy of the sensors is 0.1°C.

To describe the altitudinal variation data from 303 m, 634 m and 850 m a.s.l. are used. All these three stations were located in wind-exposed parts of the landscape, in passes or on mountain summits, without any significant snow coverage. Data were downloaded annually. They showed no signs of snow cover preventing quick temperature variations. The data series are almost continuous, as only very short periods of maximum 34 hours of failure occurred. However, for the 850 m station, the sensor was damaged after a few months of operation in 1995 and was not replaced before May 1996.

The mean monthly air temperature (MMAT) (Fig. 2 and table 1) shows the same general annual variation at the different altitudes, but with the largest amplitude (13°C) registered for the higher parts of the landscape, while the amplitude is somewhat smaller (10°C) close to sea level.

The coldest month varies from November to March. In contrast, the warmest month is always either July or August, but it varies at each station for each individual year. The MMAT difference between stations is largest during winter when the lapse rate generally is at maximum (−0.7 to −0.9°C/100 m), while in summer it is generally smaller (−0.4 to −0.5°C/100 m) presumably due to increased insolation and lack of topographic induced shading on the high ground. During summer, the highest ground may penetrate above the cloud cover, and therefore receive more direct radiation than the valleys below.

The fact that the monthly variations show an identical pattern for all stations, including the official station in Tórshavn, suggests that the distribution of stations used in the present analysis ensures well-ventilated temperature sensors due to a combination of an open landscape without trees and frequent high wind speeds.
3.1 Mountain air temperature reconstruction back to AD 1867

Using the correlation between MMAT values for the 1995–2002 Slettaratindur series area and the official meteorological station in Tórshavn, a MAAT reconstruction back to 1867 for different altitudes was carried out for the Slettaratindur area (Fig. 3). The correlation between MMAT at altitudes of 303, 634 and 850 m a.s.l. and the Tórshavn data was 0.92, 0.95, 0.94 (r-squared values), respectively, for the period 1995–2002. As mentioned above, this rather high correlation is presumably derived from efficient wind ventilation at all altitudes.

For the reconstructed temperature series since AD 1867 the warmest period falls in the early part of the measurement period, actually within the LIA, whereas the coldest period is registered after the official end of the LIA, from 1950 to 1985. Figure 3 shows that MAAT in the highest mountains presumably approached 0°C during certain cold periods in the 20th century, such as 1917–1920 and 1979–1981.

3.2 Freezing, thawing and growing degree days

Freezing degree days (FDD), thawing degree days (TDD) and growing degree days (GDD) (Molau and Mølgård, 1996) have been calculated for the different altitudes in the Slettaratindur area, based on daily mean air temperature values 1995–2002 (Fig. 4). There are less FDD than TDD recorded at all altitudes, indicating permafrost to be absent. The number of FDD exceeds the number of GDD for altitudes above 600–700 m a.s.l. Significant plant growth, generating a closed plant cover, ceases above 300 m a.s.l., suggesting a GDD value of about 500 to represent a critical value for modern vegetation on the Faroe Islands. TDD has a much larger interannual variation,
particularly at lower altitudes, than both FDD and GDD. FDD has the largest interannual variation at high altitudes and show only little interannual variation close to sea level, reflecting the importance of nearby sea surface temperatures.

Figure 4 also shows reconstructed FDD and TDD for the warmest year on the Faroese meteorological record (1872) and the coldest year (1979), respectively, thereby defining limits for the annual variation during the observational period (since AD 1867). The period 1995–2002 clearly plots within the colder part of the empirical FDD envelope, but are still close to average for TDD. Interestingly, the maximum FDD and minimum TDD do overlap above 820 m a.s.l., indicating that in the highest parts of the Faroese landscape there might well be sites with a negative TDD-FDD balance during cold years.

4 GROUND TEMPERATURES

Ground temperatures have been measured at 3 sites in the Slettaratindur area. These data series are not continuous because of thermistor problems. However, a continuous data series on soil temperatures has been measured at the meteorological station on the Sornfelli mountain summit plateau (Christiansen and Mortensen, 2002), 26 km S of the Slettaratindur area. Here an 11 m borehole was drilled at an altitude of 722 m a.s.l., in the summer of 1999, instrumented for ground temperature monitoring in November 1999 and has operated satisfactorily since June 2000 (Fig. 5).

Figure 5 shows seasonal freezing to start in late December, continuing to late April, but only from mid February to late April does the 0°C isotherm reach depths of 30–40 cm. Due to high soil water content, only the upper 10–15 cm of the soil cools below −2°C during winter. The seasonal ground freezing is thus characterised by near 0°C conditions prevailing during much of the winter, suggesting that all available soil water never freezes. The mean annual ground surface temperature (MAGST) (June 2000–June 2002) was 3.7°C and the mean annual ground temperature (MAGT) was 3.8°C at both 5 and 10 cm depth. At 1 m depth, the MAGT was almost identical, 3.7°C. The maximum temperature range at the terrain surface was 39.1°C, decreasing to 22.0°C at 5 cm depth, 18.9°C at 10 cm, 13.6°C at 20 cm, while at 1 m depth the annual temperature range was only 7.2°C.

5 PATTERNED GROUND

As the annual ground freezing is shallow, reaching depths of 10–40 cm (Fig. 5), this presumably explains why the vertical sorting of the widespread small scale sorted circles (Fig. 6) generally extends only to depths of 5–10 cm (Humlum & Christiansen, 1998b). The surface geomorphic activity is, however, considerable. Recurrent annual photography 1995–2002 of sorted circles and −stripes, at 634 m a.s.l. in the Slettartindur massif, demonstrates that particles up to 3–4 cm are involved in the annual surface movement. Surface displacements of up to 1 cm/yr have been observed on horizontal ground, while the annual movement may be considerably larger on sloping ground. Large particles (>5 cm) are usually stable in the prevailing periglacial environment, as is suggested by their lichen cover.

6 PRECIPITATION AND SNOW COVER

Precipitation on the Faroe Islands is considerable, ranging from less than 800 mm (w.e.) on peripheral islands to more than 3000 mm in certain central highlands (Cappelen and Laursen, 1998). Much of the precipitation is solid, and snow may fall in the mountains in any month of the year. In Tórshavn, close to sea level, snow covers the ground for 44 days annually (Cappelen
and Laursen, 1998). To obtain information on the snow cover duration and timing in the highlands, automatic digital photography (Christiansen, 2001) has been applied from June 1999 to July 2002.

A daily photograph was taken showing an east-facing cirque, Givrabotnur, below the summit of the highest mountain in the Faroe Islands, Slættaratindur (882 m a.s.l.). The automatic camera was located approximately 700 m from the headwall of the cirque. From the photographs the daily snow cover was mapped.

Based on analysis of the daily photos obtained from June 1999 to July 2002, the seasonal, continuous snow cover was established by mid November in 1999, by mid December in 2000 and by late January in 2002, respectively. A continuous, although thin, snow cover also occurred outside the main winter season, e.g. from late September to mid November 1999, from late October 2000 to mid December 2000, and in June 2001. The thickest snow cover existed from late March to early April in 1999, 2000 and 2001, but occurred in February–March in 2002. Melting of the continuous snow cover started late April and occurred mainly in May, but snowpatches existed long into the summer (Fig. 7). The last snow disappeared 29 July in 1999, 30 August 2000, between 17 and 20 July in 2001, and between 30 June and 9 July in 2002. Due to very frequent wind activity the most exposed parts of the landscape, like the Slættaratindur mountain top and ridges are very seldom snow covered.

Geomorphic activity such as snow avalanches and rock falls was recorded during late winter all observation years. In 2000 snow avalanche activity was recorded on 29 April and 1 May (Fig. 7). In 2002 rock fall activity and debris slides were recorded between 30 April and 6 May (Fig. 7), as well as during and following a heavy rainstorm on 18 September 2000.

7 DISCUSSION

At the Faroe Islands low temperatures and high precipitation presumably enhances ongoing periglacial activity such as weathering and sorting processes. From this point of view, the Faroe Islands have experienced improved climatic conditions for increased periglacial activity towards the end of the 20th century. Today, significant sorting phenomena occur down to about 150–200 m a.s.l. MAAT is only slightly above 0°C at the highest mountains on the Faroe Islands and presumably the present climate is relatively close to providing background for glaciation but particularly for permafrost establishment in the highest mountains.

In contrast to this, the relatively warm period 1925–1940 was characterised by less precipitation and was therefore, presumably, a period of relatively low periglacial activity (only activities such as needle ice action, sorting and soil erosion by wind). The lower limit for periglacial activity at that time was probably located 100–150 m above the present position (Fig. 8).

Figures 7 and 8. Approximate climatic constraints for glaciation, periglaciation and permafrost (Humlum and Christiansen, 1998a). The shaded envelope indicates the 1950–1985 climatic position of the Faroese landscape, while the dotted envelope indicate the position during the warm period 1925–1940. The highest Faroese mountains are apparently close to fulfilling climatic requirements for glaciation but particularly for permafrost establishment.
At the onset of the 21st century there is no indication of any exceptional climatic warming in the Faroe Islands, and the small MAAT increase since 1980 is presumably a normal recovery following the relatively cold period 1950–1980. However, should a significant warming commence sometime in the future, as suggested by GCMs (Houghton et al. 2001), the unique meteorological record from Tórshavn together with continued climatic monitoring in the Faroese mountains could provide an important means for estimating environmental effects on the Faroese landscape, using a graphic approach as indicated in Fig. 8.

8 CONCLUSIONS

The Faroe Islands represent an extreme maritime modern southern limit of the Northern Hemisphere periglacial zone. According to the natural tree line, the modern periglacial environment extends almost to sea level. The lower occurrence of active periglacial features such as patterned ground and sorted stripes, however, suggest the periglacial boundary to be located within a range from 150 to 300 m a.s.l. Temperatures as well as exposure to wind and insolation control this altitudinal range. Above the modern periglacial boundary the plant cover rapidly becomes patchy and periglacial sorting phenomena widespread.

The seasonal snow cover duration is about 44 days near sea level. The snow distribution is mainly controlled by the large wind activity. In the highest mountains the snow cover may locally last for more than 300 days in lee sites where snowpatches accumulate, while the exposed parts of the landscape, such as mountaintops and ridges, do not have any significant snow cover. The maximum snow cover thickness is usually attained in the period late March to early April.

The modern limit of periglacial activity on the Faroe Islands corresponds to a MAAT of about 3.5–3.4°C. This is somewhat warmer than what is usually suggested (French, 1996), and the difference most likely reflects the windy character of the Faroese climate, leading to overall difficult growing conditions for plants.

The land areas above the periglacial boundary (presently about 50% of the total land area) represent a typical arctic environment from a geomorphological point of view. MAAT presently is only 1–2°C above 0°C, and the TDD/FDD balance is around 1.3–3.4 at the highest mountains. Presumably the highest mountains are close to fulfilling climatic conditions for glaciation but particularly for permafrost establishment.

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