BOREAS An international journal of Quaternary research

Seasonal changes in basal conditions at Briksdalsbreen, Norway: the winter–spring transition

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BOREAS

Rose, K. C., Hart, J. K. & Martinez, K. 2009 (August): Seasonal changes in basal conditions at Briksdalsbreen, Norway: the winter–spring transition. *Boreas*, Vol. 38, pp.579–590. 10.1111/j.1502-3885.2008.00079.x. ISSN 0300-9483

The winter–spring transition is a dynamic time within the glacier system, because it marks a period of instability as the glacier undergoes a change in state from winter to summer. This period is normally associated with sudden pressure fluctuations resulting in hydrological instabilities within the subglacial drainage system. New data are presented from wireless multi-sensor subglacial probes incorporated within the till at Briksdalsbreen, Norway. Water pressure readings recorded a two-phase winter–spring transition. Event 1 occurred early in the year (December–January) and marked the start of activity within the subglacial environment following the winter. However, this did not result in any permanent changes in subglacial activity and was followed by a period of quiescence. Event 2 occurred later in the year in accordance with changing external weather conditions and the retreat of the snow pack. It was characterized by high-magnitude pressure peaks and diurnal oscillations in connected regions. The variations in sensor trends that followed this event suggested that a transition in the morphology of the subglacial drainage system had occurred in response to these pressure fluctuations. Event 2 also showed some similarities with spring events recorded at valley glaciers in the Alps. A conceptual model is presented associating the form of the winter–spring transition with respect to the location of the probes within connected and unconnected regions of the subglacial drainage system. These data provide further evidence for temporal and spatial heterogeneous subglacial drainage systems and processes. The identification and analysis of subglacial activity during the winter–spring transition can contribute to the interpretation of hydro-mechanical processes occurring within the subglacial environment and their effect on glacier dynamics.

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The dynamics of glaciers vary seasonally and are largely controlled by subglacial processes (Boulton & Jones 1979; Alley *et al.* 1987a, b; Clarke 1987; Alley 1989; Kamb 1991). Glacier response to temporal changes in subglacial hydrological conditions continues to be of interest. Locally, increases in water pressure can promote sliding by causing decoupling between the ice and its bed, or can initiate enhanced bed deformation by weakening subglacial sediments (e.g. Fischer & Clarke 1997, 2001; Fischer *et al.* 1999). However, the variability inherent to water pressure means that subglacial processes, and thus the dynamics of glacier movement, may be equally as variable. On a global scale, investigating the relationship between glacier hydrology and dynamics has become more important, because enhanced meltwater production has increased the amount of water passing through, and reaching the bed of, ice masses. Current trends suggest this as a possible cause of the increased motion and thinning of outlet glaciers in areas such as Greenland (Zwally *et al.* 2002). Recently, the observation of supraglacial lakes draining to the bed of ice masses (Das *et al.* 2008) has demonstrated that there is still much to learn a bout the effect of meltwater inputs on the subglacial environment.

The winter–spring transition is a dynamic time within the glacier system, because it marks a period of instability as the glacier undergoes a change in state between winter and summer conditions. In the winter, glaciers are characterized by a period of quiescence, when a reduction in meltwater inputs causes the hydrological system to shut down and velocities to be at a minimum (e.g. Willis 1995; Hubbard & Nienow 1997; Fountain & Walder 1998). In the spring, hydrological and mechanical instability can occur within the subglacial environment as a result of large and sudden meltwater inputs into a poorly developed, low capacity, winter drainage system. The variations in water pressure produced by these meltwater inputs act as the driving mechanism for seasonal changes in subglacial drainage (e.g. Willis *et al.* 1990; Nienow *et al.* 1996, 1998; Gordon *et al.* 1998) and glacier dynamics (e.g. Iken *et al.* 1983; Iken & Bindschadler 1986; Mair *et al.* 2001, 2002; Harper *et al.* 2002; MacGregor *et al.* 2005). In the summer, 'steady-state' conditions resume. The new subglacial drainage system is more efficient, well connected and spatially extensive in response to augmented external temperatures and meltwater inputs (Willis 1995; Fountain & Walder 1998). Glacier velocities are elevated in comparison to the winter, but often remain stable as high summer meltwater discharges can be accommodated by a more efficient drainage system. As a result, the spring is arguably the most important period of the year, because it marks a phase of

DOI 10.1111/j.1502-3885.2008.00079.x

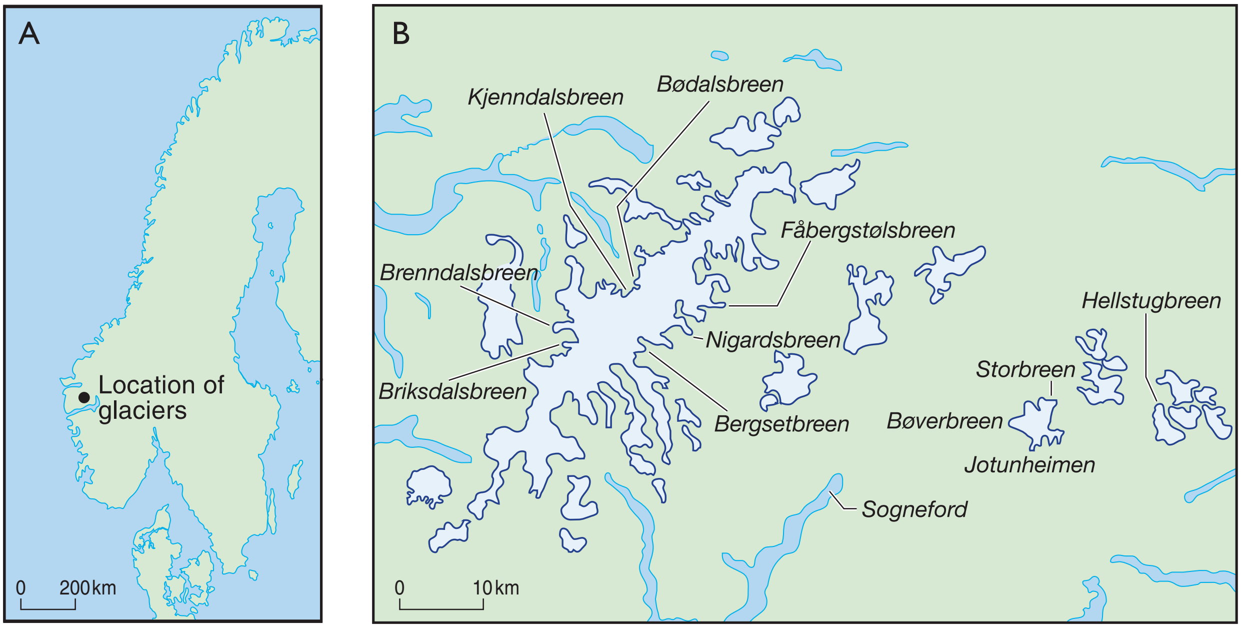

Fig. 1. Maps showing the location of (A) Briksdalsbreen in southern Norway and (B) the glacier within the Jostedalsbreen ice cap. This figure is available in colour at http://www.boreas.dk

dynamic instability and change as the glacier transitions from a winter to summer regime.

This investigation aims to assess subglacial hydrological conditions during the winter–spring transition at Briksdalsbreen, Norway, with the use of a new wireless multi-sensor probe (Martinez *et al.* 2004; Hart *et al.* 2006). This new instrument is designed to monitor several parameters within the subglacial environment, as part of an Environmental Sensor Network (ESN) (Hart & Martinez 2006). This enables long-term monitoring and allows daily data retrieval; while wireless capabilities permit the probe to move independently within the subglacial environment. The data retrieved from these instruments will be examined to identify the seasonal changes in basal conditions operating within the subglacial environment.

Briksdalsbreen, Norway

Briksdalsbreen is a temperate valley glacier located in southern Norway (Fig. 1). It is an outlet glacier of the Jostedalsbreen ice cap, roughly 11.94 km^2 in size and ranging in altitude from 350 to 1915 m a.s.l. Briksdalsbreen terminates in a proglacial lake and is underlain by unlithified sediments (approx. 30 cm) which overlie a Precambrian gneiss bedrock. Glacier depths averaged 70 m in 2004 and 60 m in 2005. The glacier flows down a steep ice fall into the lake and has a zone of crevassing that runs west–east near the central flow line. The glacier surface is very clean and free from debris, with only small, seasonal supra-glacial streams. Briksdalsbreen advanced over 300 m between 1988 and 1996, in association with a positive phase of the North Atlantic Oscillation (Nesje & Dahl 2003). However, it is currently in a phase of retreat, and in 2007 it retreated up to and out of the proglacial lake, past the 1955 previous point of minimal retreat (Fig. 2A). The foreland comprises flutes and push moraines (Winkler & Nesje 1999; Hart 2006). The presence of flutes and sedimentological studies (proglacial and *in situ*) has indicated that these sediments have undergone subglacial deformation (Hart 2006; Rose & Hart 2008).

Methods

The work carried out at Briksdalsbreen in the period 2004 to 2006 aimed to develop the instruments and techniques used to monitor the subglacial environment *in situ*. A new wireless probe developed to measure subglacial conditions was designed to represent a small subglacial clast to enable it to become incorporated into the deforming bed and behave naturally within that environment. The probe contains a variety of microsensors; notably for temperature, water pressure, case strain, resistance (a proxy for conductivity) and tilt (Table 1). Resistance provides a coarse indication of the relative ‘wetness’ of the subglacial environment. High values (10–20 M Ohm) indicate little or no water is present, whereas low values (0 M Ohm) indicate an increase in water content. The probe is set within an ESN (Fig. 3). It collects data six times a day and transfers that information daily to a base station at the glacier surface via radio communications. The base station acts as a relay point and transfers the probe data down valley to a reference station, which uploads the

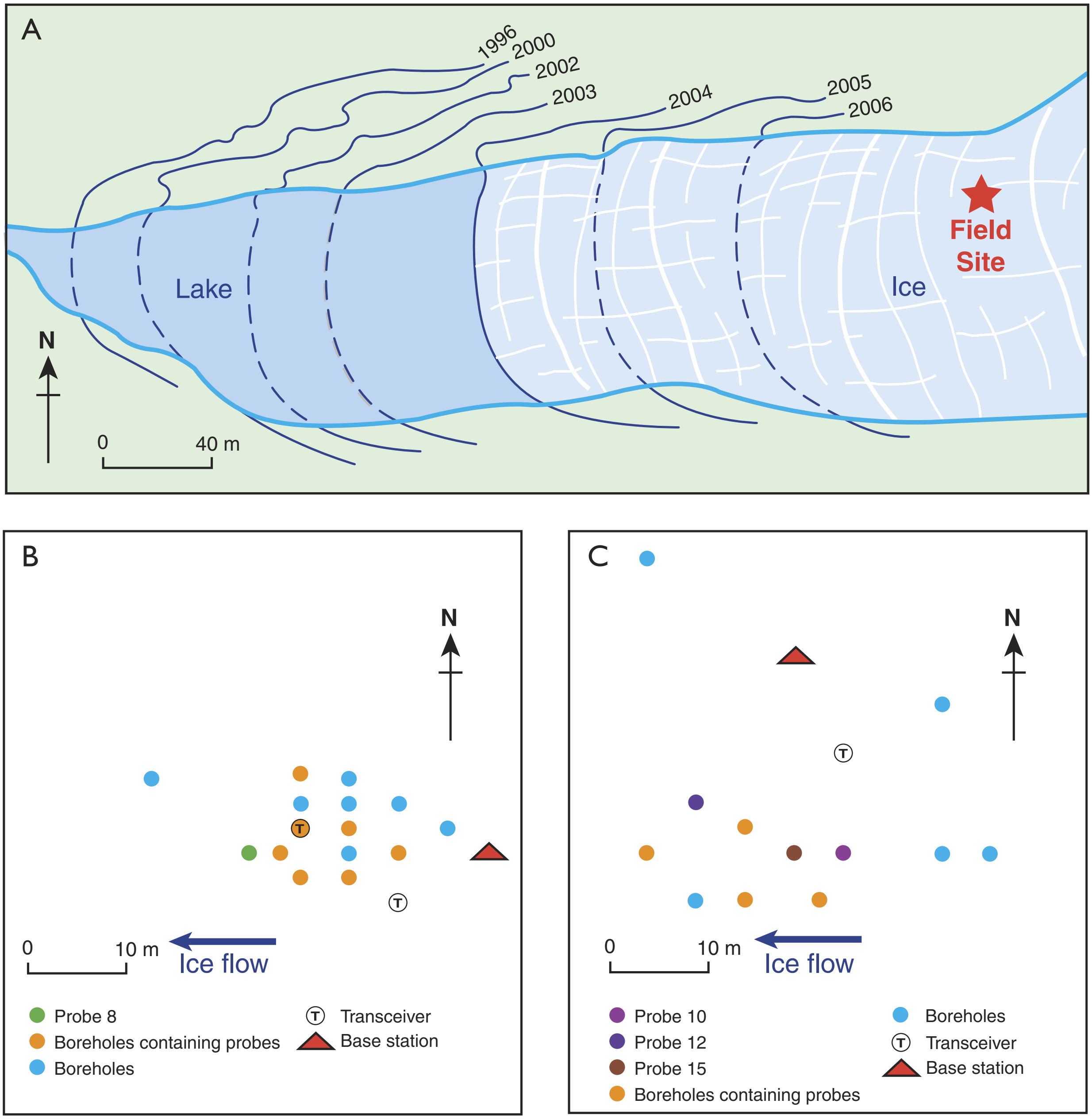

Fig. 2. Diagrams showing (A) the retreat of the glacier and the boreholes created in (B) 2004 and (C) 2005. This figure is available in colour at http://www.boreas.dk

Table 1. Technical specifications for probe micro-sensors.

Sensor	Technical specifications	Resolution (step size)	Range
Temperature sensor	ADT7301ARMZ	0.0625 °C	–15 °C to +15 °C
Pressure transducer	Honeywell 24PCGFM6G	6.8 kPa	0–250 psi 0–1724 kPa
Strain gauges	Strain gauge	0.006%	0–1023% micro strain
Resistance bridge	Resistance bridge	0.01 M Ohm	0–10 M Ohm (2004) 0–20 M Ohm (2005)
Tilt sensor 1	Dual axis 180° MEM sensor accelerometer	0.048°	–90° to +90°
Tilt sensor 2	Dual axis 180° MEM sensor accelerometer	0.048°	–90° to +90°

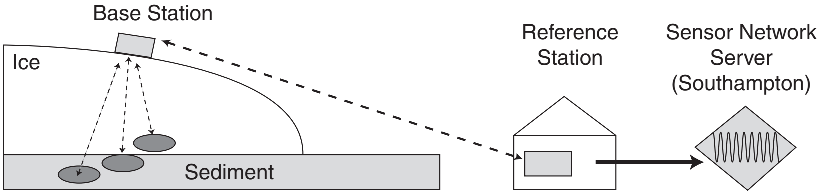

Fig. 3. Schematic diagram of the environmental sensor network (ESN) established at Briksdalsbreen, Norway. There are four main components to the ESN: the sensor nodes (or probes), the base station, the reference station and the sensor network server. The base station was also equipped with GPS capabilities and a weather station.

Table 2. Location of Norwegian meteorological stations in comparison to the base station weather station at Briksdalsbreen. Irrespective of distance, weather stations that showed the greatest correlation with data obtained *in situ* from the base station were used.

Location	Station no.	Latitude	Longitude	Approximate separation
Base station weather station	–	61.40	6.57	–
Stryn	58900	61.9157	6.5592	30 km
Sogndal	55700	61.1500	7.1333	60 km

information onto a sensor network server (the Internet) for remote access by an end user (Hart *et al.* 2006). The base station was also equipped with GPS (global positioning system) capabilities and a weather station. Weather data were obtained from the base station and, during periods of mechanical failure, a transfer function applied to data from neighbouring Norwegian meteorological stations (eKlima, Norwegian Meteorological Office) (Table 2).

During the 2004 and 2005 field seasons, a series of boreholes was drilled to the bed of the glacier using a Kärcher HD1000DE jet wash system (Fig. 2B, C). A custom-made CCD (charged coupled device) video camera was used to check for the presence of till at the base of the boreholes. If till was observed, a probe was lowered to the glacier bed in the depression within the till that results from hot water drilling (Blake 1992). It was then assumed that the till would close in around the probe as the glacier continued to move over the location of deployment. The probes became incorporated within the deforming bed during the autumn (Hart *et al.* 2006).

Probes were deployed in August; eight in 2004 and seven in 2005. In the first season, one probe lasted for longer than a year (probe 8), whereas in 2005, two probes lasted for more than a year (probes 10 and 12). The records for probe temperature, water pressure and resistance are examined, in combination with weather data, as a means of identifying and characterizing the winter–spring transition in basal hydrological conditions at Briksdalsbreen.

Results

A total of four probes set within the deforming bed produced full records covering the winter–spring transition, from 1 December to 30 April (days 335–120): probe 8 (2004/5) and probes 10, 12 and 15 (2005/6). Figure 4 displays annual records of probe water pressure highlighting the differences in probe activity over the course of a year. An initial period of activity on deployment is followed by a phase of quiescence corresponding to the winter period. The spring represents the period when sensor activity begins to increase again and abrupt, often high magnitude, sensor fluctuations are recorded. The summer period follows this, and is marked by a change in sensor readings, showing stable patterns and only minor fluctuations. The winter–spring probe records are displayed in Figs 5 and 6, in combination with the weather records for these periods. To highlight trends in probe temperature, a moving weekly average of values is displayed on the secondary y-axis. As a result of probe incorporation into the till, the pressure transducers were deemed to measure porewater pressure (p_w). Readings are displayed as a percent of overburden pressure (p_i) to enable comparison between years. All probe micro-sensors were functional with the exception of the probe 12 resistance sensor.

All of the probes displayed minimal sensor activity during December. Probes 10 and 12 sustained this pattern until March. However, probes 8 and 15 began to record variations in the winter months, as early as January and late December, respectively. The greatest sensor activity, for all the probes, was recorded in water pressure. Two phases, separated by a period of quiescence, became apparent in the pressure readings and as a result the records have been divided into Event 1 (days 20–42, 2005; days 355–51, 2006) and Event 2 (days 77–120, 2005; days 52–120, 2006). Generally, increases in water pressure during these events were accompanied by decreases in probe temperature and resistance. The pressure peaks associated with Event 2 were of a greater magnitude than those recorded during Event 1. In addition, a change in sensor patterns was recorded following Event 2.

External weather conditions during the winter–spring transition were characterized by sudden fluctuations in temperature. At the start of this time period, external temperatures showed broad fluctuations, recording values as high as 10 °C and as low as −15 °C. Temperatures were lowest between February and March (~days 42–89) before, at the end of March (~day 90), values rose above 0 °C permanently. Precipitation events were more numerous and of a greater

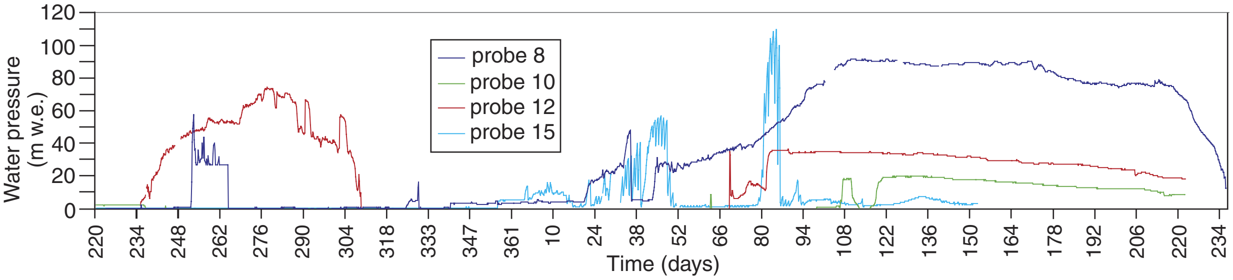

Fig. 4. Complete water pressure records for probes 8, 10, 12 and 15. This figure is available in colour at http://www.boreas.dk

magnitude at the start of this period (~days 355–48). The snowpack at the Briksdalsbreen study sites was relatively thin (< 1 m) and normally began to retreat from the ablation zone by the start April.

Discussion

The probe sensor readings can provide us with information about the nature of the subglacial environment, its response to changes in external conditions and any variations in the processes operating between winter and spring. In particular, readings of water pressure can provide an indication as to the location of the probes with respect to the subglacial drainage system in connected, unconnected or alternating (those displaying both trends) regions of the bed (Murray & Clarke 1995). It may also be possible to identify any changes in drainage morphology over time.

Triggers

The start of activity in water pressure recorded by the probes occurred very early in the year. In particular, the pressure fluctuations displayed at the end of December (probe 15) and at the start of January (probe 8) are not normally presented in the literature. The sudden pressure rises suggest that these events were triggered by a fresh influx of meltwater to the glacier bed. Typically, spring pressure fluctuations can be associated with external weather conditions, but significant meltwater production was not expected this early in the year, at a time of winter quiescence.

Despite this, in 2005, for example, numerous precipitation events were recorded between days 1 and 19 and temperatures were elevated (up to 8.6 °C), suggesting that precipitation was in the form of rainfall (Fig. 5A). Conditions such as these, during the springs of 2005 and 2006, were obviously sufficient to produce meltwater (Figs 5A, 6A). Elevated temperatures would generate melt and allow the snowpack to become isothermal (0 °C). Once isothermal, meltwater can move freely within the pack, enabling it to access the glacier bed (Harper *et al.* 2005). The snowpack at the study sites was generally thin (< 1 m), which would aid this process. In addition, elevated night-time temperatures would prevent refreezing and allow continued surface melt. These conditions could generate sufficient meltwater to result in the pressure peaks recorded.

Where correlations with external weather conditions were weak, it was difficult to suggest an alternative trigger to the pressure trends. However, a direct correlation between external weather conditions (assumed to reflect meltwater inputs) and pressure fluctuations may not be feasible at this time of year. Correlations documented in the literature tend to refer to pressure patterns during the summer rather than in the winter (e.g. Hubbard *et al.* 1995). In the winter–spring, even if the snowpack is isothermal, there may be a delay before meltwater reaches the bed of the glacier. In addition, meltwater can be stored or abruptly released from crevasses or englacial cavities. An alternative explanation for the pressure peaks is the release of meltwater from such stores in response to elevated external temperatures and increased precipitation events (Kavanaugh & Clarke 2001). This would be possible at Briksdalsbreen, given the zone of crevassing that divides the north and south sides of the glacier, and the icefall up-glacier of the study site.

Subglacial processes

Event 1 (days 20–42, 2005; days 355–51, 2006). – Event 1 was highly unusual, occurring very early in the year at a time that would ordinarily be associated with winter conditions and minimal subglacial activity. However, the previous section demonstrated that the required external physical conditions for such activity were recorded at this time. As a result, Event 1 appears to mark the start of activity within the subglacial environment, following a period of sensor inactivity in the preceding months.

The probe 8 record (2005) displayed a relatively gradual build-up of pressure in Event 1 (days 20–42). Readings did not exceed overburden and were accompanied by a decrease in probe temperature (Fig. 5B). The lack of accompanying sensor variations suggests that the increase in water pressure did not have a significant effect on subglacial conditions. In 2006, probe 15 was the

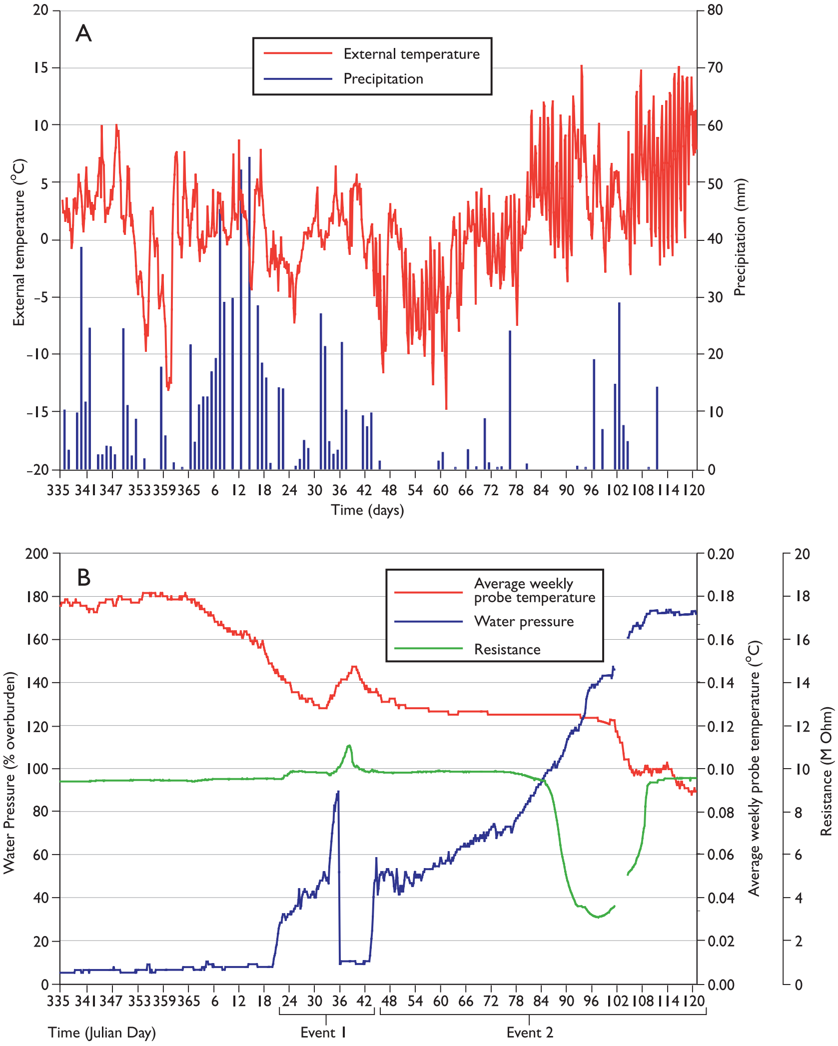

Fig. 5. Spring records (2004/5) showing (A) external weather conditions and (B) probe 8 sensor readings for average weekly probe temperature, water pressure and resistance. This figure is available in colour at http://www.boreas.dk

first (and only probe) to display sensor activity, during Event 1 (days 355–51, Fig. 6D). This event exhibited a variety of pressure fluctuations, including diurnal oscillations, some of which exceeded overburden pressure (Fig. 7A). The pressure fluctuations progressed over a period of 1.5 months, indicating a gradual increase in hydrological activity within the till (days 355–38). This activity culminated in the sudden high magnitude pressure oscillations recorded between days 39 and 51. During this time, resistance and probe temperature decreased, suggesting a large influx of meltwater to the glacier bed (Fig. 6D).

It is during this event that hydrological activity has begun to develop at the ice-bed interface and within the till. The drop in resistance that accompanies the pressure fluctuations highlights the increase in water present within the subglacial environment. Under these conditions the mechanical properties of the till will begin to change as the amount of water present within the till increases. This will also cause subglacial flow pathways to undergo modification. However, these changes were not sustained.

The sensor oscillations displayed by probes 8 and 15 were followed by a period of quiescence, where water pressures returned to base values and sensor fluctuations decreased. This was probably due to the external weather conditions (reduced temperatures and precipitation events) at this time (Figs 5A, 6A), which could not support a sustained increase in subglacial activity. In addition, in 2006, probe 15 was the only probe to show activity at this time of year, suggesting that this event was highly localized. As such, it is unlikely that Event 1 represents lasting glacier-wide changes in subglacial conditions. Instead, the timing and occurrence of this event are more likely the result of localized annual weather conditions.

Event 2 (days 77–120, 2005; days 52–120, 2006). – All four probes displayed pressure fluctuations during Event 2. In 2005, probe 8 water pressure exceeded overburden, as probe temperature and resistance decreased rapidly (Fig. 5B). These trends in combination suggest that Event 2 marked a significant influx of water into the till, resulting in important changes in the

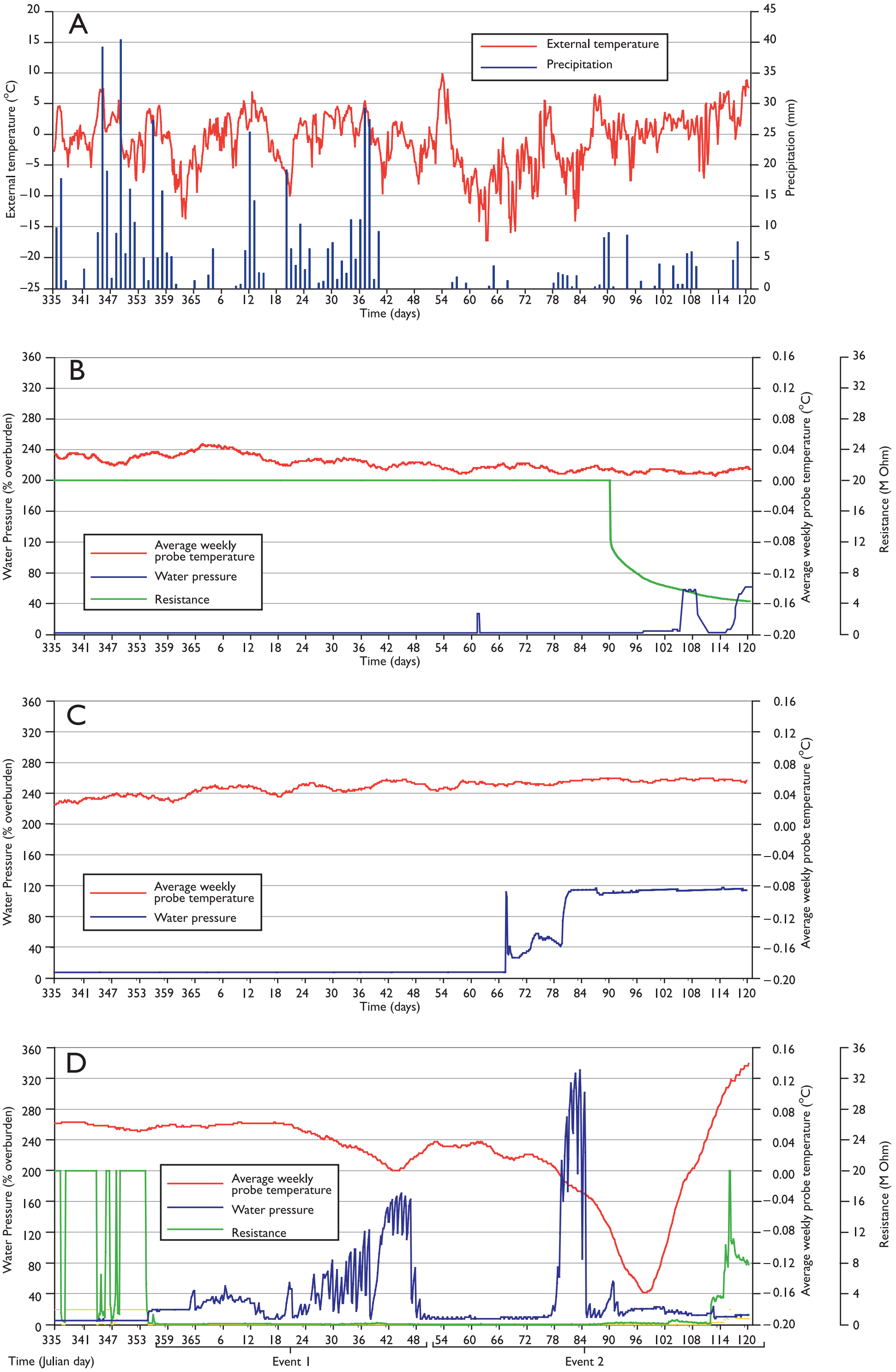

Fig. 6. Spring records (2005/6) showing (A) external weather conditions, (B) probe 10, (C) probe 12 and (D) probe 15 sensor readings for average weekly temperature, water pressure and resistance. Note: probe 12 resistance is not displayed owing to a dysfunctional sensor. This figure is available in colour at http://www.boreas.dk

physical properties (water content) and drainage conditions within the subglacial environment. This was demonstrated by the sustained pressures that followed this event, implying that flow pathways within this area of the bed had become established.

Event 2 for probes 10, 12 and 15 was characterized by a series of pressure variations (Fig. 6B–D). The initial small pressure peaks experienced by probes 10 and 12 implied that hydrological activity had begun within these areas of the bed (Fig. 6B, C). The following pressure rises, recorded by all three probes, occurred suddenly and, with the exception of probe 10, exceeded overburden. However, only probe 15 displayed diurnal fluctuations (Fig. 7B). Probes 10 and 12 displayed

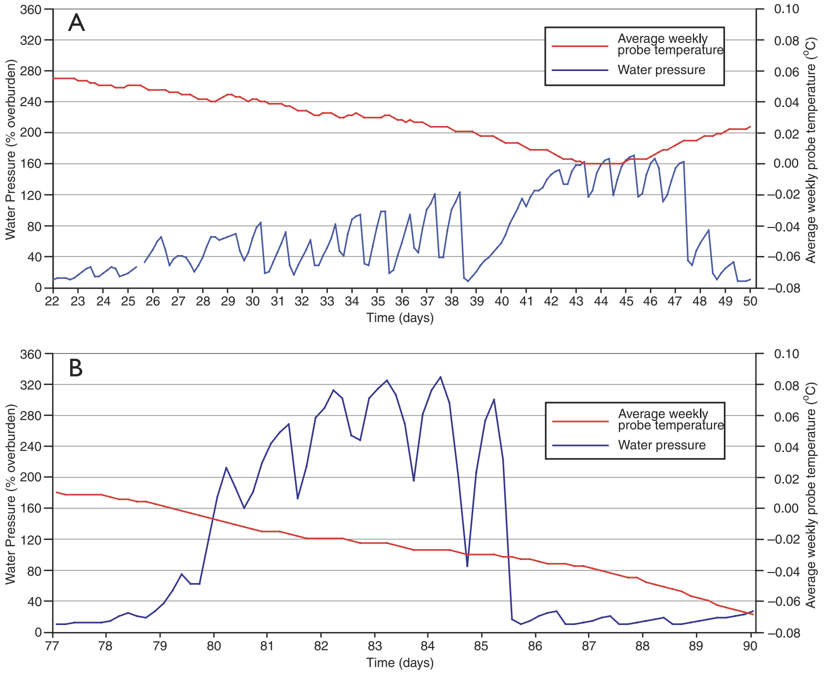

Fig. 7. Probe 15 sensor record showing diurnal fluctuations (A) days 23–50, during Event 1; (B) days 78–88, during Event 2. This figure is available in colour at http://www.boreas.dk

sustained pressure readings following Event 2. In contrast, probe 15 recorded a decline and small fluctuations in water pressure, as well as a change in resistance and probe temperature sensor patterns. The pressure peaks and subsequent variations in sensor readings displayed suggest that this event was of sufficient magnitude to result in lasting changes in the properties of, and processes operating within, the subglacial environment.

Drainage network

The moderate fluctuations and sustained pressures displayed by probes 8, 10 and 12 were indicative of unconnected drainage regions (Figs 5B, 6B, C). Diurnal signals were not recorded, implying that changes in pressure originated from independent sources at the ice-bed interface. In contrast, the highly fluctuating pressures (predominantly characterized by diurnal oscillations) recorded by probe 15 implied that it was located in a connected region (Figs 6D, 7). In the summer, connected subglacial drainage systems tend to have a significant source of meltwater derived directly from surface inputs (e.g. via moulins). As a result, there tends to be a correlation between external weather conditions (i.e. diurnal melt cycles and/or precipitation events) and trends in water pressure (e.g. Hubbard *et al.* 1995; Fountain & Walder 1998; Mair *et al.* 2003). The occurrence of diurnal oscillations implies that a daily cycle of meltwater was being generated at the glacier surface and that summer drainage conditions had become established.

However, the pressure oscillations of probe 15 displayed peaks at 08.00 h and minima at 16.00 h. The 'normal' summer signal associated with glacial environments records peak flows in the afternoon and low flows at night and in the mornings (Elliston 1973). This is in response to the cycle of surface meltwater generation, which peaks in the afternoon in accordance with maximum exposure to solar radiation. The opposite is true for minimum flows. The record of probe 15 was 180° out of phase with this normal trend.

The simplest explanation for this pattern is that probe 15 was recording a lagged response between meltwater production at the surface and water reaching the glacier bed. This is feasible at this time of year, when even a thin, isothermal, snowpack could act to dampen the water reaching the subglacial environment. Observations of peaks in proglacial discharge during this time would provide further evidence of this, but such measurements were not collected at Briksdalsbreen.

Alternatively, the pressure signal observed may be the result of 'pressure forcing' from neighbouring connected regions of the bed (Murray & Clarke 1995). High pressures within connected regions can cause the glacier to become decoupled from its bed through a process of hydraulic jacking. This allows the spatial extent of the connected region to expand in order to accommodate the increase in water inputs. This change relieves the pressure in unconnected regions causing pressure to drop while pressure is still high in connected regions (Murray & Clarke 1995). If this is the case, the signal recorded by probe 15 can be considered as a proxy (albeit 180° out of phase) for the processes occurring within a connected region.

The differences between connected and unconnected probe sensor readings are most readily described in Fig. 8.

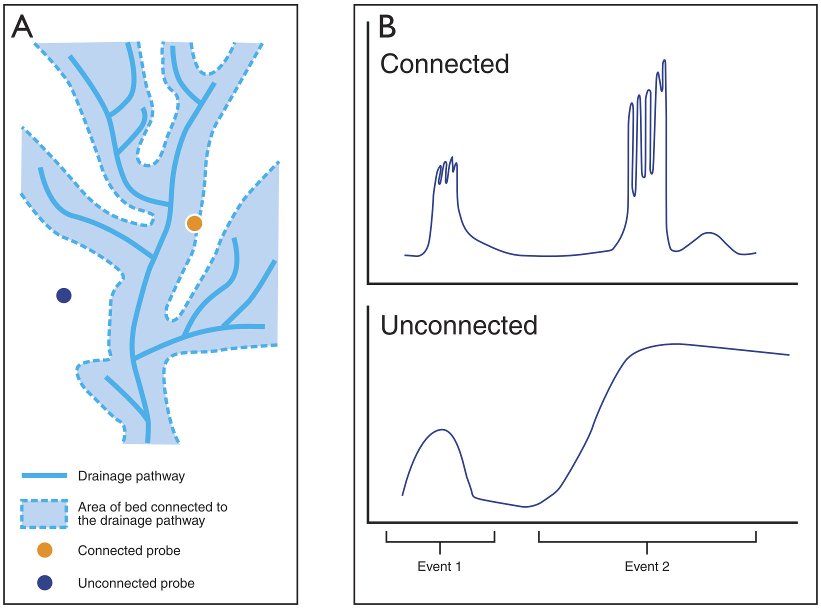

Fig. 8. Conceptual model demonstrating the different characteristics of the winter–spring transition showing (A) the potential location of the probes in each scenario within a hypothetical drainage system and (B) the form of the pressure records according to their location in connected and unconnected regions of the bed. This figure is available in colour at http://www.boreas.dk

In the first diagram (A), probe 15 is positioned proximal to the connected region of the bed, while probes 8, 10 and 12 are located in unconnected regions, and solely affected by independent basal flows. The second diagram (B) outlines the winter–spring transition at Briksdalsbreen in terms of the water-pressure record. The pressure peaks recorded in the connected region were 'flashy' (probe 15). Pressures both rose and fell suddenly and rapidly, with diurnal variations increasing the short-term variability of the records. In general, the magnitudes of the pressure peaks were also much greater that those in the unconnected regions, where pressure responses were damped. In unconnected regions, pressure fluctuations were often abrupt, but subsequent readings displayed a gradual increase in pressures, which did not always exceed overburden (probes 8, 10 and 12). The lack of diurnal oscillations reduced the variability of readings, and pressures were sustained following Event 2. This conceptual model highlights the relative timing, and variations in the form, of pressure response between Events 1 and 2 during the winter–spring transition.

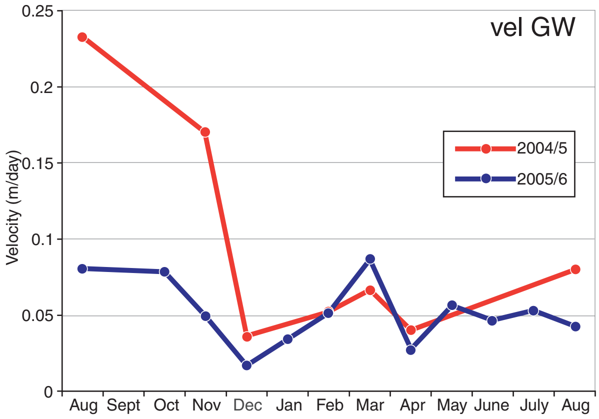

Fig. 9. Average monthly changes in glacier velocity for Briksdalsbreen (2004–2006). This figure is available in colour at http://www.boreas.dk

Drainage morphology

Long-term changes in subglacial processes associated with seasonal transition from a winter to summer drainage morphology can also be detected. The low mildly undulating water pressures recorded by the probes at the start of the winter–spring were indicative of minimal meltwater inputs in a low capacity distributed drainage network, normally associated winter conditions (e.g. Willis 1995; Hubbard & Nienow 1997; Fountain & Walder 1998). After Event 2, the probes displayed a change in sensor patterns. For probe 15, resistance began to fluctuate and increase with probe temperature as water pressure fell, thus indicating a net loss of water from this area of the bed. The change suggested that a well-developed, high capacity, drainage network, normally associated with a summer regime, had become established. The system could accommodate and transfer large quantity meltwater inputs more efficiently, causing a reduction in water pressure in this area of the bed. This transition terminated the pressure forcing in the area.

The precise morphology and capacity of the connected system is difficult to assess from this record alone. However, studies elsewhere have suggested that such a transition is likely to result in the formation of a discrete, arborescent drainage morphology beneath the ice (e.g. Willis *et al.* 1990; Nienow *et al.* 1996; Hubbard

Table 3. Comparison of the parameters associated with spring events from records at the case study sites of Haut Glacier d'Arolla, Hubbard *et al.* (1995) and Mair *et al.* (2001, 2002, 2003), Trapridge Glacier, Kavanaugh & Clarke (2001) and Bench Glacier, Harper *et al.* (2005).

Location/probe	Timing of spring events	Snowpack removal	Weather conditions	In excess of overburden pressure?	Diurnal oscillations?	Variations in discharge/ turbidity?	Increase in glacier velocity?
Haut Glacier d'Arolla, Switzerland	June–July	June/July	Correlated	Yes	Yes	Yes	Yes
Trapridge Glacier, Canada	June–July	–	Correlated	Yes	Yes	Yes	Yes
Bench Glacier, Alaska	April–June	July	Not correlated	Yes	Yes	Yes	Yes
Probe 8	January-March	April	Correlated	Yes	No	?	Yes
Probe 10	March–April	April	Correlated	No	No	?	Yes
Probe 12	March	April	Correlated	Yes	No	?	Yes
Probe 15	December–March	April	Correlated	Yes	Yes	?	Yes

& Nienow 1997), and that, taking into account surface slopes at a valley glacier such as Briksdalsbreen, R-channels are likely to form in such a discrete network (Walder & Fowler 1994).

Although located in unconnected regions, probes 8, 10 and 12 also support the idea of a winter–summer transition in drainage morphology. The sustained pressures following the spring event indicate the development of a strong hydraulic gradient with a newly established high capacity discrete drainage network (Murray & Clarke 1995). These patterns demonstrate that the probe records can identify large-scale shifts in subglacial drainage characteristics, even if they are unable to provide greater evidence of the precise morphology of the subglacial drainage system. This, however, is an area of study that the probes can add to, given wider spatial coverage of the glacier bed in future investigations.

The spring event

Interestingly, Event 2 shows some comparison with what others have described in the literature as the 'spring event' (Table 3). Spring events have been well documented at valley glaciers in the Alps. They constitute sudden high magnitude pressure events, which are triggered by external weather conditions, and result in significant hydrological and mechanical instability within the subglacial drainage system. In particular, it is thought to drive the seasonal reorganization of the subglacial drainage system from a winter to summer regime (e.g. Willis *et al.* 1990; Gordon *et al.* 1998; Mair *et al.* 2001, 2002) and trigger variations in glacier dynamics (Iken *et al.* 1983; Iken & Bindschadler 1986; Kavanaugh & Clarke 2001; Harper *et al.* 2002; Mair *et al.* 2003; MacGregor *et al.* 2005). Proglacial stream discharge and turbidity are also often affected, as this event increases the amount of water and sediment evacuated from the bed of the glacier (Kavanaugh & Clarke 2001; Mair *et al.* 2003; Harper *et al.* 2005).

In accordance with these findings, Event 2 is relatively short-lived and occurs later in the year (March), at a time that is more in keeping with spring weather conditions at Briksdalsbreen (Table 3). It is triggered by sudden meltwater inputs resulting from external weather conditions and is coincident with the removal of the snowpack. It is characterized by high magnitude pressure fluctuations in excess of overburden pressure and results in a seasonal reorganization of the subglacial drainage system. Unfortunately, discharge readings were not obtained from Briksdalsbreen, so comparisons cannot be made with turbidity and discharge measurements made in the literature. However, monthly GPS readings did reveal a sudden increase in glacier velocities in March, which again agrees with the timing of Event 2 (Fig. 9).

Conclusions

The evidence discussed above highlights the winter–-spring transition in 2005 and 2006 using the first long-term records of porewater pressure obtained from wireless subglacial probes. The transition occurred in two phases, categorized as Events 1 and 2. Identification of these events was based on the characteristics of the pressure peaks recorded and new supporting evidence from the other probe sensor readings. Event 1 marked the start of hydrological activity within the subglacial environment following a period of quiescence during the winter. This event occurred in response to short-lived variations in external weather conditions. In contrast, the high magnitude pressure peaks of Event 2, and the change in sensor patterns that followed, signified a permanent transition in subglacial processes and the morphology of the subglacial drainage system. Event 2 also showed some comparison with spring events recorded at valley glaciers in the Alps, which have a similar effect on subglacial conditions. Notably, glacier velocities at Briksdalsbreen increased coincident with the timing of Event 2, similar to the spring event.

A conceptual model was presented associating the form of the winter–spring transition with respect to the location of the probes in connected and unconnected regions of the subglacial drainage system. The conceptual model simplifies the spatial heterogeneity of the subglacial drainage system across the glacier bed and its response to hydrological instability during the winter–spring transition. These data provide further evidence for temporal and spatial heterogeneous subglacial drainage systems and processes. The identification and analysis of subglacial activity during the winter–spring transition can contribute to the interpretation of hydro-mechanical processes occurring within the subglacial environment and their effect on glacier dynamics.

Acknowledgements. – We thank: the Glacsweb team for help with data collection (Royan Ong, Richard Waller, Al Riddoch, Ahmed Elsaify, Gang Zou, Paritosh Padhy, Elisa Anderson, Hannah Brown, Kim Dowsett, John Hunt, Natalie Jarman, Daniel Miles, Celine Ragault, Sarah Stafford, David Vaughn-Hirsch, Sarita Ward, Sue Way and Mathew Westoby); Inge and Gro Melkevol for help with logistics; and Intellisys, BTExact, TOPCOM and eKlima for support. Thanks also go to Bob Smith and his colleagues in the Cartographic Unit, School of Geography, for help with figure preparation. This research was funded by the Royal Society Paul Instrument Fund, the Royal Society and the UK Engineering and Physical Sciences Research Council. The article was improved substantially following the comments of I. C. Willis and D. W. F. Mair. Jasper Knight, University of Exeter, guest-edited the article.

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