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Reconstruction and regional significance of the Coire Breac palaeoglacier, Glen Esk, eastern Grampian Highlands, Scotland.

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Abstract

We present a glaciological and climatic reconstruction ofa former glacier in Coire Breac, an isolated cirque within the Eastern Grampian plateau of Scotland, 5 km from the Highland edge. Published glacier reconstructions of presumed Younger Dryas-age glaciers in this area show that equilibrium line altitudes decreased steeply towards the east coast, implying a maritime glacial environment. Extrapolation of the ELA trend surface implies that glaciers should have existed in suitable locations on the plateau, a landscape little modified by glaciation. In Coire Breac, a 35 ha cirque glacier existed with an equilibrium-line altitude of 487 ± 15 m above present sea level. The equilibrium line altitude matches closely the extrapolated regional equilibriumline altitude trend surface for Younger Dryas Stadial glaciers. The mean glacier thickness of 24 m gives an ice volume of 7.8 x 10^6 m^3, and a maximum basal shear stress of c.100 kPa^{-1}. Ablation gradient was c. -0.0055 m m^{-1}, with a mean July temperature at the equilibrium line altitude of c. 5.1°C. The reconstruction implies an arctic maritime climate of low precipitation with local accumulation enhanced by blown snow, which may explain the absence of other contemporary glaciers nearby. Reconstructed ice flow lines show zones of flow concentration around the lower ice margin which help to explain the distribution of depositional facies associated with a former debris cover which may have delayed eventual glacier retreat. No moraines in the area have been dated, so palaeoclimatic interpretations remain provisional, and a pre-Lateglacial Interstadial age cannot be ruled out.

Key words

Glacier reconstruction palaeoclimatic reconstruction Younger Dryas equilibrium-line altitude Grampian Highlands

Introduction

The Last Glacial-Interglacial Transition is marked by a complex climatic response to forcing mechanisms at a variety of spatial and temporal scales. In the British Isles, a range of proxy records demonstrate that climate was influenced by the interaction of oceanic, atmospheric and cryospheric factors around the North Atlantic (Clark *et al.* 2009; Bromley *et al.* 2014). This created a series of rapid, high-amplitude environmental changes that are well expressed in Greenland ice cores, now defined by an established event chronostratigraphy of stadial and interstadial conditions (Rasmussen *et al.* 2006; Lowe *et al.* 2008; Hoek *et al.* 2008). One of the most notable events during this period was the cold phase of the Younger Dryas Stadial (YDS, equivalent to Greenland Stadial 1 (GS1) 12.9-11.7 ka, Lowe *et al.* 2008) that marked an extreme climatic deterioration in the northern hemisphere during a longer period of climatic amelioration into the Holocene (Carlson 2013).

In many mountain areas of the British Isles, there is geomorphological evidence for palaeoglaciers during the Younger Dryas (in Britain, the Loch Lomond) Stadial. Reconstruction of these palaeoglaciers has provided a data source for climatic reconstructions based on ELA calculations (cf. Golledge 2010). In Scotland, the main Stadial icecap developed over the western Grampian Highlands (Thorp 1986; Golledge *et al.* 2008) with numerous smaller icefields over massifs in north-west Scotland (e.g. Lukas and Bradwell 2010; Finlayson *et al.*2011). Conversely, the eastern Grampian Highlands had restricted glacier extent in the form of small ice fields and valley glaciers that appear to have formed only over the highest plateaux (Fig. 1) (Sissons 1972; Sissons and Grant 1972). A similar pattern has been demonstrated in the Cairngorm Mountains, where a cold, arid climate limited glacier growth to only a few cirques (Sissons 1979; Hubbard 1999; Kirkbride *et al.* 2014). Stadial climate showed greater seasonality in precipitation across Scotland both from west to east and from north to south (Golledge 2010).

The topography of eastern Scotland made glacial cover particularly sensitive to equilibrium line altitude (ELA) fluctuations. However, the terrain of this area lacks the topographic character of glaciated uplands. Previous geomorphological mapping in the Eastern Grampians has allowed the definition of the former glacier extent, calculation of former ELAs, reconstruction of regional climate during the Stadial based on a palaeo-ELA surface across the area (Fig. 1) (Sissons and Sutherland 1976). Smaller ice masses suggest that these mountains were marginal to glacier development, and that the glaciers may have been in mass balance deficit and therefore dependent on site-specific topoclimatic controls (Mitchell 1996; Coleman *et al.* 2009; Carr *et al.* 2010).

Extrapolation of Sissons and Sutherland's (1976) ELA trend surface to the south-east implies that glaciers could have formed close to the eastern Highland boundary where higher parts of the plateau intersected the ELA trend surface. Therefore, a reconnaissance survey was undertaken of areas of the Eastern Grampian Highlands where former glaciers have not previously been identified. Previously unmapped moraines and associated meltwater channels were located only in Coire Breac, on the northern side of the Hill of Wirren (678 m OD) between Glen Esk and Glen Lethnot (Fig. 1). The glacier lay 7 km east of previously reported YDS glaciers (Sissons 1972) and within 5 km of the plateau edge as defined by the Highland Boundary Fault. The glacier location is significant for testing Sissons and Sutherland's ELA trend surface and its associated palaeoclimatic inferences.

The steep south-eastwards decline in the trend surface is a product of the original geomorphological interpretation of a series of extensive plateau icefields to the north-west of the area, but glens to the south and east being characterised by low-altitude cirque and valley glaciers (Sissons 1972). Such a reconstruction influences the ELA pattern because plateau icefields give higher calculated ELAs because of their extensive high-altitude accumulation zones. Estimated ELAs from valley glaciers will necessarily be lower if surrounding plateaux are mapped as ice-free ground. Since Sissons (1972) first mapped the area, it has become appreciated that plateau icefields in Britain were probably more extensively developed than previously envisaged, given that many accumulation areas left no geomorphological signature (cf. McDougall 2013). Some of the nearby topographically-constrained valley glaciers constructed by Sissons (1972), such as in the Water of Saughs and Glen Effock (Fig. 1), may be better understood as outlet glaciers from more extensive plateau ice, which may require modification to ELA trend surface reconstructions.

However, these interpretive uncertainties are circumvented for Coire Breac because the glacier occupied a discrete cirque with a suite of landforms that allows the clear reconstruction of the former cirque glacier. This detailed reconstruction permits the glaciological and climatic environments to be interpreted for a glacier unusually close to the east coast of Scotland.

The preceding introduction rests on a presumption that the Coire Breac Glacier existed during the YDS, consistent with many other local studies of undated moraines in Scotland (e.g. Benn and Ballantyne 2005; Harrison *et al.* 2006; Golledge 2010; Lukas and Bradwell 2010). We conclude by considering the possibility that the moraine may predate the YDS, and briefly consider the implications for the palaeo-ELA surface.

Study site

The eastern Grampian Highlands form the most extensive high plateau in Scotland (Bremner 1919) and is traditionally called The Mounth (Watson 1992). The Hill of Wirren (56° 52′ N, 2° 47.5′ W, 678 m above sea level) forms part of an undulating upland bounded to the south-east by the Highland

Boundary Fault, to the north by the major valley of Glen Esk (Fig. 1), and to the south-west by Glen Lethnot. The topography comprises broad ridges incised by v-shaped river valleys, except where a number of valleys have been modified into large, broad glacial troughs, such as Glen Esk. Bedrock geology is mainly quartz-mica schist and psammite of the Southern Highland Group of the upper Dalradian (Strachan *et al.* 2002). The area is one of the driest in the Scottish Highlands; mean 1981-2010 precipitation and temperature records for nearby lowland sites are: Forfar 791 mm and 8.1°C; Aboyne 780 mm and 7.9°C; and Braemar 932 mm and 6.9°C. The nearest high-altitude site (The Cairnwell, 933 m) has a mean annual temperature of 2.7°C (Met Office 2013).

Coire Breac is the only valley head in the immediate area with the glacial characteristics of a cirque. It forms an asymmetric bowl with steep 120 m–high western slopes with exposed bedrock, but no major cliffs (Fig. 2). It is bounded to the west by the spur of West Wirren (628 m), and to the east by the minor spur of Black Shank. The backwall and eastern slope are lower angled and vegetated. The present stream, the Burn of Corriebreac, is incised into the sediment-covered cirque floor, and the incision extends all the way up the head slope. The gentlest sloping section of the cirque floor lies at an altitude of 420-440 m. The cirque floor is occupied by a number of asymmetric transverse ridges or moraines, in contrast to the small valley east of Black Shank which has smooth, moraineless slopes suggesting a periglacial origin.

Methods

Geomorphology

Geomorphological mapping of the glacial landforms was completed using a topographic base map at a scale of 1:6250 using established procedures (Mitchell 1996; Knight *et al.* 2011). Field mapping was checked against Google imagery with locations fixed using a Garmin Etrex hand-held global positioning system (GPS). Attention was focussed on identifying moraine ridges and associated meltwater channels.

Glacier reconstruction

The geomorphological map (Fig. 3) formed the basis of the glacier reconstruction. Calculation of the equilibrium line altitude and snow blow thereby allowed determination of the stadial climate in terms of temperature and precipitation (e.g. Sissons 1974; Benn and Ballantyne 2005; Carr *et al.*

2010). The glacier reconstruction was used to determine the ice surface topography, thickness, volume, bed shear stress and velocity. Glacier reconstruction follows several steps from defining the initial glacier outline to deriving glaciological parameters. The glacier perimeter was superimposed on a base map of the present-day topography to contour the former glacier surface at 20 m intervals. A flow line map was produced by marking points of flow origin at 100 m intervals around the accumulation zone margin and tracing lines from each point downglacier, crossing each surface contour perpendicularly until the flow line thus derived intersected the ice margin in the ablation zone. The ratio of distances between points of flow origin and ablation-zone margin intersection points has been used to calculate a flow concentration factor (FCF), indicating sectors of the ablation zone where supraglacial debris was either relatively dispersed or concentrated by glacier flow.

Ice thickness was reconstructed by sampling the intersection points between surface and bed contours at a 10 m interval. No adjustment was made for postglacial sediment accumulation on the cirque floor: this introduces an underestimate of former ice thickness of ≤ 4 m at the terminus, decreasing to almost zero towards the former equilibrium line altitude.

A 100 m grid was superimposed within the glacier outline as a sampling tool for surface slope and basal shear stress, providing 36 nodal points. At each point, the surface slope was calculated from the surface contours. Basal shear stress was calculated for each node according to the standard formula $\tau_b = \rho g h \sin\alpha$, where ρ is ice density (0.9 t m^3), g is the gravitational constant (9.8 m s^{-1} s^{-1}), h is ice thickness (m), and α is the surface slope in degrees. No adjustment for the shape factor was introduced for calculating point values of τ_b, but a shape factor was introduced for calculating area-averaged values of τ_b (after Carr and Coleman 2007).

Reconstruction of equilibrium line altitude

The equilibrium line altitude was calculated using standard methods (Nesje and Dahl 2000; Benn and Evans 2010; Carr *et al.*2010). The maximum elevation of lateral moraines (MELM) was calculated as the mean of altitudes of the highest identifiable point on each lateral moraine when walked out in the field. Toe-headwall area ratio (THAR) employed a value of 0.4 (after Nesje and Dahl 2000). Median glacier elevation (MEG) was read off at the 50th percentile of area on the hypsometric curve. The accumulation area ratio adopted a value of 0.6 ± 0.05, appropriate for cirque glaciers (Nesje and Dahl 2000), and accommodated the area-altitude distribution by deriving a range of ELA values from the hypsometric curve. ELAs were calculated to the nearest metre, but a preferred value for the glacier is given, more realistically, from the AAR method with an uncertainty of ± 5% of the glacier area. ELAs have also been estimated from the area-altitude balance ratio (AABR, Furbish and

Andrews 1984; Rea 2009) for values from 1.67 to 2.0 (cf. Ballantyne 2002; Benn and Ballantyne 2005; Lukas and Bradwell 2010). A range of values is preferred for comparison with other ELA estimation methods, though the effect on ELA is only a few metres (Finlayson et al. 2011), and associated summer temperature estimates differ by only c. 0.1°C within this range. Rea's (2009) global dataset shows considerable variation in AABR values within regions, as well as a trend towards lower values in more continental climates.

Reconstruction of temperature, ablation gradient, mass flux, and ice motion

Palaeotemperature at the ELA was calculated based on a survey of present day temperatures from six meteorological stations, and a chironomid-based July temperature estimate for the YDS from Abernethy Forest, 62 km north-west of Coire Breac (Brooks *et al.* 2012). Present-day climate averages were downloaded from the UK Met Office website for the 1981-2000 reference period, for stations at Aboyne, Aviemore, Braemar, The Cairnwell, Cairngorm, and Forfar (see Fig. 1 for locations). These stations cover the whole eastern Grampian area and range in altitude from 92 m to 1245 m. Mean temperatures were calculated for each station for January, July, November through April, May through October, as well as the annual mean. Mean temperatures from the six stations correlate strongly with altitude (r^2> 0.99, Fig. 8). A regional lapse rate is calculated between the stations with the greatest difference in altitude, Forfar at 92 m and Cairngorm at 1245 m. An annual lapse rate of 0.65°C per 100 m was derived. For comparison, two stations in closer proximity but with an altitude difference of 654 m (Braemar and Cairnwell) gave an annual lapse rate of 0.63°C per 100 m. The lapse rate was then applied to all station data to estimate the mean temperature at the former ELA of 490 m. Lapse rate-adjusted temperatures show the most consistent values for summer months. This is encouraging, because palaeoprecipitation estimates are based on relationships with summer temperature.

The methodology of Carr *et al.* (2010) was adopted to estimate palaeoglaciological parameters. Chironimid-derived mean July Stadial temperatures for Abernethy Forest (Brooks *et al.* 2012) were adjusted using an empirical present-day lapse rate to the equivalent ELA temperature. Mean summer (MJJASO and JJA) temperatures were derived using the ratio between mean July temperature from present-day data and these longer summer periods. Carr *et al.*'s (2010) relationship for modern glaciers of mean JJA temperature to ELA total accumulation was applied to estimate accumulation at the ELA. The ablation gradient was also estimated using Carr *et al.*'s (2010) method. Ablation gradient was then used to calculate net annual mass loss from each 20 m elevation band, and then summed to give the total annual ablation of the glacier. Assuming steady-state conditions at the ice maximum, this equates to the balance flux through the ELA (the discharge of ice required to transfer the annual net accumulation total to the ablation zone). Dividing by the glacier cross-sectional area at the ELA gives the area-averaged balance velocity. This was partitioned into creep and sliding components by calculating the area-averaged creep rate and subtracting this from the balance velocity to derive the sliding velocity. Mean creep rate through the ELA was calculated using the formula $U_o = 2hA(\tau_{av})^n/(n+2)$, where h is mean ice thickness, A is the temperature-dependent flow law parameter (assumed here to be a temperate-ice value of 5.3 x 10^{-15} sec^{-1} kPa^{-n}, Booth 1986), τ_{av} is the mean basal shear stress adjusted using a shape factor dependent on the width-depth ratio of the cross section, and n is the flow law exponent (assumed to be 3). Values of h and τ_{av} are width-averaged values at the ELA.

By this method, sliding velocity becomes a variable dependent on ice discharge and creep rate, which is glaciologically questionable (Kirkbride *et al.* 2014). However, it does allow first-order estimation of former glacier dynamics to be derived from empirical relationships from modern glaciers.

Reconstruction of snow blow areas and snow blow factor

Previous studies have demonstrated that small glaciers often have a mass deficiency when ELA is calculated by standard techniques (Carr and Coleman 2007; Coleman *et al.* 2009) requiring local factors to contribute and/or preserve additional mass to allow glacier formation. One of these factors is enhanced accumulation by blown snow from surrounding areas onto the glacier surface (Sissons and Sutherland 1976; Robertson 1989; Purves et al. 1999) Calculations of potential snow blow areas have followed the procedure of Mitchell (1996) and Coleman *et al. (*2009) who assume that all ground which lies adjacent and above the accumulation area, as defined by the calculated ELA of the palaeoglacier (Fig. 9A), has the potential to blow snow on to the glacier surface. Given that not all areas of potential snow blow have an equal chance of contributing mass, particularly with distance from the palaeoglacier, a snow blow factor can be calculated as the square root of the ratio of glacier area to potential snow blow area, following Sissons (1980). Both potential snow blow area and snow blow factor can then be plotted with respect to wind direction as polar plots in 15^o sectors (Figs. 9B and C).

Results

Geomorphology

Ice marginal landforms are well-preserved in this cirque, as are forms possibly associated with a retreat-stage supraglacial debris cover (Fig. 2B). The terminal moraine forms a loop that has been breached by the Burn of Corriebreac (Fig. 4A). West of this stream, the outer moraine ridge is well-defined with a steep 4 m-high distal slope (Fig. 4B). Here, the moraine forms an asymmetric ridge in the lower part, with a meltwater channel along the foot of the distal slope (Fig. 4C). East of the stream, the moraine is less continuous, and an embayment in the moraine has a morphology suggesting meltwater incision into the moraine during deglaciation ("E" in Fig. 3).The outer moraine becomes smaller upslope, and above the beginning of the meltwater channel ("M" in Fig. 3) it is broader and less defined, but traceable to an elevation of 470 m. The lower right-lateral distal limit is marked by elongated morainic hummocks paralleling the ice margin, which in this sector lies on gently-sloping ground below the spur of Black Shank. Upglacier, where the slope steepens, the margin is marked by a small but distinct sloping ramp in the grassy hillside which eventually peters out at an elevation of 485 m. The ramp is interpreted to be the remnant of a small lateral moraine which survived post-depositional degradation due to the lack of channelized runoff or mass movement on the slope. It is a very subtle feature ("L" in Figure 3), but visible on photographs from across the cirque (Fig. 4D). Within this outer moraine, two further transverse moraine ridges ("R" in Fig. 3), accentuated by meltwater channels, occupy ground towards the present stream and indicate ice-marginal fluctuation during recession. Other meltwater channels occur upstream beyond the moraine ridges and are incised into a more general drift cover.

Small-scale ridge-furrow topography, which is difficult to determine on the ground but is visible on imagery (Fig. 2B), occurs near the new track and is suggestive of a flow-deformational origin ("F" in Fig. 3). Ridges and furrows arc upslope towards the left-lateral moraine and indicate creep of an ice-cored moraine beneath a thick debris cover, probably abandoned by retreat of the active ice margin. This interpretation of the morphology implies that debris-covered ice was thick enough to survive to allow slow internal deformation to impart ridge-and-furrow morphology to the debris cover. The infill of debris behind the lower ice-marginal moraines also indicates that a thick debris cover accumulated after the ice maximum. The absence of headwall indentations associated with large rock falls or rock avalanches and the densely-jointed bedrock in the cirque indicate that supraglacial debris accumulation would have been by frequent small rock falls and not by high-magnitude events.

The landform assemblage does not provide evidence of an ice source in an accumulation zone on the plateau above the cirque (cf. McDougall 2001, 2013; Rea and Evans 2003). Three lines of evidence militate against a plateau-ice source: (1) meltwater channels are confined to the margins of the ablation zone in the lower cirque, and do not extend upslope towards the plateau; (2) there are no recessional moraines indicating the dynamic retreat of active ice upslope, and (3) no other valleys draining the plateau show any landform evidence of small outlet glaciers. Instead, a cirque glacier supplied by direct snowfall and wind-drifted snow is interpreted from the geomorphological evidence.

Glacier surface reconstruction

The surface slope distribution determines zones of longitudinally extending and compressing ice flow, the latter being associated with the emergence of englacial debris. The reconstructed glacier surface was of rather uniform gradient, widening from the highest point at c. 630 m to a maximum of 500 m at 520 m above sea level (Fig. 5A). Slope angles exceed 25° only in a narrow apron along the upper accumulation zone margin below the head scarp (Fig. 5B), where the bergschrund would have separated the glacier from steep snow slopes fringing the cirque rim, supplied by blown snow and avalanching from the head scarp. Below a gentle central area of < 15°, a ramp of ≤ 22° between c. 480 and 400 m a.s.l. graded into a low angle (c. 13°) terminal lobe.

Glacier hypsometry (Fig. 6) shows a modal elevation of 540-560 m, but a fairly uniform distribution of area with altitude. 89% of glacier area was between 400 and 600 m elevation, making the glacier AAR sensitive to ELA fluctuations within this interval. The flow line pattern (Fig. 5C) indicates the concentration of supraglacial debris between supply from the cirque head wall and delivery to the margin of the ablation zone (Fig. 7). The method provides a useful indicator which helps to understand ice-marginal landforming processes. Flow lines intersecting the upper ablation zone margins show less concentration of debris (lower FCF values), while the latero-terminal sectors show higher concentration factors (higher FCF values). This indicates that if debris inputs from the cirque headwall were uniform in distribution and rate, the ice-marginal moraines created by deposition of this debris will vary in volume per unit length of glacier margin. When the flow line pattern is compared to the geomorphological map (Fig. 3), relationships emerge. The well-developed left-lateral moraine increases in size downstream, corresponding to the increase in flowline concentration, and enhanced by the higher head slope on the south-west side of the cirque. Moraine size reflects greater delivery of high-level debris to the ice margin where debris from a wide source head slope segment is focused into a narrow depositional segment.

The lowest FCF values are located on the upper right ablation zone margin where a very subtle lateral moraine (Fig. 4D) is manifest as no more than a slight inflection in slope angle. In contrast to the left latero-terminal area, no distinct lateral moraine ridge is found. Instead, ice was unconfined by a steep lateral slope and spread thinly across the gently-sloping foreland. The former ice margin is marked by the distal edge of a linearly-hummocked till sheet rather than an ice-marginal moraine ridge.

Glacier bed reconstruction

Ice thickness and shear stress were sampled at 36 nodes of a 100 m grid (Fig. 5D). Isopachs show a predictable pattern of ice thickness (Fig. 5E). Glacier depth exceeded 50 m below the gentle central portion around the former equilibrium line. Mean thickness and ice volume were 24 m and 7.8 x 10^6 m^3 (Table 2). A region of thick (> 40 m) ice extended over 450 m downstream and 250 m in width over the central cirque floor. Ice thinned very slowly towards the thin, gently lobate terminus.

The pattern of bed shear stress is largely determined by ice thickness variation (Fig. 5F), because surface slope changes gradually across the glacier. Maximum shear stresses attain c. 100 kPa in the central zone, indicating that the glacier reconstruction is glaciologically realistic, and average 43 kPa across the ELA profile (Table 2).

Equilibrium-line altitude reconstruction

Given the simple glacier morphology and hypsometry, it is unsurprising that different methods of ELA reconstruction yield similar estimates of ELA (Table 1). The MELM method gives values of 470 m and 485 m for the left- and right-lateral moraines respectively (mean of 478 m) which are close to estimates based on the other methods and confirm that ice-marginal landforms extend close to the the ELA. The MEG method overestimates ELA compared to other methods, as it has been found to do elsewhere (Nesje and Dahl 2000). The mean ELA for the MELM, MEG, THAR and AAR = 0.6 methods is 487 ± 15 m. An AAR of 0.6 is equivalent to an AABR value of 1.67 (ELA = 493 m), appropriate for the drier eastern Highlands. An ELA of 490 m is therefore used for the Coire Breac glacier.

Palaeoclimatic reconstruction

Present-day temperatures at 490 m shows no horizontal trend, with mean July temperatures varying by a maximum of 1.2°C around a mean of 12.1 ± 0.3°C. The Abernethy data are therefore used in the YDS temperature reconstruction without adjustment for lateral variation. Mean July temperature for the period c. 14.5 to 10.5 k yr BP has been derived from the Abernethy Forest chironomid record

(Brooks *et al.* 2012). A rather constant temperature of c. 6.8°C existed between 12.5 and 11.7 k yr BP at the site altitude of 230 m. Assuming the temperature lapse rate was similar to today, this gives a mean July temperature at 490 m of 5.1°C, a temperature depression of 7.0°C from the 1981-2000 average. Mean JJA and MJJASO temperatures (variously used in palaeoclimatic reconstructions by different authors) have been estimated from the ratios of modern summer temperatures for the six climate stations (Fig. 8). Ratios vary by less than 10% between climate stations. Mean Stadial summer temperature estimates at the ELA are shown in Table 2.

The total contemporary accumulation at the ELA can be estimated from modern relationships between summer temperature and accumulation. Although such relationships show significant scatter (Ohmura *et al.* 1992), data are highly correlated and best-fit relationships allow cautious estimates to be made, though modern total accumulation data vary by a factor of two for a given summer temperature. Carr *et al.*'s (2010) regression yields an ELA total accumulation value of 1.83 m for a mean JJA temperature of 4.3°C. Total accumulation is also correlated with ablation gradient, allowing annual ice loss from the ablation zone to be estimated for each 20 m elevation band. The sum of these represents the balance mass flux through the ELA, from which the balance velocity is derived. Carr *et al.*'s formula gives an ablation gradient of -0.0055 m H_2O per m altitude, yielding a balance flux of 33.3 x 10^3 m^3 yr^{-1} through an ELA cross-section of 28.6 x 10^3 m^2, equivalent to an area-averaged balance velocity of 1.2 m yr^{-1}. Subtraction of the calculated creep velocity of 0.2 m yr^{-1} from the balance velocity yields an estimated mean sliding velocity of 1.0 m yr^{-1}, or 84% of glacier motion (Table 2). It should be emphasised that these estimates are dependent on assumptions of (for example) how valley-side friction retards ice motion, and on the selection of a flow-law parameter *A* for temperate ice, which may not have been the case at Coire Breac.

Carr et al.'s (2010) method assumes dominantly winter accumulation on YDS glaciers, a climate scenario which is questioned by Golledge et al. (2010), who argue that greater seasonality in the YDS invalidates a winter-accumulation model. They give an alternative relation between JJA mean temperature and total accumulation based on a dominantly summer-accumulation model, arguing that sea ice suppressed winter snowfall (see Discussion), combined with a much greater amplitude of seasonal temperature regime and extremely cold dry winters. Applying the Golledge et al. (2010) relation to Coire Breac yields a total annual accumulation of 1.54 m, 16% lower than the winter-accumulation based estimate.

Potential snow blow areas can be ascertained from the large area of plateau lying above and to the east of the cirque (Fig. 9A). Plotting of this distribution shows a preferred orientation (Table 3; Fig. 9B) with a pronounced concentration within the north-eastern and eastern sectors, with two main areas between 60-74° (ENE) and more extensively between 121 and 180° (SSE). This suggests that the extensive areas of high plateau, of which the Hill of Wirren is part, were important snow source areas for the Coire Breac glacier in combination with dominant winds from an easterly sector. This is further emphasised by the snow blow factor (Table 3; Fig. 9C) which again demonstrates the importance of this east/south-eastern sector in redistributing blown snow to the former glacier. This finding is consistent with the glacier draining from the south-east corner of the cirque (Fig. 3).

Discussion

The glacio-geomorphological environment of the Highland boundary during the Younger Dryas Stadial

The far eastern location of the Coire Breac glacier makes a glaciological reconstruction interesting because it allows an exploration of the glacial and climatic environment of the eastern Highland boundary during the YDS. Snow-bearing winds from the south-east have been inferred from the regional ELA gradient (Sissons and Sutherland 1976), implying enhanced precipitation from snow-bearing winds from the proximal moisture source of the North Sea. Reconstruction of YDS sea level in Eastern Scotland suggests that relative sea level was 40 m lower than present with a contemporary shoreline c. 10 km east of the present coast (Stoker et al., 2009). Paradoxically, Coire Breac appears to be the only site where a local glacier formed, in spite of the extensive land above the extrapolated ELA surface.

Estimates of palaeo-ice dynamics reveal some useful insights, although we regard these reconstructions as indicative rather than quantitative because of the assumptions which underlie the method. First, the annual accumulation of the Coire Breac Glacier was about twice the modern annual precipitation value of 1020 $\pm$ 80 mm (mean of 1981-2000 annual precipitation for Aboyne, Braemar, Aviemore and Forfar extrapolated to 490 m altitude). It is unlikely that precipitation was higher in the YDS, because lower evaporation from the North Sea would have occurred at lower temperatures under a climate of greater seasonality (Bromley *et al.*, 2014) and with a seasonally-frozen sea surface (Golledge et al., 2010). Therefore the higher-than-modern annual accumulation suggests that blown snow enhanced precipitation significantly, a process favoured by cold, dry winters and high winds. The local topoclimate of Coire Breac has been shown to favour secondary accumulation by snow blow (Fig. 9), which may also explain why glacier accumulation was so restricted at elevations above the regional ELA. Potential accumulation zones existed at altitudes mostly less than 100 m above the regional ELA surface, but wind redistribution of available snow was unable to form sufficiently deep accumulations in shaded locations elsewhere in the Glen Esk hills. It is likely that firn fields or even thin glaciers covered some hillsides, but did not survive long enough between severely negative balance years to accumulate to significant depth to have a driving stress sufficient to leave a geomorphological signature. Gentle valley-side slopes with high insolation lacked shaded north-facing hollows for snow to survive summer thaw. In comparison to glaciers close to the west coast in Wales and in the northern Highlands (Carr *et al.* 2010), ELA temperatures in the far eastern Highlands were c. 4°C cooler, and mass loss at the ELA was perhaps 10-20 % lower.

Our interpretation of a glacier with low mass turnover and little geomorphological potential has wider implications. The ELA is consistent with the regional ELA gradient of Sissons and Sutherland (1976), but their palaeoclimatic inference of a high rate of snowfall is questioned. A more arctic-maritime environment is suggested in which snow blow was significant along the peripheral uplands of the eastern Highlands (*cf*. Harrison *et al.* 2014). This was most likely associated with a synoptic situation of low pressure systems passing to the south to introduce easterly snow-bearing winds, with a blocking anticyclone to the north.

How certain is the Younger Dryas age of the Coire Breac glacier?

In keeping with all other studies in the area, a Younger Dryas age of the Coire Breac moraine is assumed but not supported by any direct dating. Thus, palaeoclimatic interpretations based on this and other former glaciers in the region must remain provisional until absolute ages of Lateglacial landforms in the area are available. The last Scottish Ice Sheet retreated from the study site between 17 and 16 k yr (Clark *et al.* 2012), so that up to two millennia of very cold climate persisted before the start of the Lateglacial Interstadial at c. 14.9 k yr, during which local glaciers may have formed. The south-eastwards decline in the regional ELA surface may therefore be apparent rather than real, an artefact of false correlation of undated moraines (cf. Kirkbride and Winkler 2012). If this is the case, YDS aridity along the Highland boundary prevented glaciers from forming at all.

This study has implications for future cosmogenic dating in the far eastern Highlands, because the low erosion potential of glaciers may mean that isotope concentrations in boulder surfaces will include a significant inherited component. Age distributions may have to be regarded as maximum ages of glacial events, so that pre-YDS ages may not necessarily mean that a moraine pre-dated the YDS. Whether careful site selection and sampling can overcome this problem remains to be determined. However, absolute dating is essential to verify the palaeo-ELA trend surface on which interpretations of synoptic climate rest.

Conclusions

1. The study identifies well-preserved evidence of a former cirque glacier closer to the Highland Boundary than any previously found, but consistent with Sissons and Sutherland's (1976) regional ELA surface. The glacier reconstruction is very well-constrained by landform evidence, and the cirque avoids the ambiguity of interpretation affecting larger and more complex glaciers and icefields.
2. The study supports the view that south-easterly snow-bearing winds from the North Sea (Sissons and Sutherland 1976; Sissons 1979) allowed small glaciers to form in favourable topoclimatic niches in the lower hills close to the Highland boundary, but argues that a cold arctic-maritime environment existed in which enhanced accumulation by blown snow compensated for reduced overall precipitation.
3. The glaciological reconstruction reveals a low-turnover glacier in spite of its location and low altitude. It was incapable of significant erosion, consistent with the lack of geomorphological evidence of glacial landscape modification across the extensive plateaux of the Eastern Grampian Highlands.
4. It remains imperative to obtain age control from glacial landforms in the eastern Highlands, because interpretation of Stadial palaeoenvironment entirely rests on an assumed YDS age of glacial moraines.

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Table 1.
Calculation of equilibrium line altitudes by different methods.

Method	ELA (m)
Maximum elevation of lateral moraines (MELM)	478
Median Elevation of Glacier (MEG)	507
Toe-Headwall Area Ratio (THAR 0.4)	473
Accumulation Area Ratio (AAR 0.6)	491
BR = 1.7	493
BR = 1.8	500
BR = 1.9	506
BR = 2.0	514
Mean of MELM, MEG, THAR, AAR methods	487 ± 15

Table 2. Reconstructed steady-state glaciological parameters for the Coire Breac Glacier.

Parameter		Units
Equilibrium-line altitude	490	m above sea level
Mean July temperature at ELA	5.1	°C
Mean Jun-Aug temperature at ELA	4.3	°C
Mean May-Oct temperature at ELA	2.4	°C
Mean Oct-Apr accumulation at ELA[1]	1.83	m H_2O
Mean annual accumulation at ELA[2]	1.54	m H_2O
Mean basal shear stress at ELA	43	kPa
Ablation gradient	-0.0055	m m^{-1} yr^{-1}
Mass flux	33,301	m^3 yr^{-1} H_2O
Cross-section at ELA	28,594	m^2
Balance velocity at ELA	1.16	m yr^{-1}
Mean creep velocity at ELA	0.18	m yr^{-1}
Mean basal sliding velocity at ELA	0.98	m yr^{-1}
Sliding as % of total velocity	84	%

[1]Based on Ohmura's winter accumulation relation (Carr et al., 2010).[2]Based on Golledge et al's (2010) summer accumulation relation.

Table 3. Values of potential snow blow areas and factors (km^2) by 90^o sectors. Bold type highlights maximum values.

	Glacier Area (km^2)	Total Snowblow Area (km^2)	NE (0-90^o)	SE (91-180^o)	SW (181-270^o)	NW (271-360^o)	S (135-224^o)	E (46-135^o)
Area (km^2)	0.35	**5.18**	1.59	**3.59**	1.15	0.58	2.34	**3.29**
Factor	0.35	**3.85**	2.13	**3.20**	1.81	1.29	2.59	**3.06**

Figure Captions

Figure 1

Digital Elevation Model (DEM) of the Eastern Grampians showing the reconstructed icefields and outlet glaciers over the Gaick and Mounth plateaux (after Sissons, 1972, 1974; Sissons and Grant, 1972). The box shows the reconstructed trend surface line generated from the reconstructed ELA values after Sissons and Sutherland, 1976). The location of Coire Breac is indicated by a white dot. Letters refer to locations mentioned in the text: A = Glen Esk; B = Water of Saughs (Glen Lethnot); C = Glen Effock. Location of weather stations indicated on inset map. Hill shading illuminated from the northwest, generated from the OS Profile 10,000 DTM © Crown copyright Ordnance Survey. An EDINA/DIGIMAP/JISC supplied service.

Figure 2A

Oblique Google imagery for Hill of Wirren showing the overall location of Corrie Breac.

Figure 2B

Detailed vertical Google image showing the moraine ridges and meltwater channels of the former Corrie Breac palaeoglacier. Note the small ridges indicating flow deformation of part of the glacial debris cover (F). © Google Earth.

Figure 3

Geomorphological map of Corrie Breac. Letters refer to features described in the text: E: meltwater incision at glacial margin; M: beginning of meltwater channel; L: upper limit of right-lateral moraine; R: moraine ridges; F: flow deformation ridges. Dotted line indicates inferred glacier margin above the ELA.

Figure 4A

The former glacier terminus, showing the depth of incision through the terminal moraine. Figure for scale (arrowed).

Figure 4B

The pronounced distal slope along the western (true left) side of the terminal moraine.

Figure 4C

The distal slope of the left-lateral moraine and marginal meltwater channel. Figure for scale (arrowed).

Figure 4D

The subtle upper section of the right-lateral moraine (arrowed) viewed from across the cirque. The moraine extends uphill (to the right) to very close to the former equilibrium-line altitude.

Figure 5

Glacier reconstruction. A: surface topography, 20 m contour interval; B: distribution of surface slope angles (degrees); C: flow line model; D: grid nodes used for sampling; E: isopachs at 10 m intervals; F: basal shear stress in kPa.

Figure 6

Glacier hypsometry. Heavy line = percentage of glacier area per 20 m altitude class; light line = cumulative percentage area by altitude class. Horizontal and vertical lines indicate the ELA for five different values of AAR, where an AAR of 0.6 = 40% area below the ELA.

Figure 7.

Variation in flow line concentration factors (FCF) along the perimeter of the ablation zone. Positive values indicate concentration of debris between the cirque headwall and the ablation-zone margin. The greatest focusing of till is to the true left margin of the terminal lobe, downstream of the steepest part of the source headwall.

Figure 8.

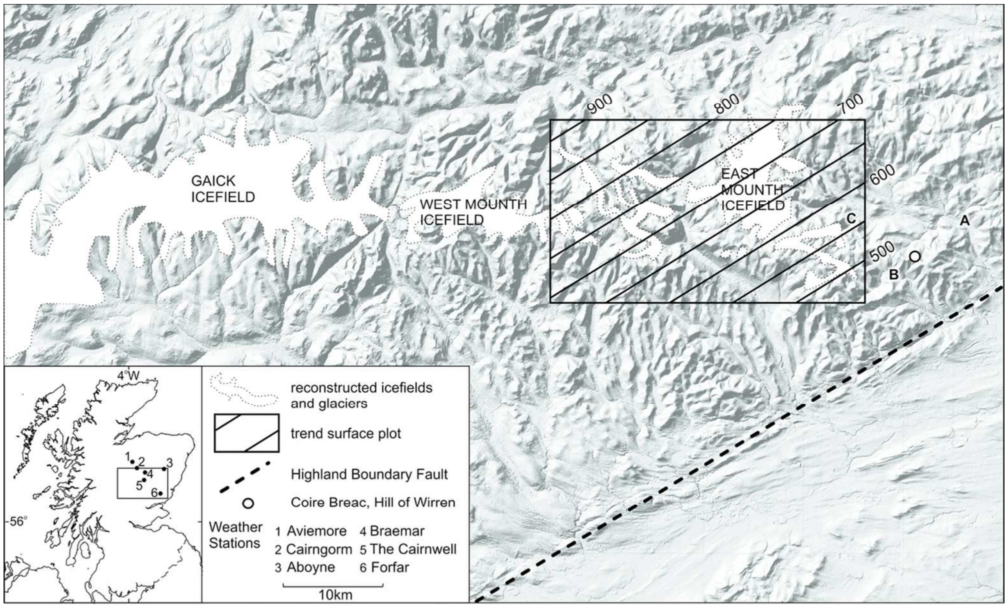
Relationships between 1981-2000 mean temperature and altitude for six climate stations in the eastern Highlands. Each vertical set of points gives the mean temperature for a single station for different combinations of months. Stations are arranged by altitude, demonstrating the constant linearity of altitudinal lapse rate across the region. Stations by altitude are: Forfar (92 m); Aboyne (140 m); Aviemore (228 m); Braemar (339 m); Cairnwell (993 m); Cairngorm (1245 m).

Figure 9

A. Potential snow blow area for Corrie Breac defined with respect to surfaces adjacent to the former glacier lying upslope of the ELA; N/I indicates areas that have not been included in the calculations.

B. Polar plot of the snow blow area and orientation by 15 degree sector.

C. Polar plot of snow blow factor and orientation by 15 degree sector.



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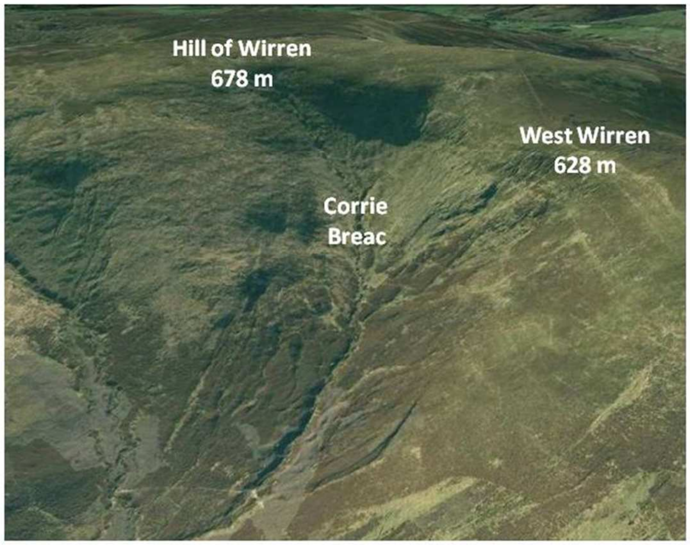


Figure 2A
Oblique Google imagery for Hill of Wirren showing the overall location of Corrie Breac.

254x190mm (96 x 96 DPI)

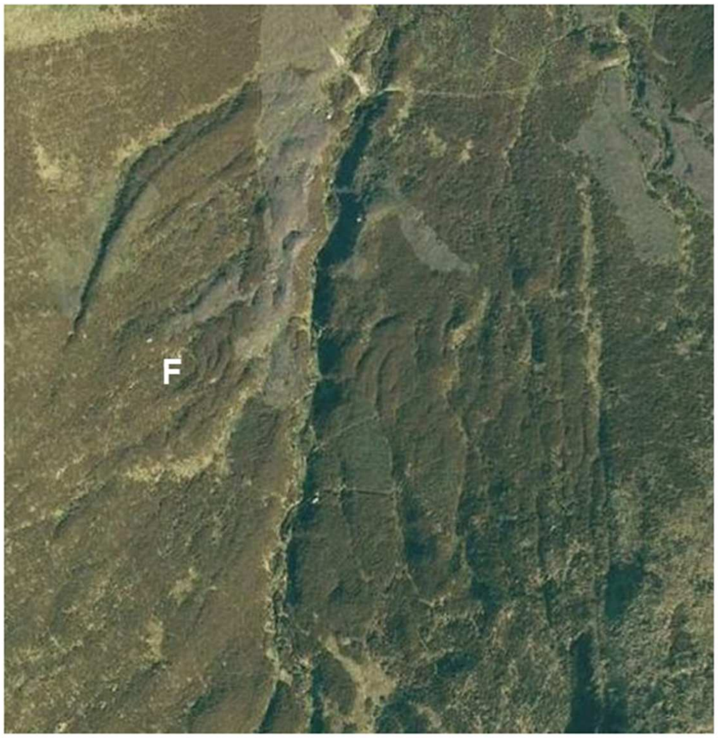
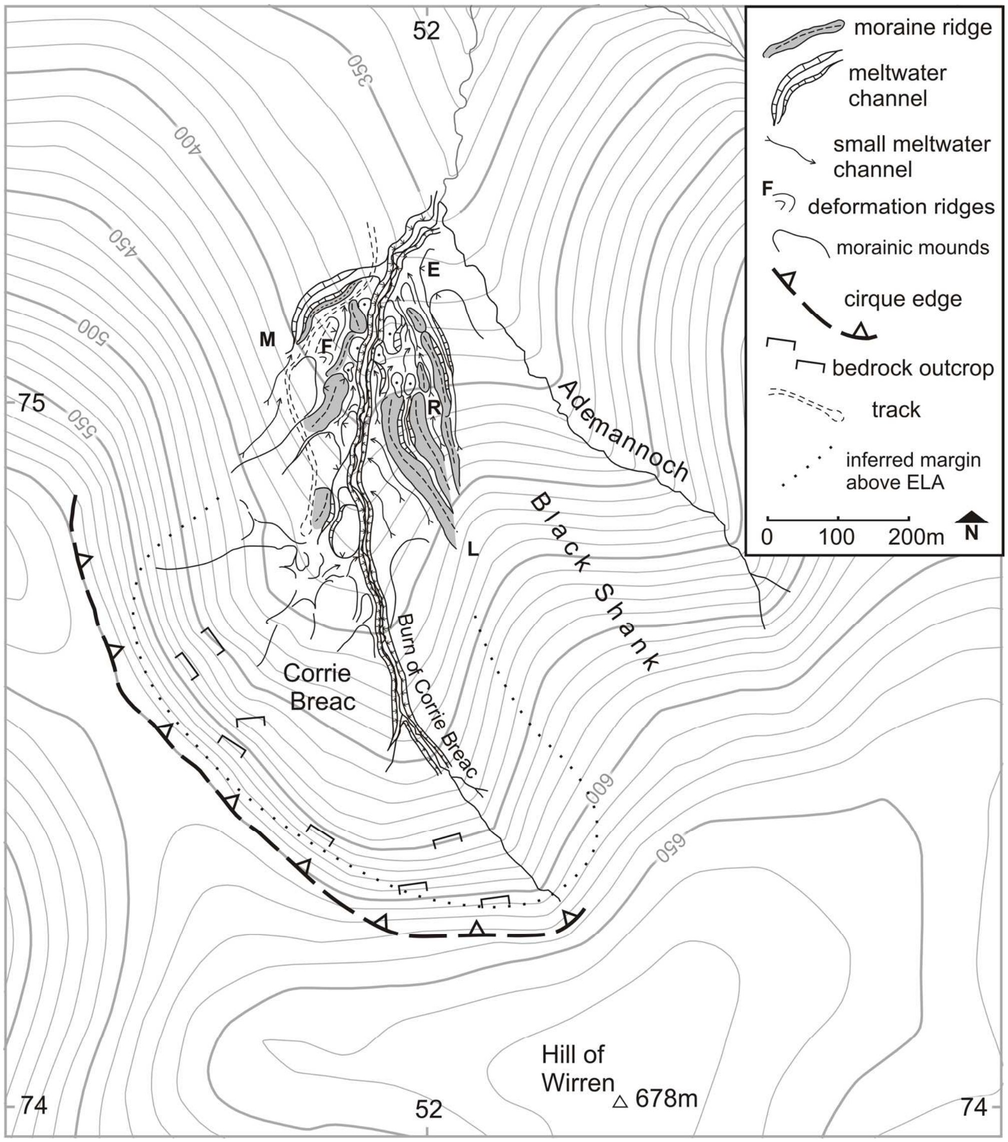


Figure 2B
Detailed vertical Google image showing the moraine ridges and meltwater channels of the former Corrie Breac palaeoglacier. Note the small ridges indicating flow deformation of part of the glacial debris cover (F).
© Google Earth.

190x254mm (96 x 96 DPI)



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159x180mm (300 x 300 DPI)

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The former glacier terminus, showing the depth of incision through the terminal moraine. Figure for scale (arrowed).

254x190mm (96 x 96 DPI)

Figure 4B
The pronounced distal slope along the western (true left) side of the terminal moraine.

190x254mm (96 x 96 DPI)

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254x190mm (96 x 96 DPI)

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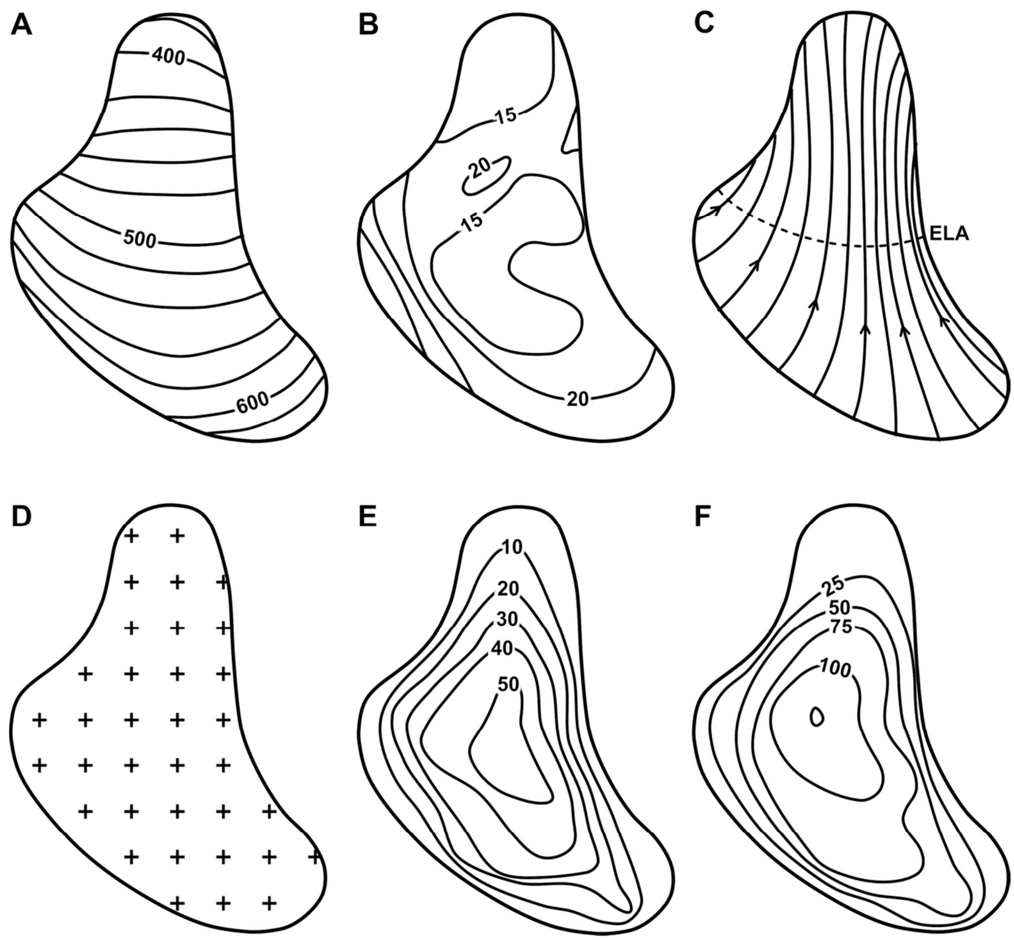

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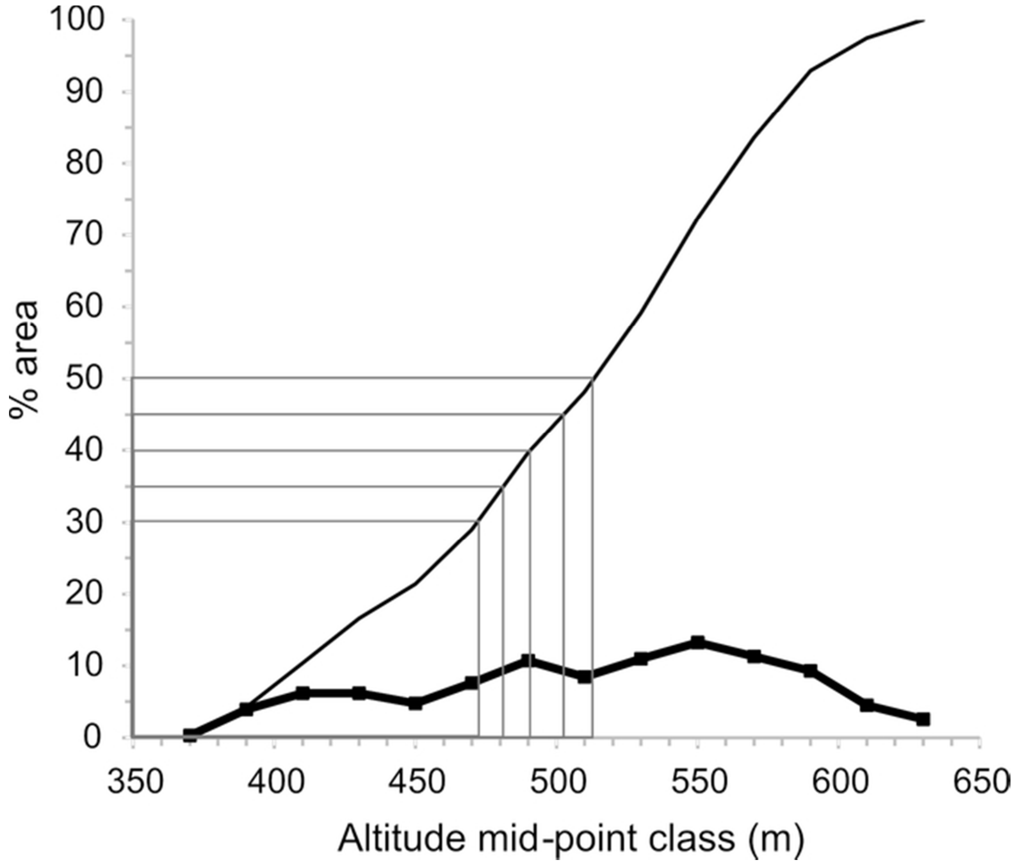

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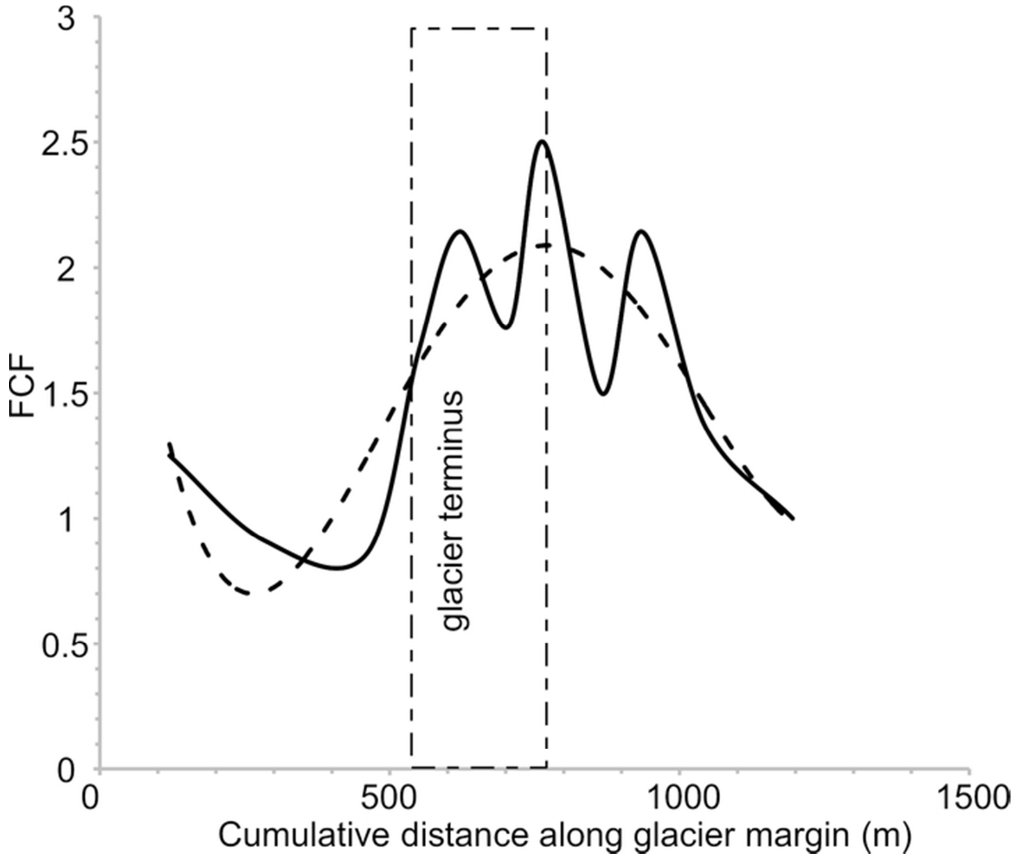

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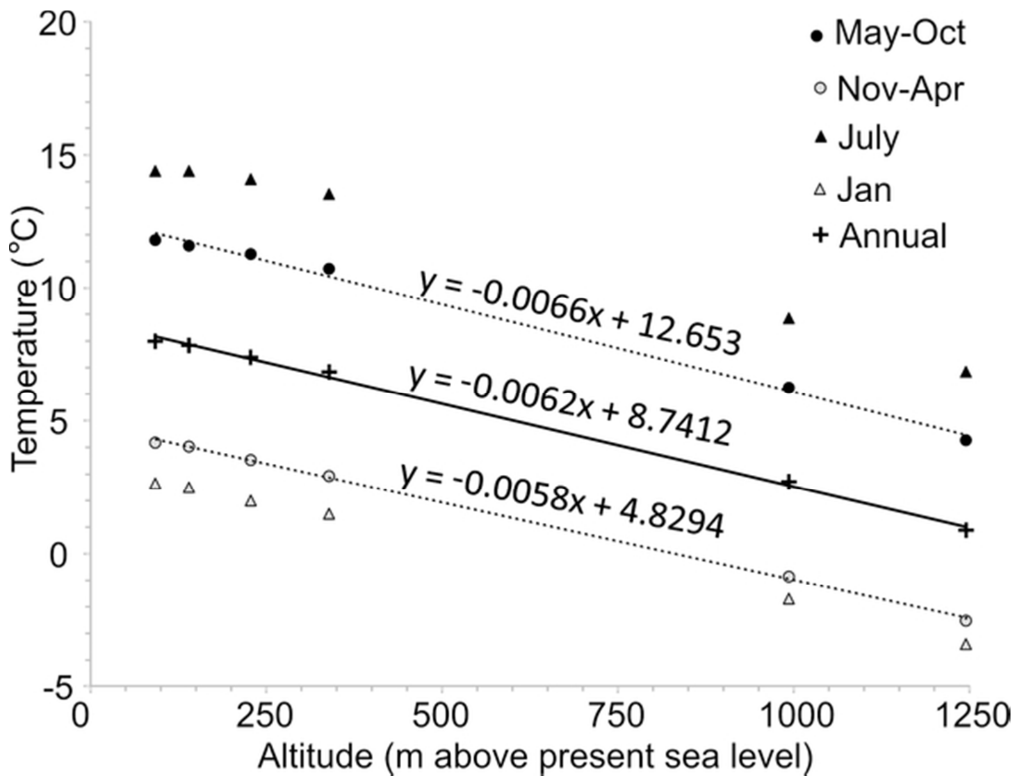

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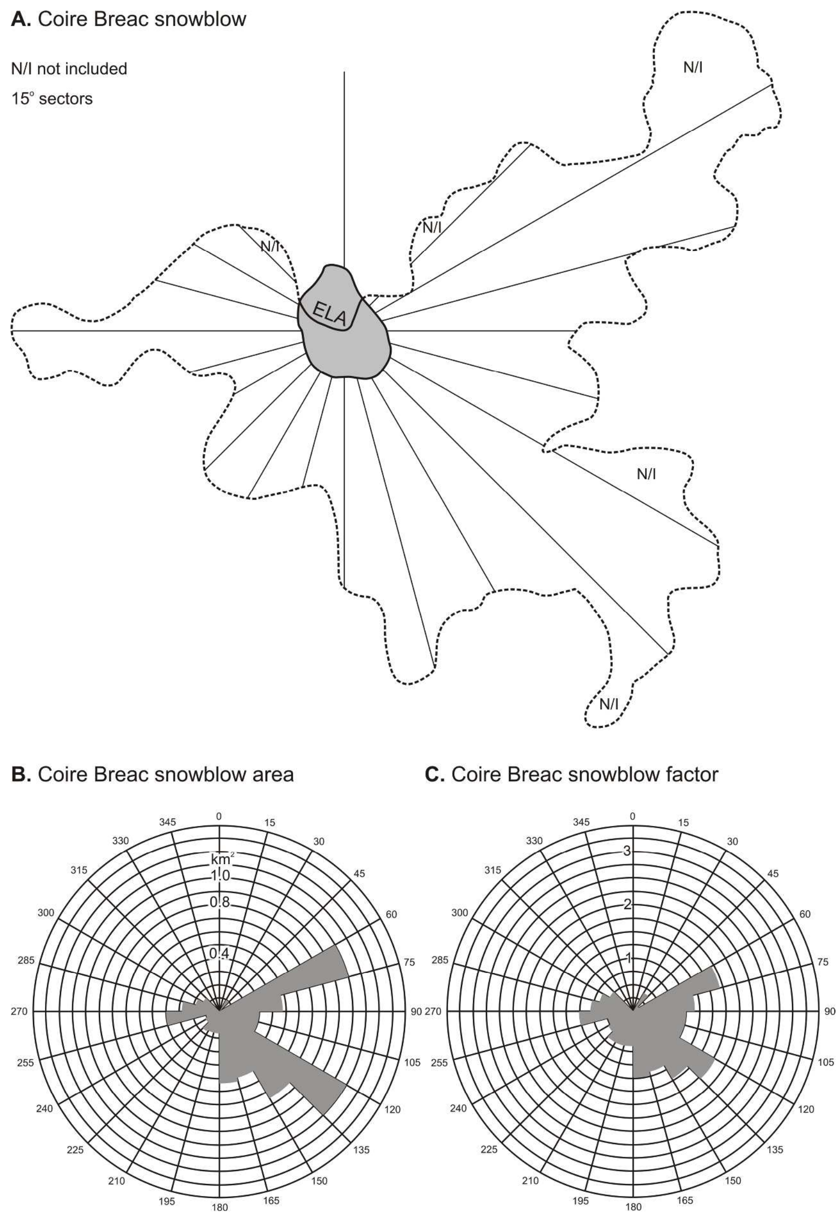

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C. Polar plot of snow blow factor and orientation by 15 degree sector.

201x293mm (300 x 300 DPI)