2015

A palaeoclimatic reconstruction of the Cadair Idris area of Snowdonia, using geomorphological evidence from Younger Dryas cirque glaciers

Radbourne, B.

A palaeoclimatic reconstruction of the Cadair Idris area of Snowdonia, using geomorphological evidence from Younger Dryas cirque glaciers

Bethany Radbourne

Project Advisor: Stephanie Mills, School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth, PL4 8AA

Abstract

The importance of glacier reconstruction lies in the empirical relationship between glacier mass balance and climate. Small glaciers are particularly sensitive to changes in temperature and precipitation, thus the reconstruction of small palaeoglaciers can provide an understanding of past climatic changes in an area. This study conducts glacier and palaeoclimatic reconstructions for four potential palaeoglaciers at Cadair Idris, southern Snowdonia. Three of these are assigned a Younger Dryas age by referring to published literature, and the fourth is assumed to have existed during an earlier glaciation, possibly reflecting deglaciation from the Last Glacial Maximum (LGM). Schmidt Hammer relative age dating is carried out to establish relative ages between landforms within the cirque areas, however the results from this are inconclusive as the process is subject to many errors. The topographically-constrained Younger Dryas cirque glaciers, referred to as Cwm Cau, Cwm Gadair and the small eastern glacier, occupied a total area of $0.963km^2$. Calculations of Equilibrium Line Altitudes (ELAs) yield an average local ELA of 607m asl. Subsequent palaeoclimatic reconstructions indicate that during the Younger Dryas, annual precipitation levels were similar to, or higher than, present levels, averaging at 2850mm a^{-1}. Consideration is given to the potential for additional mass to be added to the glaciers through snowblow, but it is concluded that the relatively small snowblow factors, ranging from 0.71 to 1.32, would not have contributed much mass to the glaciers. Total avalanche factors range from 0.27 to 0.92 and are suggested to be more likely to contribute mass to the glaciers. Solar radiation maps for the ablation season indicate that the high cirque walls would have provided shading from the most intense incoming solar radiation, thus protecting certain parts of the glaciers and encouraging initial ice accumulation and preservation, possibly explaining the existence of a western lobe of the Cwm Gadair glacier. Finally, calculations of the glaciological dynamics of the glaciers indicate that the small eastern glacier was not, in fact, viable as a glacier under the reconstructed palaeoclimatic conditions.

Introduction

The Younger Dryas was a period of climatic change circa. 12.9 to 11.7 ka cal. BP (Lowe et al., 2008). It occurred during a time of high summer insolation and enhanced seasonality, and had a pronounced impact in the northern hemisphere. In the North Atlantic region, a range of proxy data indicate a return to full glacial conditions (McDougall, 2013), resulting, in the UK, in readvance of ice masses which had not fully receded following the Last Glacial Maximum (LGM) of ca. 21,000 ka cal. BP (Cronin, 2010), and the development of new glaciers. This is evident in Snowdonia, where the cirques which can be seen today were last occupied with ice during the Younger Dryas stadial (Hughes, 2009). Much work in the UK has been conducted on identifying former glacial deposits and geomorphological evidence of Younger Dryas glaciation, and subsequently reconstructing the palaeodimensions and dynamics of these former glaciers. The research presented here builds on this knowledge by conveying Younger Dryas glacier and palaeoclimatic reconstructions in the Cadair Idris area of southern Snowdonia, Wales.

Primitive glacier reconstructions can be traced back to the late nineteenth century, but over the last few decades increasingly sophisticated ice sheet and glacier reconstructions have been undertaken (Benn & Evans, 2010). The inherently geographical nature of this work is evident in the fact that glacier reconstructions are useful at a variety of scales, from reconstructing the vast ice sheets of the Last Glacial Maximum to reconstructing smaller scale regional and local glaciers. The importance of glacier reconstruction lies in the fact that glaciers are intrinsically driven by climate, a point recognised by Paterson (1994) who, in essence, justifies the rationale for both the study of modern day glaciers and the reconstruction of palaeoglaciers by asserting that the extent and behaviour of glaciers is determined not only by the physical properties of ice but also by climate. This review examines literature related to the reconstruction of smaller scale ice masses, and the importance of this in relation to regional climatic changes.

Palaeoclimatic estimations based on glacier reconstructions work on the premise that any changes in temperature or the amount of precipitation will affect the mass balance of a glacier, leading to movement of the Equilibrium Line Altitude (ELA), consequently causing glacier growth or recession. Generally, changes in ELA can be considered a result of changes in summer temperature and snow accumulation (Benn & Evans, 2010). If temperature increases, an increase in ablation of the glacier will occur leading to a higher ELA, whereas if snowfall increases then the accumulation area of the glacier will increase in response leading to a lower ELA. Although there is a very close connection between the ELA of a glacier and local climate (Benn & Lehmkuhl, 2000), it is important to note that local topography can account for noticeable variations between ELAs of different glaciers in the same region (López-Moreno et al., 2006), with potential for additional snow to be blown onto the glacier and add mass, or topography to affect the distribution of solar radiation over a glacier. However, due to their sensitivity to climate, glaciers still remain key indicators of climate change; as acknowledged by the Intergovernmental Panel on Climate Change (IPCC) in their latest report, stating that "there is robust evidence that large-scale internal climate variability governs interannual to decadal variability in glacier mass" (IPCC, 2013: p.909). As well as existing glaciers acting as indicators of climate change, former glaciers can act as palaeoclimatic proxies, so their reconstruction allows an understanding of past regional climatic conditions. In

the UK, work related to this has generally focused on reconstructing mountain glaciers from the Younger Dryas (c. 12.9 – 11.7 ka cal. BP) (Carr & Coleman, 2007).

Geomorphological mapping and subsequent glacier reconstruction was introduced by Sissons (1974) who used geomorphological evidence to reconstruct a former ice cap in the central Grampian Mountains in Scotland. By mapping geomorphological features, Sissons (1974) established the margins of the ice cap, and calculated the ELA (at the time referred to as the 'firn line'). By averaging precipitation at the ELA, the curve proposed by Ahlmann (1948, as seen in Sissons 1974) was used in order to estimate mean summer temperature. This curve has since been updated by Ohmura et al., (1992), and used in numerous studies (for example Ballantyne, 2007; Lukas & Bradwell, 2010, Trelea-Newton & Golledge, 2012). Sissons (1980) utilised his technique again in a reassessment of Younger Dryas glaciation in the Lake District, but McDougall (2013) argues that although Sissons was confident that the glaciers were accurately reconstructed, the positions of the ice margins were still predominantly inferred, relying on professional judgement rather than definitive ice-marginal evidence. Highlighting the subjectivity of discriminating ice margins, Carr et al., (2010) note that correct interpretation of geomorphological features is critical when reconstructing former marginal or niche glaciers, in particular, stating that the confusion between glacially-derived features and non-glacially derived ones can imply very different landscape and climatic significance. Resulting from these limitations, the technique involved in glacier reconstruction has undergone advances over time in order to improve the accuracy and reduce the error involved.

To improve the discrimination of geomorphological features, and attempt to reduce the need for professional judgement, Carr (2001) proposed a method using glaciological parameters to aid the interpretation of the origins of ambiguous depositional ridge features in the Brecon Beacons. It is argued that identifying small ridge systems within cirques can be difficult, with glacial, periglacial and mass movement origins all being plausible. Rather than relying purely on geomorphological evidence, the paper models the dynamics and behaviour of small former glaciers, suggesting the glaciological approach to be widely applicable and particularly useful in the interpretation of many ambiguous Younger Dryas features in upland Britain. Following this, Carr & Coleman (2007), arguing that most reconstructions of glacier mass-balance still remained compromised by a lack of glaciological considerations, offer a clear approach to glacier reconstruction based on independent temperature data which drives mass balance modelling (using an empirical relationship between ablation gradient and mass loss at the ELA), to further aid reconstructions using glaciological parameters. This method allows ablation gradients, average balance velocities, basal shear stress, ice deformation rates and basal motion to be calculated, and has been used in several studies (Carr & Coleman, 2007; Coleman & Carr, 2008; Carr et al., 2010) to test the viability of niche glaciers.

When reconstructing glaciers, a potential source of error is the use of personal judgement in placing the glacier ice surface contours. As a result of this, a significant improvement to the methodology of glacier reconstructions came from Benn & Hulton (2010). In order to improve ice surface reconstructions, an Excel^{TM} spreadsheet called *Profiler* was introduced, utilising mapped landforms as constraining evidence for long profile modelling, and allowing the surface long profiles of former glaciers to be calculated using a 'perfectly plastic' glacier model.

Inputs required are the long profile of the bed topography beginning at the glacier terminus, 'target elevations' such as the elevations of lateral moraines or trimlines, shape factors and yield stress for each step. *Profiler* has proved valuable in many glacier reconstructions, including that of Trelea-Newton & Golledge (2012) who used a range of realistic ice profiles in order to establish the ELAs of former Younger Dryas glaciers in Scotland.

Reconstructions of Younger Dryas glaciers have taken place in the high mountain regions of Wales, both in Snowdonia and the Brecon Beacons. Notable work in the Brecon Beacons includes Shakesby & Matthews' (1996) reinterpretation of the Craig Cerrig-gleisiad cirque glacier depositional landforms. Previously the formation of the cirque was attributed to more than one glacier advance during the late Devensian, but on reassessment of the depositional evidence, an origin of both landslide development and a single phase of glacier development during the Younger Dryas is suggested (Shakesby & Matthews, 1996). It is highlighted how misinterpretation of deposits as glacial can lead to an incorrect view of the maximum glacier extent, thus may introduce error in any subsequent palaeoenvironmental reconstruction. Moving to Snowdonia, Hughes (2002) uses the method introduced by Sissons (1974) to present geomorphological mapping and glacier reconstruction of an area in the Aran and Arenig mountains, North Wales, revealing evidence for four sites of local glacier occupation. Following this, in 2009, Hughes presented new evidence for former glaciers in North Wales in order to contribute to the gap in knowledge noted by Evans (2006), that the Younger Dryas occupation of 83 cirques in Snowdonia remained uncertain. The climate at the ELA is calculated using both regression and degree-day model approaches, revealing a colder and wetter climate in Snowdonia during the Younger Dryas period (Hughes, 2009).

Bendle & Glasser (2012) furthered research in Snowdonia by mapping 38 Younger Dryas cirque glaciers and calculating their ELAs. The reconstructed ELAs range from 380 to 837 metres above sea-level (m asl), and reveal the trend of a north-eastward rise across Snowdonia. Following palaeoclimatic reconstructions using a degree-day model, it is indicated that during the Younger Dryas period the climate in North Wales was both colder and drier than at present (a different result to Hughes, 2009). Bendle & Glasser (2012) call for investigations at other sites along the west coast of Britain, highlighting a clear gap in research which this study aims to fill by reconstructing the Cadair Idris area of Snowdonia.

The Cadair Idris area has previously been subject to geomorphological mapping, by Sahlin and Glasser (2008). The 1:10,000 scale geomorphological map shows glacial, periglacial and postglacial landforms, and covers an area of 8.5 x 9km. Although this mapping is detailed and useful, no glacier reconstructions or palaeoclimatic inferences were made, a gap which this research intends to fill. Previous research by Lowe (1993) did reconstruct the cirques at Cadair Idris but this remains unpublished. One notable area of contention in reconstructions at Cadair Idris is the Younger Dryas limit of local glaciation in Cwm Cau (Ballantyne, 2001). [According to Evans (2006), approximately 35% of cirques in Wales are named 'cwm']. Lowe (1993) believed the downvalley limit of the glacier to be immediately outside the rock step that dams the lake, Llyn Cau, but an alternative possibility is that the glacier extended to the edge of a hanging valley which drops into the larger valley of Tal-y-llyn. This interpretation is supported by Larsen (1999 as seen in Ballantyne, 2001) who used Schmidt Hammer exposure age dating to show that values on bedrock

outcrops within this larger potential glacier limit are significantly higher than values on outcrops just outside of the potential limit. These younger Schmidt Hammer exposure ages are consistent with glacial advance and erosion of bedrock, suggesting that Cwm Cau did at some stage extend to the edge of the hanging valley. However, it is still likely that the Younger Dryas limit of glaciation was at the moraine which dams Llyn Cau. Further research is needed to reassess and age the geomorphological evidence within the contentious area in order to gain a better understanding of the limits of the Cwm Cau glacier.

According to Shakesby et al., (2006), many studies have used Schmidt hammer rebound (R-) values to determine rock surface hardness and the degree of surface weathering, and hence length of exposure thus relative age. The Schmidt Hammer's first application for dating glacial surfaces was in 1984, by Matthews & Shakesby, who used R-values from boulders on moraines, along with lichen size measurements, to show that certain glaciers in Norway reached their maximum extent before the Little Ice Age of ca. AD 1750. Absolute dating using cosmogenic isotopes, for example, is perhaps preferable in constraining ages for glaciation, but in the absence of time and funding, the Schmidt Hammer (despite its limited temporal resolution) provides a reasonably rapid preliminary assessment of the relative age of glacial features in question.

Over the last few decades, advances in geomorphological mapping and glacier reconstruction techniques have enabled a better understanding of Younger Dryas glacial environments in the UK. Using advances in technology to guide palaeoreconstruction, such as the use of *Profiler* (Benn & Hulton, 2010), and employing relationships between mean summer temperature and precipitation (Ohmura et al., 1992), has allowed for increasingly accurate palaeoclimatic interpretations to be undertaken. This study furthers research in Snowdonia by presenting reconstructions of former Younger Dryas glaciers and their glaciological dynamics, as well as the former larger extent of Cwm Cau. Palaeoclimatic inferences have been made, and an estimation of the climate in southern Snowdonia delivered. The aims of this research are therefore to:

1. Undertake glacier reconstructions in the Cadair Idris area of Snowdonia.
2. Establish the climatic conditions in the area during the Younger Dryas.
3. Calculate glaciological dynamics of the former glaciers.

These aims were achieved through several objectives:

- Create a geomorphological map using ArcGIS showing present day depositional and erosional features in and around the cirques of the Cadair Idris area.
- In the field, identify the locations of smaller scale features such as striae.
- Assess relative ages of bedrock outcrops and moraines using Schmidt Hammer R-values.
- Reconstruct the 3D forms of the glaciers using *Profiler* to guide ice surface contour drawing.
- Calculate the Equilibrium Line Altitudes (ELAs) for the glaciers.
- Infer the climate at the ELAs.
- Consider the roles of snowblow, avalanching and solar radiation on ice accumulation and preservation.

- Calculate glaciological characteristics of the glaciers and assess their viability.

Study area

The Cadair Idris massif is located in Southern Snowdonia (52°42'N; 03°54'W), 5km south of Dollgellau. Cadair Idris consists of a plateau ridge with a distinctive 8km long north-facing escarpment. The highest summit is Penygadair, towards the western end of the ridge, rising to an altitude of 893m asl (Ballantyne, 2001). Penygadair, and the subsidiary peaks Mynydd Moel (855m asl) and Craig Cwm Amarch (798m asl) enclose the cirque known as Cwm Cau, considered one of the finest examples of a cirque in the UK (Sahlin & Glasser, 2008). To the north of Penygadair lies the cirque Cwm Gadair, another fine example. Grasslands, heaths and bogs are the predominant vegetation types in the area, and the upland soils tend to be shallow and immature, dominated by variants of peaty gleyed podsols (Lowe, 1993). The geology of the area is varied, but the Cadair Idris peaks are formed from resistant Ordovician igneous rocks (Lowe, 1993).
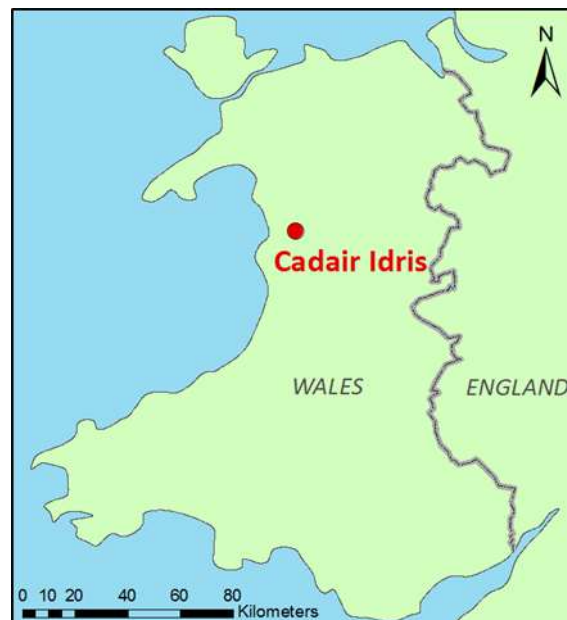

Figure 1: Location map showing the position of Cadair Idris in Wales.
Source: Author's own.

Glacial History

During the Last Glacial Maximum the Welsh Ice Cap fed ice movement from the north-east to the south-west, following glacially-deepened valleys such as Tal-y-llyn, before joining the Irish Sea glacier (Sahlin & Glasser, 2008). There is evidence that during the Younger Dryas stadial, glaciers reformed in some of the cirques at Cadair Idris. It is important to constrain the age of local cirque glaciation in order to ensure the palaeoclimatic reconstruction is placed in the right period of time (Bendle & Glasser, 2012). A Younger Dryas age for local cirque occupation at Cadair Idris was first suggested by Gray (1982) who argued that the available dating evidence and morphostratigraphic relationships between mapped landforms support glacier occupancy during the Younger Dryas period. Sediment cores extracted from inferred cirque ice limits in Snowdonia reveal basal pollen stratigraphic sequences characteristic of the transition from the Younger Dryas stadial to the Holocene epoch, and additional basal radiocarbon dating suggests an age of approximately

10,000 ^{14}C years BP (Ince, 1983). In this study, it is likely that the cirques in question were occupied by glacier ice during the Younger Dryas; the glaciers in Cwm Gadair and the small eastern cirque reaching their terminal moraines visible today, and the glacier in Cwm Cau reaching the moraine which dams the lake. There are further moraines in the valley of Cwm Cau but it is tentatively suggested that these may reflect deglaciation from the LGM, in which small cirque glaciers reformed following dissolution of the ice sheet (Bendle & Glasser, 2012). However, absolute dating was not conducted so these are assumptions only.

Research methodology

Creation of geomorphological maps, and subsequent fieldwork
A preliminary geomorphological map of the Cadair Idris area was produced using satellite imagery in ArcGIS. Depositional and erosional landforms in and around the cirques were mapped, including former ice limits (such as terminal moraines), ice movement direction indicators (striae and roche moutonnées) and relict periglacial features (such as talus slopes). One of the issues with geomorphological mapping is the subjective nature in distinguishing the origin of ambiguous features and the precise locations of former ice margins, a point recognised by McDougall (2013) who, when evaluating the work of Sissons (1974), noted that rather than relying on geomorphological evidence alone, professional judgement was used in order to infer the positions of the ice margins.

The features identified from the satellite imagery were verified in the field by ground truthing, and smaller scale evidence which was not visible on the satellite imagery, such as striae, had their locations recorded using a hand-held GPS. These were later added to the geomorphological maps, following post-processing in order to improve the accuracy of the GPS positions. Also when in the field, Schmidt Hammer R-value readings were taken from bedrock outcrops and boulders on moraines in order to establish relative ages of these features. Sampling for this was opportunistic, but ten readings were taken at each point following the methods of Shakesby et al., (2006). The mean R-value was calculated, and differences between mean R-values were considered using 95% statistical confidence intervals, following the methods of Klapyta (2013).

Glacier reconstruction
The outlines of the former glaciers were mapped based on the geomorphological evidence, but in areas where glacier delineation was difficult, reconstruction was guided by the present day topography and known characteristics of glacial ice, an example being placing the upper limit of the glacier to an altitude of 30m below the confining headwall scarp, as Gray (1982) suggests this to be the minimum depth required for snow to transform to glacier ice. Ice surface contours were mapped referring to the calculated long profile from the Excel spreadsheet *Profiler* (Benn & Hulton, 2010) as a guide, and by analogy to the characteristic contour pattern of contemporary glaciers (increasing curvature with increasing distance from the ELA). *Profiler* also enabled the likely three-dimensional forms of the glaciers to be reconstructed by mathematic modelling of the longitudinal profile. In order to establish the required bed elevation for *Profiler*, the lake bathymetry for Cwm Cau was sourced from Lowe (1993), and georeferenced into ArcGIS. A range of shear stress values were used in order to select those which gave the most realistic ice

surface profiles. A shear stress value of 50kPa was used for Cwm Gadair, 50kPa for the small eastern glacier, 125kPa for the Younger Dryas extent of Cwm Cau and 125kPa for the larger extent of Cwm Cau. These values fit within the range of shear stress values for modern day glaciers undergoing steady-state movement suggested by Paterson (1994), who states that basal shear stress values usually lie between 50 and 150kPa.

Calculating ELAs
After reconstructing their form, the ELA for each glacier was calculated. A number of techniques can be used to work out the ELA of former glaciers, with Toe to Headwall Altitude Ratio (THAR), Accumulation Area Ratio (AAR) and Area Altitude Balance Ratio (AABR) being three of the most frequently used, although often an average of several methods is used as each ELA method produces slightly different results (Carr & Coleman, 2007). In this study, the average ELA was calculated by taking the mean of the AAR and AABR results, as the THAR is simply calculated by using a fixed ratio between the toe of the glacier and the headwall, so the ELAs established using this method vary considerably compared to the AAR and AABR methods.

THAR
With this method, the ELA is deduced by employing a fixed ratio between the toe of the former glacier, established via terminal moraines, and the headwall. Although this method is very crude as it takes no account of climatic factors or glacier hypsometry, it is useful for providing a quick estimate of former ELAs (Benn & Evans, 2010). Osipov & Khlystov (2010) argue that glaciers generally have a THAR of 0.35 to 0.45, therefore THAR values of 0.35 and 0.45 were used in this study. The equation used to calculate ELA using the THAR method is as follows (Osipov & Khlystov, 2010):

$$\text{ELA} = \text{lowest elevation of glacier} + (\text{vertical range} \times \text{THAR})$$

AAR
This method assumes that the accumulation area of a glacier occupies a fixed proportion of the glacier area (Benn et al., 2005). It requires contoured maps of former ice surfaces so can only be used where accurate topographic data are available (Benn & Lehmkuhl, 2000). Steady-state AARs for mid- and high-latitude glaciers lie in the range 0.5–0.8, usually between 0.55–0.65 (Porter 1975 as seen in Benn et al., 2005), so AAR values of 0.55 and 0.65 were used in this study. An AAR value of 0.44 was also used, as Kern & László (2010) found that for glaciers with areas in the range 0.1-1 km^2, 0.44 is the best applied AAR value. Benn & Lehmkuhl (2000) note the difficulty in establishing which AAR value to use in ELA reconstruction, stating that AARs are highly variable between glaciers even in small regions. It is also noted that the AAR method does not take into account debris cover in the ablation zone and the importance of direct snowfall and avalanching in the accumulation zone.

AABR
The AABR method builds on the AAR method by taking into account both mass balance gradients and reconstructed glacier hypsometry. This method was originally found to produce slightly inaccurate results, so was modified by Osmaston (2005) who programmed a spreadsheet for use by researchers. Benn and Lehmkuhl (2000)

argue the AABR method to be the most rigorous method for use in palaeoglaciology. AABR values of 1.67, 1.8 and 2.0 were used in this study, following the methods of Bendle & Glasser (2012), who conducted glacier reconstructions in northern Snowdonia on glaciers of similar size to those at Cadair Idris. These values are also in agreement with the optimum AABR value found by Rea (2009) for mid-latitude maritime environments; 1.9 ± 0.81.

Palaeoclimatic inferences

Ohmura et al., (1992) demonstrated, through climatic data from a global set of contemporary glaciers, that the correlation between annual summer temperature and annual precipitation is strong at glacier ELAs, therefore providing one of the variables can be determined independently, the other can be calculated. Palaeoprecipitation can be hard to quantify due to a lack of proxies, therefore palaeotemperatures are frequently used in order to establish estimates for past precipitation. The relationship, which yields a standard error of ±200mm, is as follows:

$$P_a = 645 + 296\,T_3 + 9\,T_3{}^2$$

Where; P_a = annual precipitation/mm at the ELA and T_3 = 3-month mean summer temperature/°C.

In this study, 3-month mean summer temperatures at the ELAs of the Younger Dryas glaciers were sourced from sea-level temperatures. Walker et al., (2003) used entomological proxy temperature data from LLanilid, South Wales, to establish a mean July sea-level temperature (T_j) during the Younger Dryas of 10.5°C. This figure was converted to mean 3-month summer sea-level temperatures using the equation (Benn & Ballantyne, 2005):

$$T_3 = 0.97\,T_j$$

Where; T_3 = 3-month mean summer temperature/°C and T_j = mean July sea-level temperature/°C.

This gave a mean 3-month summer sea-level temperature for South Wales during the Younger Dryas of 10.19°C. This figure was then extrapolated up to the ELAs using environmental lapse-rates of 0.006°C m^{-1} and 0.007°C m^{-1} to gain the figures used in the equation by Ohmura et al., (1992). Lapse rates of both 0.006°C m^{-1} and 0.007°C m^{-1} are commonly used when extrapolating sea-level temperature up to ELAs (Ballantyne, 2002; Bendle & Glasser, 2012), in order to gain the range of possible temperatures.

Snowblow and avalanching

The roles of snowblow and avalanching in ice accumulation of the Younger Dryas glaciers were assessed as, in some cases, additional snow can lower the ELA resulting in palaeoclimatic reconstructions that do not reflect the conditions at the time, with Benn & Evans (2010) arguing that in mountain areas, topographic factors and redistribution of snow by wind strongly affect accumulation of glaciers.

The methods of Mitchell (1996) were followed, whereby all ground lying above the ELA and sloping towards the glacier surface was considered to have had the potential to contribute snow onto the accumulation area of the glacier. Additionally,

any area sloping away from the glacier up to an angle of 10° was included as this is the threshold at which it is considered viable for snow to be blown upwards (Coleman et al., 2009). This zone was marked for each glacier and the overall potential snowblow area was calculated. The role of avalanching was considered by marking a separate zone of topography 20° or steeper sloping directly onto the glacier (Coleman et al., 2009). The potential snowblow and avalanche areas were split into 15° segments (Mitchell, 1996; Coleman et al., 2009), centred on the ELA / glacier centre-line intersect, in order to assess the relative significance of different wind directions. The information was summarised in tables describing snowblow and avalanche factors (ratio of glacier area to potential snowblow and avalanche areas) for each 90° quadrant (NE, SE, SW, NW). The snowblow factor was calculated by taking the square root of the ratio (Mitchell, 1996), which removes the problem of large areas further away from the glacier having lower potential to contribute snow due to the further distance snow would have to travel (Coleman et al., 2009). Calculating snowblow and avalanche factors allows for comparison between the Younger Dryas glaciers at Cadair Idris, and also glaciers elsewhere.

Solar radiation

With insolation being a direct impact on glacier ablation, the importance of solar radiation and topographic shading in affecting the mass balance of the three Younger Dryas glaciers was considered. To assess which areas at Cadair Idris would have received high or low solar radiation, the solar radiation tool on ArcGIS was utilised; with a 5m resolution DEM and a default sky resolution of 200. Average solar radiation maps for the months of June, July and August were created, as well as a map showing average solar radiation for all three months. The months were chosen as they make up the most intense months of incoming solar radiation of the ablation season of a glacier. Additionally, solar radiation is the most important energy balance component of a glacier when clear sky conditions exist in summer (Benn & Evans, 2010). Therefore it is at these times of the year that solar radiation could potentially have the biggest impact on melting existing ice or preventing accumulation of ice.

Glaciological dynamics

The glaciological dynamics of the three Younger Dryas glaciers were calculated following the methods of Carr & Coleman (2007), in order to consider whether the ablation gradients, balance velocity and basal motion fit within the range of values for modern glaciers. Basal shear stress was also calculated, however a value for this had already been used in the Profiler spreadsheets, so the resulting figure should be expected to be similar to that which was used. Because the existence of the small eastern glacier was the most uncertain of the three glaciers (due to its small size and thin ice, Figure 7), this glaciological approach was used to 'test' the geomorphological interpretation, thus the viability of the glacier and its modelled dynamics (Carr et al., 2010). The first part of this process involved using the results of the palaeoclimatic reconstructions to calculate an ablation gradient for each glacier, which describes the change in ablation consequent with a change in elevation (Carr & Coleman, 2007):

$$a_z = 0.7809 P_a^2 - 0.5681 P_a + 3.3342$$

Where; a_z = ablation gradient/mm m^{-1} and P_a = mass loss at ELA/m a^{-1}.

Andrews (1972) demonstrated that for a glacier in steady-state equilibrium, there is a positive relationship between ablation gradient and mass loss at the ELA. This study follows the methods of Carr et al., (2010), who build on the relationship suggested by Andrews (1972) by adding data from a global dataset, proposing that winter accumulation should be used as a figure for mass loss. The equation to calculate winter accumulation is as follows:

$$b_w = 13.285\,T_3^2 + 229.81\,T_3 + 453.23$$

Where; b_w = Winter accumulation at the ELA/m a^{-1} and T_3 = Temperature at ELA/°C.

Once the ablation gradient was established, it was used to derive cumulative ablation within each contour belt of the glacier below the ELA, allowing total ablation in m^3, water equivalent, to be calculated. By dividing this figure by an assumed density of ice (0.91), the total volume of ice (m^3) discharged through the ELA was established. Following this, the volume of ice was divided by the cross-sectional area at the ELA enabling an average balance velocity (U_s in m a^{-1}) to be established. Basal shear stress could then be calculated using the equation:

$$\tau_b = (\rho g H \sin\alpha) / 100{,}000$$

Where; τ_b = Basal shear stress (Bars), ρ = density of ice (910kg m^3), g = acceleration due to gravity (9.81 m/s^2), H = ice thickness at ELA (m), α = ice surface slope angle at ELA (degrees).

The equation can include a constant, 'F', expressing a glacier shape factor (typically 0.8), however it was excluded in this study in order to keep the basal shear stress values similar to those used in the Profiler spreadsheets, where the shape factor was also excluded.

Finally, ice deformation was calculated using an equation based on Glen's Flow Law (Glen, 1952, as seen in Carr & Coleman, 2007). The adapted flow law equation for glacier ice (Carr & Coleman, 2007) is as follows:

$$V_c = (2A\tau_b^n H) / (n+1)$$

Where; V_c = ice centre-line deformation (m a^{-1}), A = a temperature-dependent constant of flow law (typically 0.167) and n = an exponential constant of flow law (typically 3).

The ice deformation value was subtracted from the total average balance velocity (U_s) in order to gain an estimation of basal motion, which was converted to a percentage of total glacier motion.

Geomorphological evidence and Schmidt Hammer relative age dating

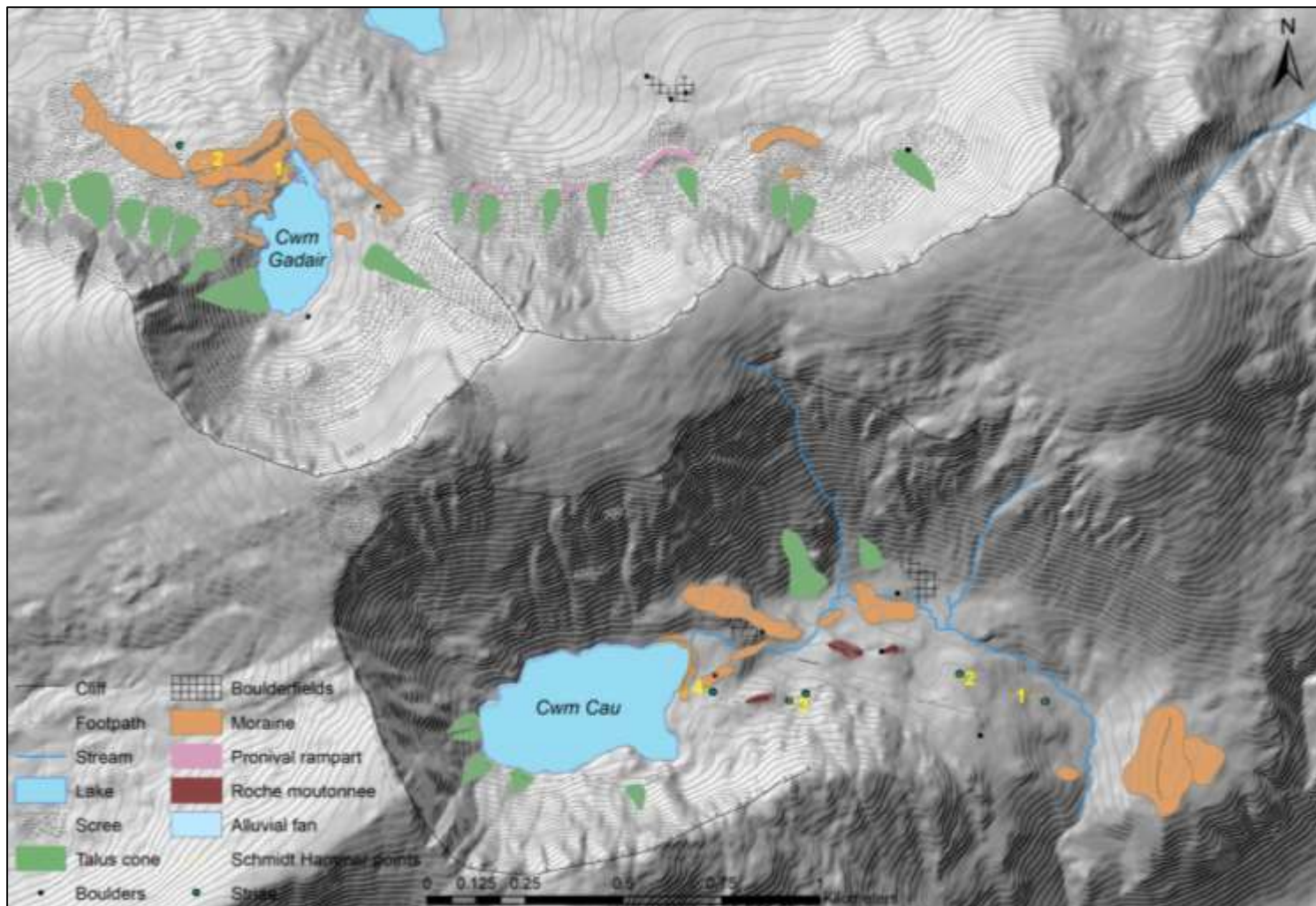**Geomorphological evidence (Figure 2)**

Figure 2: Geomorphological map describing the features, both glacial and periglacial, seen in the area of Cadair Idris. Following this, 'Cwm Cau', 'Cwm Gadair' and 'small eastern glacier' will be used to distinguish between the three cirques.

Cwm Cau
Cwm Cau is an east-facing cirque at the head of a hanging valley which extends eastwards before dropping into the larger valley Tal-y-llyn. The cirque has steep headwalls surrounding it on its north, west and south sides. Features marking the extent of the glacial limit in Cwm Cau include notable moraines. A 283m long and 40m high terminal moraine exists in the east of the hanging valley, and within the valley area, between the lake (Llyn Cau) and the terminal moraine, six smaller moraines can be seen. An arcuate moraine, 260m long and 5m high, damming the lake has been interpreted by Lowe (1993) as a terminal moraine from local cirque glaciation during the Younger Dryas stadial. This led to the interpretation that the larger terminal moraine at the eastern end of the hanging valley and the smaller moraines between the two terminal moraines were created during an earlier glaciation.

Within the valley, periglacial features can be seen, including scree slopes and talus cones, some of which extend down to the lake, Llyn Cau. Erosional features include three roche moutonnées and five areas of bedrock which exhibit striae, indicating ice flow to the east. Depositional features include two areas of clustered boulders, identified as boulderfields, as well as numerous erratics along the valley floor. However, these features are unlikely to be of Younger Dryas origin, and were probably deposited when the glacier extended to its maximum extent, most likely following the LGM. During the Younger Dryas it is assumed that the cirque was smaller in size, and terminated at the moraine which today dams the lake, Llyn Cau, an interpretation supported by Lowe (1993).

Cwm Gadair
The former limit of the north-facing Cwm Gadair is marked by an arcuate terminal moraine, 363m in length (although it has been bisected by a meltwater channel) and 7m high. To the west of this moraine lies another moraine, interpreted as a product of a lobe of the glacier flowing to the west. There is evidence of striated bedrock here also, indicating that at some time ice did flow in the western area. Multiple smaller moraines surround the lake, Llyn y Gadair, which is also flanked by periglacial features including notable talus cones and areas of scree on the cliff backwalls.

Eastern areas on the northern escarpment
To the east of Cwm Gadair three small arcuate ridges exist at the base of the cliffs, ranging in length from 55m to 170m, and in height from 1m to 3m. They were discounted as being moraines as they are situated less than 100m from the back wall, thus were identified as pronival ramparts. This proximity to the talus cones on the cliffs of the back wall is, according to Hughes (2009), insufficient space for dynamic glacier ice to form. Sedimentological study on the ridges, as used by Hughes (2009), would be beneficial in their identification. Further east from these ridges, another arcuate ridge exists which was interpreted to be a moraine due to its greater distance from the cliff in comparison to the previous three ridges. It is 190m in length and 3m in height. As well as this, a small, potentially recessional, moraine was identified between the larger ridge and the cliff. Although the areas behind the ridges described at the start of this section are too small to have accommodated glaciers, firn could have built up behind the ridges, creating perennial snow patches, whereas it is possible a small glacier could have formed behind the easternmost

ridge. The viability of this glacier is later tested using the glaciological technique proposed by Carr & Coleman (2007).

Schmidt Hammer relative age dating
Schmidt Hammer relative age dating was used at four sites in Cwm Cau and two sites in Cwm Gadair, (Figure 2), to assess relative ages of bedrock outcrops and moraines. Although the effective range of Schmidt Hammer dating is still unclear, and R-values can be influenced by factors including chemical and mineral composition of rocks, surface roughness and moisture content, as a method it is still capable of providing an index of the degree of weathering of coarse inorganic deposits such as moraines and glacially scoured bedrock (Klapyta, 2013). According to Shakesby et al., (2006), R-values reflect the development over time of increased surface roughness caused by chemical breakdown of surface rock and structural weakening, reflected in varying resistance to weathering of surface minerals, with higher R-values indicating a more recently exposed surface.

Table 1 and Figure 3 display the results of the Schmidt Hammer relative age dating for Cwm Cau, with the results for Cwm Gadair shown in Table 2 and Figure 4.

The confidence intervals for the Schmidt Hammer R-value means of Cwm Cau do not overlap thus the means are statistically significantly different at the 95% confidence level. However, as it can be expected that more recently exposed bedrock will have a higher Schmidt Hammer R-value, these results do not show any expected pattern. The results suggest Point 1 (furthest from the lake) to be the youngest of the bedrock exposure surfaces, with a mean R-value of 47.6 ± 2.51, followed by Point 2 as the oldest (33.2 ± 2.26) with Point 3 in between (41.8 ± 2.74). If the likely glacial history for Cwm Cau is interpreted as the valley being filled by a large glacier during the LGM, followed by glacial retreat, and then the redevelopment of a cirque glacier during the Younger Dryas (Ballantyne, 2001), then it would be expected that Point 3 would be the most recently exposed surface therefore would have the highest R-value, followed by Point 2 then Point 1.

Although Point 4 (R-values measured on the moraine which dams the lake, Llyn Cau) does have the highest mean R-value, 60.2 ± 2.18, this does not indicate that the boulder surface is younger than the bedrock surfaces further down the valley. The lithology of this boulder may be different to the bedrock lithology, as the Cadair Idris area consists of varying geology (Ballantyne, 2001). Additionally, only one boulder on the moraine was sampled rather than several, which could further limit the accuracy.

The results for Cwm Gadair suggest that the boulder surface on the moraine by the lake is older than the boulder surface on the moraine further from the lake, with mean R-values of 42.4 ± 2.76 and 51.5 ± 4.20 respectively. Assuming Cwm Gadair was glaciated during the Younger Dryas, and retreated without any readvances, it would be expected that the moraine by the lake should be the youngest surface therefore have the highest R-values, so these results may not be accurate. However, because the readings were taken very close to each other, it is more likely to expect to see very little difference between R-values, which also implies that the results are inaccurate. Again, the sampled boulders may be of different lithologies which could impact on the resulting R-values. Another explanation is that the ten readings were

only taken from one boulder on each moraine, rather than different boulders, which could explain the variation in the results.

Although the Schmidt Hammer results are inconclusive and do not offer much in the way of dating the geomorphology of the cirques, secondary literature allows a Younger Dryas age to be assigned to the cirque glaciers (Lowe, 1993; Ballantyne, 2001). Unfortunately no age estimates can be made for the larger extent of Cwm Cau as absolute dating could not be carried out on the terminal moraine.

Table 1: The range of R-values for each sample location in Cwm Cau, and mean R-values with their 95% confidence intervals.

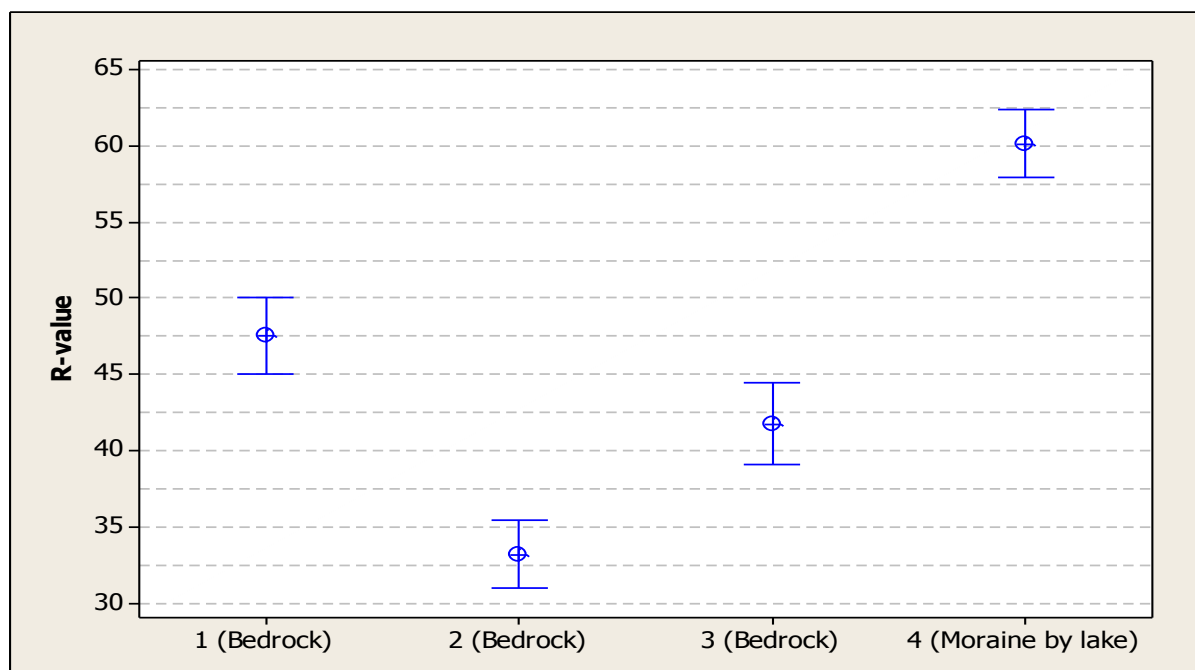| Sample Location	1 (Bedrock)	2 (Bedrock)	3 (Bedrock)	4 (Moraine by lake)
Range	42 - 52	28 - 36	36 - 48	54 - 62
Mean R-values ± 95% confidence intervals	47.6 ± 2.51	33.2 ± 2.26	41.8 ± 2.74	60.2 ± 2.18

Figure 3: Interval plot showing the mean R-values and 95% confidence intervals for the four sample points in Cwm Cau.

Table 2: The range of R-values for each sample location in Cwm Gadair, and mean R-values with their 95% confidence intervals.

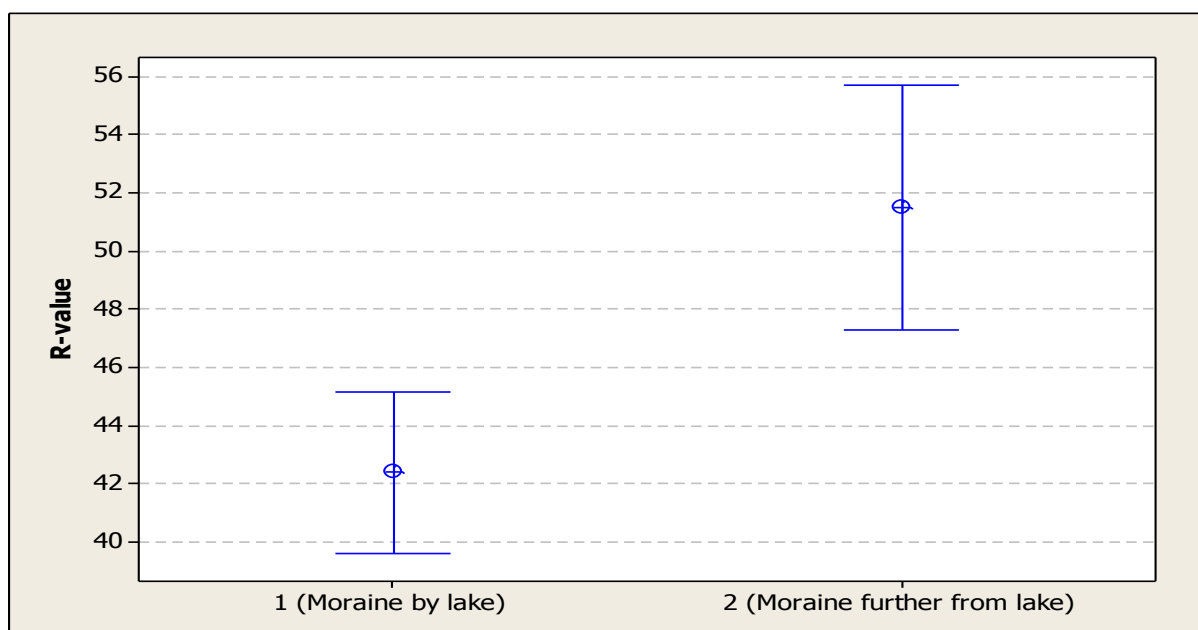| Sample Location	1 (Moraine by lake)	2 (Moraine further from lake)
Range	36 - 48	38 - 56
Mean R-values ± 95% confidence intervals	42.4 ± 2.76	51.5 ± 4.20

Figure 4: Interval plot showing the mean R-values and 95% confidence intervals for the two sample points in Cwm Gadair.

Glacier and ELA reconstructions

The geomorphological evidence described above enabled the reconstruction of the four topographically constrained cirque glaciers; three considered to have existed during the Younger Dryas period and one from a previous, most probably more extensive, glaciation. The former Younger Dryas glaciers can be seen in Figure 9, and assuming the maximum extent of ice was reached simultaneously between the glaciers, the Younger Dryas ice occupied a total area of 0.963km^2. The reconstruction of the larger extent of Cwm Cau is displayed in Figure 10, in which the ice occupied an area of 1.176km^2.

Ice surface profiles for each reconstructed glacier are shown in Figures, 5, 6, 7 and 8, where it can be seen that the maximum ice thickness is estimated to be 174m for the larger extent of Cwm Cau. For the Younger Dryas glaciers, maximum ice thicknesses of 126m, 68m and 24m for Cwm Cau, Cwm Gadair and the small eastern glacier respectively, are suggested. The relatively thin ice of the small

eastern glacier leads to an uncertainty about its viability as a glacier. This uncertainty is later tested by considering glaciological dynamics.

Table 3 shows the results of the ELA calculations for the three Younger Dryas glaciers. The average ELAs calculated for Cwm Cau and Cwm Gadair were 560m asl and 619m asl respectively, and the average ELA for the small eastern glacier was calculated to be 642m asl. The ELA results for the larger extent of Cwm Cau yielded an average ELA of 529m (Table 4).
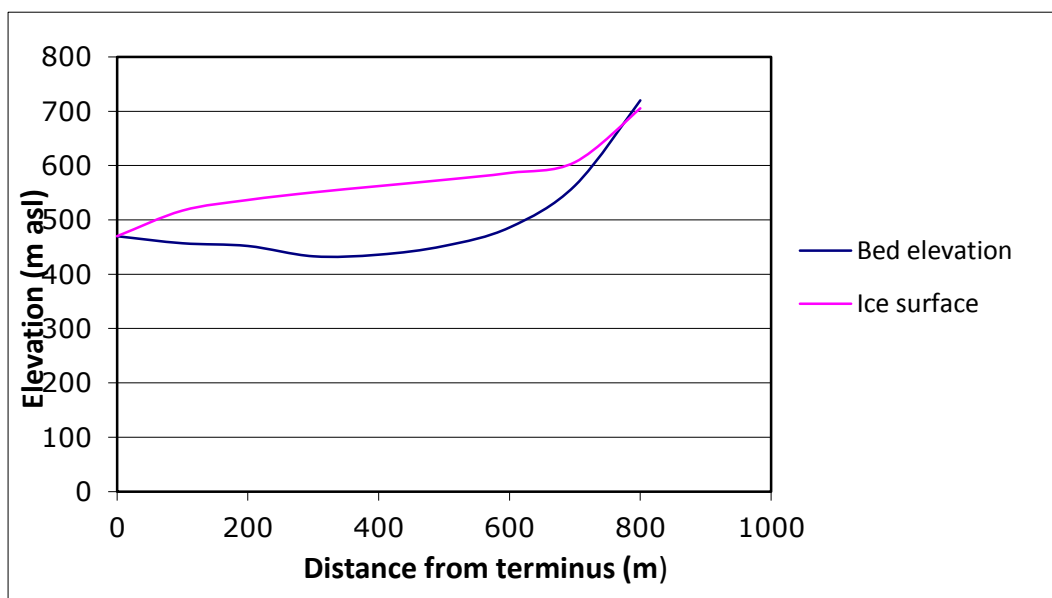

Figure 5: Reconstructed ice surface profile for Cwm Cau, Younger Dryas extent.
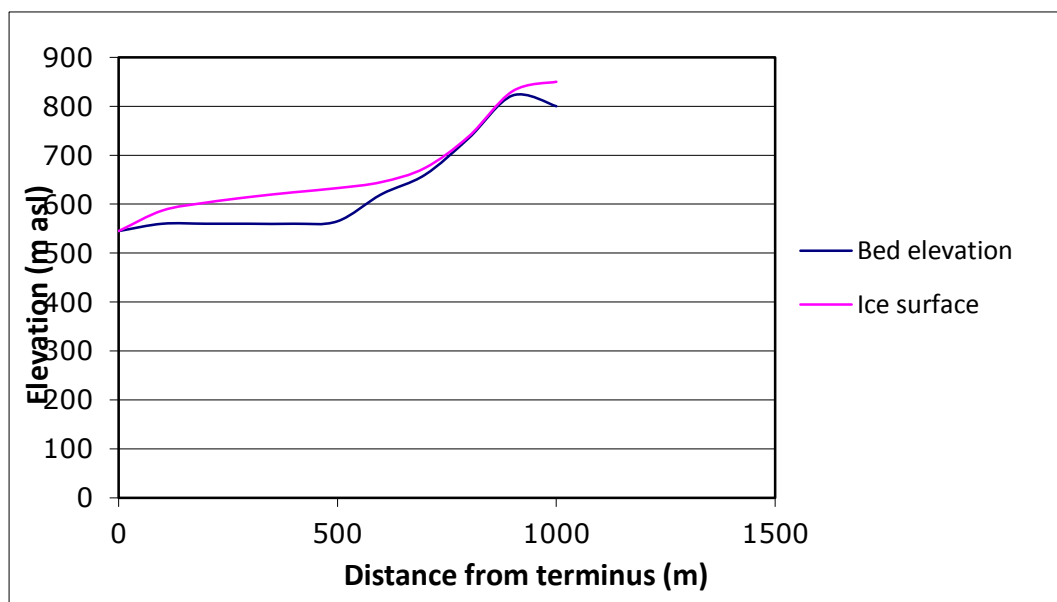

Figure 6: Reconstructed ice surface profile for Cwm Gadair.
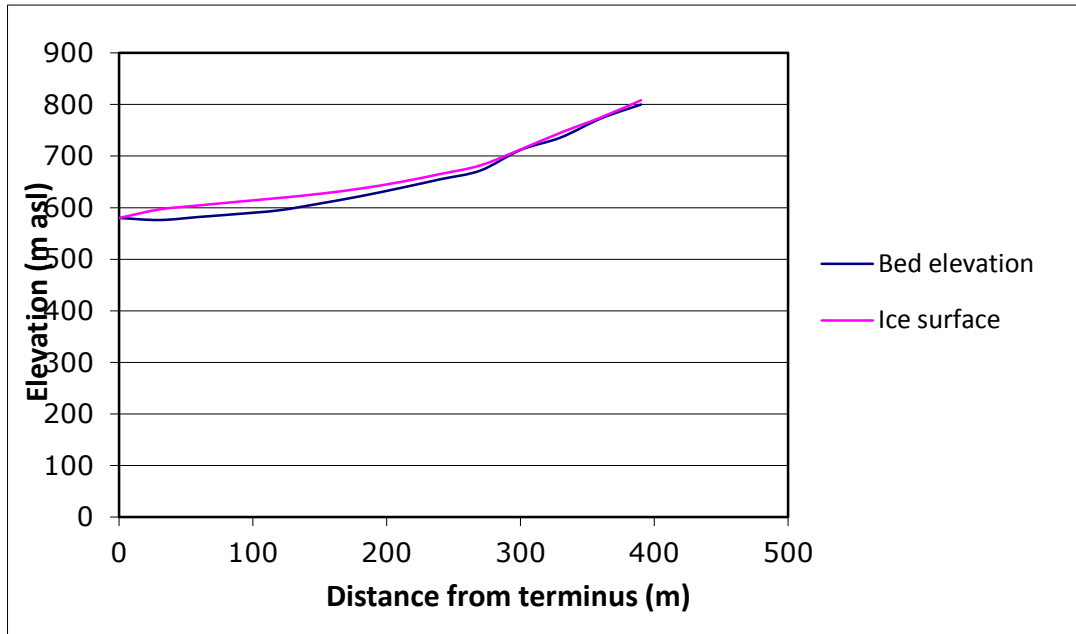
Figure 7: Reconstructed ice surface profile for the small eastern glacier.
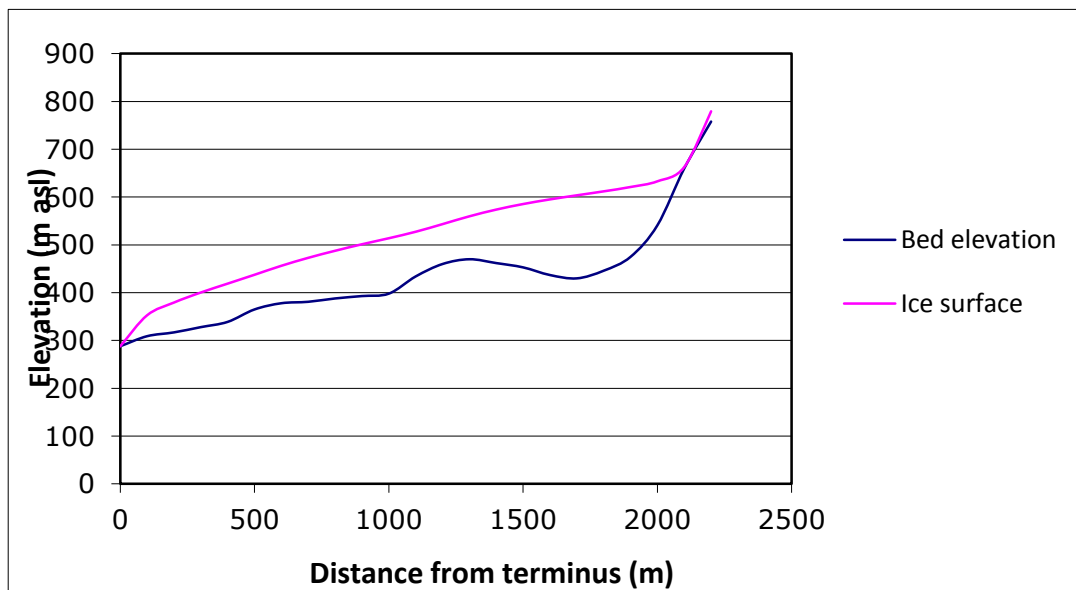
Figure 8: Reconstructed ice surface profile for the larger extent of Cwm Cau.

Figure 9: Map showing the reconstructed Younger Dryas glaciers occupying Cwm Cau and Cwm Gadair, as well as the small eastern glacier. The red lines show the reconstructed ELA values.

Figure 10: Map showing the reconstructed larger extent of the glacier occupying Cwm Cau from an unknown glaciation. The red line shows the reconstructed ELA value.

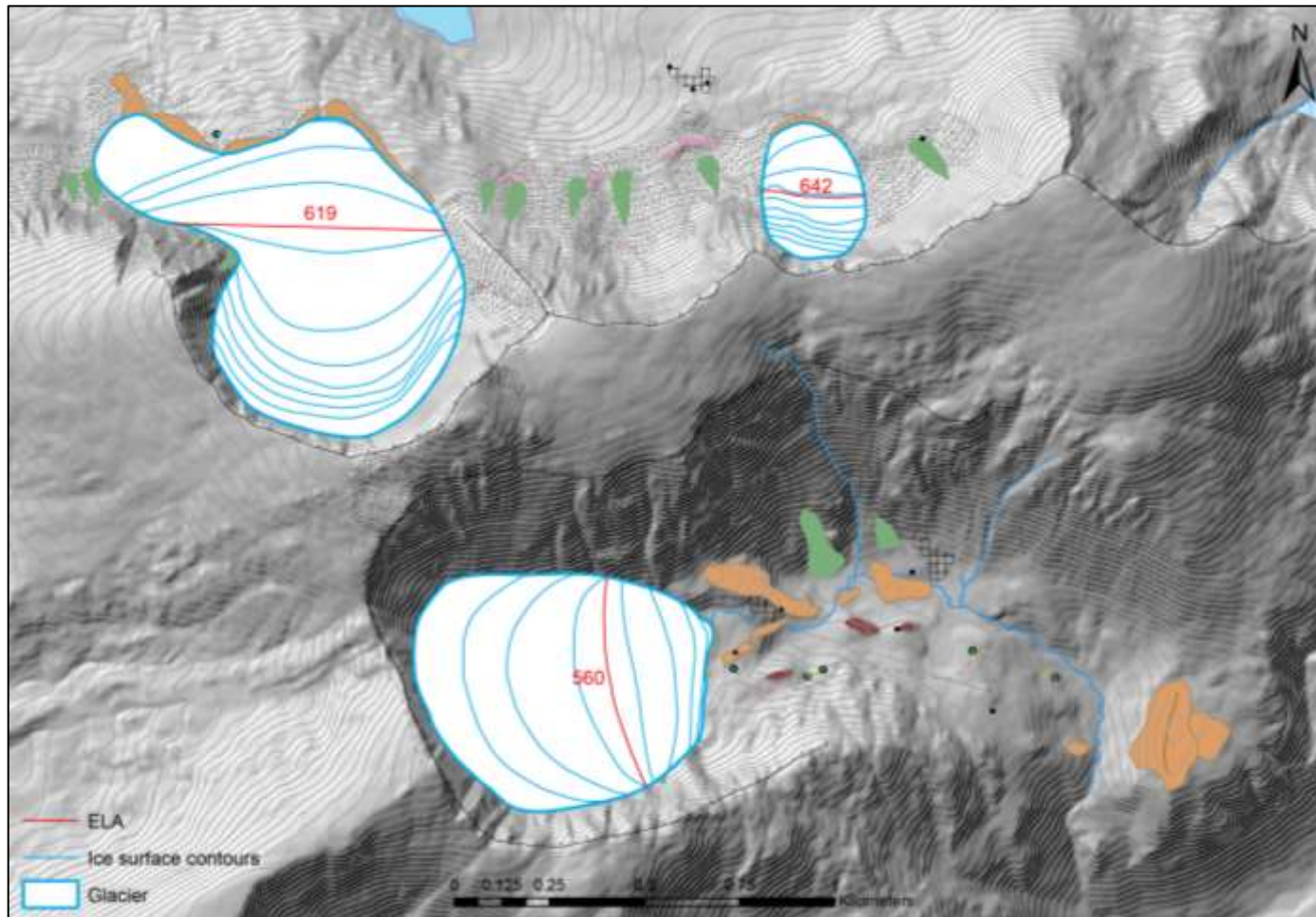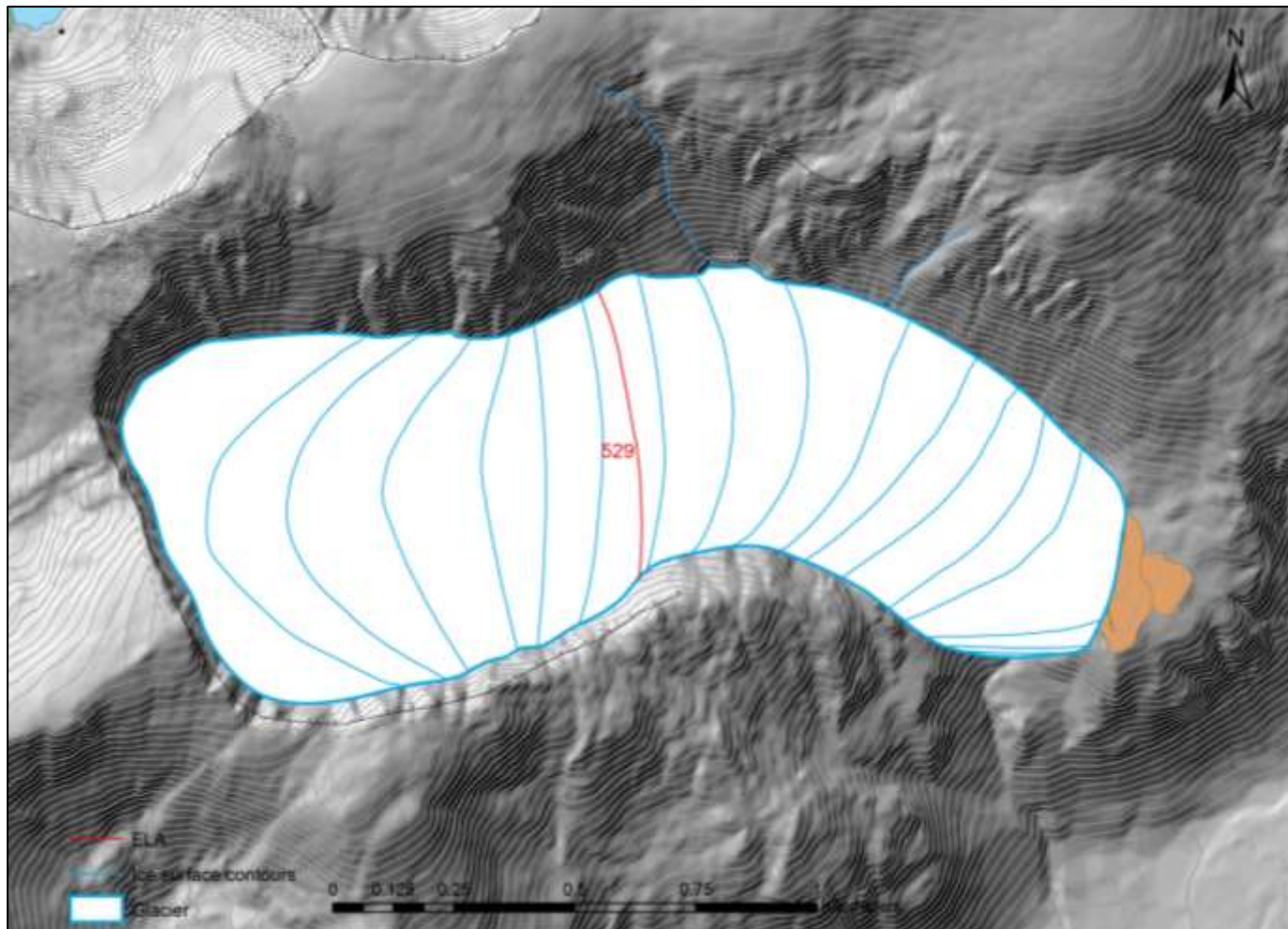**Table 3:** Reconstructed ELAs for the Younger Dryas glaciers, using the THAR, AAR and AABR methods. The average shows the mean ELA value for the AAR and AABR methods.

Reconstructed Equilibrium Line Altitude (m asl)

Glacier name	Area (km²)	THAR (0.35)	THAR (0.45)	AAR (0.44)	AAR (0.55)	AAR (0.65)	AABR (1.67)	AABR (1.8)	AABR (2.0)	Average
Cwm Cau (Y.D. extent)	0.392	547	569	577	567	537	560	559	558	560
Cwm Gadair	0.493	589	620	632	621	611	617	616	614	619
Small eastern glacier	0.078	647	666	653	640	625	645	644	642	642

Table 4: Reconstructed ELAs for the larger extent of Cwm Cau, using the THAR, AAR and AABR methods. The average shows the mean ELA value for the AAR and AABR methods.

Reconstructed Equilibrium Line Altitude (m asl)

Glacier name	Area (km²)	THAR (0.35)	THAR (0.45)	AAR (0.44)	AAR (0.55)	AAR (0.65)	AABR (1.67)	AABR (1.8)	AABR (2.0)	Average
Cwm Cau (larger)	1.176	413	450	572	536	506	521	520	516	529

Palaeoclimatic reconstructions

The results of the palaeoclimatic reconstructions can be seen in Table 5. Average 3-month summer temperatures of 6.8°C and 6.3°C at the ELA of Cwm Cau yielded annual precipitation figures of 3086mm and 2867mm. For Cwm Gadair, average 3-month summer temperatures of 6.5°C and 5.9°C at the ELA produced annual precipitation results of 2950mm and 2705mm. With regard to the small eastern glacier, average 3-month summer temperatures of 6.3°C and 5.7°C generated annual precipitation figures of 2867mm and 2625mm.

Considering these results, precipitation at Cadair Idris during the Younger Dryas is estimated to have been between 2625mm a^{-1} and 3086mm a^{-1}. However, the equation by Ohmura et al., (1992) takes into account all mass added to the glaciers, including mass gained from snowblow and avalanching, so it may not accurately reflect atmospheric precipitation. Despite this, it does give an estimate of the likely range of precipitation at Cadair Idris during the Younger Dryas, and allows glaciological factors such as ablation gradients to be considered.

Table 5: Calculation of annual precipitation / mm at the average ELAs for the Younger Dryas glaciers, using two different environmental lapse rates.

ELA and lapse rate used for extrapolation of sea level temperature	3-month average summer temperature during Younger Dryas / °C	Annual precipitation / mm
Cwm Cau 560m asl **0.006 °C m^{-1}**	6.8	3086
Cwm Cau 560m asl **0.007 °C m^{-1}**	6.3	2867
Cwm Gadair 619m asl **0.006 °C m^{-1}**	6.5	2950
Cwm Gadair 619m asl **0.007 °C m^{-1}**	5.9	2705
Small eastern glacier 642m asl **0.006 °C m^{-1}**	6.3	2867
Small eastern glacier 642m asl **0.007 °C m^{-1}**	5.7	2625

Roles of snowblow and avalanching

It is suggested by Mitchell (1996) that smaller glaciers can sometimes form due to local factors rather than a regional ELA pattern, a point reinforced by Plummer & Phillips (2003), who discuss how the impact of local topoclimatic variables such as snowblow and avalanching can have a disproportionate impact on smaller glaciers compared to larger ones. Mitchell (1996) argues that mass is not only added to the accumulation area of a glacier through direct precipitation, but also through snow

blowing onto the glacier surface, avalanching from the slopes above the cirque or by the collapse of cornices (which would develop on the cliff edge of a cirque). In areas of marginal glaciation snowblow can be critical in the development of glaciers, dependent on the prevailing wind direction. It can also be an explanation for why some glaciers are able to form at low altitudes (Mitchell, 1996).

Figure 11 shows the three Younger Dryas glaciers and their potential snowblow and avalanche areas.

The potential snowblow and avalanche areas are shown in Tables 6 and 8, as a whole and separated into 90° (NE, SE, SW and NW) quadrants. For better comparison, the snowblow and avalanche factors can be seen in Tables 7 and 9.

With regard to snowblow, the small eastern glacier has the highest total snowblow factor, 1.32, Cwm Cau has a factor of 1.24, and Cwm Gadair has the lowest total snowblow factor, 0.71. However, during the Younger Dryas the prevailing winds in Wales came from the south-west (Bendle & Glasser, 2012), so when considering the south-west sectors alone, the small eastern glacier has a snowblow factor of 0.80, Cwm Cau of 0.64 and Cwm Gadair of 0.46. With regard to avalanching, Cwm Cau has the highest total avalanche factor, 0.92, the small eastern glacier has a total avalanche factor of 0.42 and Cwm Gadair has the lowest total avalanche factor of 0.27.
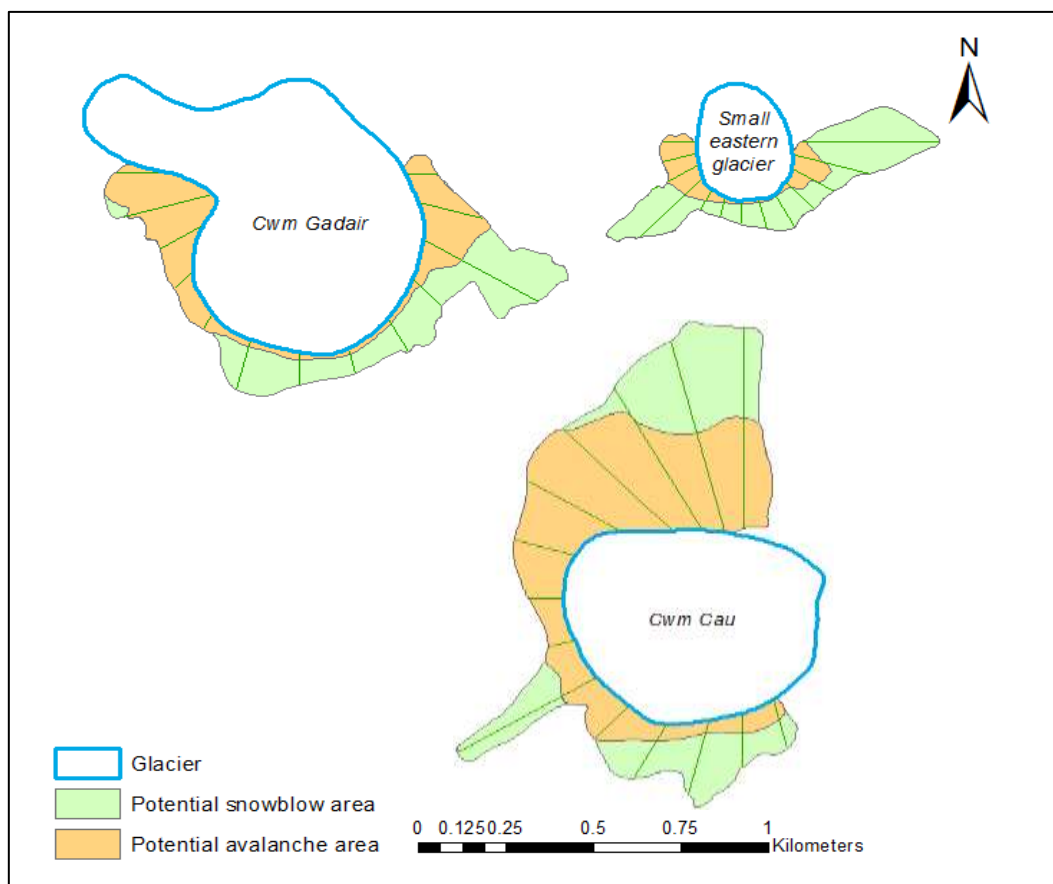

Figure 11: Diagrams showing the potential snowblow and avalanche areas for each of the Younger Dryas cirques, split into 15° segments.

Table 6: Total snowblow area (km^2) for the Younger Dryas cirque glaciers, and snowblow area by 90° sector for each cirque.

Glacier name	Area / m^2	ELA / m asl	Total snowblow area / km^2	Snowblow area (km^2) by 90° sectors and (% of total snowblow area)			
				NE (0 - 90°)	SE (91 - 180°)	SW (181 - 270°)	NW (271 - 360°)
Cwm Cau	0.392	560	0.601	0.037 (6.2)	0.022 (3.7)	0.162 (27.0)	0.380 (63.1)
Cwm Gadair	0.493	619	0.248	0.002 (0.8)	0.142 (57.3)	0.103 (41.5)	0.001 (0.4)
Small eastern glacier	0.078	642	0.137	0.024 (17.5)	0.063 (46.0)	0.049 (35.8)	0.001 (0.7)

Table 7: Total snowblow factor for the Younger Dryas cirque glaciers, and snowblow factors by 90° sector for each cirque.

Glacier name	Area / m^2	ELA / m asl	Total snowblow area / km^2	Ratio	Total snowblow factor	Snowblow factor by 90° sectors			
						NE (0 - 90°)	SE (91 - 180°)	SW (181 - 270°)	NW (271 - 360°)
Cwm Cau	0.392	560	0.601	1.53	1.24	0.31	0.24	0.64	0.98
Cwm Gadair	0.493	619	0.248	0.50	0.71	0.06	0.54	0.46	0.05
Small eastern glacier	0.078	642	0.137	1.76	1.32	0.56	0.90	0.80	0.11

Table 8: Total avalanche area (km^2) for the Younger Dryas cirque glaciers, and avalanche area by 90° sector for each cirque.

				Avalanche area (km^2) by 90° sectors and (% of total avalanche area)			
Glacier name	Area / m^2	ELA / m asl	Total avalanche area / km^2	NE (0 - 90°)	SE (91 - 180°)	SW (181 - 270°)	NW (271 - 360°)
Cwm Cau	0.392	560	0.363	0.025 (6.9)	0.008 (2.2)	0.073 (20.1)	0.257 (70.8)
Cwm Gadair	0.493	619	0.130	0.004 (3.0)	0.048 (37.0)	0.076 (58.5)	0.002 (1.5)
Small eastern glacier	0.078	642	0.033	0 (0)	0.012 (36.4)	0.019 (57.6)	0.002 (6.0)

Table 9: Total avalanche factor for the Younger Dryas cirque glaciers, and avalanche factor by 90° sector for each cirque.

					Avalanche factor by 90° sectors			
Glacier name	Area / m^2	ELA / m asl	Total avalanche area / km^2	Total avalanche factor	NE (0 – 90°)	SE (91 - 180°)	SW (181 - 270°)	NW (271 - 360°)
Cwm Cau	0.392	560	0.363	0.92	0.06	0.02	0.19	0.65
Cwm Gadair	0.493	619	0.130	0.27	0.01	0.10	0.15	0.01
Small eastern glacier	0.078	642	0.033	0.42	0	0.15	0.24	0.03

Role of solar radiation

It is argued that the distribution of insolation over a glacier can be modified by local topography, in relation to aspect, slope and potential for shading, thus solar radiation can initiate ice accumulation in certain places within a region but not others (Chueca & Julián, 2004). Figures 12 to 15 show average incoming solar radiation maps for

the months of June, July and August, and the whole ablation season (the three months), respectively. It is clear from these figures that spatial variations in solar radiation caused by local topography do exist, as it can be seen that north-facing areas receive considerably less solar radiation during the ablation season than south-facing areas. However, with regard to temporal differences in amount of solar radiation during the ablation season, there are very few, except north-facing areas receive slightly less solar radiation in August than they did in June and July, due to the slightly lower position of the sun in the sky.

In the east-facing cirque Cwm Cau, the differences in amount of solar radiation received between north- and south-facing cirque walls is well demonstrated. The south-facing wall of the cirque clearly receives higher solar radiation than the north-facing wall, with small topographic features creating shading. The back wall of the cirque generally has lower values of solar radiation, apart from towards the northern part.

In Cwm Gadair, with its north-facing aspect, the highest values of solar radiation exist on the terminal moraine in the north of the cirque, with the rest of the cirque generally receiving moderate amounts of insolation. The other north-facing areas at Cadair Idris also receive less solar radiation, including the area to the west of Cwm Gadair extending along the western moraine ridge. In the north-facing small eastern cirque, only the small north-east part of the cirque received high levels of solar radiation, with the southern area of the cirque mostly shaded by the high north-facing escarpment.

It is important to note that during the Younger Dryas the amount and intensity of solar radiation reaching the glaciers would have been different due to the enhanced seasonality at the time. It is suggested that insolation was higher, with summer insolation peaking at 11ka yr BP at 60°N and declining to the present day (Berger & Loutre, 1991; as seen in Cronin, 2010), thus insolation could have had a substantial impact on the glaciers. Furthermore, although the cirque walls are over 300m high, the glaciers themselves would have been many metres above the current topography so would have received more solar radiation onto their surfaces. Despite this, Figure 15 illustrates that there were areas of shading which would have provided conditions necessary to sustain the initial growth of the glaciers and allow them to develop.
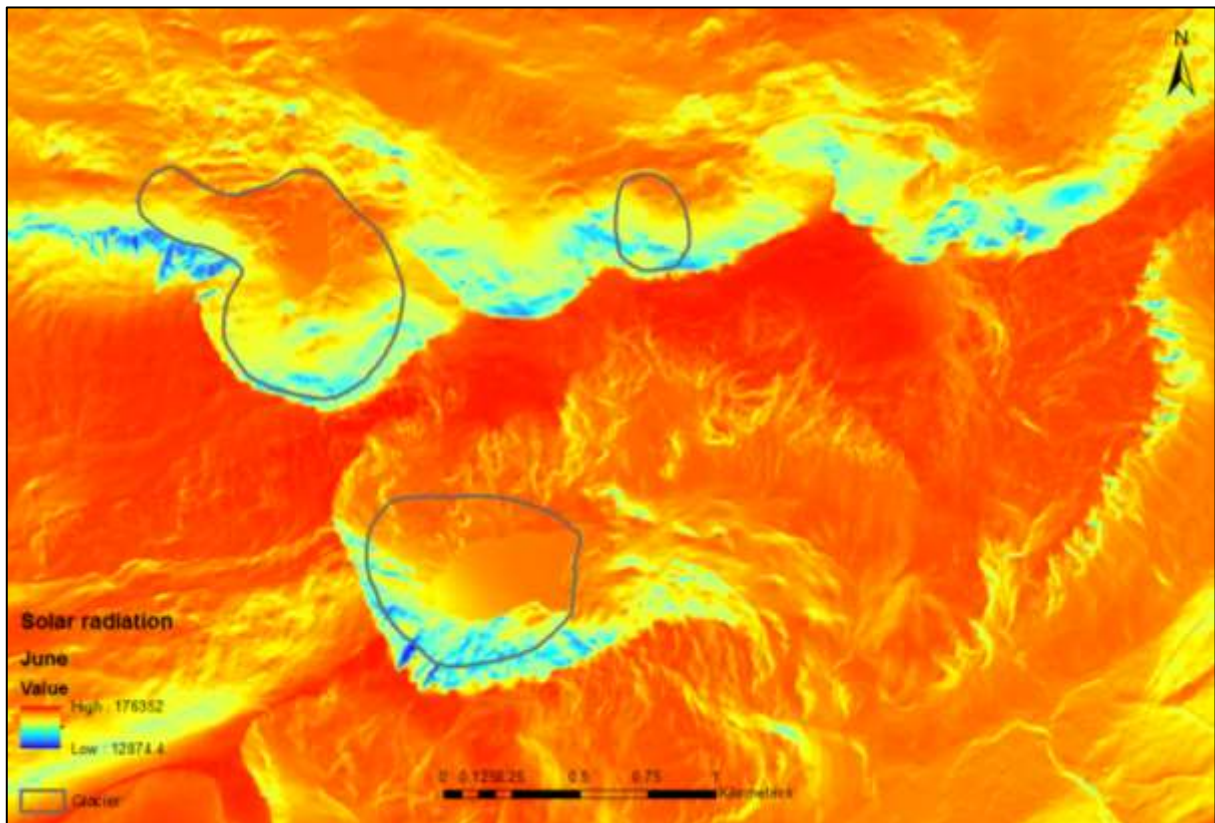
Figure 12: Solar radiation shown for the month of June. Red to orange values show high levels of solar radiation, and blue values show lower levels.
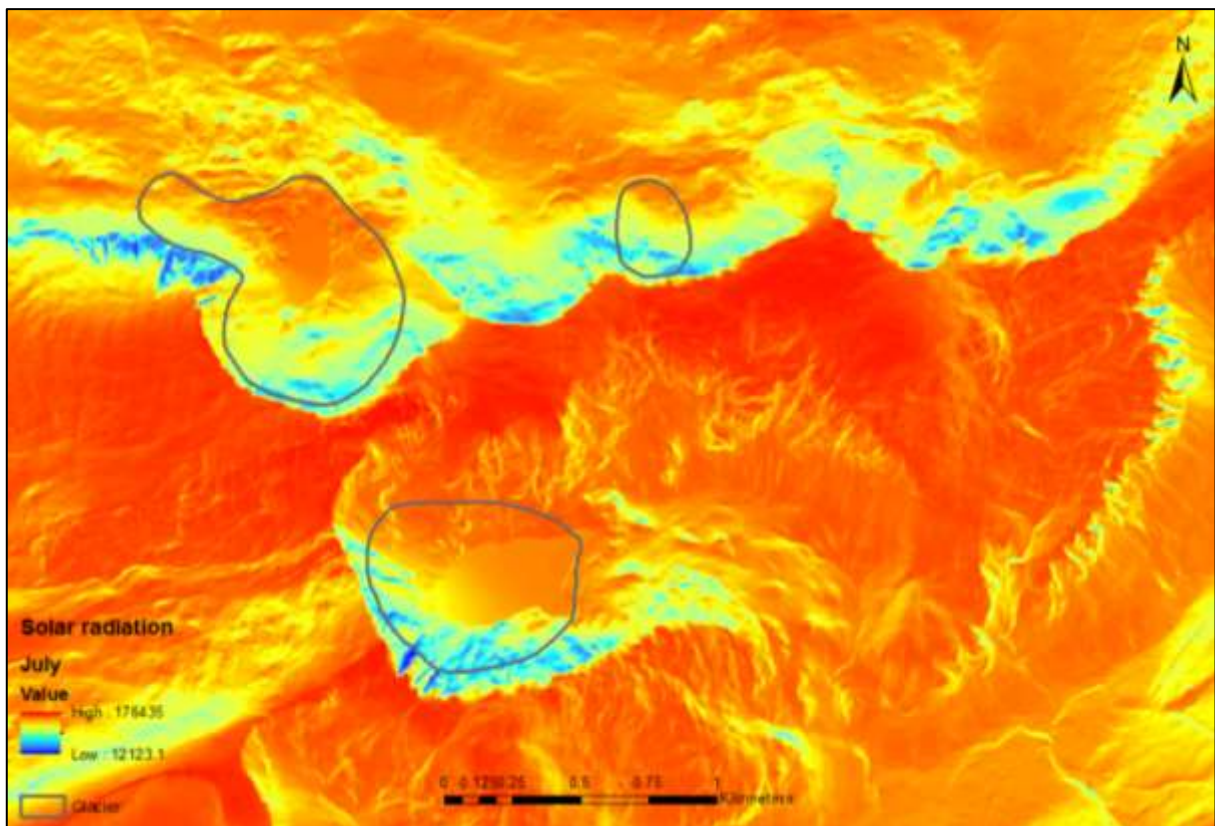

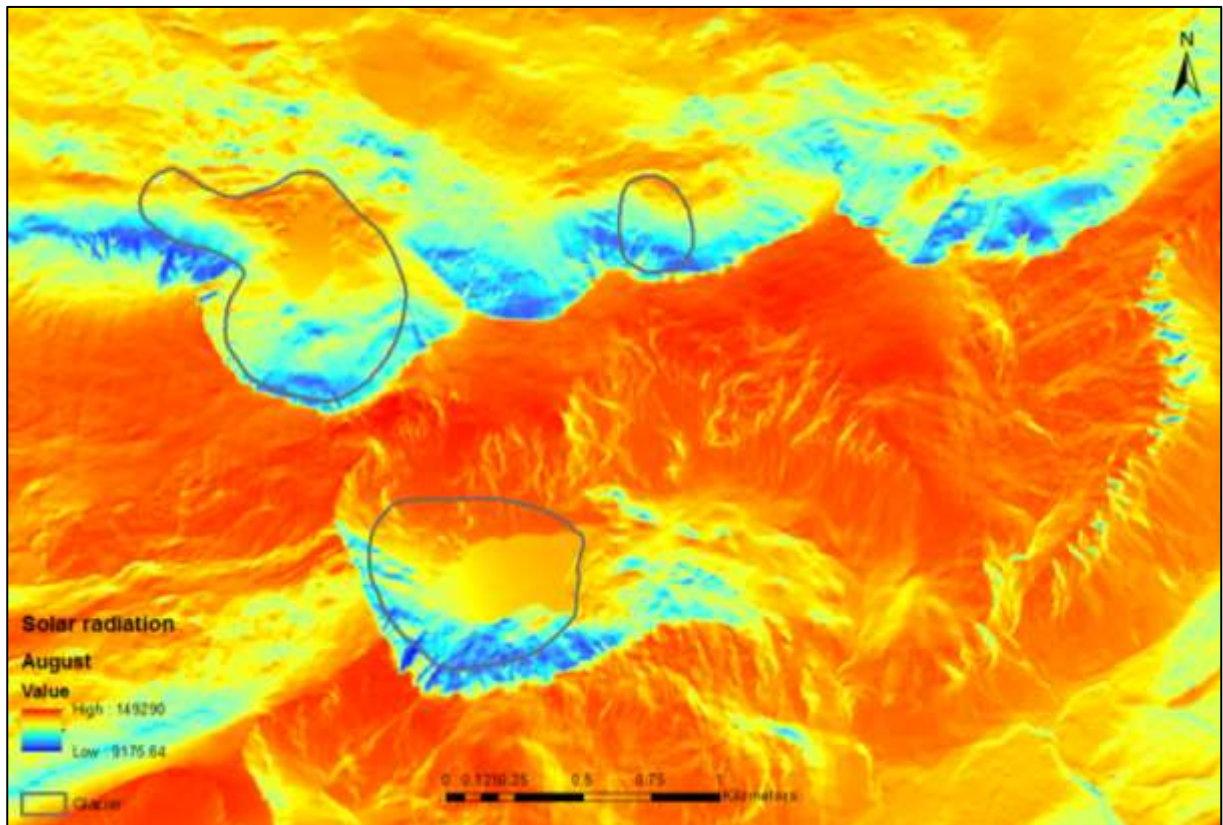**Figure 13:** Solar radiation shown for the month of July.

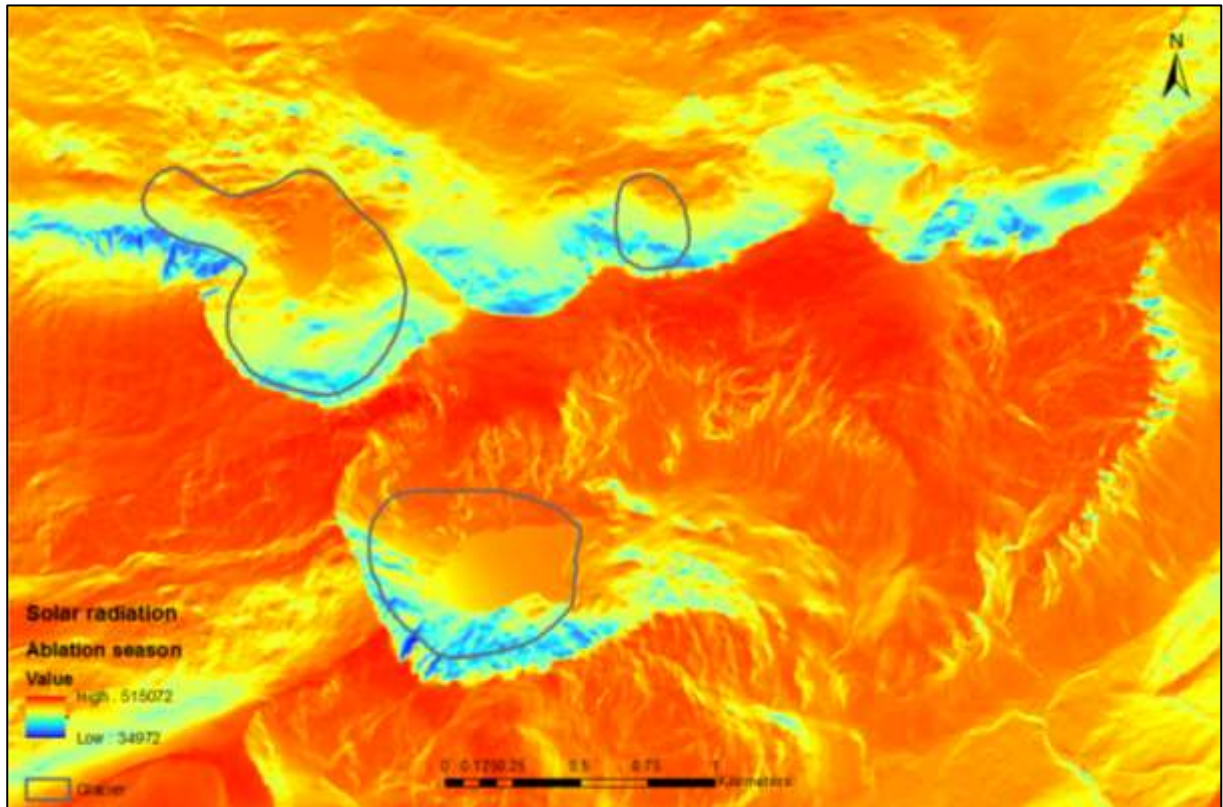**Figure 14:** Solar radiation shown for the month of August.

Figure 15: Solar radiation shown for the ablation season (June, July and August).

Glaciological dynamics

To test whether the Younger Dryas glaciers could have functioned within the climatic conditions reconstructed (Carr, 2001), glaciological dynamics relating to mass balance and flow dynamics were calculated, seen in Table 10 below.

The three Younger Dryas glaciers have similar ablation gradients, but differ considerably in other factors including glacier thickness and slope angle at the ELA, as well as balance velocity and proportion of basal motion.

Table 10: Glaciological dynamics of the Younger Dryas glaciers.

	Cwm Cau	Cwm Gadair	Small eastern glacier
ELA (m asl)	560	619	642
T_3 Temperature at ELA (°C)	6.4	6.2	6.0
Mass loss at ELA (m a^{-1}) / Winter accumulation	2.47	2.39	2.31
Ablation gradient (mm m^{-1})	6.7	6.4	6.2
Ablation (m^3 H$_2$O)	27252.5	52997.2	6683.1
Mass flux (m^3 Ice)	29947.9	58238.6	7344.1
Ice thickness at ELA (m)	126	60	14
Cross-sectional area (m^2)	46500	26939	2660
Balance velocity at ELA (m a^{-1})	0.6	2.2	2.8
Surface Slope at ELA (degrees)	6	5	23
Basal shear stress at ELA (Bars)	1.18	0.47	0.49
Ice deformation (m a^{-1})	17.1	0.51	0.14
Basal Motion as % of total velocity	0	77	95

Discussion

ELAs
When the three Younger Dryas ELAs (Table 3) are averaged, the resulting local ELA for Cadair Idris is 607m asl. This is similar to Bendle & Glasser's (2012) findings of an average ELA of 587m asl for Snowdonia, as well as Lowe's (1993) suggestion of an average local ELA at Cadair Idris of ca. 600m asl. The results also agree with Lowe's (1993) ELA reconstructions for the individual cirques, in which an ELA of 560m asl was calculated for Cwm Cau, 622m asl for Cwm Gadair and 620m asl for the small eastern glacier. The small differences between the results from this study and Lowe's (1993) estimations could be explained by the different approaches used to calculate the ELAs, with Lowe (1993) using linear generalisation of accumulation and ablation gradients, which is a less accurate way of calculating ELAs compared to the averaging of AAR and AABR as used in this study.

The most likely explanation for the differences in ELAs found between Cwm Cau, Cwm Gadair and the small eastern glacier is the addition of snow to the accumulation areas of the glaciers from snowblow and avalanching; the impact of which will be discussed later. Although previous research has suggested a general north-eastwards rise in ELAs across Snowdonia (Hughes, 2009; Bendle & Glasser, 2012), caused by a strong precipitation gradient allowing the south-westerly cirques to effectively capture snow and build their accumulation areas leading to lower ELAs, this precipitation gradient is unlikely to be responsible for the differences between ELAs of the cirques in this study. Cwm Cau, Cwm Gadair and the small eastern glacier are too close in proximity to each other to be affected by any climatic precipitation gradient. This point is recognised by Hughes (2009) who believes that, as well as regional precipitation gradients, differences in local factors are also likely to create the spatial variability of ELAs across Wales.

The average ELA for the larger extent of Cwm Cau was calculated to be 529m asl. This figure is lower than the ELA for the Younger Dryas extent, which is logical as the glacier was bigger and therefore likely to have had a larger accumulation area. Furthermore, if the larger glacier existed following deglaciation from the LGM, climatic conditions would have been different to the Younger Dryas, with lower levels of insolation, lower temperatures and potentially more precipitation to increase the size of the accumulation area and the glacier.

Palaeoclimate
Average contemporary precipitation (for the years 1981–2010) at Gogerddan weather station, the closest weather station to Cadair Idris (ca. 30km away at an altitude of 31m asl) is 1048mm a^{-1} (Met Office, 2014), however, the figure is likely to be much higher at the cirques of Cadair Idris due to their higher altitude. Average precipitation at the Capel Curig weather station in northern Snowdonia, which lies at 216m asl, is 2612mm a^{-1} (Met Office, 2014). The cirque floor altitudes of Cwm Cau, Cwm Gadair and the small eastern glacier are ca. 470m asl, 560m asl and 600m asl respectively, therefore, although the exact precipitation could not be calculated due to the non-linearity of precipitation-elevation gradients (Ballantyne, 2002), it can be estimated that present day average precipitation in the Cadair Idris area lies at least above 2000mm a^{-1}. If an average regional Younger Dryas annual precipitation figure is calculated from the six different estimations (Table 5) the result is 2850mm a^{-1}.

This reveals that average annual Younger Dryas precipitation at Cadair Idris was likely to have been similar to, or slightly higher than, today.

When considering the results of the palaeoclimatic estimations, it is revealed that, at Cadair Idris, the Younger Dryas was colder and wetter than at present. Similar findings have been published in other studies of Younger Dryas palaeoglaciers in the UK. In Snowdonia, Hughes (2009) found that annual accumulation values of 2428-2925mm for the Younger Dryas period are similar to modern-day values, suggesting that this is a result of active depressions close to the polar front, situated, at latitude ca. 45-50°N, to the south-west of the British Isles at the time. Another study suggesting higher precipitation levels during the Younger Dryas is that of Ballantyne (2002), who proposes a best estimate of 3200mm a^{-1} at the regional ELA for palaeoglaciers on the Isle of Mull, west coast of Scotland, signifying that precipitation totals were higher than at present, with vigorous airmass circulation suggested as a cause. Conversely, the results of the palaeoclimatic reconstruction for glaciers in northern Snowdonia by Bendle & Glasser (2012) indicate that during the Younger Dryas, Wales had lower annual precipitation values than at present, however, a different approach was used to calculate this which could explain the different result.

With regard to geomorphological evidence of palaeoclimate, the presence of recessional moraines can be used to indicate periods of glacier stabilisation or in some cases readvance. Bendle & Glasser (2012) note that many of the cirques in northern Snowdonia contain recessional moraines, which reflect transitional climate change during the deglaciation of the area. However, in southern Snowdonia and the Cadair Idris area, neither Cwm Cau nor Cwm Gadair exhibit evidence of recessional moraines between their Younger Dryas terminal moraines and the headwalls of the cirques. This indicates that after reaching their maximum extent, the glaciers underwent sustained negative mass balance and receded rapidly following the onset of deglaciation and the warming of the climate at the end of the Younger Dryas stadial. However, the area of the small eastern glacier does contain evidence of a potential small recessional moraine, indicating a possible pause in its deglaciation. With regard to the larger extent of Cwm Cau, the recessional moraines in the hanging valley east of Cwm Cau indicate that during deglaciation of the glacier from its maximum extent in a former glaciation, the glacier paused, reflecting standstills in the warming of the climate or perhaps return to colder conditions.

Roles of snowblow and avalanching
Because the importance of the snowblow area is a function of the size of the glacier it is related to, snowblow factors will be compared here. It can be seen from Table 7 that the small eastern glacier has the highest snowblow factor (1.32), followed by Cwm Cau (1.24), then Cwm Gadair (0.71). However, in comparison to calculated snowblow factors for other glaciers (Mitchell, 1996; Coleman et al., 2009), these snowblow factors are relatively small which could be reflected in the somewhat limited extent of glaciation in this area during the Younger Dryas. Mitchell (1996) analysed five glaciers in the Lake District, calculating snowblow factors ranging from 2.34 to 5.81, and Coleman et al., (2009) established snowblow factors ranging between 3.16 to 5.58 for two glaciers at different stages in their development, in the Brecon Beacons.

The most significant snowblow sectors vary between the Cadair Idris glaciers. For Cwm Cau the most significant sector is the north-west, making up 63.1% of the total potential snowblow area (Table 6) with a snowblow factor of 0.98 (Table 7). Interestingly, the most significant sector for both Cwm Gadair and the small eastern glacier is the south-east, equating to 57.3% of the total potential snowblow area, with a snowblow factor of 0.54 (Cwm Gadair) and 46.0% of the total potential snowblow area, with a snowblow factor of 0.90 (small eastern glacier). Yet although being the greatest sectors by area, they are unlikely to have contributed snow to the glacier as previous studies suggest that during the Younger Dryas prevailing winds in the UK and Snowdonia came from southerly and westerly directions (Sissons, 1980; Hughes, 2009; Bendle & Glasser, 2012). Thus, the south-westerly sectors of each potential snowblow area are the most likely of all sectors to have contributed snow to the glaciers.

If the south-westerly sectors alone are considered, then the snowblow factors for Cwm Cau, Cwm Gadair and the small eastern glacier are 0.64, 0.46 and 0.8 respectively. The fact that Cwm Cau has a higher snowblow factor for the south-west sector than Cwm Gadair could suggest that it had a greater chance of having additional snow added, thus increasing the accumulation area and lowering the ELA. This compares well with the ELA calculations, as Cwm Cau does have a lower ELA than Cwm Gadair; 560m asl compared to 619m asl. Therefore this difference could be explained by the variations in size of the potential snowblow areas between the two glaciers, under prevailing south-westerly winds during the Younger Dryas. However, the small eastern glacier has the highest of all snowblow factors for the southwest sector, 0.80, which would suggest it should have the lowest ELA. Yet this is not the case as the ELA was calculated to be 642m asl. A possible explanation for this is that avalanching also played a part in contributing snow to the glaciers.

If total avalanche factors are considered (Table 9), then Cwm Cau has the highest potential for avalanching, with a total factor of 0.92, followed by the small eastern glacier with a factor of 0.42, then Cwm Gadair with a factor of 0.27. Again, Cwm Cau has the highest potential for addition of snow thus lowering of the ELA, which could explain why it has the lowest ELA of the three glaciers. In comparison with the avalanche factors found in the Brecon Beacons, which range from 0.18 to 0.42 (Coleman et al., 2009), the potential for avalanche-derived snow being added to the glaciers in this study is similar. The potential for avalanching can be explained by the well-developed cirque topography, with all three glaciers existing in cirques with steep and high headwalls.

Role of solar radiation
As well as potential snowblow and avalanching impacting on the accumulation areas, the glaciers may also have been altered by the amount of solar radiation they received. Surface energy balance of a glacier is directly affected by solar radiation and, according to Hopkinson et al., (2010), most of the energy used in melt production on temperate glaciers is sourced from solar radiation. However, the amount of radiation that a glacier can receive is affected by the topography surrounding it, with Chueca & Julián (2004) arguing that topography can affect the distribution of insolation over a glacier through variability in elevation, surface orientation (slope and aspect) and the effect of topography casting shadows which can create strong local gradients of insolation.

The results of solar radiation mapping for the Cadair Idris area (Figures 12 to 15) highlight key spatial differences between north- and south-facing slopes, illustrating the impact of aspect on incoming solar radiation, and agreeing with Basagic & Fountain (2011) who state that most glaciers occur on north or north-east facing slopes as a result of topographic-induced solar radiation reduction. During the Younger Dryas, the north-facing cirque glaciers (Cwm Gadair and the small eastern glacier) are estimated to have received less solar radiation than the east-facing glacier in Cwm Cau, as roughly half of the glacier in Cwm Cau would have had the potential to receive high levels of solar radiation (Figure 15). This could indicate that during ablation seasons in the Younger Dryas stadial, Cwm Cau may have experienced more melting than Cwm Gadair and the small eastern glacier. Additionally, the fact that the northern part of the glacier in Cwm Cau would have received more solar radiation than the southern part may suggest that higher melt rates on the northern part would have promoted glacier recession towards the south-east, where solar radiation is low. Once melting from solar radiation begins, it is argued by Arnold et al., (2006) that the incoming solar radiation leads to rapid warming and melting of a glacier, which in turn reduces the surface albedo thus amplifying the impact of the solar radiation, a situation which could have enhanced the melting and deglaciation of the Younger Dryas glaciers in this study.

The area beneath the cliffs to the west of Cwm Gadair likely received very little solar radiation (Figure 15), being shaded by the steep escarpment of Cadair Idris. This potentially explains the development and existence of the western lobe of the glacier, as this shading would have protected it from high solar radiation levels in the ablation season. However, for all three glaciers, it can be seen that beyond the Younger Dryas extents the areas are exposed to considerably more solar radiation, with very little shading. This reason could partially explain the limited extents of the glaciers, being restricted to the more shaded and protected areas within the local topography. This suggestion of solar radiation limiting glacier extent is supported by López-Moreno et al., (2006), who demonstrate, through the example of glaciers in the Pyrenees mountain range in Spain, how for niche glaciers, the combination of altitude and incoming solar radiation, thus the resultant shading, are the most significant influences in defining glacier location.

Consideration must be given to the fact that, with glaciers filling the cirques during the Younger Dryas, the surface would have been many metres higher than the current cirque floor altitude, possibly reducing the effect of shading from the walls of the cirque. With the difference in altitude between the surface of the glaciers and the top of the cirque walls reduced, the glaciers (at their full extent) may have been able to receive more solar radiation. However, during their initiation, the high headwalls would have shaded the glaciers enabling their development.

Glaciological dynamics
It can be seen from Table 10, that the ablation gradients for the three Younger Dryas glaciers all lie above 6mm m^{-1}, agreeing with the theory that ablation gradients for mid-latitude glaciers should lie above 5mm m^{-1} (Schytt 1967, as seen in Carr & Coleman, 2007). The ablation gradients are also similar to those calculated by Carr & Coleman (2007) for four small Younger Dryas glaciers in the UK, which range from 5.01mm m^{-1} to 7.71mm m^{-1}, as well as for three glaciers in the Brecon Beacons with

ablation gradients ranging from 5.16mm m^{-1} to 5.96mm m^{-1} when calculated using the same method as this study, employing winter accumulation as a figure for mass loss (Carr et al., 2010).

Balance velocities for Cwm Gadair and the small eastern glacier are 2.2m a^{-1} and 2.8m a^{-1} respectively, whereas the balance velocity for Cwm Cau is lower, at 0.6m a^{-1}, indicating that it was relatively slower moving. The basal shear stress values for Cwm Gadair and the small eastern glacier are both close to 0.5 Bars, with a higher value of 1.18 Bars for Cwm Cau. These values do fall within the range suggested by Paterson (1994) for normal glaciers (between 0.5 and 1.5 Bars), and are similar to the values input into the Profiler spreadsheets to calculate the long-surface profiles of the glaciers.

With regard to glacier motion, Cwm Gadair has an ice deformation value of 0.51m a^{-1}, with 77% of the total balance velocity estimated to be basal motion. This figure falls below the 90% limit suggested by Carr & Coleman (2007) for accepting glaciological viability, confirming that the glacier would have been able to operate within the reconstructed palaeoclimatic conditions during the Younger Dryas. Cwm Cau had a much higher ice deformation value, 17.1m a^{-1}, which far exceeds the balance velocity of 0.6m a^{-1}. This does not suggest the glacier was cold-based, just that basal slip was not required to transfer mass through the ELA. An explanation for this is the existence of an over-deepened basin in the form of the lake, Llyn Cau, and the thickness of the ice, 126m at the ELA. The basal shear stress, 1.18 Bars, was sufficient enough to generate ice strain accommodating all the necessary mass flux through the ELA.

With regard to the small eastern glacier, it is suggested that it was not, in fact, viable as a glacier. The thickness of the ice, only 14m at the ELA and 24m at its thickest point (Figure 7), initially raises the question of its viability, as these values are below the suggested 30m in which snow is converted to glacier ice (Gray, 1982). Furthermore, the required basal motion is 95%, which lies above the threshold for glacier viability suggested by Andrews (1972) and Carr & Coleman (2007), amongst others. This value implies that the glacier would have behaved as a rigid body in order to transfer the necessary ice flux through the ELA to maintain equilibrium. It is possible that the ridge identified as a moraine in Figure 2, was formed through a non-glacial process, a suggestion which could be tested with a methodology similar to that of Coleman & Carr (2008), combining the glaciological approach with geomorphological and sedimentological approaches in order to identify the origin of the ridge. An alternative suggestion is that the ridge was formed by the glacier under colder conditions during the Lateglacial, possibly during the LGM, resulting in a considerably different ablation gradient thus mass balance conditions of the glacier. This is supported by evidence of a small recessional moraine (Figure 2), potentially suggesting that the small eastern glacier existed during a different glaciation in which it receded with a standstill in climate, as discussed previously. It is also possible that, during the Younger Dryas, the small eastern glacier originated as a snow patch but grew in size due to addition of snow. This suggestion is supported by the fact that it had the highest snowblow factor overall and for the SW sectors, which, combined with a steep ice slope angle (23°), could have led to deposition of the ridge.

Limitations and sources of potential error

This research has been subject to several possible limitations and sources of error, which need to be borne in mind when considering the results of the glacier and palaeoclimatic reconstructions. One of the initial potential sources of error was the subjective nature in deciding the origin of some features, and the need to employ subjectivity when establishing glacier margins resulting from a lack of precise geomorphological features to indicate lateral and vertical extent. Following this, although the use of *Profiler* (Benn & Hulton, 2010) improved the accuracy of drawing ice surface contours, certain assumptions still had to be made as there were no target elevations, such as lateral moraines or trimlines, to guide the programme. Furthermore, a variety of shear stress values had to be tried until a 'best-fit' scenario was reached and the contours looked plausible.

The calculation of the average ELA may have introduced error by amplifying each ELA technique's own inherent errors. Additionally, these errors may also have been amplified in the palaeoclimatic reconstruction. The approach used followed the methods of Ohmura et al., (1992), in which the equation is based on a global dataset of contemporary glaciers. An issue with this is noted by Bendle & Glasser (2012), who describe how estimates of precipitation totals using this method may be erroneously high as the equation does not take into account the influence of regional climatic seasonality.

Although the method for outlining the potential snowblow and avalanche areas is fairly robust, no method for quantifying the volume of snow which could have been added to the glaciers was used. This would have to take into account precise topography, wind speed and wind direction, and could only be achieved through modelling. As well as this, using the solar radiation function on ArcGIS as an estimation for incoming solar radiation in the Younger Dryas meant that assumptions had to be made that the intensity and amount of incoming solar radiation during the ablation seasons were similar to the present day values.

One particular reservation of the glaciological calculations is highlighted by Carr et al., (2010), who suggest that the use of 90% basal motion as the threshold for viability of glaciers should be viewed tentatively until further observation of glacier velocity and instrumentation of basal motion for smaller valley, cirque and niche glaciers has been published.

A final important limitation to be noted is the potential for cumulative error throughout the whole process. Plummer & Phillips (2003) acknowledge that considerable uncertainty exists in each stage of a glacier reconstruction. However, it is difficult to quantify the uncertainty, therefore the amount of error in this study is unknown, but it is important to recognise that it exists.

Conclusion

This research has addressed the need for further glacier reconstructions along the west coast of Britain, called for by Bendle & Glasser (2012), by reconstructing three assumed Younger Dryas cirque glaciers and one larger glacier at Cadair Idris in southern Snowdonia. The Younger Dryas glaciers were assigned their age by assessing secondary literature, as although relative ageing in the form of Schmidt Hammer surface exposure ageing was carried out, no absolute ageing could be

conducted. Although the geomorphological landscape of the cirques at Cadair Idris has previously been mapped by Sahlin & Glasser (2008), no glacier reconstructions or palaeoclimatic inferences for the area have been published. This research has contributed to this gap in knowledge by successfully addressing three aims; firstly to undertake glacier reconstructions in the Cadair Idris area of Snowdonia, secondly to establish the climatic conditions in the Cadair Idris area during the Younger Dryas and thirdly to calculate glaciological dynamics of the former glaciers and assess their viability.

Geomorphological mapping indicates that during the Younger Dryas, the three glaciers occupied a total ice area of 0.963km^2. Although Cwm Cau extended to the moraine which dams the lake, Llyn Cau, it is suggested that during the LGM it reached the large terminal moraine at the edge of the hanging valley, at which time it would have occupied an ice area of 1.176km^2. Modelled ice profiles created for all four glaciers, using the Excel^{TM} spreadsheet *Profiler* (Benn & Hulton, 2010), enabled ice surface contours to be established before ELA estimations were conducted. Cwm Cau (Younger Dryas extent), Cwm Gadair and the small eastern glacier yielded ELA values of 560m asl, 619m asl and 642m asl respectively. The average ELA for the larger extent of Cwm Cau was calculated to be 529m asl, implying that colder temperatures and higher levels of precipitation during a previous glaciation encouraged glacier growth.

Younger Dryas 3-month mean summer temperatures at the ELAs of the glaciers were estimated to lie in the range of 5.7°C to 6.8°C. Using the equation established by Ohmura et al., (1992), estimated palaeoprecipitation values ranged from 2625mm a^{-1} to 3086mm a^{-1}, with an average of 2850mm a^{-1}. From these results, it was concluded that during the Younger Dryas the climate was both cooler and wetter than it is today, results similar to other studies on the western sea-board of the UK, including that of Ballantyne (2002) and Hughes (2009).

Consideration of the potential role of snowblow in increasing the accumulation areas of the glaciers, thus lowering the ELAs and impacting on subsequent climatic reconstructions, revealed that Cwm Cau had a total snowblow factor of 1.24, Cwm Gadair of 0.71 and the small eastern glacier of 1.32. When considering the south-west sectors alone, as during the Younger Dryas the prevailing winds came from this direction (Bendle & Glasser, 2012), it was shown that Cwm Cau had a snowblow factor of 0.64, Cwm Gadair of 0.46 and the small eastern glacier of 0.80. Consideration of the potential for additional snow being added to the glaciers by avalanching revealed that Cwm Cau had a total avalanche factor of 0.92, Cwm Gadair of 0.27 and the small eastern glacier of 0.42. These avalanche factors reflect the steep topography of the well-developed cirques in which the Younger Dryas glaciers formed. It is suggested that the small differences between the ELAs of the cirques at Cadair Idris result from these different potentials to gain snow in the accumulation areas of each glacier.

The potential role of solar radiation in altering the glaciers was also taken into account, with solar radiation maps produced for the ablation season. The maps illustrate the possibility for shading of the ice from the high walls of the cirques, suggested as a reason for the existence of the western lobe of Cwm Gadair. The

higher levels of incoming solar radiation outside of the Younger Dryas ice limits is also proposed as a possible reason for the limited extents of the three glaciers.

Finally, the glaciological characteristics of the three Younger Dryas glaciers were assessed, in which it was found that the small eastern glacier was not actually viable as a glacier under the reconstructed palaeoclimatic conditions. Calculated basal motion was 95%, which is above the threshold for accepting viability suggested by Carr & Coleman (2007). Cwm Cau and Cwm Gadair were considered viable, with their ablation gradients, basal shear stress values, and basal motion all within the range of normal maritime mid-latitude glaciers.

Despite successfully completing the aims of the study; to undertake glacier reconstructions in the Cadair Idris area of Snowdonia, to establish the climatic conditions in the area during the Younger Dryas and to consider glaciological dynamics of the glaciers, consideration must be given to the potential for cumulative error throughout the process. Furthermore, other factors which may have influenced the glaciers were not taken into account, such as the possibility of debris cover insulating the ice, or the effect of albedo on melting of the glaciers.

These limitations give scope for future research in the area, in order to overcome them and better understand the glaciation of Cadair Idris. Suggestions for further research include a reassessment of the terminal moraine at the east of the hanging valley in Cwm Cau, in order to establish an age for the glaciation in which the glacier extended that far. As well as this, although glacier reconstructions have improved greatly over the past few decades, developments are still occurring, for example in the use of modelling. With regard to this research, a model-based approach could be valuable in providing greater accuracy for snowblow and solar radiation analysis, and for establishing the necessary climatic conditions which would be required to produce some of the geomorphological features which can be seen today (an approach which is particularly useful for smaller-scale glaciation). However, overall, this study has enabled a better understanding of the landscape and climate of the Cadair Idris area of Snowdonia during the Younger Dryas stadial, providing reconstructions of the palaeoglaciers which existed there.

Acknowledgements

References

Ahlmann, H. W., 1948. Glaciological research on the North Atlantic coasts. *Royal Geographical Society Research Series,* Volume 1, pp. 84.

Andrews, J. T., 1972. Glacier power, mass-balance, velocities and potential erosion. *Zeitschrift für   Geomorphologie Supplementbände,* Volume 13, pp. 1-17.

Arnold, N. S., Rees, W. G., Hodson, A. J. & Kohler, J., 2006. Topographic controls on the surface energy balance of a high Arctic valley glacier. *Journal of Geophysical Research,* Volume 111, F02011.

Ballantyne, C. K., 2001. Cadair Idris: A Late Devensian Palaeonunatak. In: M. J. Walker & D. McCarroll, eds. *The Quaternary of West Wales.* London: Quaternary Research Association, pp. 126-131.

Ballantyne, C. K., 2002. The Loch Lomond Readvance on the Isle of Mull, Scotland: glacier reconstruction and palaeoclimatic implications. *Journal of Quaternary Science,* 17(8), pp. 759-771.

Ballantyne, C. K., 2007. Loch Lomond Stadial glaciers in North Harris, Outer Hebrides, North-west Scotland: glacier reconstruction and palaeoclimatic implications. *Quaternary Science Reviews,* Volume 26, pp. 3134-3149.

Basagic, H. J. & Fountain, A. J., 2011. Quantifying 20th Century Glacier Change in the Sierra Nevada, California. *Arctic, Antarctic and Alpine Research,* 43(3), pp. 317-330.

Bendle, J. M. & Glasser, N. F., 2012. Palaeoclimatic reconstruction from Lateglacial (Younger Dryas Chronozone) cirque glaciers in Snowdonia. *Proceeding of the Geologists' Association,* Volume 123, pp. 130-145.

Benn, D. I. & Hulton, N., 2010. An Excel(TM) spreadsheet program for reconstructing the surface profile of former mountain glaciers and ice caps. *Computers & Geosciences,* Volume 36, pp. 605-610.

Benn, D. I. & Ballantyne, C. K., 2005. Palaeoclimatic reconstruction from Loch Lomond Readvance glaciers in the West Drumochter Hills, Scotland. *Journal of Quaternary Science,* 20(6), pp. 557-592.

Benn, D. I. & Evans, D. J., 2010. *Glaciers & Glaciation.* 2nd ed. Oxon: Routledge.

Benn, D. I. & Lehmkuhl, F., 2000. Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments. *Quaternary International,* Volume 65/66, pp. 15-29.

Benn, D. I., Owen, L. A., Osmaston, H. A., Seltzer, G. O., Porter, S. C., Mark, B., 2005. Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers. *Quaternary International,* 8(21), pp. 138-139.

Berger, A. & Loutre, M., 1991. Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews,* Volume 10, pp. 297-317.

Carr, S. J., 2001. A glaciological approach for the discrimination of Loch Lomond Stadial glacial landforms in the Brecon Beacons, South Wales. *Proceedings of the Geologists' Association,* Volume 112, pp. 253-261.

Carr, S. J. & Coleman, C. G., 2007. An improved technique for the reconstruction of former glacier mass-balance and dynamics. *Geomorphology,* Volume 92, pp. 76-90.

Carr, S. J., Lukas, S. & Mills, S. C., 2010. Glacier reconstruction and mass-balance modelling as a geomorphic and palaeoclimatic tool. *Earth Surface Processes and Landforms,* Volume 35, pp. 1103-1115.

Chueca, J. & Julián, A., 2004. Relationship between solar radiation and the development and morphology of small cirque glaciers (Maladeta mountain massif, Central Pyrenees, Spain). *Geografiska Annaler,* 86A(1), pp. 81-89.

Coleman, C. G. & Carr, S. J., 2008. Complex relationships between Younger Dryas glacial, periglacial and paraglacial landforms, Brecon Beacons, South Wales. *Proceedings of the Geologists' Association,* Volume 119, pp. 259-276.

Coleman, C. G., Carr, S. J. & Parker, A. G., 2009. Modelling topoclimatic controls on palaeoglaciers: implications for inferring palaeoclimate from geomorphic evidence. *Quaternary Science Reviews,* Volume 28, pp. 249-259.

Cronin, T. M., 2010. *Paleoclimates: Understanding Climate Change Past and Present.* New York: Colombia University Press.

Evans, I. S., 2006. Allometric development of glacial cirque form: Geological, relief and regional effects on the cirques of Wales. *Geomorphology,* Volume 80, pp. 245-266.

Gray, J. M., 1982. The last glaciers (Loch Lomond advance) in Snowdonia, N. Wales. *Geological Journal,* Volume 17, pp. 111-133.

Glen, J. W., 1952. Experiments on the deformation of ice. *Journal of Glaciology,* Volume 2, pp. 111-114.

Hopkinson, C., Chasmer, L., Munro, S. & Demuth, M. N., 2010. The influence of DEM resolution on simulated solar radiation-induced glacier melt. *Hydrological Processes,* Volume 24, pp. 775-788.

Hughes, P. D., 2002. Loch Lomond Stadial glaciers in the Aren and Arenig Mountains, North Wales, Great Britain. *Geological Journal,* Volume 37, pp. 9-15.

Hughes, P. D., 2009. Loch Lomond Stadial (Younger Dryas) glaciers and climate in Wales. *Geological Journal,* Volume 44, pp. 375-391.

Ince, J. J., 1983. Two postglacial pollen profiles from the uplands of Snowdonia, Gwynedd, North Wales,. *New Phytologist,* Volume 95, pp. 159-172.

IPCC Working Group I, 2013. *Climate Change 2013: The Physical Scence Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge: Cambridge University Press.

Kern, Z. & László, P., 2010. Size specific steady-state accumulation-area ratio: an improvement for equilibrium-line estimation of small palaeoglaciers. *Quaternary Science Reviews,* Volume 29, pp. 2781-2787.

Klapyta, P., 2013. Application of Schmidt Hammer relative age dating to Late Pleistocene moraines and rock glaciers in the Western Tatra Mountains, Slovakia. *Catena,* Volume 111, pp. 104-121.

Larsen, K. A., 1999. *The Late Devensian glacial history of Cadair Idris.* Unpublished MA thesis, University of St Andrews, 65pp.

López-Moreno, J. I., Noguéz-Bravo, D., Chueca-Cía, J. & Julián-Andrés, A., 2006. Glacier development and topographic context. *Earth Surface Processes and Landforms,* Volume 31, pp. 1585-1594.

Lowe, J. J. et al., 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. *Quaternary Science Reviews,* Volume 27, pp. 6-17.

Lowe, S., 1993. *The Devensian Lateglacial and Early Flandrian stratigraphy of southern Snowdonia, North Wales,* University of London: Unpublished PhD thesis.

Lukas, S. & Bradwell, T., 2010. Reconstruction of a Lateglacial (Younger Dryas) mountain ice field in Sutherland, northwestern Scotland, and its palaeoclimatic implications. *Journal of Quaternary Science,* Volume 25, pp. 567-580.

Matthews, J. A. & Shakesby, R. A., 1984. The status of the 'Little Ice Age' in southern Norway: relative-age dating of neoglacial moraines with Schmidt hammer and lichenometry. *Boreas,* Volume 13, pp. 333-346.

McDougall, D., 2013. Glaciaton style and the geomorphological record: evidence for Younger Dryas glaciers in the eastern Lake District, northwest England. *Quaternary Science Reviews,* Volume 73, pp. 48-58.

Met Office, 2014. *Capel Curig climate.* [Online]
Available at: http://www.metoffice.gov.uk/public/weather/climate/gcmnn3630
[Accessed 14. 12. 2014].

Met Office, 2014. *Gogerddan climate.* [Online]
Available at: http://www.metoffice.gov.uk/public/weather/climate/gcm4k8cnp
[Accessed 14. 12. 2014].

Mitchell, W. A., 1996. Significance of snowblow in the generation of Loch Lomond Stadial (Younger Dryas) glaciers in the western Pennines, northern England. *Journal of Quaternary Science,* 11(3), pp. 233-248.

Ohmura, A., Kasser, P. & Funk, M., 1992. Climate at the equilibrium line of glaciers. *Journal of Glaciology,* Volume 38, pp. 397-411.

Osipov, E. Y. & Khlystov, O. M., 2010. Glaciers and meltwater flux to Lake Baikal during the Last Glacial Maximum. *Palaeogeography, Palaeoclimatology, Palaeoecology,* Volume 294, pp. 4-15.

Osmaston, H., 2005. Estimates of glacier equilibrium line altitudes by the Area x Altitude, the Area x Altitude Balance Ratio and the Area x Altitude Balance Index methods and their validation. *Quaternary International,* Volume 138-139, pp. 22-31.

Paterson, W. S. B., 1994. *The Physics of Glaciers.* 3rd ed. Oxford: Pergamon.

Plummer, M. A. & Phillips, F. M., 2003. A 2-D numerical model of snow/ice energy balance and ice flow for palaeoclimatic interpretation of glacial geomorphic features. *Quaternary Science Reviews,* Volume 22, pp. 1389-1406.

Porter, S. C., 1975. Equilibrium line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand. *Quaternary Research,* Volume 5, pp. 27-47.

Rea, B. R., 2009. Defining modern day Area-Altitude Balance Ratios (AABRs) and their use in glacier-climate reconstructions. *Quaternary Science Reviews,* Volume 28, pp. 237-248.

Sahlin, E. A. & Glasser, N. F., 2008. A geomorphological map of Cadair Idris. *Journal of Maps,* pp. 299-314.

Schytt, V., 1967. A study of 'ablation gradient'. *Geografiska Annaler,* Volume 49A, pp. 327-332.

Shakesby, R. A. & Matthews, J. A., 1996. Glacial activity and paraglacial landsliding in the Devensian Lateglacial: evidence from Craig Cerrig-gleisiad and Fan Dringarth, Fforest Fawr (Brecon Beacons, South Wales). *Geological Journal,* Volume 31, pp. 143-157.

Shakesby, R. A., Matthews, J. A. & Owen, G., 2006. The Schmidt Hammer as a relative-age dating tool and its potential for calibrated-age dating in Holocene glaciated environments. *Quaternary Science Reviews,* Volume 25, pp. 2846-2867.

Sissons, J. B., 1974. A Late-Glacial Ice Cap in the Central Grampians, Scotland. *Transactions of the Institute of British Geographers,* Volume 62, pp. 95-114.

Sissons, J. B., 1980. The Loch Lomond Advance in the Lake District, northern England. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 71(1), pp. 13-27.

Trelea-Newton, M. & Golledge, N. R., 2012. The Younger Dryas glaciation in the southeastern Monadhliath Mountains, Scotland: glacier reconstruction and palaeoclimatic implications. *BOREAS: An international journal of Quaternary research,* Volume 41, pp. 614-628.

Walker, M. J. C., Coope, G. R., Sheldrick, C., Turney, C. S. M., Lowe, J. J., Blockely, S. P. E., Harkness, D. D., 2003. Devensian Lateglacial environmental changes in Britain: a multi-proxy environmental record from Llanilid, South Wales, UK. *Qauternary Science Reviews,* Volume 22, pp. 475-520.