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Spatial Analysis of Cirques from Three Regions of Iceland: Implications for Cirque Formation and Palaeoclimate

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Abstract

This study is a quantitative analysis of cirques in three regions of Iceland: Tröllaskagi, the East Fjords and Vestfirðir. Using Google Earth and the National Land Survey of Iceland Map Viewer, we identified 347 new cirques on Tröllaskagi and the East Fjords region, and combined these data with 100 cirques previously identified on Vestfirðir. We used ArcGIS to measure length, width, aspect, latitude and distance to coastline of each cirque. Palaeo-equilibrium-line altitudes (palaeo-ELAs) of palaeo-cirque glaciers were calculated using the altitude-ratio method, cirque-floor method and minimum-point method. The mean palaeo-ELA values in Tröllaskagi, the East Fjords and Vestfirðir are 788, 643 and 408 m a.s.l, respectively. Interpolation maps of palaeo-ELAs demonstrate a positive relationship between palaeo-ELA and distance to coastline. A positive relationship between palaeo-ELA and latitude is observed on Vestfirðir, a negative relationship is observed on Tröllaskagi and no statistically significant relationship is present on the East Fjords. The modal orientation of cirques on Tröllaskagi and Vestfirðir is northeast, while orientation of cirques in the East Fjords is north. Palaeo-wind reconstructions for the LGM show that modal aspect is aligned with the prevailing north-northeast wind directions, although aspect measurements demonstrate wide dispersion. Cirque length is similar on Tröllaskagi and the East Fjords, but cirques are approximately 200 m shorter in Vestfirðir. Cirque widths are similar in all three regions. Comparisons with a global data set show that cirques in Iceland are smaller and more circular than cirques in other regions of the world. Similar to glaciers in Norway and Kamchatka, our results demonstrate that access to a moisture source is a key parameter in determining palaeo-ELAs in Iceland. Temperatures interpreted from palaeo-ELA depressions suggest that these cirques may have been glaciated as recently as the Little Ice Age.

Keywords

Cirques, Iceland, climate record, glaciers, ice caps

Disciplines

Climate | Environmental Sciences | Environmental Studies

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Spatial analysis of cirques from three regions of Iceland: Implications for cirque formation and palaeoclimate

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Cirques are a common glacial erosive landform present in alpine regions. They are bowl-shaped depressions with a steep headwall and a gently sloping floor, created by an isolated, rotationally flowing glacier, and they periodically contain small climate-sensitive glaciers (e.g. Evans & Cox 1974; Porter 2001; Brook *et al*. 2006). The morphology, location, and aspect of ice-free cirques provide evidence of past glaciations and fluctuations in climate (e.g. Evans 1977; Meierding 1982; Evans 2006; Anders *et al*. 2010; Barr & Spagnolo 2013; 2015a,b). Quantifying cirque morphology provides information about the distribution of cirques and processes impacting cirque formation (Evans 2006; Barr & Spagnolo 2013; 2015a,b). Palaeoclimate records are commonly interpreted from cirque equilibrium line altitudes (ELAs), the elevation at which annual accumulation of snow equals annual ablation (e.g. Meierding 1982; Benn & Lehmkuhl 2000; Porter 2001). Reconstructing palaeo-ELAs is useful for palaeoclimate research because they are determined by changes in temperature and precipitation that affect the mass balance of glaciers over time (e.g. Garcia-Ruiz *et al.* 2000; Brook *et al.* 2006; Benn & Evans 2010; Bathrellos *et al.* 2014).

Synthesizing global datasets of cirques is useful for understanding morphometric parameters and the utility of cirques as palaeoenvironmental indicators. Barr & Spagnolo (2015a) provide an in-depth analysis of cirque properties including global distribution, aspect, palaeo-ELAs and morphometry. Mitchell & Humphries (2015) provide a comprehensive analysis of ice-free cirques from 56 different study areas from around the world. They quantify the altitude and relief of more than 14,000 cirques in order to demonstrate the relationship of cirque glaciation to mountain height (Mitchell & Humphries 2015).

The purpose of our study is to add to these global datasets by providing a regional analysis of ice-free cirques from three regions of Iceland. We conduct a quantitative analysis of cirques and palaeo-ELAs in Tröllaskagi, the East Fjords, and Vestfirðir (Fig. 1). We build upon morphometric analyses of cirque glaciers on Vestfirðir by Principato & Lee (2014) and expand our analyses to include Tröllaskagi and the East Fjords region in order to create a regional comparison of cirques on Iceland. We focus our cirque analyses on morphology and palaeo-ELA reconstructions of palaeo-cirque glaciers and compare our results from Iceland to a global dataset compiled by Barr & Spagnolo (2015a). It is generally accepted that ELA rises from the poles to the equator, although this relationship may be complicated at times by differential precipitation patterns (Benn & Evans 2010). Wind and radiation often combine to complicate the relationship between morphologic parameters and aspect (Evans 1977). Studies in Romania suggest that cirques generally have an aspect opposite the prevailing wind direction because glaciers tend to form on the leeward side of mountain ranges, where accumulation is greater (Mîndrescu *et al.* 2010). Evans (1977) suggests that glaciers generally form in shaded regions and with poleward aspects because there is a higher potential solar radiation on south-facing slopes in mid- to high-latitude regions. Radiation received increases with the steepness of slope angle relative to the position of the sun in a given area, although this relationship can also be affected by local weather (Evans 1977; Barr & Spagnolo 2013). Previous studies show that distance to moisture sources and proximity to the ocean influences the elevation of palaeo-ELAs (e.g. Benn & Evans 2010 Principato & Lee 2014; Barr & Spagnolo 2015a,b).

Study area

Iceland is located on the Mid-Atlantic Ridge and is composed primarily of basaltic volcanic rocks (Einarsson & Albertsson 1988). The bedrock in all three regions of our study, Tröllaskagi, the East Fjords, and Vestfirðir, is upper Tertiary basalt (Sigmundsson & Sæmundsson 2008). The oldest bedrock, located in east and west Iceland, is approximately 14 - 15 Ma, and bedrock in the north is approximately 12 Ma (Sigmundsson & Sæmundsson 2008). All three regions are located outside the active rift zone in central-eastern Iceland, and volcanic activity does not influence cirque glacier dynamics in these areas (Rubin 1990).

The climate in Iceland is cold-temperate and maritime, owing to its location in the path of the North Atlantic and the high-altitude westerly jet streams (Eiríksson & Geirsdóttir 1991). The Irminger Current (IC), the East Greenland Current (EGC), and the East Iceland Current (EIC) affect glaciers on Iceland (Fig. 2; Hopkins 1991; Ingolfsson *et al.* 1997; Stötter *et al.* 1999; Valdimarsson & Malmberg 1999; Principato 2008). The IC is a warm branch (> 5-8 °C) of the North-Atlantic Current (NAC) that flows north from latitudes south of Iceland (Hopkins 1991; Valdimarsson & Malmberg 1999). This current meets the cold EGC (< 0°-2 °C) near the Greenland-Iceland Ridge, where it splits. One branch flows around the northwest peninsula of Iceland and eastward off the northern coast. A coastal current also runs clockwise around Iceland (Hopkins 1991; Valdimarsson & Malmberg 1999; Andresen *et al*. 2005). The movement of the polar front, which represents the zone between the ECG and the IC, causes changes in glacial ice extent on Iceland (e.g. Malmberg 1985; Justwan *et al*. 2008). The polar front also creates a climate gradient across Iceland from the colder northern areas to the warmer southern areas (e.g. Stefannson 1969; Geirstdóttir *et al.* 2009). Glaciation on Iceland presumably began in the Miocene and follows a glacial-interglacial cycle of about 100,000-years periodicity (Geirsdóttir

& Eiríksson 1994). Wastl *et al.* (2001) suggest that cirque glaciers on Tröllaskagi retreated from and reoccupied their cirques many times throughout Holocene. Modern glaciers are present in some cirques on Tröllaskagi, and surging behaviour has been studied by Brynjólfsson *et al.* (2012). Cirque glaciers on Vestfirðir most likely experienced similar retreat and reoccupation throughout the Pleistocene (Principato & Lee 2014), but active glaciers do not currently occupy the cirques on Vestfirðir or in the East Fjords region.

Current precipitation and temperature on Iceland are recorded by the Icelandic Meteorological Office (http://en.vedur.is/). Three weather stations on Vestfirðir and two weather stations on Tröllaskagi have continuous records from 2000 – 2011 (Table 1). The most recent continuous records from the East Fjords are from 1990 – 2001, which are recorded at three stations (Table 1). Using the methods of Dahl & Nesje (1996), Bakke *et al.* (2005) and Paasche *et al.* (2007) from studies in Norway, seasonal variations were also calculated using 1 May to 30 September for summer temperature and 1st October to 30th April for winter precipitation (Table 1). Mean annual temperature for all eight stations is similar, and variations in precipitation are observed as distance from coastline increases. Within each of the three regions, the stations closest to the coastline have the highest mean annual precipitation and higher winter precipitation compared to stations further from the coastline. Winds are stronger in the winter than summer, due to decreased insolation and heating (Einarsson 1984; Blöndal *et al.* 2011; Nawri *et al.* 2012). The dome shape of Iceland's topography generates higher wind speeds over the interior highlands, with the west and east regions of Iceland experiencing the lowest wind speeds due to sheltering (Nawri *et al.* 2012).

Methods

Locating cirques

Cirques on Vestfirðir were identified and mapped by Principato & Lee (2014) using a combination of Google Earth and satellite imagery provided by the online map viewer of the National Land Survey of Iceland (NLSI) (http://atlas.lmi.is/kortasja_en/). We significantly expanded the cirque dataset for Iceland by also identifying and mapping cirques on the East Fjords and Tröllaskagi using the same methods. For all three regions, after identifying a cirque by its characteristic bowl shape in Google Earth, we imported these locations to ArcGIS. We overlaid the cirques on a 20 m digital elevation model of Iceland provided by the NLSI. Although modern cirque glaciers are also present on Iceland, we were unable to quantify subglacial bedrock topography so only ice-free cirques are used in our study.

Morphometric analyses

Morphometric characteristics for cirques on the East Fjords and Tröllaskagi, including length, width, altitudinal range, size, area, cirque-floor elevation, latitude, and distance to both the open ocean and fjord coastlines, were quantified using ArcGIS to supplement measurements made by Principato & Lee (2014) for Vestfirðir. Cirque boundaries were defined by polygons drawn manually around each landform (Fig. 3). The location of each cirque was taken as the point in the center of the cirque-floor (Bathrellos *et al.* 2014). Cirque length (L) is the length of the line dividing each cirque into two equal parts (i.e. the long axis), which connects the headwall to the toewall. Cirque width (W) is the longest line drawn orthogonal to the long axis. Altitudinal range (H), or cirque relief, is the minimum altitude in the cirque minus the maximum altitude (Barr & Spagnolo 2013). The minimum altitude was generally at the same elevation as the cirque-floor, while the maximum altitude fell along the headwall of the cirque. From these measurements, we also determined cirque size using the equation defined by Barr & Spagnolo (2013): $(L \times W \times H)^{1/3}$. Ratios of L/H, W/H, and L/W were also quantified. The L/H ratio expresses a measure of cirque steepness, where a lower value indicates a greater rate of change in elevation (Porter 2001). L/W ratio defines cirque elongation, and a high value represents a long cirque and a low value represents a wide cirque. The W/H ratio is a measure of cirque incision, and a higher value indicates less incision.

Following the methods of Principato & Lee (2014), we measured coastal distances on Tröllaskagi and the East Fjords using the minimum distance between each cirque and the coastline in ArcGIS. The closest coastline to a given cirque could be either a fjord or the open ocean, depending on its location. We drew a polygon along the coast of each study area in ArcGIS to represent the boundary between land and the open ocean. This polygon helped us to differentiate the influence of the open ocean and the impact of fjord proximity. Spatial relationships between distance to the coastline and palaeo-ELAs were quantified using the Inverse Distance Weighting (IDW) tool in ArcGIS.

Palaeo-ELA calculations

We used three techniques to reconstruct palaeo-ELAs for Tröllaskagi and the East Fjords: the cirque-floor (CF) method, the altitude-ratio (THAR) method (summarized in Porter 2001), and the minimum-point (MP) technique (summarized in Barr & Spagnolo 2015b). Principato & Lee (2014) calculated palaeo-ELAs for Vestfirðir using the THAR and CF methods. Although some studies recommend using the glaciation limit instead of palaeo-ELA (e.g. Østrem 1966; Andrews

1975), we chose to use palaeo-ELA to be consistent with the methods of Principato & Lee (2014).

Cirque-floor altitude represents a useful proxy for palaeo-ELAs because when cirques are occupied by glaciers confined within their limits, the steady-state ELA is generally close to the average altitude of the cirque floor (Porter 2001). We used ArcGIS to determine the elevation of cirque floors on Iceland. We created a raster file based on the first derivative of the topography to determine the slope surface of the study area. Using the methods of Principato & Lee (2014), three lines were manually drawn over each cirque: one along central axis of the cirque, and two lines to the right and left, equidistant from the central axis. Profile graphs of each line were generated by ArcGIS to identify the headwall, toewall, and cirque floor (Fig. 3). The headwall is the point of greatest elevation of the cirque, and the toewall is the second highest well-defined peak (Fig. 3). The cirque floor is interpreted as the lowest point between the headwall and toewall. We exported elevation data to Microsoft Excel to calculate the average elevation of the cirque floors along the three profile lines and used this value as the cirque-floor altitude. The median and minimum points along each line and their averages were also calculated to identify outliers or a skew in the data. Following the methods of Principato & Lee (2014), cirques that did not have easily identifiable headwalls and toewalls were omitted from palaeo-ELA analyses, as it is likely that these cirques experienced periglacial processes or mass movement resulting in postglacial modification (Beylich 2000; Decaulne & Sæmundsson 2006; Sanders *et al.* 2010). For this reason, we chose not to use the cirque floor altitude as the absolute minimum altitude of each cirque (e.g. Spagnolo *et al*. 2017).

The THAR method is a second useful way to evaluate palaeo-ELAs because the firn limit on temperate glaciers at the end of the ablation season has been observed vertically approximately midway between the head of a glacier and its lower limit when looking at its cross-section (Meierding 1982; Porter 2001). Glaciers with THAR values between 0.35-0.4 generated the most accurate results relative to actual ELA for glaciers in mid to high latitudes (Meierding 1982), and the ratio between the altitudinal range (H) of a glacier above the equilibrium line and the total altitudinal range is assumed to be 0.4 for this study. To calculate palaeo-ELAs, we used the equation summarized by Porter (2001): $\text{ELA} = A_t + \text{THAR}\ (A_h - A_t)$, where A_h is the mean headwall altitude, and A_t is the mean toewall altitude for each cirque. We calculated average headwall and toewall elevations for each cirque based on the values determined from the CF technique above.

For cirques on Tröllaskagi and the East Fjords where the toewall was difficult to identify from the DEM and slope surface, we used the MP technique (Barr & Spagnolo 2015b). Toewall locations were determined by a peak in elevation at the outlet of a cirque, also known as the cirque threshold (Barr & Spagnolo 2015b). We drew a polygon based on inflection points from a 20 m contour layer created from the DEM in ArcGIS. The polygons represent the boundary of each cirque landform area, providing useful morphometric information for these additional cirques (Fig. 3). We used the minimum elevation within the polygon shape as the palaeo-ELA for the MP technique.

Cirque aspect

Aspect was measured on cirques with profile lines used to calculate CF and THAR palaeo-ELAs, following the methods of Platt (2014). We excluded cirques analyzed using the MP technique from our analyses of aspect because it is not possible to quantify aspect without the profile lines in ArcGIS. We created an aspect raster from the DEM and converted it from degrees to radians.

Cosine and sine rasters were created from this raster, and the zonal means of the cosine and sine rasters along each cirque's profile lines were calculated and exported to Microsoft Excel. The average aspect for each cirque was calculated using the arctan2 function. The average aspect for each cirque was plotted on a linear histogram. To calculate the mean direction of all cirques for each of the three study areas, we used the methods of Davis (1986). Mean resultant length was calculated to measure the dispersion of aspect (Davis 1986). Rayleigh's test was used to determine whether or not the data were randomly or non-randomly distributed (Evans 1977). We converted all of the aspect measurements to northness before running regression analyses. Northness represents a continuous north-south gradient with values ranging from 1 for north-facing slopes and -1 for south-facing slopes (Platt 2014). Unlike aspect, which is a circular measure, northness may be used directly in linear regression.

Statistical analyses

We completed statistical analyses in Microsoft Excel, VassarStats (http://vassarstats.net/), and SPSS Statistics version 22. Linear regression analyses determine relationships between cirque length, width, altitudinal range, their ratios, palaeo-ELAs, distance to ocean and coast, aspect, and latitude, using the correlation and regression tools. T-tests were completed using SPSS in order to determine which morphometric characteristics have the most statistically significant relationship to palaeo-ELA in each study area. Statistical analyses of aspect discussed above were calculated in either Microsoft Excel or manually using the methods of Davis (1986).

Results

Landform locations

We identified 347 new cirques on Tröllaskagi (186 cirques) and the East Fjords region (161 cirques), and combined these new data with 100 cirques previously identified on Vestfirðir by Principato & Lee (2014) (Table S1). The East Fjords has the highest density of cirques, followed by Tröllaskagi and Vestfirðir. The majority of cirques in Vestfirðir and the East Fjords are evenly spread throughout the study area, but are concentrated closest to the coastline. In Tröllaskagi, cirques are spread uniformly into the interior (Fig. 4). The range of latitude for each of the three study areas is small but is largest for the East Fjords region at 0.9 degrees latitude (Table 2). The median latitude of cirques on Vestfirðir and Tröllaskagi is 65.9° N, and cirques on the East Fjords have a median latitude of 65.1° N.

Palaeo-ELA calculations and morphometric analyses

Palaeo-ELAs are highest in Tröllaskagi, and lowest in Vestfirðir. In Tröllaskagi, mean palaeo-ELA of cirques is 788 ± 188 m using the THAR method, 760±190 m using the CF method, and 697±208 m using the MP method. Cirques in the East Fjords region have palaeo-ELAs of 643±180 m using the THAR method, 590±184 m using the CF method, and 531±177 m using the MP method. Mean palaeo-ELA of Vestfirðir cirques is 423±12 m using the THAR method, and 395±14 m using the CF method (Principato and Lee, 2014) (Table 2). In all three regions, cirques closer to the coastline have lower palaeo-ELAs compared to cirques further inland (Fig. 5). Error values represent one standard deviation for each measurement.

Cirques are longest in the East Fjords (mean length of 706 m) compared to Vestfirðir and Tröllaskagi, but they are widest in Vestfirðir (mean width of 752 m). In Tröllaskagi and the East Fjords, cirques are rounder and have larger areas than in Vestfirðir. Cirques in Tröllaskagi are also generally located further from both fjord coastlines and the open ocean on average compared to the other two study areas (Fig. 6; Table 2).

At least 45 statistically significant relationships exist for each morphometric parameter measured in the overall dataset (Table 3). Aspect and area have the fewest number of significant relationships with other morphometric characteristics of cirques on Iceland (Table 3). A strong positive correlation exists between palaeo-ELA and a cirque's distance to a water source (e.g. open ocean or fjord coastlines) in all three study areas ($R = 0.69$ for East Fjords; $R = 0.62$ for Vestfirðir; $R = 0.75$ for Tröllaskagi; $p < 0.01$) (Fig. 7). Statistically significant correlations ($p < 0.01$) also exist between palaeo-ELA and latitude on Tröllaskagi ($R = -0.77$) and Vestfirðir ($R = 0.35$), but no statistically significant correlation is observed on the East Fjords ($R = 0.10$; $p < 0.01$) (Fig. 8).

Cirque aspect

The modal aspect of the cirques on Tröllaskagi and Vestfirðir is northeast, with mean directions of 71° and 75° respectively (Fig. 9). Rayleigh's test indicates that the northeast distribution of cirques is not random for either Tröllaskagi ($n = 186$, $z = 16.65$, $p < 0.05$) or Vestfirðir ($n = 101$, $z = 24.4$, $p < 0.001$). The modal aspect of cirques in the East Fjords is north with a mean direction of 51°, and it is also non-randomly distributed ($n = 103$, $z = 25.4$, $p < 0.001$) (Fig. 9). All three regions have low values (≤ 0.10) for mean resultant length of aspect showing that there is a large amount of dispersion (Davis, 1986) (Fig. 9). Based on reconstructions of global winds during the Last Glacial Maximum (LGM) by Bush & Philander (1999), the modal aspects of cirques on Iceland have the same orientation as prevailing winds on the island at that time. Present day winds are weaker, but are also generally in the north-northeast direction (Bush &

Philander 1999). It is not known whether cirques were submerged during the LGM or not, and the consistency of prevailing wind patterns from the LGM through present likely influenced cirque glacier formation.

Global comparison

L, W, H, and L/W ratios for cirques on Iceland differ from those studied in other parts of the world (Table 4). A single sample t-test shows that size parameters of Icelandic cirques overall are significantly different from the average L, W, and H values recorded for cirque studies globally. However, cirques in Iceland are within one standard deviation of the median of L, W, H, and L/W ratios from the global dataset. The L/W ratio for Iceland is close to 1, suggesting that cirques in Iceland are rounder than cirques in other areas around the world. Cirques in Spain (Garcia-Ruiz *et al.* 2000) and Antarctica (Aniya & Welch 1981) are more elongate than the rest of the global dataset. Most cirques in the northern hemisphere have a north or northeast aspect, similar to cirques in Iceland (Table 4). In a direct comparison with cirques studied in Kamchatka, Russia by Barr & Spagnolo (2013; 2015b), ratios between L, W, and H in Iceland exhibit similar patterns.

Discussion

Morphometric analyses and palaeo-ELA correlations

The strong positive, linear relationship between palaeo-ELA and distance to the open ocean in Vestfirðir, Tröllaskagi, and the East Fjords suggests that access to a moisture source is critical to cirque glacier survival in Iceland. Distance to coastline and latitude are related for cirques on Tröllaskagi, more directly than in Vestfirðir and the East Fjords. On Tröllaskagi, higher latitude locations are also closer to the coastline, and both correspond to lower cirque palaeo-ELAs. The opposite is true for cirques on Vestfirðir. The East Fjords region exhibits no significant relationship between cirque palaeo-ELA and latitude, but it has the largest range of latitude compared to our other two study areas. Analyses of cirques on the East Fjords illustrate the importance of distance to coastline in determining palaeo-ELA because cirques in the southern latitudes of the region are located at similar distances from the coastline as those at northern latitudes. The cirques closest to the coastline in the East Fjords have lower palaeo-ELAs regardless of their latitude. The variation in relationships between palaeo-ELA and latitude in our three study areas suggests that latitude is not as important in determining palaeo-ELA as is distance to a moisture source in Iceland. Modern weather station data (Table 1) shows that precipitation is higher closer to the coastline compared to further inland. This finding is similar to decades of measurements of ELAs on modern glaciers in Norway, which also demonstrate that glaciers closer to the coastline have lower ELAs (e.g. Chorlton & Lister 1971; Whalley 2004).

Although distance to coastline has a large influence on palaeo-ELA, it is not strongly related to the size and shape of cirques. Other studies have suggested that location may not be as important in determining cirque morphometric characteristics as are other localized factors (e.g. Evans 2006; Barr & Spagnolo 2015a). Wind direction and local weather conditions, which vary between different regions of Iceland, may play a larger role than other processes in dictating cirque size and shape (Porter 2001; Federichi & Spagnolo 2004; Barr & Spagnolo 2015a). Statistically significant relationships observed between cirque characteristics such as L, W, H, size, and area are easily explained by the fact that length and width determine size and area by definition.

Palaeo-ELAs are highest in Tröllaskagi, lower in the East Fjords, and lowest in Vestfirðir. Cirques in the East Fjords are roundest, followed by those on Tröllaskagi and Vestfirðir. Although the bedrock lithology is similar in these three regions, regional differences in temperature, wind, and precipitation likely contribute to variations in cirque morphology (Federici & Spagnolo 2004; Benn & Evans 2010; Barr & Spagnolo 2015a). The differences in average palaeo-ELA could be attributed to coastline shapes in the three regions of study. Both Vestfirðir and the East Fjords have winding coastlines, and most of the landmass within the bounds of our study areas is close to the ocean. Tröllaskagi's coastline is smoother than that of Vestfirðir and the East Fjords, so cirques are less likely to be in close proximity to the ocean or fjord coastline (Fig. 1). Tröllaskagi is also dryer, cooler, and windier than Vestfirðir and the East Fjords, and it is not as strongly influenced by the warm temperatures of the Irminger Current. Cirques in Tröllaskagi may receive less snow accumulation due to wind removal compared to other regions of Iceland because of higher observed wind speeds (Evans 2006).

Cirques in Iceland are round and shallow. Deepening of cirques is considered to be primarily governed by sub-glacial erosion (Benn & Evans 2010), and horizontal dimensions of cirques are thought to be dictated by freeze–thaw processes, glacial erosion, and bedrock geology (Sanders *et al.* 2012). The specific shape and size of cirques on Iceland are likely a result of the bedrock lithology and structure. As suggested by Principato & Lee (2014), due to lithological weaknesses, the Upper Tertiary flood basalts of Iceland are easier to erode horizontally as opposed to vertically for cirque formation on Vestfirðir, Tröllaskagi and the East Fjords (Einarsson 1973; Kristjánsson & Jóhannesson 1994; Hardarson *et al.* 1997).

Cirque aspect

The majority of cirques in Iceland have a north-northeast aspect, similar to global analyses of cirques in the northern hemisphere (e.g. Aniya & Welch 1981; Evans & Cox 1995; Brook *et al*. 2006; Barr & Spagnolo 2015a). However, the prevailing wind direction across Iceland is in the same direction as modal cirque aspect, rather than opposite, as suggested by Mîndrescu *et al.* (2010). Although modal aspect is north-northeast, each compass direction is represented in our three regions of study (Fig. 9). The large dispersion in the aspect of cirques in Iceland suggests that the direction that cirques face is the result of a combination of many climate processes acting differently upon each cirque over time (Evans 1977, 2006).

Aspect is not significantly correlated with morphometric characteristics of cirques in Iceland. Although some studies (e.g. Aniya & Welch 1981) show that cirque glaciers with north-northeast aspect are larger, cirques in our study did not follow this pattern. Others have suggested that wind speed and snow accumulation may also dictate ELA and glaciation limits for cirques (e.g. Purves *et al.* 1999). However, our data are based on unglaciated cirques and we were unable to quantify glaciation limits or snow accumulation levels. Our results indicate that aspect is not as important as other factors in determining the morphometric features of each cirque. In support of this conclusion, other studies have found that local variations in snow accumulation, solar radiation, and/or preexisting morphological characteristics of cirque sites play a larger role in cirque formation than aspect (Evans & Cox 1995; Federici & Spagnolo 2004; Bathrellos *et al.* 2014).

Regional and global comparison

The palaeo-ELAs calculated for this study on Tröllaskagi are approximately 200 m lower than ELAs of 48 modern cirque glaciers measured by Caseldine & Stotter in the same region (1993).

At least a few glaciers on Tröllaskagi, such as Búrfellsjökull and Teigarjökull, are surging glaciers (Brynjólfsson *et al.* 2012), which may complicate palaeo-ELA interpretations. Modern cirque glaciers are not present on either Vestfirðir or the East Fjords region of this study, and a direct ELA comparison between modern cirque glaciers and glacier free cirques is not possible. However, Drangajökull, the modern icecap on eastern Vestfirðir, has an ELA of approximately 550-660 m a.s.l. (Björnsson 1979; Principato 2008). If this modern ELA is used as a frame of reference for cirque glaciers on Vestfirðir, then the region has experienced 127 – 237 m rise in ELA since these cirques were glaciated. Using a lapse rate of -6 °C km^{-1} following the methods of Bakke *et al*. (2005) & Paasche *et al*. (2007), a 200 m change in ELA is interpreted as a 1.2 °C change in temperature. Based on weather station data collected from 1871 – 2000, a warming of ~ 0.7 – 1.6 °C is observed (Hanna *et al.* 2004), which suggests that several of the cirques in this study were glaciated as recently as the Little Ice Age.

Compared with a compilation of global cirque data by Barr & Spagnolo (2015a), cirques in Iceland are somewhat distinctive (Table 4). In terms of geographic location, we expect Icelandic cirques to be comparable in shape and size to those at similar latitudes. There are similarities with other cirque populations globally, since most average values for the parameters measured in other studies are within one standard deviation of mean values for Iceland. The standard deviations of morphometric measurements of cirques in this study are quite large however, suggesting that cirques in Iceland are very diverse in shape and size. Average measurements hide some of the localized differences in our study compared to others. Iceland experiences variability in changes in ocean currents and climatic conditions, with potential for different regional responses that may lead to variations in cirque morphology (e.g. Hopkins 1991; Ingolfsson *et al.* 1997; Valdimarsson & Malmberg 1999; Andresen *et al.* 2005).

The similarly strong correlations between palaeo-ELA and access to a moisture source in Iceland and Kamchatka, Russia are likely a result of comparable site characteristics (Barr & Spagnolo 2013, 2015b). Kamchatka and Iceland are both strongly influenced by ocean currents (Valdimarsson & Malmberg 1999; Barr & Spagnolo 2013, 2015b), and both are located near volcanic zones, which could potentially influence bedrock structure and lithology in similar ways (Bernal *et al.* 2014). The bedrock in Kamchatka is dominated by Quaternary and Miocene–Pliocene volcanic complexes (Persits *et al.* 1997; Avdeiko *et al.* 2007; Barr & Spagnolo 2015b), which would presumably exhibit characteristics similar to the Upper Tertiary basalts in Iceland. However, cirques in Iceland are much more circular and smaller than those on Kamchatka, Russia. The presence of valley glaciation and ice caps on Iceland throughout the Pleistocene may have focused erosion further down valley away from cirques, leading to smaller cirques on Iceland than on Kamchatka.

Barr & Spagnolo (2013, 2015b) suggest that there is little evidence for geological control on cirque characteristics in Kamchatka. They conclude that the intensity of freeze–thaw cycles and/or glacial erosion resulted in the large and deep cirques found in their study area (Barr & Spagnolo 2013, 2015b). Glacial erosion patterns in Iceland during the LGM have not been thoroughly studied or recorded with the exception of a study conducted by Principato & Johnson (2009). However, ice streams and ice divides for the Icelandic ice sheet have been suggested (e.g. Bourgeois *et al*. 1998; Hubbard *et al.* 2006; Principato *et al.* 2006, 2016; Patton *et al.* 2017). Past analyses of marine sediment cores and seismic activity specify that the outer margins of the Icelandic ice sheet were offshore around much of the island during the LGM, unlike in Russia (e.g. Syvitski *et al.* 1999; Geirsdóttir *et al.* 2002; Principato *et al.* 2006). Consequently, variation in cirque dimensions between Iceland and Kamchatka may be partly related to the differences in levels of intensity of erosion and climatic cycles throughout the Pleistocene and Holocene.

Conclusions

We provide detailed morphometric analyses and palaeo-ELA reconstructions of cirques in three regions of Iceland: Vestfirðir, Tröllaskagi, and the East Fjords, and build on the findings of Principato & Lee (2014). In the East Fjords region, cirques are more circular and larger than cirques in Vestfirðir and Tröllaskagi. Compared to other cirques globally, cirques in Iceland are rounder and smaller. The round shape is likely due to the structure of the basalt flows and the ease of lateral erosion. Modal cirque aspect in Iceland is north/northeast, aligned with prevailing wind direction during the LGM. The modal aspect and vector mean of cirques in Iceland match the aspect of most northern hemisphere cirques, and the wide dispersion of cirque aspect in Iceland is likely due to local weather anomalies.

Relationships between latitude and palaeo-ELA differ for all three regions with a positive relationship on Vestfirðir, a negative relationship on Tröllaskagi, and no relationship in the East Fjords. Our results suggest that the most important factor in determining past ELAs is access to a moisture source because cirques closest to the open ocean in all three regions have the lowest palaeo-ELAs. Temperatures interpreted from palaeo-ELA depressions suggest that these cirques may have been glaciated as recently as the Little Ice Age, which is consistent with previous studies.

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List of Figures

1. Location of the study area on Vestfirðir (V), Tröllaskagi (T), and East Fjords (E) in Iceland.

2. Surface ocean currents in the North Atlantic Ocean surrounding Iceland: North Atlantic Current (NAC), Irminger Current (IC), East Icelandic Current (EIC), and East Greenland Current (EGC) (modified from Justwan *et al.* 2008).

3. A. Slope of DEM of cirque from the East Fjords with three profile lines used for analysis. B. Profile from central axis of cirque illustrating easily identifiable headwall, cirque-floor, and toewall based on changes in slope. C. Photograph of a cirque from the west fjords. D. Polygon of a cirque used to calculate the minimum elevation of the cirque floor using the MP technique. Contour lines have a 20m interval.

4. Location of cirques from all three study areas on Vestfirðir (V), East Fjords (E), and Tröllaskagi (T). Each cirque is denoted by a red dot on the map.

5. Interpolation surface on Vestfirðir (V), East Fjords (E), and Tröllaskagi (T) created using Inverse Distance Weighting (IDW) in ArcGIS. The pattern demonstrates that cirques with low ELAs are located close to the ocean and cirques with higher ELAs are further from the ocean.

6. Average morphometric shape of cirques illustrating the difference in area (shaded polygon), length (solid line), and width (dashed line) of cirques from Vestfirðir (V), East Fjords (E), and Tröllaskagi (T).

7. Distance to coastline versus palaeo-ELA of cirque glaciers reconstructed using the THAR method for Vestfirðir, Tröllaskagi, and the East Fjords.

8. Latitude versus palaeo-ELA of cirques on Vestfirðir, Tröllaskagi, and the East Fjords reconstructed using the THAR method.

9. Linear histograms of aspect data for the three study regions Vestfirðir (A), Tröllaskagi (B) and East Fjords (C). Mean direction of aspect for each study area (VM) and mean resultant length or dispersion (RL) are calculated using the methods of Davis (1986).

List of Tables

Table 1. Mean annual temperature (MAT), mean annual precipitation (MAP), summer temperature (Summer T), winter precipitation (Winter P), and distance to ocean (km) collected from weather stations in Vestfirðir, Tröllaskagi, and the East Fjords. Temperature and precipitation data are provided by the Icelandic Meteorological Office.

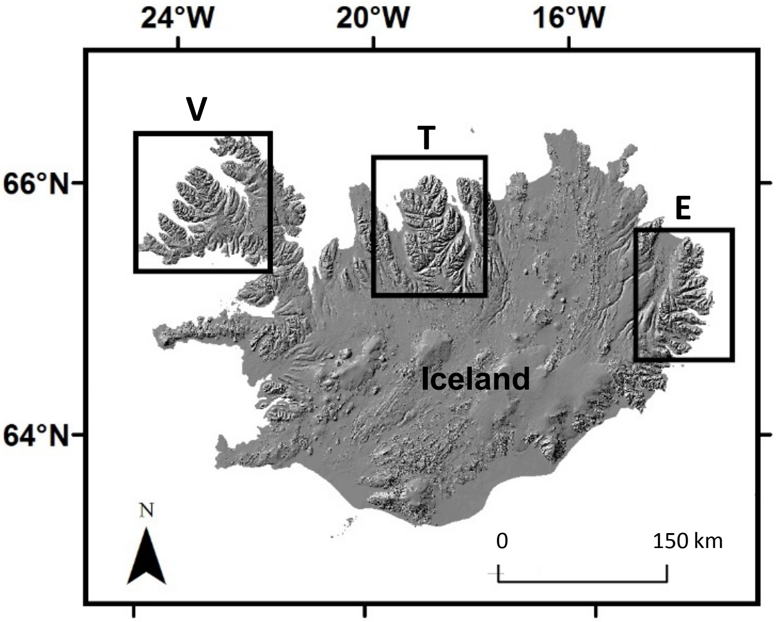
Table 2. Comparison of morphometric parameters across all datasets. Values specify means for each study area.

Table 3. Correlation coefficients for relationships between each morphometric parameter measured in this study. One star indicates significance at p = 0.05 ; two stars indicates significance at p = 0.01.

Table 4. Global comparison of cirque morphometry.

Supporting Information

Table S1. Latitude and longitude of all cirques used in this study. DD refers to decimal degrees.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64°N
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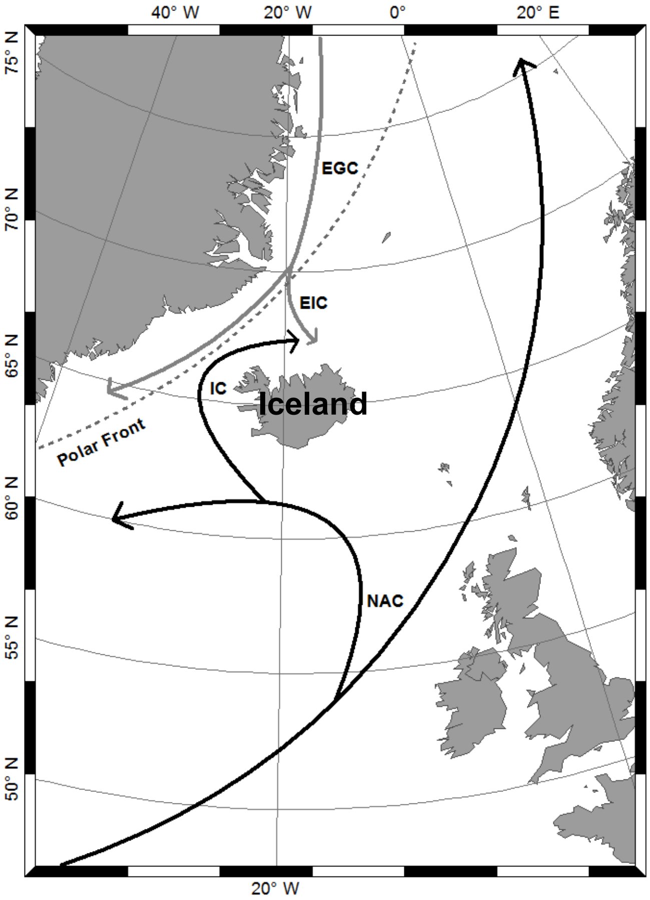
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20° W
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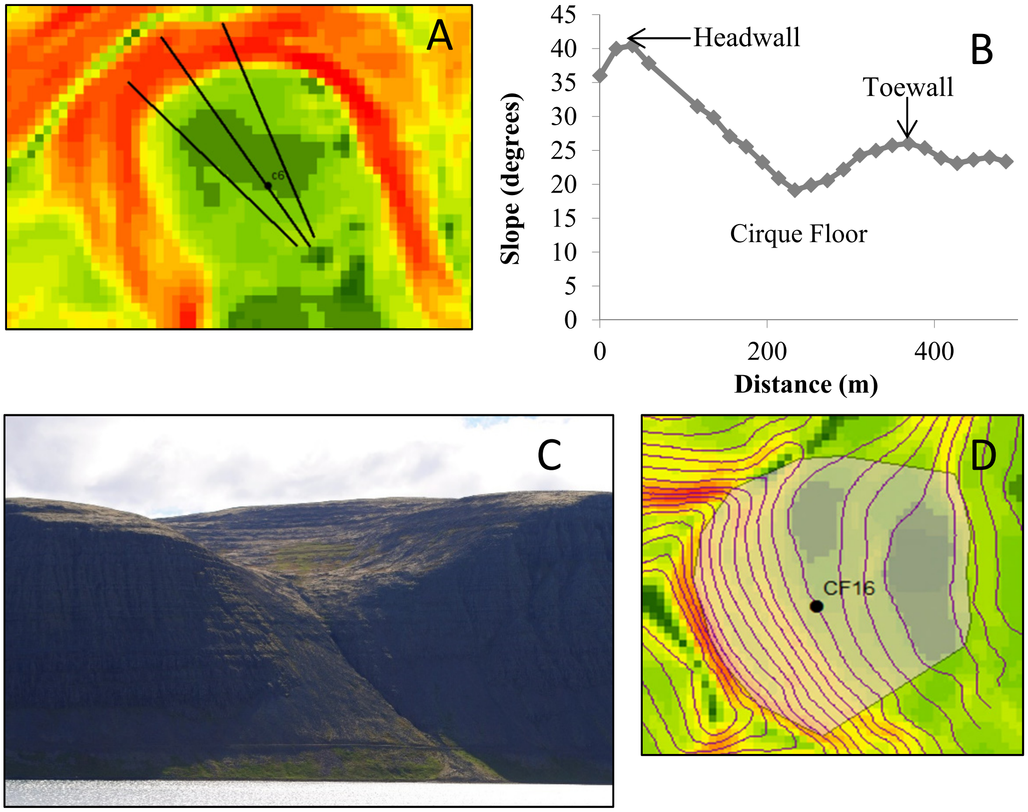
20° E
75° N
70° N
65° N
60° N
55° N
50° N
EGC
EIC
IC
Iceland
Polar Front
NAC


A
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B
Headwall
Toewall
Cirque Floor
Slope (degrees)
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40
45
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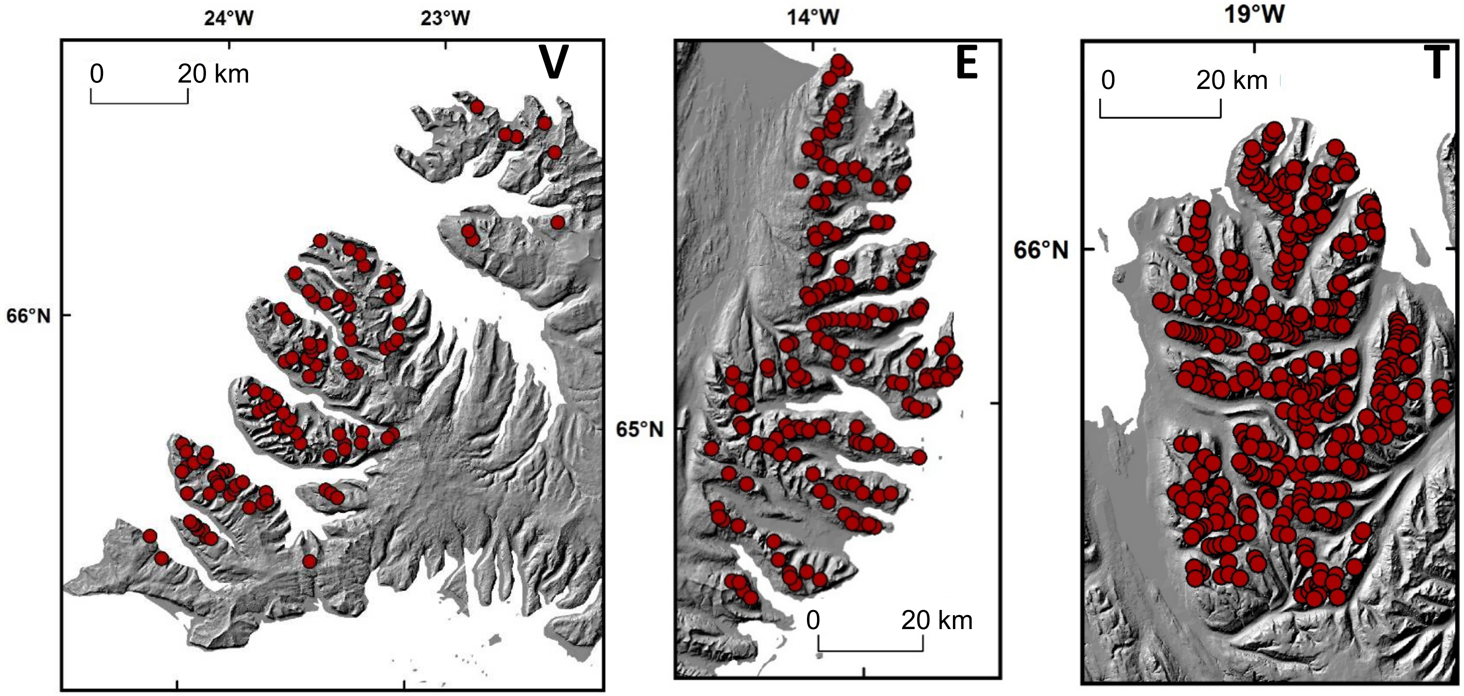
200
400
Distance (m)
C
D
CF16



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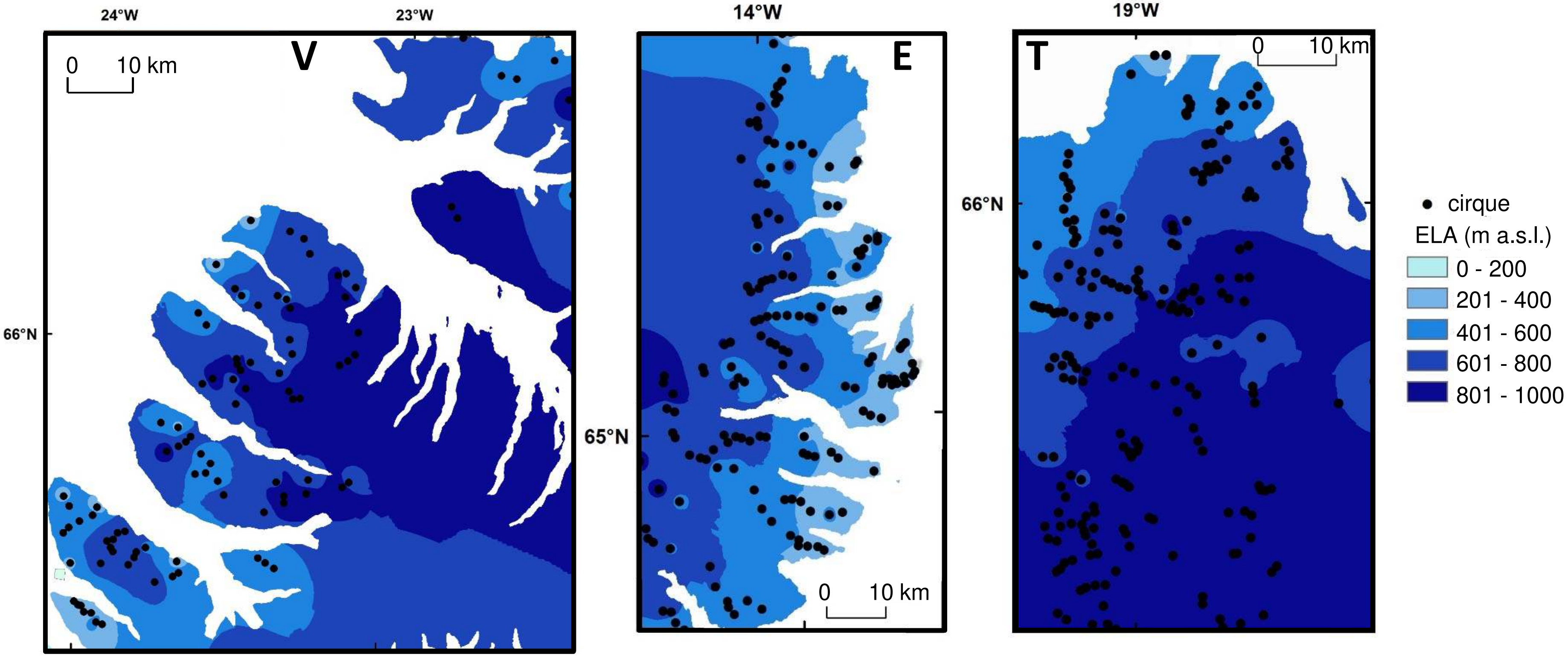
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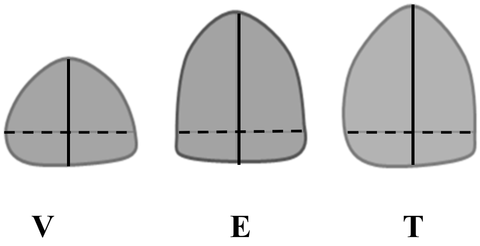
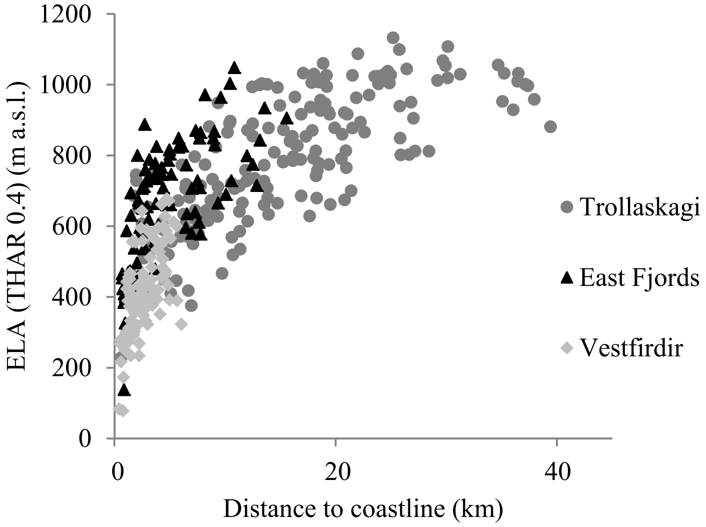
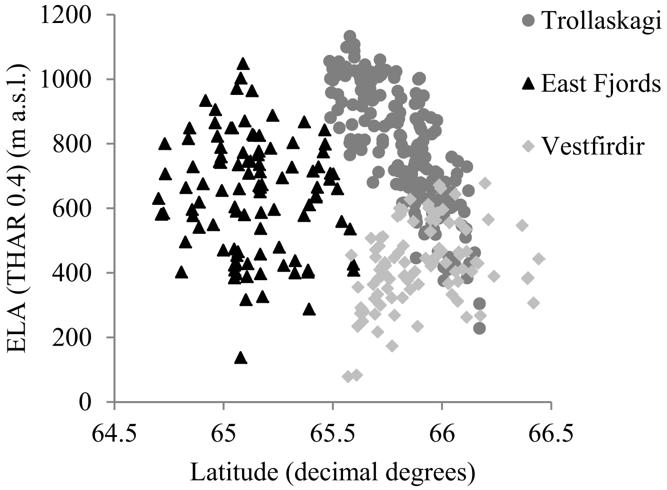
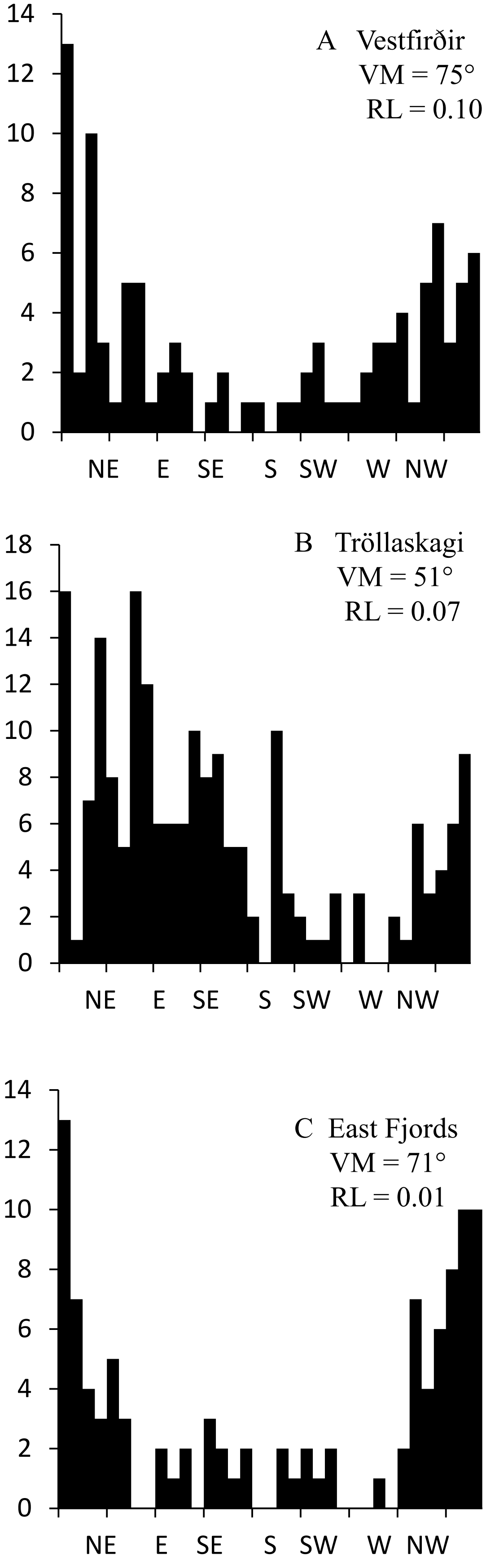
ELA (m a.s.l.)
0 - 200
201 - 400
401 - 600
601 - 800
801 - 1000


V
E
T


1200
1000
800
600
400
200
0
ELA (THAR 0.4) (m a.s.l.)
0
20
40
Distance to coastline (km)
● Trollaskagi
▲ East Fjords
◆ Vestfirdir


1200
1000
800
600
400
200
0
ELA (THAR 0.4) (m a.s.l.)
64.5
65
65.5
66
66.5
Latitude (decimal degrees)
● Trollaskagi
▲ East Fjords
◆ Vestfirdir


A Vestfirðir
VM = 75°
RL = 0.10
0
2
4
6
8
10
12
14
NE
E
SE
S
SW
W
NW
B Tröllaskagi
VM = 51°
RL = 0.07
0
2
4
6
8
10
12
14
16
18
NE
E
SE
S
SW
W
NW
C East Fjords
VM = 71°
RL = 0.01
0
2
4
6
8
10
12
14
NE
E
SE
S
SW
W
NW

	MAT (°C)	MAP (mm)	Summer T (°C)	Winter P (mm)	Distance to ocean (km)
Vestfirðir					
Æðey	4.03	653	8.36	62.81	34
Bolungarvík	4.02	848	8.2	87.69	8
Lambavatn	4.81	919	9.08	80.08	1
Tröllaskagi					
Akureyri	4.3	549	9.22	54.46	57
Sauðanesviti	4.3	864	7.23	71.32	0.2
East Fjords					
Egilsstaðir	3.56	853	8.62	90.4	33
Neskaupstaður	4.23	1945	7.83	208.2	2
Seyðisfjörður	4.08	1641	8.17	182.3	14

	Length (m)	Width (m)	Area (km^2)	Lat. range	Dist. to fjord (km)	Dist. to ocean (km)	Modal aspect	ELA (THAR = 0.4)	ELA (CF)	ELA (MP)
Vestfirðir	515	752	0.27	0.8	2.7	13.8	NE	423	395	--
Tröllaskagi	701	662	0.42	0.7	15.4	26.4	NE	788	760	697
E. Fjords	706	715	0.39	0.9	4.6	15.1	N	643	590	531

	L	W	H	Area	Min. Elev.	Max. Elev.	THAR= 0.4	CF	Dist. to Coast	Dist. to Ocean	Lat.	Long.	Aspect
L	1	0.7**	0.7**	0.8**	-0.3**	0.1	-0.2*	-0.1*	0.02	-0.1	0.1	0.1	-0.04
W		1	0.6**	0.9**	-0.2*	0.2*	-0.1	-0.1	0.02	-0.03	0.1	0.1	-0.04
H			1	0.7**	0.4**	0.1	-0.2**	-0.2**	-0.1	-0.1	0.2*	0.2**	0.03
Area				1	-0.2**	0.1	-0.1	-0.1	0.04	-0.03	0.04	0.1	-0.05
Min. elev.					1	0.9**	0.9**	0.99**	0.7**	0.7**	-0.8**	0.1	-0.2*
Max. elev.						1	0.9**	0.9**	0.8**	0.7**	-0.7**	0.2**	-0.2*
THAR = 0.4							1	0.96**	0.8**	0.7**	-0.8**	0.2*	-0.2*
CF								1	0.8**	0.7**	-0.8**	0.1*	-0.2*
Dist. to coast									1	0.8**	-0.8**	0.2**	-0.1
Dist. to ocean										1	-0.8**	0.2**	-0.1
Lat.											1	0.1	0.1
Long.												1	0.1
Aspect													1

Region	Number of cirques	L (mean)	W (mean)	H (mean)	L/W	Aspect
Victoria Valley, Antarctica[1]	56	2116	1679	849	1.26	NE
Ben Ohau Range, New Zealand[2]	92	489	536	216	0.91	--
Cumbria, England[3]	158	620	680	241	0.91	N
Wales, UK[4]	260	667	772	269	0.86	--
Senja-Kilpisjarvi, Scandinavia[5]	539	845	888	400	0.95	NE
New Hampshire, USA[6]	49	1687	954	442	1.77	--
Central Spanish Pyrenees, Spain[7]	206	519	691	364	0.75	N
Maritime Alps: France, Italy[8]	432	672	663	355	1.01	N
Thessaly, Greece[9]	50	731	473	289	0.70	N
Bohemian Massif: Czech Republic, Germany, Poland[10]	27	788	700	272	0.95	--
Romanian Carpathians, Romania[11]	631	654	718	209	0.91	ENE
Kamchatka, Russia[12]	3520	868	992	421	0.88	N
Vestfirdir, Iceland[13]	101	515	752	241	0.68	NE
Trollaskagi, Iceland	186	701	662	238	1.06	NE
East Fjords, Iceland	161	706	715	242	1.00	N
Iceland (overall)	447	661	700	240	0.98	NNE

[1] Aniya & Welch (1981) [2] Brook *et al.* (2006) [3]Evans & Cox (1995) [4]Evans (2006) [5]Hassinen (1998) [6]Davis (1999) [7]Garcia-Ruiz *et al.* (2000) [8]Federici & Spagnolo (2004) [9]Bathrellos *et al.* (2014) [10]Křížek *et al.* (2012) [11]Mîndrescu *et al.* (2010) [12]Barr & Spagnolo (2013) [13]Principato & Lee (2014)

Table S1. Latitude and longitude of all cirques used in this study. DD refers to decimal degrees.

Cirque ID	Lat (DD)	Long (DD)
1	66.0713	-18.5801
2	66.0598	-18.5661
3	66.0500	-18.5766
4	66.0430	-18.6029
5	66.0139	-18.6789
6	66.0070	-18.6868
7	65.9476	-18.7069
8	65.8907	-18.7387
9	65.8968	-18.7568
10	65.8872	-18.6948
11	65.9144	-18.7088
12	65.9146	-18.6802
13	65.9140	-18.7632
14	65.8887	-18.8193
15	65.8978	-18.8623
16	65.8922	-18.8718
17	65.8752	-18.8513
18	65.8796	-18.8693
19	65.8756	-18.8814
20	65.8833	-18.8944
21	65.8789	-18.9013
22	65.9015	-18.9206
23	65.8846	-18.9279
24	65.9008	-18.9923
25	65.9234	-18.9919
26	65.9135	-19.0002
27	65.8935	-18.9782
28	65.9040	-19.0453
29	65.9085	-19.0670
30	65.9126	-19.0868
31	65.9040	-19.1223
32	65.9203	-19.1115
33	65.9216	-19.1505
34	65.9304	-19.1879
35	65.9550	-19.1735
36	65.9613	-19.1666
37	65.9695	-19.1755

38	65.9811	-19.1734
39	65.9447	-19.1028
40	65.9536	-19.0507
41	65.9676	-19.0515
42	65.9700	-19.0668
43	65.9696	-19.0899
44	65.9832	-19.0427
45	66.0071	-19.1924
46	66.0238	-19.1898
47	66.0308	-19.2036
48	66.0574	-19.1894
49	66.0457	-19.1930
50	65.9519	-19.2766
51	65.9884	-19.0873
52	65.9804	-18.8553
53	65.9517	-18.8852
54	65.9545	-18.8975
55	65.9690	-18.8932
56	65.9756	-18.8955
57	66.1488	-19.0128
58	66.1709	-18.9139
59	66.0255	-18.8115
60	66.0333	-18.8101
61	66.0366	-18.7888
62	66.0392	-18.7652
63	66.0447	-18.7739
64	66.0427	-18.7978
65	66.0680	-18.8015
66	66.0841	-18.7592
67	66.0902	-18.7375
68	66.1072	-18.7608
69	66.1100	-18.8460
70	66.1145	-18.8449
71	66.1201	-18.8519
72	66.0435	-18.5655
73	65.7802	-18.3259
74	65.6720	-18.6222
75	65.6696	-18.6380
76	65.6711	-18.6508
77	65.6418	-18.6771
78	65.6465	-18.6963

79	65.6450	-18.7418
80	65.7276	-18.8254
81	65.7424	-18.8377
82	65.7608	-18.8827
83	65.7706	-18.6666
84	65.7896	-18.6729
85	65.7818	-18.6697
86	65.9034	-18.8347
87	65.8460	-18.6471
88	65.8377	-18.7704
89	65.8285	-18.8421
90	65.7915	-18.9449
91	65.7965	-18.8889
92	65.7891	-18.8485
93	65.7804	-18.8295
94	65.8056	-19.0031
95	65.8701	-19.0765
96	65.8693	-19.1125
97	65.8708	-19.1289
98	65.8698	-19.1737
99	65.8755	-19.2019
100	65.8750	-19.2195
101	65.8739	-19.2288
102	65.8789	-19.2439
103	65.8800	-19.2626
104	65.8805	-19.2714
105	65.8828	-19.2841
106	65.8607	-19.1317
107	65.8107	-19.1649
108	65.8175	-19.1768
109	65.8245	-19.1863
110	65.8257	-19.1943
111	65.8139	-19.2057
112	65.8227	-19.2277
113	65.8066	-19.1376
114	65.8013	-19.0629
115	65.7959	-19.1476
116	65.7973	-19.1772
117	65.7998	-19.2008
118	65.8112	-19.2415
119	65.8120	-19.0357

120	65.7213	-18.9913
121	65.7357	-19.0421
122	65.7205	-19.0340
123	65.7142	-19.0174
124	65.7152	-18.9968
125	65.7273	-19.0004
126	65.7090	-19.0112
127	65.7157	-18.8121
128	65.6780	-19.0285
129	65.6796	-19.0365
130	65.6835	-19.0538
131	66.1014	-18.8546
132	65.7089	-19.2592
133	65.7087	-19.2286
134	65.6750	-19.2073
135	65.6882	-19.1796
136	65.6829	-19.1523
137	65.6627	-19.1957
138	65.6454	-19.1132
139	65.6148	-19.2428
140	65.6292	-19.2523
141	65.6232	-19.1423
142	65.6189	-19.1394
143	65.5975	-19.1054
144	65.6449	-19.2143
145	65.6321	-19.1783
146	65.6311	-19.1494
147	65.6273	-19.1162
148	65.6290	-19.2086
149	65.5962	-19.1259
150	65.6371	-18.9504
151	65.6391	-18.9617
152	65.5902	-19.1752
153	65.5871	-19.1969
154	65.5804	-19.2091
155	65.5773	-19.2197
156	65.5559	-19.1530
157	65.5586	-19.1368
158	65.5775	-19.0554
159	65.5618	-19.0838
160	65.5161	-19.1194

161	65.5220	-19.1921
162	65.5292	-19.2161
163	65.5170	-19.0769
164	65.5108	-19.0543
165	65.5978	-18.7179
166	65.5974	-18.7289
167	65.5397	-18.8135
168	65.4884	-18.8289
169	65.4927	-18.7987
170	65.4995	-18.7935
171	65.5032	-18.7755
172	65.4983	-18.7703
173	65.4880	-18.7720
174	65.5226	-18.7656
175	65.5129	-18.7579
176	65.4846	-18.7044
177	65.5764	-18.6223
178	65.6155	-18.6795
179	65.5270	-18.6458
180	65.9184	-19.3157
181	65.9225	-19.3356
182	65.9152	-19.2175
183	66.1247	-18.6742
184	66.1131	-18.6573
185	66.0069	-18.6646
186	66.1704	-18.9458
187	65.6145	-23.9250
188	65.6264	-23.9433
189	65.6276	-23.9673
190	65.6354	-23.9788
191	65.6359	-23.9887
192	65.6405	-24.0028
193	65.5693	-24.1159
194	65.6084	-24.1769
195	65.6920	-24.0253
196	65.5842	-23.4558
197	65.7403	-24.0389
198	65.7322	-24.0557
199	65.7818	-24.0642
200	65.7693	-24.0441
201	65.7497	-24.0062

202	65.7592	-23.9633
203	65.7707	-23.9514
204	65.7405	-23.8525
205	65.7380	-23.8768
206	65.7287	-23.8900
207	65.7258	-23.9094
208	65.7170	-23.8967
209	65.7121	-23.8874
210	65.6955	-23.8332
211	65.6950	-23.9250
212	65.7064	-23.8157
213	65.7141	-23.8101
214	65.7209	-23.7809
215	65.6750	-23.7427
216	65.6843	-23.6846
217	65.7052	-23.6745
218	65.6901	-23.6657
219	65.7176	-23.4084
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223	65.8214	-23.1452
224	65.8286	-23.2603
225	65.8092	-23.2632
226	65.8044	-23.3366
227	65.7949	-23.3352
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231	65.8183	-23.5585
232	65.8257	-23.6361
233	65.8283	-23.6006
234	65.8417	-23.5867
235	65.8533	-23.6207
236	65.8538	-23.7345
237	65.8619	-23.6968
238	65.8685	-23.6734
239	65.8759	-23.6596
240	65.8873	-23.7029
241	65.8918	-23.7609
242	65.9382	-23.3050

243	65.9366	-23.3282
244	65.9469	-23.3433
245	65.9708	-23.3794
246	65.9245	-23.5172
247	65.9465	-23.4884
248	65.9579	-23.5323
249	65.9711	-23.5100
250	65.9825	-23.4778
251	65.9786	-23.5215
252	65.9858	-23.5261
253	65.9488	-23.6331
254	65.9567	-23.6003
255	66.0445	-23.6645
256	66.0288	-23.6339
257	65.9866	-23.1808
258	65.9934	-23.1536
259	66.0027	-23.1317
260	66.0328	-23.1252
261	65.9977	-23.3406
262	66.0171	-23.3533
263	66.0599	-23.3592
264	66.0713	-23.3730
265	66.0759	-23.4036
266	66.0606	-23.4661
267	66.0724	-23.5236
268	66.0813	-23.5469
269	66.1120	-23.6160
270	66.0800	-23.1756
271	66.0937	-23.1443
272	66.1118	-23.1782
273	66.1089	-23.2058
274	66.1357	-23.3048
275	66.1555	-23.3283
276	66.1642	-23.3766
277	66.1753	-23.5105
278	66.1966	-22.8168
279	66.2118	-22.8393
280	66.2372	-22.4333
281	66.3660	-22.4641
282	66.4184	-22.5194
283	66.3906	-22.6440

284	66.3936	-22.6977
285	66.4417	-22.8341
286	65.6130	-23.9040
287	65.5939	-13.8763
288	65.4550	-14.0221
289	64.7135	-14.4525
290	64.7015	-14.4246
291	64.7320	-14.4940
292	64.7297	-14.4654
293	65.4618	-14.0514
294	65.4337	-13.9905
295	65.4276	-13.9685
296	65.4220	-13.9118
297	65.4224	-13.8677
298	65.3851	-13.7762
299	65.3859	-13.6836
300	65.3904	-13.6744
301	65.3913	-13.9880
302	65.5930	-13.9065
303	65.4079	-14.0945
304	65.3689	-14.0382
305	65.3672	-14.0118
306	65.3166	-14.0563
307	65.3122	-13.9733
308	65.3269	-13.7950
309	65.3253	-13.7576
310	65.2740	-13.6236
311	65.2673	-13.6244
312	65.2538	-13.6982
313	65.5783	-13.9423
314	65.2303	-13.7078
315	65.2239	-13.9407
316	65.2139	-14.1068
317	65.1776	-13.6453
318	65.1682	-13.6710
319	65.1710	-13.6522
320	65.1668	-13.7721
321	65.1675	-13.7918
322	65.1746	-13.8470
323	65.1572	-13.8798
324	65.5397	-13.9036

325	65.1608	-13.8956
326	65.1631	-13.9287
327	65.1658	-13.9719
328	65.1664	-14.0105
329	65.1665	-14.0428
330	65.1628	-14.0708
331	65.1604	-14.0895
332	65.1377	-14.0711
333	65.1316	-14.1841
334	65.1291	-14.2039
335	65.5018	-13.9531
336	65.0886	-14.2848
337	65.0960	-14.2886
338	65.0702	-14.1428
339	65.0661	-14.1826
340	65.1015	-13.5751
341	65.0940	-14.1868
342	65.1095	-13.5547
343	65.0771	-13.5363
344	65.0653	-13.5314
345	65.0485	-13.5670
346	65.5202	-13.9232
347	65.0582	-13.5706
348	65.0594	-13.5397
349	65.0501	-13.6516
350	65.0488	-13.5971
351	65.0477	-13.6165
352	65.0569	-13.6239
353	65.0580	-13.6450
354	65.1062	-13.5665
355	65.0509	-13.7831
356	65.1098	-13.9794
357	65.4880	-13.9530
358	65.1136	-13.9970
359	65.1228	-14.0226
360	64.9981	-13.6654
361	64.9707	-14.2740
362	64.9915	-14.2317
363	65.0777	-14.4350
364	65.0882	-14.4297
365	65.0596	-14.4019

366	65.0324	-14.4024
367	65.0388	-14.4286
368	65.4849	-14.0078
369	64.9879	-14.1892
370	64.9849	-14.1693
371	64.9797	-14.1409
372	64.9863	-14.1029
373	64.9517	-13.9388
374	64.9602	-14.3228
375	64.9052	-14.1382
376	64.8871	-14.0320
377	64.8867	-14.0064
378	64.8586	-13.8774
379	65.4638	-14.0242
380	64.8061	-13.9068
381	64.8246	-13.9933
382	64.8554	-14.0849
383	64.9614	-14.5392
384	64.9164	-14.4768
385	64.7238	-14.1432
386	64.8262	-14.4534
387	64.8376	-14.5123
388	64.8437	-14.5295
389	64.8590	-14.5336
390	64.7194	-14.2437
391	64.8321	-14.0221
392	64.8142	-13.9648
393	64.8120	-13.9294
394	64.8161	-13.9966
395	64.8821	-13.9762
396	64.8665	-13.9445
397	64.8613	-13.8310
398	64.9191	-13.7062
399	64.9437	-13.8304
400	64.9532	-13.8529
401	64.7396	-14.2632
402	64.9486	-13.9131
403	64.9553	-13.9541
404	64.9799	-13.9454
405	64.9805	-14.2187
406	64.9841	-14.0803

407	64.9570	-14.3024
408	64.9435	-14.2642
409	64.9653	-14.3591
410	65.0117	-13.7271
411	65.0041	-13.7019
412	64.7630	-14.3032
413	65.0471	-13.7495
414	65.0928	-13.6777
415	65.0841	-13.6931
416	65.0846	-13.9237
417	65.0910	-14.0015
418	65.1269	-14.0406
419	65.0552	-13.6040
420	65.2719	-14.0606
421	65.2194	-14.0524
422	65.2213	-14.0373
423	64.7947	-14.3163
424	65.2232	-14.0154
425	65.2279	-13.9750
426	65.2212	-13.7997
427	65.2474	-13.6882
428	65.2574	-13.6753
429	65.2548	-13.9554
430	65.2101	-14.0659
431	65.2058	-14.0956
432	65.2717	-13.6597
433	65.3233	-14.0099
434	64.7309	-14.2622
435	65.3066	-14.0514
436	65.3922	-13.9216
437	65.4956	-13.9377
438	65.5137	-13.9407
439	65.4083	-13.8315
440	65.6068	-13.8995
441	64.7384	-14.1935
442	65.0769	-14.1654
443	64.8965	-14.4077
444	64.9933	-14.4066
445	65.0009	-14.4145
446	64.9401	-14.2058
447	64.8756	-14.1164