Understanding controls on cirque floor altitudes: insights from Kamchatka

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Abstract

Glacial cirques reflect former regions of glacier initiation and are therefore used as indicators of past climate. One specific way in which palaeoclimatic information is obtained from cirques is by analysing their elevations on the assumption that cirque floor altitudes are a proxy for climatically controlled equilibrium-line altitudes (ELAs) during former periods of small-scale (cirque-type) glaciation. However, specific controls on cirque altitudes are rarely assessed, and the validity of using cirque floor altitudes as a source of palaeoclimatic information remains open to question. In order to address this, here we analyse the distribution of 3520 ice-free cirques on the Kamchatka Peninsula (eastern Russia) and assess various controls on their floor altitudes. In addition, we analyse controls on the mid-altitudes of 503 modern glaciers, currently identifiable on the peninsula, and make comparisons with the cirque altitude data. The main study findings are that cirque floor altitudes increase steeply inland from the Pacific, suggesting that moisture availability (i.e., proximity to the coastline) played a key role in regulating the altitudes at which former (cirque-forming) glaciers were able to initiate. Other factors, such as latitude, aspect, topography, geology and neotectonics seem to have played a limited (but not insignificant) role in regulating cirque floor altitudes, though south-facing cirques are typically higher than their north-facing equivalents, potentially reflecting the impact of prevailing wind directions (from the SSE) and/or variations in solar radiation on the altitudes at which former glaciers were able to initiate. Trends in glacier and cirque altitudes across the peninsula are typically comparable (i.e., values typically rise from the north and from the south, inland from the Pacific coastline, and where glaciers/cirques are south-facing), yet the relationship with latitude is stronger for modern glaciers, and the relationship with distance to the coastline (and to a lesser degree with aspect) is notably weaker. These differences suggest that former glacier initiation (leading to cirque formation) was largely regulated by moisture availability (during winter months) and the control this exerted on accumulation; whilst the survival of modern glaciers is also strongly regulated by the variety of climatic and nonclimatic factors that control ablation. As a result, relationships between modern glacier mid-altitudes and peninsula-wide climatic trends are more difficult to identify than when cirque floor altitudes are considered (i.e., cirque-forming glaciers were likely in climatic equilibrium, whereas modern glaciers may not be).

Keywords:

cirques; glacier; palaeoclimate, climate; ELA

1. Introduction

Glacial cirques are bowl-shaped hollows formed by the erosive action of mountain glaciers (Evans and Cox, 1995; Mîndrescu and Evans, 2014). Cirques reflect former regions of glacier initiation (i.e., where topoclimatic conditions formerly allowed the development of glaciers), and as a result, they are often used as a source of palaeoclimatic information (e.g., Anders et al., 2010; Mîndrescu et al., 2010; Bathrellos et al., 2014). One specific way in which palaeoclimatic information is obtained from a population of cirques is by analysing spatial variability in their altitudes (e.g., Linton, 1959; Derbyshire, 1963; Davies, 1967; Peterson and Robinson, 1969; Hassinen, 1998; Principato and Lee, 2014) on the assumption that cirque floor altitudes are a proxy for the climatically controlled equilibrium-line altitudes (ELAs) of former cirque glaciers (i.e., glaciers that formerly occupied, and were contained within, cirques) (see Flint, 1957; Meierding, 1982; Porter, 1989; Benn and Lehmkuhl, 2000). The analysis of cirque floor altitudes is also key to understanding the role played by glaciers in eroding and regulating mountain topography at a near global scale—as part of a test for the buzzsaw hypothesis (see Oskin and Burbank, 2005; Mitchell and Montgomery, 2006; Mitchell and Humphries, 2015). However, specific controls on cirque floor altitudes are rarely assessed, meaning that the validity of using cirque floor altitudes as a source of palaeoclimatic information or for testing the buzzsaw hypothesis remains questionable (see Peterson and Robinson, 1969; Hassinen, 1998). In light of this, the aim of the present study is to assess the relative importance of various controls (i.e., latitude, aspect, proximity to the coast, topography, geology, tectonics, and volcanic activity) on cirque floor altitudes across the Kamchatka Peninsula (eastern Russia) in the hope that some of the information derived can be applied to cirque populations elsewhere globally. Kamchatka is well suited for this purpose, as the peninsula harbours a large cirque population; is topographically diverse; has varied, but comparatively simple, climate patterns; and is occupied by numerous modern glaciers—the altitudinal distribution of which is also studied here.

2. Study area

2.1. Topography and geology

The Kamchatka Peninsula is located in far eastern Russia and separates the Sea of Okhotsk to the west from the North Pacific to the south and east. The peninsula is ~ 1250 km long and is dominated by three distinct mountain regions: the Sredinny Mountains, the Vostočny Mountains, and the Eastern Volcanic plateau (EVP) (see Fig. 1). The NE–SW orientation of these mountain chains reflects their formation at the margin of the Kuril-Kamchatka subduction zone, now located ~ 150 km off the eastern shore of the peninsula (see Fig. 1). This proximity to the actively subducting North Pacific plate makes Kamchatka one of the most volcanically active arc segments on Earth (DeMets et al., 1990; Bindeman et al., 2010), currently occupied by ~ 300 extinct and 29 active volcanoes (shown in Fig. 1) (Ponomareva et al., 2007). This volcanic history is reflected by the region's bedrock, which is dominated by Quaternary and Miocene-Pliocene volcanic complexes (see Persits et al., 1997; Avdeiko et al., 2007).

[Approximate location of Fig. 1]

2.2. Glaciation

At present, Kamchatka is occupied by 503 glaciers (see Fig. 2). Though these glaciers are comparatively small (with a mean surface area of ~ 1.7 km^2) (see Khromova et al., 2014), we see evidence that the peninsula was extensively glaciated at various periods during the Late Quaternary (see Zamoruyev, 2004; Barr and Clark, 2011, 2012). The geomorphological record of former glaciation (summarised by Barr and Solomina, 2014) appears to indicate that the most extensive phase of ice advance occurred during the middle Pleistocene (c. 130-140 ka; Marine Isotope Stage, MIS, 6), when an ice sheet (~ 445,000 km^2) likely covered the entire peninsula. During the early part of the late Pleistocene (c. 60-31 ka; MIS 3) glaciers were less extensive (covering ~ 193,000 km^2) and were smaller still (covering ~ 90,000 km^2) at the global Last Glacial Maximum (gLGM; MIS 2). Additional small-scale phases of ice advance occurred during the Late Glacial and Holocene (see Barr and Solomina, 2014). Many of the peninsula's 3520 glacier-free cirques (see Fig. 3) were likely occupied during a number of these glacial phases, with active glacial erosion intensified during the onset and termination of glaciations, when glaciers were largely confined to their cirques (see Barr and Spagnolo, 2013). The morphometry (i.e., size and shape) of cirques on the peninsula has already been analysed to yield some palaeoclimatic information (see Barr and Spagnolo, 2013); here we provide specific consideration of their altitudinal distribution and its significance.

[Approximate location of Fig. 2]

[Approximate location of Fig. 3]

2.3. Climate

Because of Kamchatka's length and diverse topography, present-day climatic conditions across the peninsula vary considerably. However, in general, winter climate is dominated by the Siberian High, which drives cryoarid conditions from the interior of east Siberia in a SE direction across the peninsula (see Fig. 4), whilst summer conditions are dominated by the North Pacific High, which drives warm, moist air masses inland, from SE to NW (Shahgedanova et al., 2002; Yanase and Abe-Ouchi, 2007) (see Fig. 4). These climatic patterns result in distinct regional variations in climate, from a maritime Pacific coast to a continental interior (Čermák et al., 2006). This is exemplified by the strong SE-NW precipitation gradient, which shows the importance of the North Pacific in regulating moisture distribution across the peninsula (see Figs. 4A–D). The Sea of Okhotsk, to the west of the peninsula, serves as a secondary source of moisture, and its importance appears to peak in summer (Fig. 4B) and diminish in winter (Fig. 4C). This seasonal variation likely reflects the growth of sea ice in the Sea of Okhotsk during winter, limiting evaporation and minimising the inland advection of moisture (Fetterer et al., 2002) (see Fig. 4D). By contrast, the North Pacific remains largely devoid of sea ice throughout the year (Fetterer et al., 2002), and winter precipitation across the peninsula is almost entirely regulated by proximity to this source (see Figs. 4C and 4D),

[Approximate location of Fig. 4]

3. Methods

The cirques analysed in this study were mapped from satellite images (Landsat 7 ETM+) and digital elevation model (DEM) data (ASTER GDEM v.2, with a grid cell resolution of 30 m, and an absolute vertical accuracy of ~ 17 m; ASTER GDEM Validation Team, 2011) by Barr and Spagnolo (2013). To assess controls on cirque floor altitudes (Alt), the latitude (ϕ), longitude (λ), aspect (θ), and shortest distance to the modern coastline (x) (hereafter referred to as distance to the modern coastline) of each cirque was quantitatively analysed, and the role of topography, geology, tectonics, and volcanic activity was also considered. Floor altitudes were measured as the single lowest DEM grid cell within each cirque (calculated from the ASTER GDEM). Cirque distance to the coastline was calculated using the ArcGIS Euclidean distance tool (an approach adopted by Principato and Lee, 2014). Latitude and longitude were measured from the centre point of each cirque; and aspect was measured as the outward direction of each cirque's median axis (see Evans, 1977; Evans and Cox, 1995).

4. Results

4.1. Cirque floor altitudes

The 3520 glacier-free cirques on the Kamchatka Peninsula have floor altitudes that range from 122 to 1919 m (asl) (see Fig. 3 and Table 1). These cirques are subdivided into six populations based on the regions illustrated in Fig. 1. These include cirques on (i) the western slopes of the north Sredinny Mountains (referred to here as the NW Sredinny); (ii) the eastern slopes of the north Sredinny Mountains (referred to here as the NE Sredinny); (iii) the central Sredinny Mountains; (iv) the western slopes of the south Sredinny Mountains (referred to here as the SW Sredinny); (v) the eastern slopes of the south Sredinny Mountains (referred to here as the SE Sredinny); and (vi) the Vostočny Mountains and EVP (see Table 1).

[Approximate location of Table 1]

4.2. Variations in cirque floor altitudes with latitude and longitude

When the entire cirque data set is considered (as in Fig. 3), cirque floor altitudes are found to rise from the north and from the south, to a peak at ~ 55.5°N (see Fig. 5a and Table 2). Similarly, floor altitudes rise from the east and the west, though the westward rise is much stronger than the eastward (Fig. 5B). These trends are statistically significant ($p < 0.001$), but variations in their nature and strength within and between regions are notable (see Figs. 5A and 5B, and Table 2).

[Approximate location of Fig. 5]

[Approximate location of Table 2]

4.3. Aspect-related variations in cirque floor altitudes

When Kamchatkan cirques are considered according to their median axis aspect (θ), it is apparent that there are notable aspect-related variations in cirque floor altitudes. Specifically, south-facing cirques tend to have higher floor altitudes than north-facing examples (see Fig. 5C and Table 3). For example, when the entire cirque data set is considered, Fourier (harmonic) regression reveals that cirques facing 170° (SSE) have floor altitudes that are typically 163 m higher than those facing 350° (NNW) (Fig. 5C). Though a comparatively low proportion of variance is accounted for through this regression ($r^2 = 0.03$), the relationship is highly significant ($p < 0.001$). The trend of lower floor altitudes for north-facing cirques is consistent for all populations of cirques on the Peninsula, though some have cirque floor altitude minima toward the NNW and some toward the NNE (see Fig. 5C and Table 3).

[Approximate location of Table 3]

4.4. Cirque floor altitudes relative to the modern coastline

When the entire Kamchatkan cirque data set is considered, cirque floor altitudes appear to increase inland with distance from the modern coastline (see Fig. 5D and Table 4). When distance from the modern Pacific coastline alone is considered, this relationship is maintained (Fig. 5E and Table 4). However, when distance from the modern Okhotsk coastline alone is considered, an overarching, statistically significant relationship is not apparent (Fig. 5F and Table 4). Regional variations in these relationships are also notable. For example, some populations (e.g., in the NW Sredinny) show no statistically significant relationships (see Table 4).

[Approximate location of Table 4]

5. Controls on cirque floor altitudes

Here, potential controls on cirque floor altitudes across the Kamchatka Peninsula are considered, with a specific focus on the controls exerted by climate, topography, geology (lithology), tectonics, and volcanic activity.

5.1. Climatic controls on cirque floor altitudes

The role of palaeoclimate in regulating cirque floor altitudes on the Kamchatka Peninsula is assessed through consideration of cirque latitude (Fig. 5A), aspect (Fig. 5C), and distance to the modern coastline (Figs. 5D–F). These factors are analysed on the assumption that they are proxies for palaeoclimate. In a very general sense, latitude is considered a proxy for palaeotemperature—based on the consideration that glaciers can develop, and thereby generate cirques, at lower altitudes as latitude increases (i.e., as mean annual air temperature decreases). Aspect is considered a proxy for local climatic conditions. Specifically, direct solar radiation and/or variations in prevailing wind direction. This is based on the following assumptions: (i) glaciers can develop, and thereby generate cirques, at lower altitudes on poleward-facing slopes where the total receipt of direct solar radiation is minimised (see Evans, 1977); (ii) low altitude glaciers can also form, and thereby generate cirques, on slopes that have an aspect deflected slightly east of poleward, because these slopes receive much of their direct solar radiation in the morning when air temperatures are relatively low and ablation is therefore limited (this is referred to as the morning:afternoon effect); (iii) low altitude glaciers can form, and thereby generate cirques, on slopes with other aspects in situations where prevailing winds lead to the accumulation and preservation of snow and ice on leeward slopes (see Evans, 1977, 1990). Distance to the modern coastline is considered a proxy for palaeoprecipitation. This is based on the assumption that (i) the formation of low altitude glaciers and their cirques often depends on relatively high winter precipitation (i.e., snowfall); (ii) as at present (see Fig. 4), moisture availability during periods of cirque development was strongly controlled by proximity to the coastline; (iii) the position of the modern coastline could be considered broadly representative of conditions during periods of cirque formation (i.e., when they were occupied by cirque glaciers), as supported by the fact that even during periods of full glaciation (e.g., at the LGM when eustatic sea level was lowered by 130 m and the peninsula was covered by a series of ice fields) the peninsula's overall shape varied little from present (see Fig. 1).

Though we make this simple subdivision between different cirque attributes and the climatic conditions they potentially reflect, it appears (Fig. 4) that this is an oversimplification in some cases (e.g., precipitation also varies with latitude, although to a minor extent when compared to temperature, and temperature also varies with distance from the coastline, although to a minor extent than precipitation; see Fig. 4). Despite this, these divisions provide a framework for discussing the relative importance of different factors in regulating cirque floor altitudes on the Kamchatka Peninsula. This is discussed below, with a distinction made between interior and coastal cirque populations.

5.1.1. Interior populations

The interior populations of cirques comprise those of the NW, central, SW, and SE Sredinny Mountains. These populations are defined by their considerable distance from the modern coastline and by the fact that proximity to the North Pacific is not the clear dominant control on cirque altitudes (i.e., regional climate is not dominated by air masses from the North Pacific).

In the NW Sredinny Mountains, the only factor showing a statistically significant relationship with cirque floor altitudes is aspect. This is emphasised in Table 5, where a series of models are used to predict cirque floor altitudes across the peninsula. In the NW Sredinny, floor altitudes are typically lowest for NE-facing (23°N) cirques (see Table 3). This trend might indicate that aspect-related variations in direct solar radiation have had an impact on the altitude at which former glaciers have developed. Alternatively, the trend might reflect prevailing winds from the south or west during former periods of glaciation allowing comparatively low altitude cirques to preferentially develop on NE-facing slopes. The lack of any clear relationship between cirque floor altitudes and proximity to the sea or ocean might reflect comparatively limited variability in cirque distance from the coastline in this area where the peninsula is comparatively narrow (i.e., cirque distance to the coastline ranges by 81 km, relative to a mean of 103 km for all other regions). Alternatively, the lack of any clear relationship between cirque floor altitudes and proximity to the sea or ocean might indicate that the development of former glaciers in this region was largely dictated by controls on ablation (i.e., air temperatures and total direct solar radiation). The region is currently one of the most arid in Kamchatka (see Figs. 4A-D), and this aridity is intensified during winter months (i.e., during the accumulation season) when the Sea of Okhotsk is occupied by sea ice (see Fig. 4D). Aridity in this region was likely intensified during former periods of glaciation, as glaciers along the Pacific coast of Kamchatka intercepted moisture-bearing winds from the North Pacific and the extent and duration of ice in the Okhotsk Sea increased. Former aridity in the NW Sredinny may have limited widespread cirque development to areas where ablation was minimal (i.e., on slopes with NE aspects). Aridity may also explain why cirques in this region have comparatively high minimum floor altitudes (i.e., the lowest cirque floor is 570 m asl), as restricted accumulation prevented the development of low altitude glaciers.

In the central Sredinny Mountains, cirque floor altitudes show statistically significant relationships with latitude, aspect, and distance to the Okhotsk coastline. However, the two most important components, as suggested by the lowest root mean square error (RMSE) of a series of tested models, are cirque latitude and aspect (see Table 5). Floor altitudes are typically lowest for NW-facing (351°N) cirques (see Table 3), potentially indicating that, though the altitudes at which former glaciers were able to initiate (and thereby form cirques) were not strongly controlled by moisture availability (i.e., a strong relationship with distance to the modern coastline is not apparent), prevailing winds from the east of south may have allowed glaciers to develop at lower altitudes on leeward (NW-facing) slopes. These prevailing winds may have brought moisture to the eastern coast, which would have been largely intercepted by the Vostočny Mountains (see Barr and Spagnolo, 2014), thus keeping the central sector of the Sredinny Range comparatively moisture starved and, hence, the higher cirque floor altitudes here.

In the SW Sredinny Mountains, cirque floor altitudes show statistically significant relationships with latitude, aspect, and distance to the Okhotsk coastline; and the model that best fits the observed data (i.e., with the lowest RMSE) is based on a regression of all three of these variables (see Table 5). Interestingly, cirque floor altitudes appear to increase with latitude (see Table 2). This is counter to what might be expected if latitudinal variations in temperature exerted a control on cirque altitudes. In fact, the trend likely reflects covariance between distance to the Okhotsk coastline and latitude in this region, with proximity to the coastline increasing with decreasing latitude ($r^2 = 0.65$; $p < 0.001$). This indicates that the former has a stronger influence on cirque floor altitudes than the latter, and a regression model based on cirque aspect and distance to the Okhotsk coastline alone might be favoured (see Table 5). Aspect-wise, floor altitudes are typically lowest for NNE-facing (13°N) cirques (see Table 3), potentially indicating that the morning:afternoon effect had an impact on the altitude at which former glaciers were able to develop and thereby erode cirques.

In the SE Sredinny Mountains, cirque floor altitudes show statistically significant relationships with latitude, aspect, and distance to the Pacific coastline. Again (as in the SW Sredinny), cirque floor altitudes appear to increase with increasing latitude (see Table 2), and latitude and distance to the Pacific coastline covary ($r^2 = 0.93$; $p < 0.001$), suggesting that latitude specifically is unlikely to regulate cirque floor altitudes. In fact, the model that best fits the observed data is based on a regression of cirque aspect and distance to the Pacific coastline alone (see Table 5). Floor altitudes are lowest for cirques facing a little W of N (352°N), potentially reflecting the role of prevailing winds from the east (between NNE and SSE).

5.1.2. Coastal populations

The coastal populations of cirques comprise those of the NE Sredinny Mountains and Vostočny/EVP region. Both populations have cirque floor altitudes that show statistically significant relationships with latitude, aspect, and (in particular) distance to the Pacific coastline (see Table 5). However, the apparent relationship between cirque floor altitudes and latitude in these coastal populations is likely to reflect a covariance between latitude and distance to the Pacific coastline (with r^2 values of 0.11 and 0.12, respectively; $p < 0.001$). The RMSE derived using all three variables is only slightly lower (~ 7% and ~ 2% lower, for the NE Sredinny and Vostočny/EVP, respectively) than when based on distance to the modern Pacific coastline alone—likely reflecting the dominance of proximity to the coastline (regulating moisture availability) as a control on the altitudes at which former glaciers were able to initiate and thereby erode cirques (see Table 5). The importance of moisture availability and the supply of moisture from the North Pacific are emphasised by the fact that the lowest-lying cirques in the entire data set are present in these coastal populations (i.e., cirques are found more than 300 m below those in other populations) (see Fig. 3 and Table 1). In these coastal populations, floor altitudes are typically lowest for NW-facing cirques (with aspects of 317 and 346°N for the NE Sredinny and Vostočny/EVP, respectively), and in fact, these regions show notably large aspect-related variations in cirque floor altitudes when compared to interior populations (see alt range in Table 3). This would support the notion that winds from the North Pacific, to the SE, not only brought moisture to allow glacier development in coastal areas but also promoted the growth of comparatively low altitude glaciers on slopes that were in the lee of these prevailing winds.

5.1.3. Climatic controls on cirque floor altitudes across the peninsula as a whole

Despite regional variations (outlined in sections 5.1.1 and 5.1.2), when the entire data set of cirques across the Kamchatka Peninsula is considered, floor altitudes show statistically significant relationships with latitude, aspect, and distance to the modern coastline (see Tables 2, 3, and 4). However, evidence suggests that the relationship between latitude and cirque floor altitude can often be explained by covariance with distance to the modern coastline (see Table 2). There is clear evidence that aspect has played a role in regulating the altitude at which former glaciers have been able to initiate (see Fig. 5C and Table 3) and thereby generate cirques, with north-facing slopes allowing the development of comparatively low altitude glaciers (see Fig. 5C). Despite this, the regression model that best fits all observed cirque floor altitudes across the peninsula is based on distance to the modern Pacific coastline alone (a model based on regression of all of three variables has an ~ 11% greater RMSE) (see Table 5). The strength of this relationship appears to indicate that moisture availability played a key role in regulating the altitude at which glaciers were able to develop and erode cirques. This is supported by the fact that when distance to the modern coastline and distance to the modern Pacific coastline are considered (Figs. 5D and 5E), there is not only a general increase in cirque floor altitudes inland, but also an increase in the minimum altitude at which cirques are found. This would appear to suggest a palaeoglaciation level (see Evans, 1990; Mîndrescu et al., 2010) below which glaciers have been unable to initiate and thereby generate cirques (perhaps driven by precipitation gradients). The importance of proximity to the North Pacific, rather than the Sea of Okhotsk, likely reflects the fact that, as at present during former periods of cirque-type glaciation, this was the dominant source of moisture/precipitation to much of the peninsula, particularly during winter months (i.e., during the accumulation season) (see Figs. 4C and 4D), most likely because the Okhotsk was largely covered by sea ice.

[Approximate location of Table 5]

5.2. Topographic controls on cirque floor altitudes

Cirque altitudes in a given region are partly controlled by mountain altitudes, with high altitude glaciers only able to initiate, and thereby generate high altitude cirques, where high altitude topography exists. As a result, the inland increase in cirque floor altitudes seen across the Kamchatka Peninsula (Figs. 5D and 5E) could reflect the absence of high altitude topography in coastal areas (rather than reflecting a climatic trend). For example, such topographic gradients have been found to partly explain cirque floor altitude trends in Scandinavia (Hassinen, 1998) and Tasmania (Peterson and Robinson, 1969), though in both cases palaeoprecipitation gradients are considered the dominant control (see section 5.5). However, across the Kamchatka Peninsula an overall topographic trend inland is not apparent (see Fig. 6), and in fact, the maximum and mean topography along the Pacific coast of Kamchatka often extends well above cirque floor altitudes, with volcanic peaks (active and inactive) extending up to 2500 m above local cirque floor altitudes (Fig. 6). Thus, variation in topography is not considered to explain the overall trends in cirque floor altitudes across Kamchatka, though topography undoubtedly has some influence at a regional scale. For example, some high altitude, cirque-free peaks and ridges across the peninsula are too steep or have too little accommodation space to have allowed erosive, cirque-forming glaciers to develop (see Barr and Spagnolo, 2014). Aspect-related differences in floor altitudes between cirque populations to the east and west of the Sredinny Mountains might partly reflect a structural/topographic control on the altitudes at which former glaciers were able to initiate. However, even on different sides of the central mountain divide, ridges occupied by cirques show a range of orientations (see Fig. 1), giving little reason to believe that such structural control can explain these overarching trends.

[Approximate location of Fig. 6]

5.3. Geological controls on cirque floor altitudes

Because cirque formation is limited to regions where lithology has ‘allowed’ bedrock to be eroded into bowl-shaped hollows, regional variations in bedrock erodibility can potentially influence cirque shape (see Delmas et al., 2014, 2015) and altitude (see Mîndrescu and Evans, 2014). However, Barr and Spagnolo (2013) used a one-way analysis of variance (ANOVA) to estimate the variability in cirque floor altitudes accounted for by differences in lithology on the Kamchatka Peninsula and found little evidence for any significant relation between variables.

5.4. **Tectonic and volcanic controls on cirque floor altitudes**

As noted in section 2.1, the Kamchatka Peninsula lies close to the Kuril-Kamchatka trench, where the North Pacific plate actively subducts beneath the Eurasian plate at a rate of ~ 79 mm y^{-1} (DeMets et al., 1990; Bindeman et al., 2010). Because of this proximity, much of the peninsula is tectonically active, with uplift and deformation taking place during the past 70 Ma (Fedotov et al., 1988). In particular, Quaternary uplift should be taken into consideration when analysing cirque floor altitudes across the region, as uplift can result in cirques being displaced from altitudes at which they were formed (see Bathrellos et al., 2014). However, direct estimates of Quaternary vertical displacements on the Kamchatka Peninsula are scarce. Currently available estimates are listed in Table 6 and show regional variability; but based on visual comparison, there appear to be no systematic trends that might explain the patterns in cirque floor altitudes identified in the present study. In general the only systematic orographic trend across the peninsula is that mountain complexes become younger from west to east, reflecting the eastward migration of the Kurile-Kamchatka trench and associated volcanic front since the late Eocene. Despite this, there is little evidence that the age of each massif has had significant impact on cirque floor altitudes, as they show little systematic variation with distance from the modern Kurile-Kamchatka trench. This might indicate that the peninsula's cirques were formed during the late Quaternary, once periods of large-scale mountain building were complete.

Quaternary volcanic activity on the Peninsula has undoubtedly had (and continues to have) an impact on the dynamics of the region's glaciers (see section 6.3, in Barr and Solomina, 2014) through geothermal activity, eruptions, and tephra cover (ash blanketing). However, a lack of detailed understanding of volcanic activity on the peninsula during the last glaciation (c.f. Ponomareva et al., 2007) means that we are currently unable to account for these factors (particularly when considering impacts on cirque distribution). Despite this, most of these effects are expected to be relatively local and are unlikely to show geographical trends comparable to those found for cirque floor altitudes.

[Approximate location of Table 6]

5.5. A global comparison

As noted in section 1, controls on cirque floor altitudes are rarely assessed within the published literature. Despite this, a number of studies have analysed cirque floor altitudes across specific regions (e.g., Linton, 1959; Davies, 1967; Derbyshire, 1963; Peterson and Robinson, 1969; Hassinen, 1998; Evans, 1999; Anders et al., 2010; Principato and Lee, 2014) and at a near-global scale (e.g., Mitchell and Humphries, 2015). A common trend is that cirque floor altitudes are found to vary considerably, even within single mountain ranges (see Flint, 1957; Anders et al., 2010). At a global scale (i.e., when a comparison is made between different study regions), cirque floor altitudes are found to decrease with increasing latitude (see Mitchell and Humphries, 2015), though identifying such trends within specific regions is more difficult (see Evans. 1999). Cirque floor altitudes are also often found to vary as a function of cirque aspect, with poleward-facing cirques found at lower altitudes than those on less climatically favourable (in terms of glacier growth and survival) slopes (see Evans, 2006a). However, though this trend is found in a number of mountain ranges globally (see Evans, 2006c) and applies to modern glaciers (see Evans and Cox, 2005; Evans, 2006b,c, 2011), it is not ubiquitous (see Evans and Cox, 1995; Evans, 1999). Another characteristic common to many cirque populations globally is that floor altitudes are found to increase inland (e.g., Peterson and Robinson, 1969; Hassinen, 1998; Principato and Lee, 2014). In many cases, this is attributed to the role of precipitation in regulating the altitude of former glaciers, though the potential influence of other, nonclimatic, factors is also recognised (see Peterson and Robinson, 1969; Hassinen, 1998; Principato and Lee, 2014). For example, in SW Tasmania, Peterson and Robinson (1969) found evidence of an inland increase in cirque floor altitudes, and attribute this to an inland palaeoprecipitation gradient. However, they also recognised that, because cirque floor altitudes follow the overall topographic trend, other factors including spatial variability in topography, lithology, and structure may partly explain observed trends. Similarly, across northern Scandinavia, Hassinen (1998) found cirque floor altitudes to increase inland along a 210-km transect. This was attributed to an inland decrease in palaeoprecipitation combined with the influence of topography (i.e., the heights of the local mountains gradually increase inland but at a slower rate than cirque floor altitudes).

Thus, when cirque floor altitudes in other populations globally are considered, many of the trends identified in the present study are observed. Specifically: (i) though there is evidence for latitudinal control on cirque floor altitudes at a global scale, clear trends are often difficult to identify within individual study regions; (ii) cirque floor altitudes are typically lower on climatically favourable (often poleward-facing) slopes, though this trend is not ubiquitous; (iii) cirque floor altitudes often increase inland; (iv) spatial variability in topography, lithology, and structure may partly explain observed trends in cirque floor altitudes, but the influence of such controls is often difficult to unambiguously identify.

6. Comparison with modern glaciers

In section 5.1, it is suggested that cirque floor altitudes across the Kamchatka Peninsula primarily reflect climatic controls on the altitudes at which former glaciers were able to initiate. This assertion can be tested, to some degree, by considering the altitudes of modern glaciers. To this end, we have estimated the mid-altitude (mid-alt) (i.e., the average of the highest and lowest altitude—following Evans and Cox, 2005; Evans, 2006c) of 503 glaciers identifiable from satellite images (Landsat 8) across the Kamchatka Peninsula (see Fig. 2). A number of these glaciers, particularly the larger ones, with highest mid-altitudes, occupy active and inactive volcanoes; and their dynamics are partly controlled by this volcanic setting (Barr and Solomina, 2014). Others (n = 361) are typical cirque glaciers that have likely experienced limited volcanic control because of their comparatively restricted extent.

6.1. Trends in modern glacier mid-altitudes

Modern glaciers on the Kamchatka Peninsula are distributed throughout the region's principle mountain groups (i.e., ~ 13% in the NW Sredinny; ~ 32% in the NE Sredinny; ~ 3% in the Central Sredinny; ~ 11% in the SW Sredinny, ~ 10% in the SE Sredinny; and ~ 31% in the Vostočny/EVP region). However, regional analysis of glacier mid-altitudes in a way that might be compared to cirque floor altitudes is not possible as some regions currently contain very few glaciers (e.g., in the central

Sredinny, n = 15). When the entire data set is considered, glacier mid-altitudes range from 496 to 2970 m (asl) (Fig. 2) and rise from the north and from the south (see Fig. 7A and Table 7). When cirque-type glaciers alone are considered, this relationship strengthens (Fig. 7A and Table 7). Glacier mid-altitudes are typically lowest where glacier accumulation area aspect (taken as the mean aspect of each glacier's upper half—i.e., above the mid-altitude) is 311° (190 m lower than at 131°) (Fig. 7B)—a relationship significant at the 0.01 level (see Table 7). A similar outcome was obtained by Evans (2006c) who analysed the 398 Kamchatkan glaciers reported by the World Glacier Inventory. When cirque-type glaciers alone are considered, the relationship between altitude and aspect strengthens slightly, with glacier altitudes typically lowest where accumulation area aspect is 272°, though this relationship is only significant at the 0.05 level (see Fig. 7B and Table 7). Glacier mid-altitude increases with distance to the modern coastline (Fig. 7C) (r^2 = 0.36, p < 0.001). This relationship is maintained when distance to the Pacific coastline alone is considered (r^2 = 0.36, p < 0.001) (Fig. 7D) but is statistically insignificant with distance to the Okhotsk coastline. Similar, but slightly stronger, trends are found when cirque-type glaciers alone are considered (see Fig. 7 and Table 7).

[Approximate location of Table 7]

6.2. Comparing modern glaciers and glacier-free cirques

Given the data in Tables 2, 3, 4, and 7, it is apparent that trends in glacier mid-altitudes and cirque floor altitudes across the Kamchatka Peninsula are comparable (i.e., values typically rise from the north and from the south, inland from the Pacific coastline, and where glaciers/cirques are SE-facing). Despite this, there are also some notable differences in the strength of these relationships. Specifically, when glaciers are considered, the relationship with distance to the modern coastline (and to a lesser degree aspect) is notably weaker. This is demonstrated by the fact that the regression model that best fits glacier mid-altitudes across the peninsula is based on glacier latitude, aspect, and distance to the modern coastline (see Table 8); whereas the model that best fits all of the observed cirque floor altitudes is only based on distance to the modern Pacific coastline (see Table 5). Here we consider three hypotheses to explain these differences. **Hypothesis 1:** present-day glaciers are not comparable to former cirques because of their varying size and type. Despite this, even when the study is limited to present-day cirque glaciers (i.e., excluding those draped over volcanic peaks), differences are still identifiable. In particular, considering cirque-type glaciers alone reduces the difference between glaciers and cirques with respect to the distance from modern coastline but accentuates the difference with respect to latitude (see Table 7). **Hypothesis 2**: unlike cirque floor altitudes, glacier mid-altitudes are not a good proxy for climate. Theoretically, snowline altitudes (a surrogate for ELA) of modern glaciers could represent a much better climatically controlled parameter, assuming glaciers are in equilibrium with climate. However, snowline data are only available for 137 Kamchatkan glaciers (from the WGMS and NSIDC, 2012) and are very similar to glacier mid-altitude estimates (i.e., the RMSE between mid-altitude and snowline estimates is 137 m, $r^2 = 0.89$). As a result, replacing mid-altitude estimates with snowline estimates has very little impact on the strength or pattern of resulting trends. **Hypothesis 3:** on the Kamchatka Peninsula, former glacier initiation (cirque development) was more strongly controlled by climate than is the case for (present-day) glacier survival (i.e., cirque-forming glaciers were likely in climatic equilibrium, whereas modern glaciers may not be). In particular, the altitude at which former glaciers were able to initiate (and thereby where cirques are found) was largely governed by moisture availability during winter months and its impact on accumulation (hence the strong association between cirque floor altitudes and distance to the modern coastline). By contrast, the current distribution of glaciers is also strongly controlled by the variety of factors that limit ablation and promote glacier survival under comparatively unfavourable climatic conditions: specifically, low summer air temperatures (hence the comparatively strong relationship between cirque floor altitudes and latitude) and local topoclimatic factors (such as topographic shading). Hence, evidence suggests one dominant control on glacier initiation but multiple controls on glacier survival.

[Approximate location of Table 8]

7. Conclusions

In this paper, controls on the altitudinal distribution of 3520 cirques and 503 modern glaciers across the Kamchatka Peninsula are considered. The main study findings can be summarised as follows:

- When the peninsula is considered as a whole, the dominant control on cirque floor altitudes is proximity to the Pacific, with values increasing steeply inland from the modern coastline. This pattern would appear to indicate that moisture availability was key in regulating where former glaciers were able to initiate and thereby erode cirques; and that the North Pacific was, and in fact still is, the dominant source of moisture to much of the region (particularly during the accumulation season).
- Other factors, such as latitude, topography, geology, tectonics, and volcanic activity seem to have played a limited role in regulating cirque floor altitudes across the peninsula; though there is a statistically significant and consistent relationship with aspect (with south-facing cirques typically having higher floors than north-facing equivalents). This trend reflects the impact of variations in solar radiation, and probably prevailing wind directions, on the altitude at which former glaciers were able to develop.
- Despite peninsula-wide trends, a distinction is made between interior and coastal populations, with distance to the coastline having the strongest influence on the latter.
- The mid-altitudes of modern glaciers on the peninsula appear to reflect variations in latitude, aspect, and proximity to the modern coastline. In general, trends in glacier and cirque altitudes are comparable (i.e., values typically rise from the north and from the south, inland from the Pacific coastline, and where glaciers/cirques are south-facing), yet the relationship with distance to the modern coastline (and to a lesser degree aspect) is weaker for modern glaciers.
- Apparent differences between controls on cirque and glacier altitudes across the peninsula may indicate that while former glacier initiation (leading to cirque formation) was largely regulated by controls on accumulation (i.e., the availability of snow and ice during winter

months); the survival of modern glaciers is also regulated by the variety of climatic and nonclimatic factors that control ablation, meaning that relationships between modern glaciers and peninsula-wide climatic trends are more difficult to identify.

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Figures:

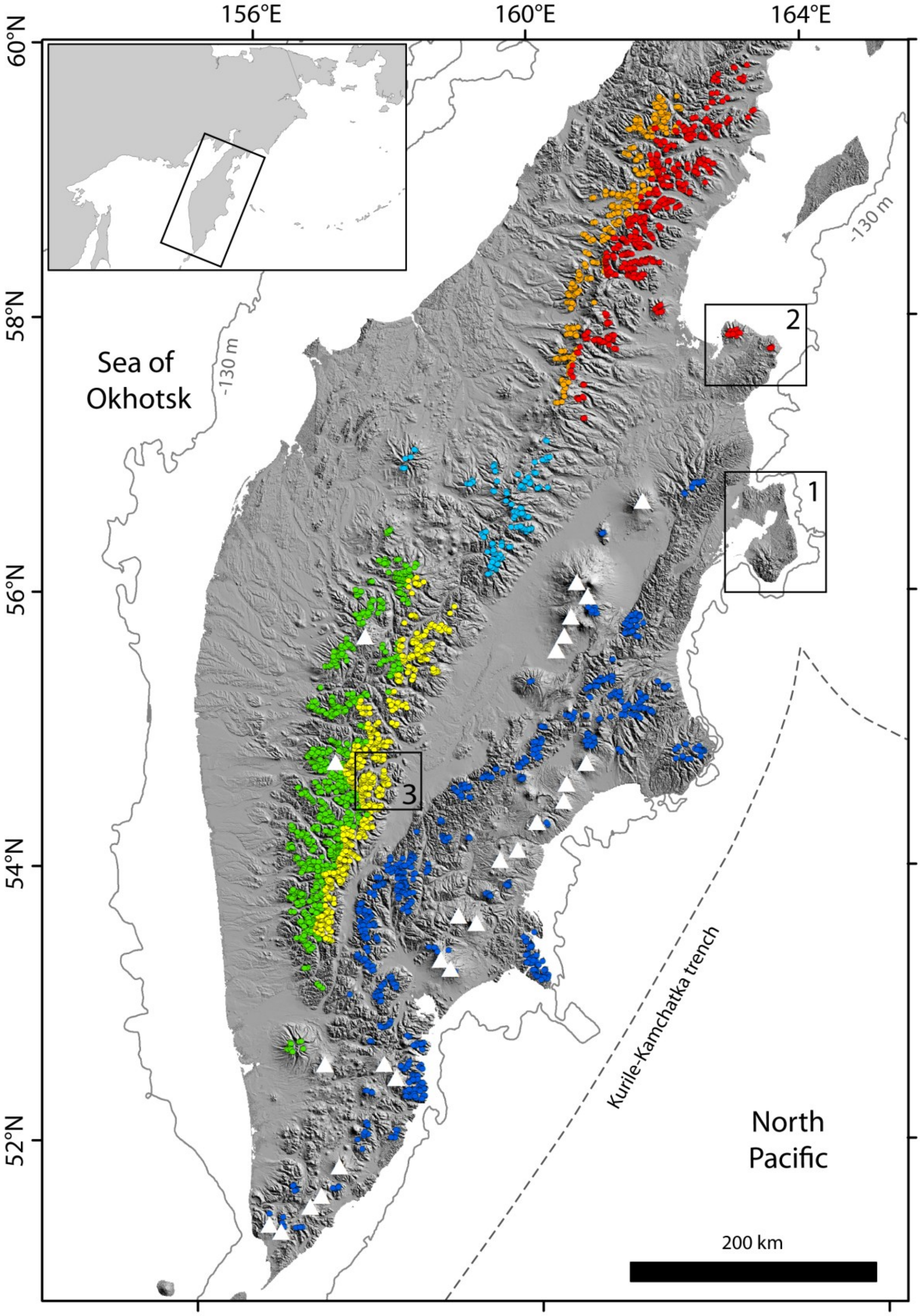

Fig. 1. Shaded relief map of the Kamchatka Peninsula. In this image, mapped cirques are shown as points, coloured according to region: NW Sredinny (orange), NE Sredinny (red), central Sredinny

(light blue), SW Sredinny (green), SE Sredinny (yellow), Vostočny and EVP (dark blue). Also shown are active volcanoes (white triangles) (from Avdeiko et al., 2007) and the LGM coastline (given a 130 m lowering of sea level relative to present). Boxed areas 1–3 are referred to in Table 6.

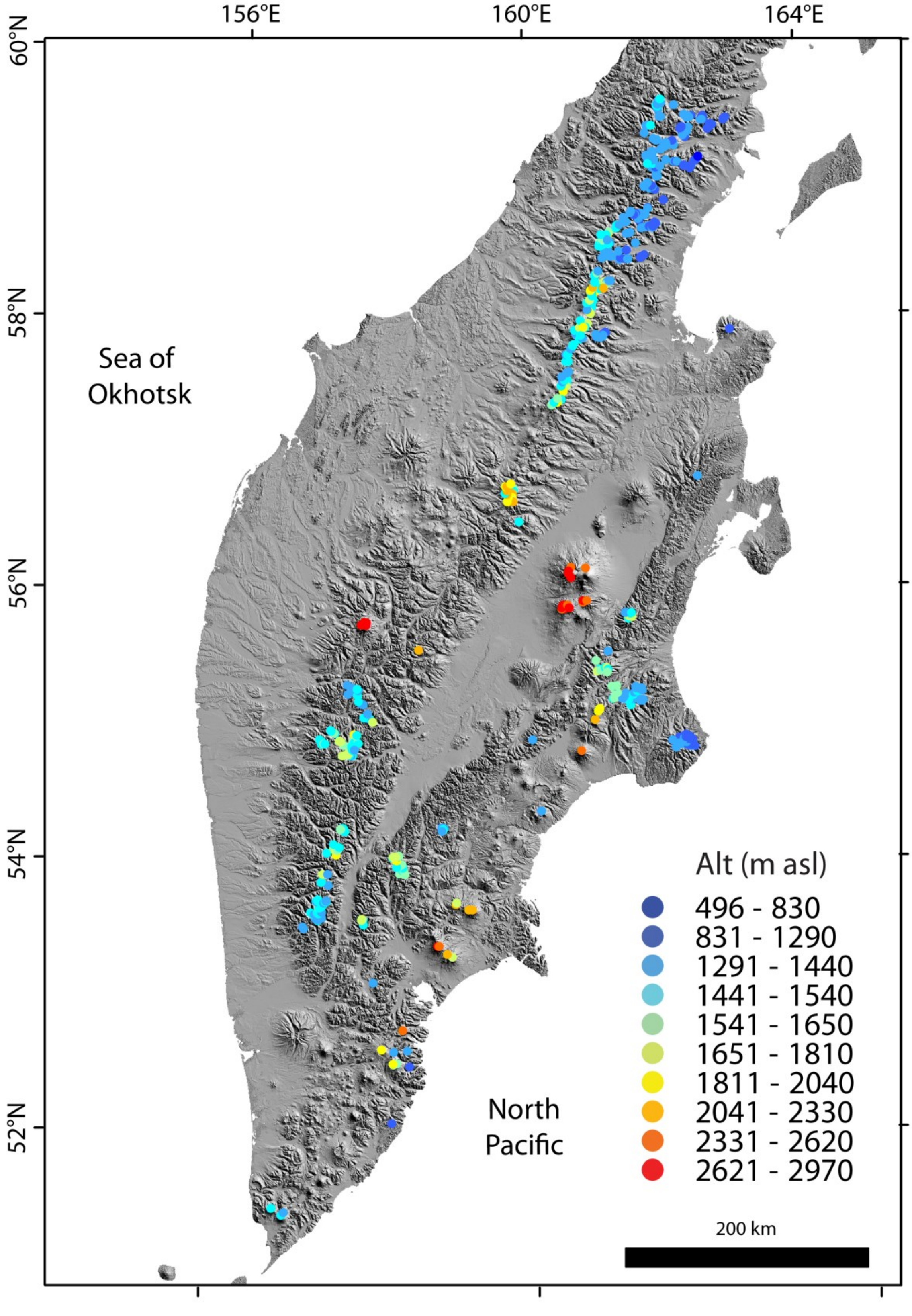

Fig. 2. Modern glaciers on the Kamchatka Peninsula, coloured according to their mid-altitudes.

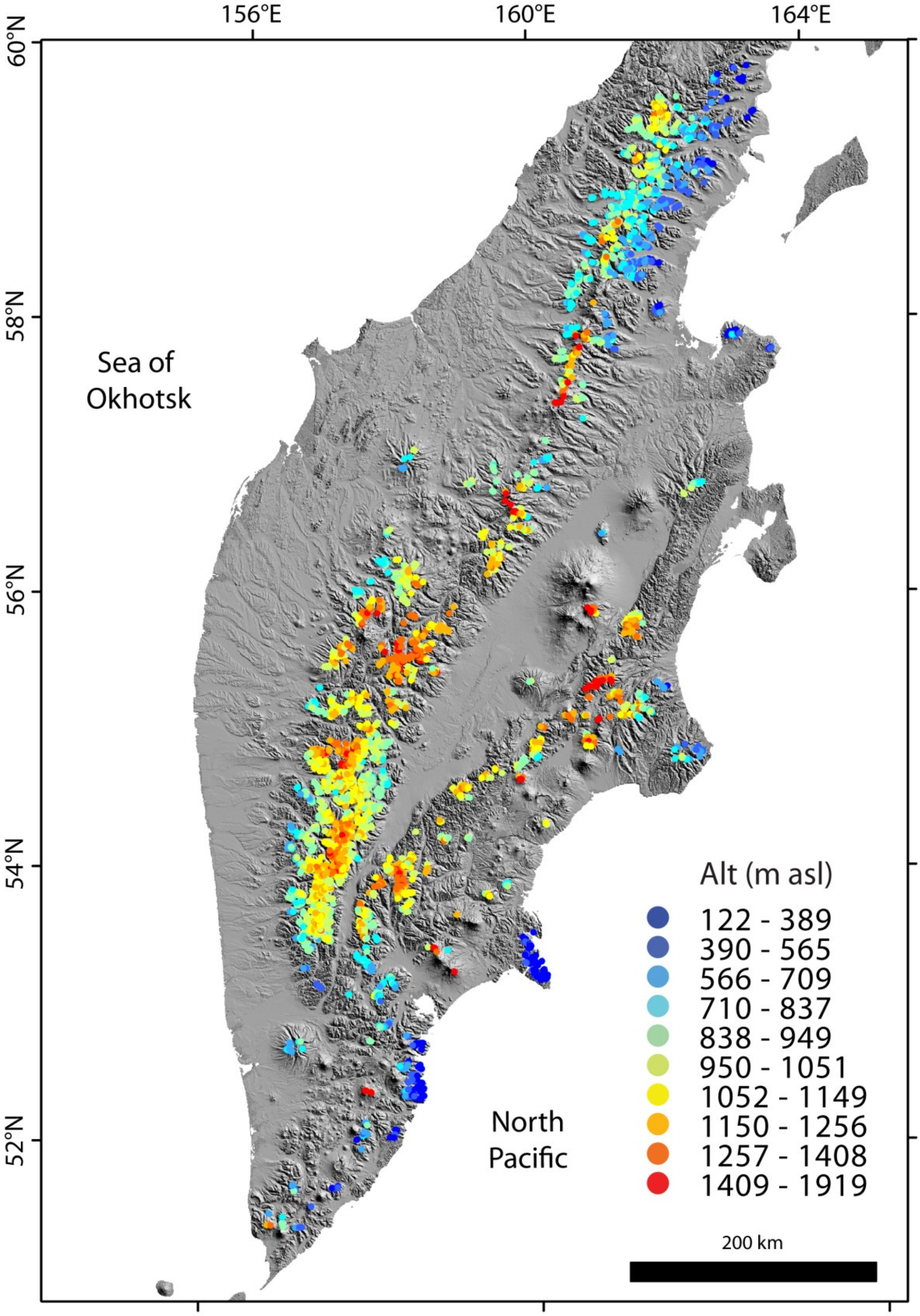

Fig. 3. Cirques on the Kamchatka Peninsula, coloured according to their floor altitudes.

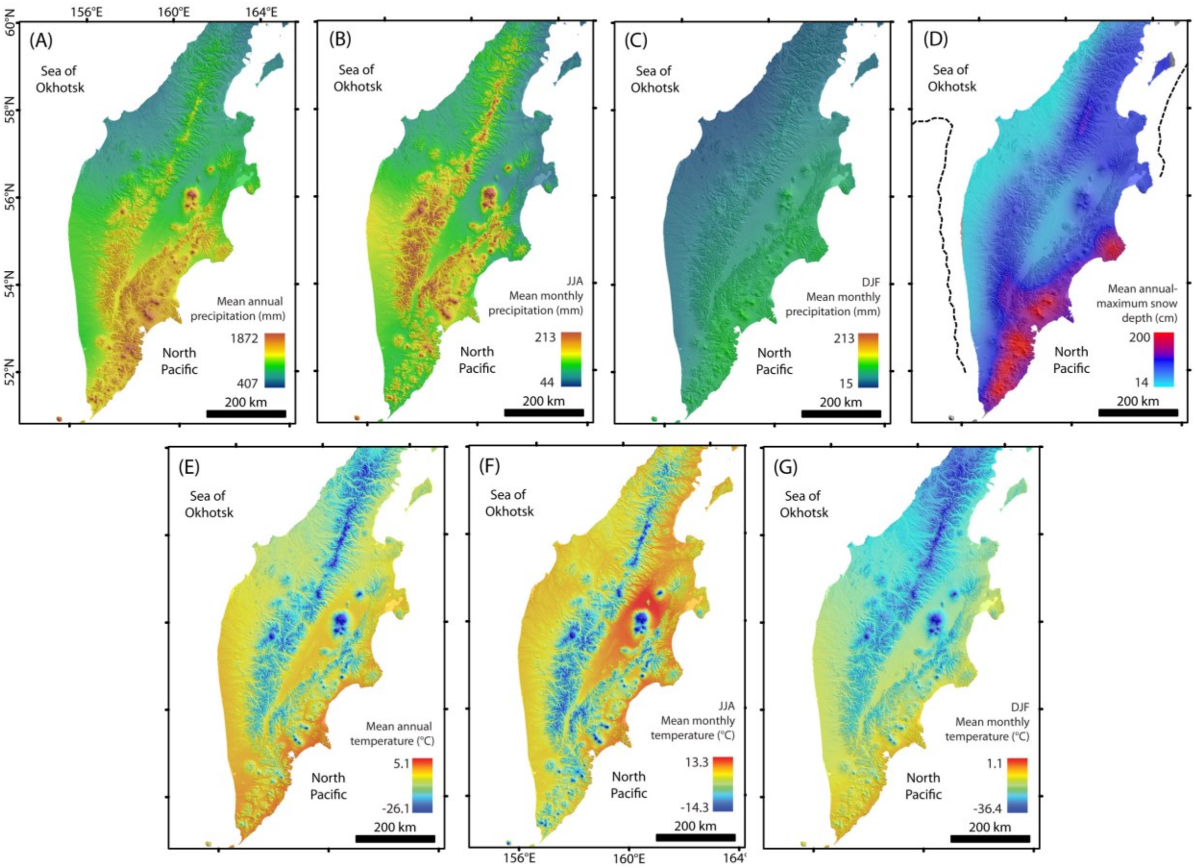

Fig. 4. Modern climatic conditions across the Kamchatka Peninsula. (A) Mean annual precipitation. Mean monthly precipitation during (B) June, July, August (JJA) and (C) December, January, February (DJF). (D) Mean annual-maximum snow depth for the 1961-1990 period. The dashed line here reflects the median sea ice extent during February (when sea ice is most extensive) for the 1979-2000 period (data from Fetterer et al., 2002). (E) Mean annual temperature. Mean monthly temperature during (F) JJA and (G) DJF. Precipitation and temperature data are from regional climate grids produced through interpolation between weather station data for the 1950-2000 period (see Hijmans et al., 2005). The snow depth map (D) is produced through interpolation of data presented by Matsumoto et al. (1997).

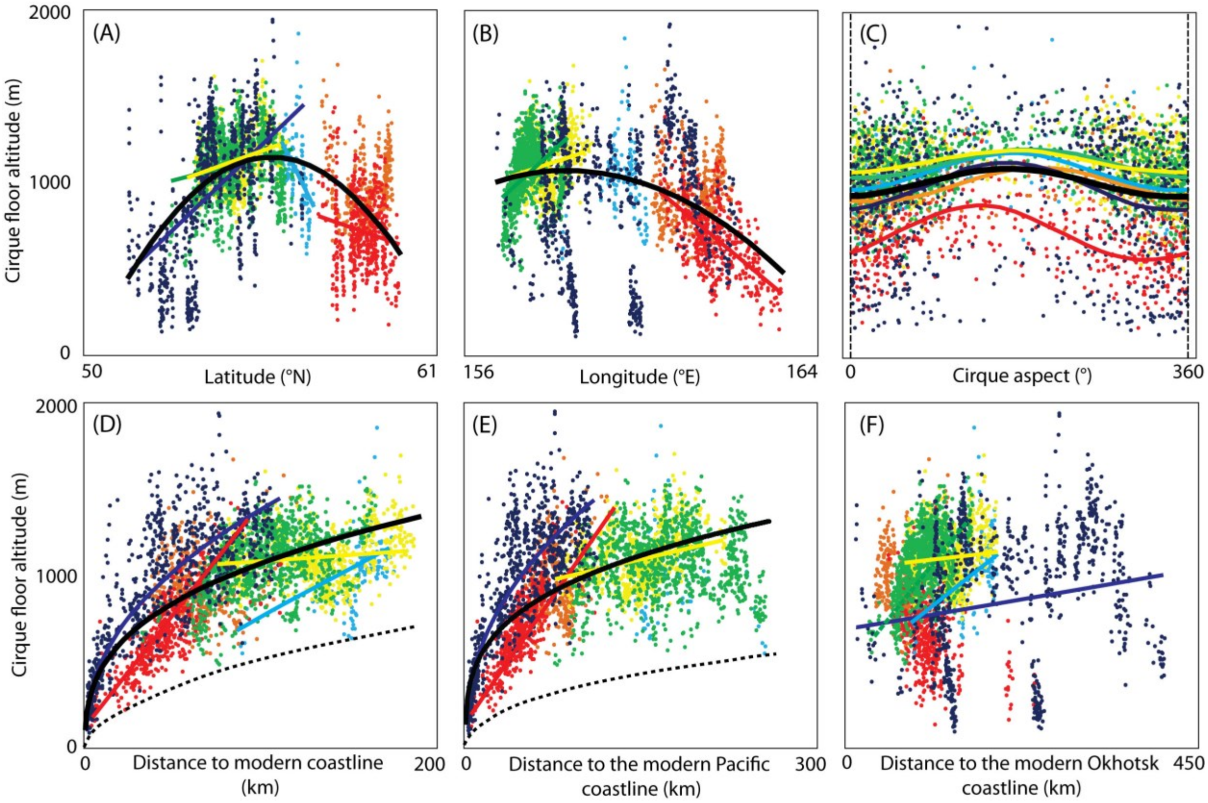

Fig. 5. Variations in cirque floor altitudes on the Kamchatka Peninsula, with (A) latitude; (B) longitude; (C) median axis aspect (analysis based on first-order Fourier regression, see Evans and Cox, 2005); (D) distance to the modern coastline (either the Pacific Ocean or the Okhotsk Sea, depending on which is the closer); (E) distance to modern Pacific coastline; and (F) distance to modern Okhotsk coastline. In each image, the solid black line reflects the trend surface for the entire cirque data set, whilst coloured lines reflect different cirque populations (lines are only shown where relationships are significant, i.e., $p < 0.001$). Colours correspond to regions shown in Fig. 1. The dashed black lines in (D) and (E) reflect apparent lower boundaries to cirque floor altitudes. Trends and r^2 values are presented in Tables 2, 3, and 4, for panels (A)–(B); (C); and (D)–(F), respectively

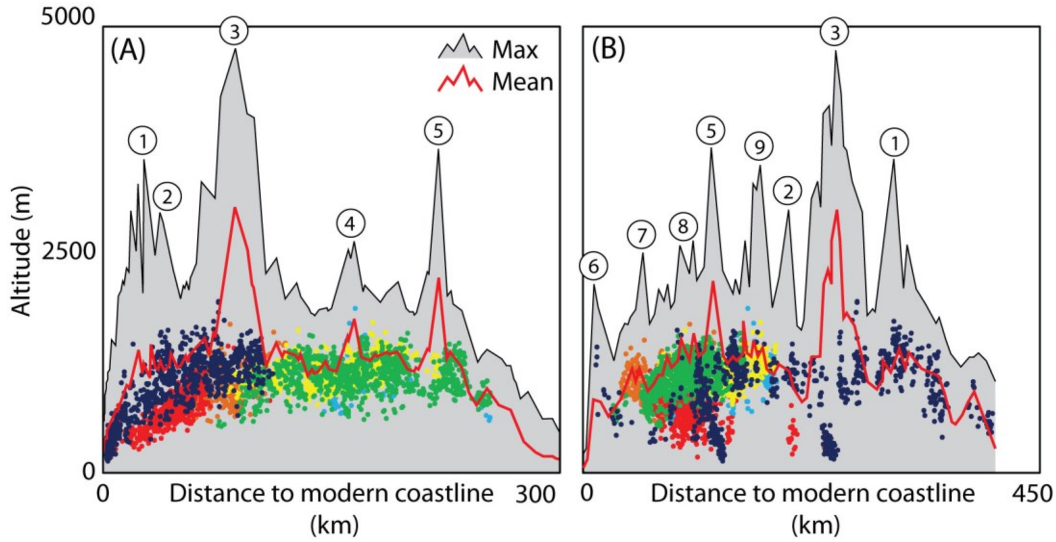

Fig. 6. Variations in cirque floor altitude (coloured dots) and topography (based on the mean and maximum altitude per 10 x 10 km grid), plotted relative to (A) the Pacific coastline and (B) the Okhotsk coastline. The cirque altitude data is the same as shown in Figs. 5E and 5F. Numbered peaks are volcanoes (or volcanic groups): (1) Kronotsky volcano; (2) Zhupanovsky volcano; (3) Klyuchevskoy volcano; (4) Alney volcanic group; (5) Ichinsky volcano; (6) Koshelev and Kambalny volcanoes; (7) Opala volcano; (8) Spokoiny volcano; (9) Kozelsky-Avachinsky-Koriaksky volcanic group. See Ponomareva et al. (2007) for details about these volcanoes.

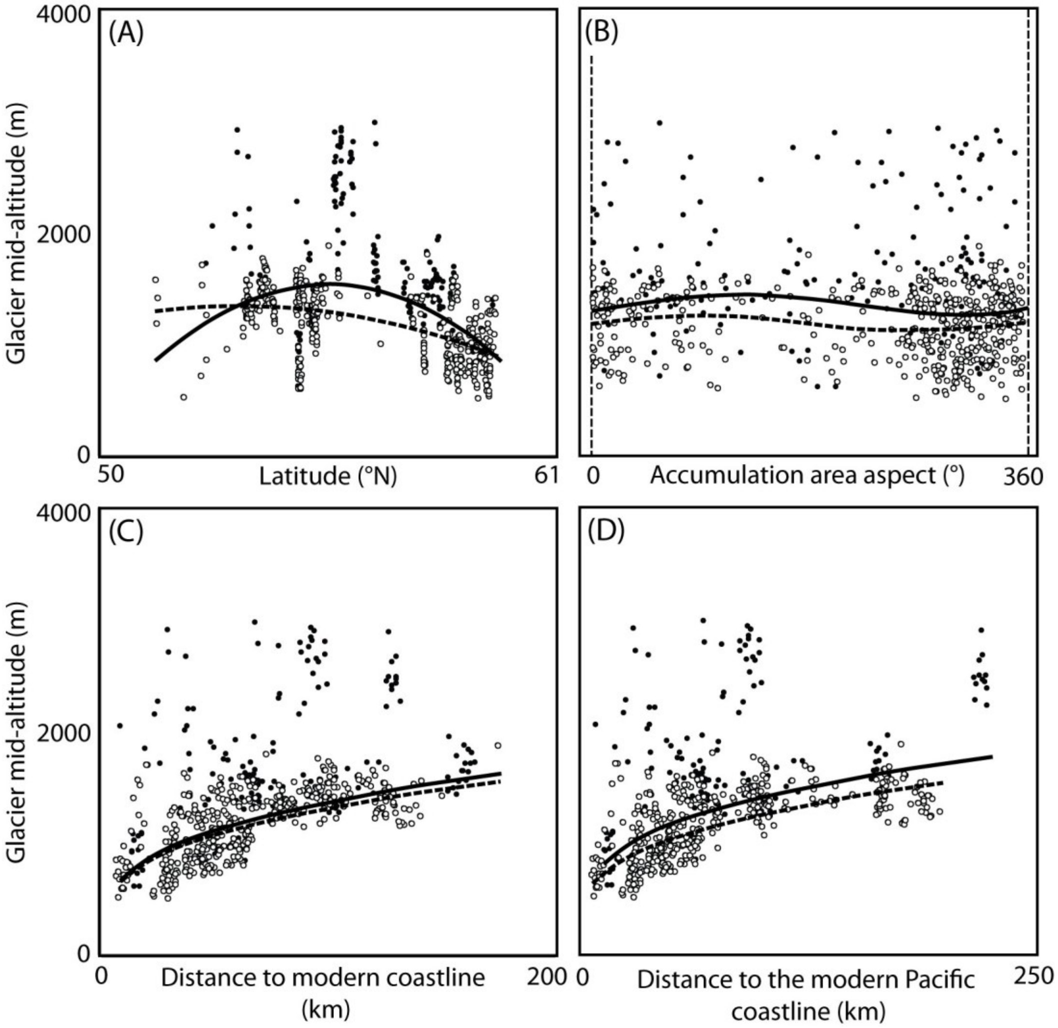

Fig. 7. Mid-altitude data from modern glaciers on the Kamchatka Peninsula, with (A) latitude, (B) accumulation area aspect, (C) distance to the modern coastline, and (D) distance to the modern Pacific coastline. In each figure, white dots reflect cirque-type glaciers (n = 361), whilst black dots are other (larger) ice masses (n = 142). The solid black lines reflect trend surfaces for the entire glacier data set, whilst dashed lines reflect tends for cirque-type glaciers alone. Trends and r^2 values are presented in Table 7.