

Manuscript Details

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Abstract

Regional scale studies of glacial cirque metrics provide key insights on the (palaeo)environment related to the formation of these erosional landforms. The growing availability of high resolution terrain models means that more glacial cirques can be identified and mapped in the future. However, the extraction of their metrics still largely relies on time consuming manual techniques or the combination of, more or less obsolete, GIS tools. In this paper, a newly coded toolbox is provided for the automated, and comparatively quick, extraction of 16 key glacial cirque metrics; including length, width, circularity, planar and 3D area, elevation, slope, aspect, plan closure and hypsometry. The set of tools, named ACME (Automated Cirque Metric Extraction), is coded in Python, runs in one of the most commonly used GIS packages (ArcGIS) and has a user friendly interface. A polygon layer of mapped cirques is required for all metrics, while a Digital Terrain Model and a point layer of cirque threshold midpoints are needed to run some of the tools. Results from ACME are comparable to those from other techniques and can be obtained rapidly, allowing large cirque datasets to be analysed and potentially important regional trends highlighted.

Keywords	glacial geomorphology; glacial cirque; morphometry; GIS
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Suggested reviewers	Sarah Principato, Marcel Mindrescu, Marc Oliva, Sara Mitchell, Magali Delmas, Kelly MacGregor, Clare Boston

Submission Files Included in this PDF

File Name [File Type]

Letter to the Editor.docx [Cover Letter]
Response to Reviewers.docx [Response to Reviewers]
ACME_7.doc [Manuscript File]
new_Figure_1.jpg [Figure]
Figure 2_new.jpg [Figure]
Figure_3_v3.jpg [Figure]
new_Fig 4.jpg [Figure]
Fig. 5.jpg [Figure]

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Berkeley, 15th of November 2016

Dear Dick,

On behalf of all co-authors, I would like to thank the reviewers for their hard work and overall positive feedback. I attach a document containing all reviewers' comments and suggestions (in blue) with details on how these have been addressed (in black). An updated manuscript has now been uploaded on EVISE. Please let me know if you prefer to use a copy of the revised manuscript with tracked changes, as I can easily send this to you via email (EVISE does not allow me to upload two *manuscript files*).

Should you decide to accept the manuscript for publication, I would like to briefly discuss how the tool could best be made available to readers (via a journal web page or as a supplementary material) as there is mention of this in the manuscript that will need to be edited accordingly. Also, I was wondering whether it would be possible to update the tool in the future, should any further improvement be made/needed (for example if a newer version of the software would require some minor editing of the tool for it work or if a minor bug is identified and fixed).

Thanks again,

Matteo

This document contains all reviewers' comments and suggestions (in blue) with details on how these have been addressed (in black).

-Reviewer 1

Congratulations to the authors for this excellent tool and paper.

This paper presents a very useful tool developed by the authors to infer several morphometric parameters characteristic of glacial cirques. Usually, these kind of studies were done manually and lately through GIS techniques. This new procedure will allow an automatic extraction of most of the commonly used parameters in a fast way that will facilitate comparisons of cirque metrics from large areas. For geomorphologists working in formerly glaciated environments, it will be also useful to understand the main factors (lithology, aspect, elevation, etc) controlling glacial cirque formation as well as to infer paleoclimate conditions.

The paper is very well written and properly organized. The description of the methods is accurate and detailed. The results are thoroughly presented and clearly separated from the discussion, with adequate and up-to-date bibliographic references. Figures are of good quality and necessary for the full comprehension of the work.

Two edits: l. 122 Space before (Fig. 3c), l. 253 "their"

Thanks for the very positive comments. The two edits have been implemented.

-Reviewer 2

This paper presents a new automated method for analyzing and quantifying cirques. The authors make a time consuming and laborious manual process computerized and greatly increase efficiency of measurements. The reproducibility of the results from Barr and Spagnolo (2013) are simply remarkable (Tables 1 & 2). I think that this tool will be useful to many geomorphologists, and personally, I am eager to try it out.

Thanks

I have a few, very minor comments.

1) The use of the term midpoint is a bit confusing (lines 90 – 94). Midpoint implies middle of the cirque, but I understand what they mean is threshold midpoint in this section. Perhaps they should consistently add the modifier of “threshold” before the word midpoint when needed. In the section about length and width, the term “the length line midpoint” (Line 104) is used, and I interpret this usage to mean the middle of the line.

“Threshold midpoint” is now substituting “midpoint” where relevant, throughout the manuscript.

2) The calculation of aspect is a bit unclear. What is meant by “vector values” (Line 146)—is it GIS term for vector format or common usage of vector meaning directional? Either way, this method of calculating aspect sounds a bit oversimplified, as usually aspect first requires the creation of an aspect raster, which is converted from degrees to radians. Then, cosine and sine rasters are created from the aspect raster, zonal statistics are exported to MS Excel and then arctan2 function is used to calculate an average aspect. I am sure that the authors already realize that it is impossible to take an average of measurements in degrees to calculate aspect.

The reviewer is correct, and the tool implements exactly the procedure s/he describes but all within ArcGis (no need to export data to Excel anymore!). We have now clarified the technique with the following sentence that describes how “aspect mean” is calculated: ...*“The tool returns the mean of all pixel aspects by converting these into radians, extracting the mean sine and cosine of these values, calculating the arctangent of the ratio between mean sine and mean cosine, then finally converting back into degrees.”*

3) Figure 2 is very busy. Perhaps the relevant information should be moved to the text and consider simplifying or deleting this figure?

We believe it is important to show this figure as readers would immediately match this with what they see on their screen after opening the tool. We agree that the figure is a bit busy, but the only way to simplify this would be to split into four distinct figures, which we believe would impinge on the flow of the article.

4) One last minor comment, I wonder if the authors considered other acronyms for this tool? ACME is a very commonly used acronym (from cartoons to corporations), and it might be better to choose a different acronym.

Yes, other acronyms were considered, but we could not find anything as simple and straightforward as ACME. ACME is also synonym of peak, which we found very pertinent given the subject of this paper. As far we know, this is the only ACME used in glaciology, and possibly geomorphology. We know it refers to cartoons too, but we feel that this does not subtract to the value of our tool.

-Reviewer 3

The manuscript describes the development of a new GIS tool for automatically extracting cirque metrics. This tool will make a valuable contribution to the discipline and save researchers a significant amount of time extracting this kind of data.

Overall the manuscript is well-written, but there are a few areas where there is repetition. I think some phrases, such as those regarding units, could just be written once at the start. There are also a number of areas where there is too much descriptive detail that I’m not convinced is needed. For example, Lines 105 to 108 and 115 to 118 make the article seem more like a user manual. Some of the information here fairly self-explanatory for any GIS user, and this is information that could be written in the ‘Tool Help’ dialogue box of the tool (it may already be there) as shown in Figure 2. Repetitions, including those relating to the

units, have now been carefully removed. Otherwise, we fully appreciate the manuscript is descriptive in places but we are reluctant to enact further reductions. This is because for many first time GIS users, and specifically students, it will be a lot easier to have a full set of instructions in the main text of the paper, along with those already provided in the Tool Help.

Section 4 “Tools test” is rather descriptive, and whilst I realise that the point of the paper is to describe the GIS tool and test its reliability, I wonder if more could be made of this section? The variable cirque width may warrant further discussion for example because the tool seems to measure cirque width in a different way to the Barr and Spagnolo (2013) dataset. What is the most common way to measure cirque width. Would the different ways in which width is defined have any effect on interpretations that are made or affect comparability with other studies for instance? The following has now been added to this section: ...“*meaning that their width measurements are consistently greater than those calculated using ACME (based on the line perpendicular to the length line and intersecting the length line midpoint). There is currently no consensus on how best to measure cirque width (Barr and Spagnolo, 2015), but given that differences between estimates are typically in the order of 10s of meters (when cirques are 100s of meters wide), this has little impact on interpretations made from the cirque record.*”.

Minor/specific comments

Line 16: the first sentence in the abstract needs re-phrasing – “where these erosional landforms formed and developed” doesn’t seem to fit. The sentence has now been rewritten.

Line 43: include further references e.g. Evans, 1977; Mindrescu et al 2010. These references have been added.

Line 79: repetition. The earlier occurrence of this repetition (in the introduction) has been removed.

Line 90: Midpoint of what? Should this be “threshold midpoint”. This has now been modified. The sentence also needs to be adjusted to make it clear in the first instance that the user has to define the mid point. Figure 1 should also be referred to here. Maybe adjust to “A threshold midpoint (point shapefile) is required and can be identified...” A reference to Fig. 1 and 3a has been added. Users are told that this is a user-defined variable two sentences above. I think more details on the midpoint and how that is derived is quite important, as it has implications for calculating length and width in section 2.2. An extra sentence explaining how the threshold midpoint can be identified has been added.

Line 97: not sure Fig 1 is that appropriate here. The reference to Fig. 1 has been removed.

Line 102: Figure numbering is in the wrong order. An earlier reference to Fig. 3a has now been included so that the order of figures is now correct.

Line 112: repetition. The earlier occurrence of this repetition has been removed.

Line 133: “Results are stored in the attribute table” – could this just be written at the start to avoid repetition. Done.

Line 137: for the Z_min, Z_max, Z_range and Z_mean statistics (also, length width etc), where the edge of the polygon is defined in relation to the cirque backwall is also quite critical. Can there be further information on this in Section 2.1? It is not the intention of this paper to discuss how different ways of mapping cirques would lead to slightly different results. However, the point is fair and we have now added a few sentences that clarify how cirques are mapped: ... *“Cirques are typically characterised by an overdeepened floor and a steep headwall. The perimeter of the cirque polygon will pass by: (i) the break of slope that delimits a cirque’s downvalley extent, i.e. the cirque threshold; (ii) the spurs that delimit a cirque laterally and which are often curving inward downvalley; and (iii) the break of slope that could be present on the upper portion of the cirque headwall, upvalley. However, as (iii) is often difficult to identify, an easier approach, and one that can guarantee more consistency in a large cirque mapping exercise, is to delimit the cirque upvalley along the crestline above the headwall.”*

Line 143: How useful is this, as it will be an average of some rather steep areas and some rather flat areas? Would separating backwall gradient and cirque floor gradient be more useful? It would, but such separation would be somewhat subjective and cannot be automatically implemented in the GIS environment. Should an expert user be willing to extract these specific metrics, each cirque could be manually split into the two components and the tool be run for both separately.

Section 2.5. This section could be condensed. We have now removed two repetitive sentences but we are unwilling to make further cuts as this might be the first time some readers explore these metrics.

Line 160: repetition. This sentence has now been removed.

Line 194: “and, specifically, cloudiness” i.e..... I think you need to briefly explain why. We have now included a few more words to explain what it is meant by cloudiness.

Lines 236 to 249: I think much of this could go earlier/be removed as it goes into instruction mode again. The last two sentences of this section has been moved to the description of the hypsometry tool

Lines 260: “some of these [metrics] require only...). ‘Metrics’ has been added.

Lines 265 to 266: The sentence implies that the metrics themselves will reveal insights, which is not true as the metrics require interpretation. Re-word the sentence as follows? “These metrics provide the potential to assess environmental conditions under which cirques are formed, including climate, offering important insight.” The sentence has been changed into: ... *“The interpretation of these metrics can reveal important insights into the environmental conditions under which cirques are formed, including climate.”*

Table 2: I don’t understand the relevance of (GIS tool) and (topo). These are not the headings used in the table. This has been corrected

Figure 1: Is an ArcGIS screen shot necessary here? Particularly as there is one for Figure 2. The figure could focus more on how the cirque outline polygon and threshold midpoint are defined. The first line of the figure caption could be moved to Figure 2. The figure has been modified following this suggestion

Figure 2: there is repetition in this figure caption with what is in the main text. This is intentional as some readers, unfortunately, will not read the text and simply look at figures, so we wanted these to be as self-explanatory as possible.

Figure 4. Should the two figures be labelled as A and B and referred to as so in the figure caption? Fig. 4 is now labelled 'a' and 'b', and the figure caption has been modified accordingly.

Figure 5. The figure caption needs to explain the differences between the two graphs. An extra explanatory sentence has been added to the figure caption: ...*‘Both the hypsometric maximum (in A) and the hypsometric integral (in B) increase with the elevation intervals and decrease with the number of intervals.’*

Clare Boston

-Reviewer 4

This Short Communications manuscript presents a new ArcGIS-based tool for quickly and uniformly measuring a variety of cirque metrics, including length, width, elevation statistics, and more. As this is not a standard research paper (it does not have a hypothesis or present original data), I will instead focus on 1) the description of the tool as presented in the manuscript, 2) the value of such a toolbox for the scientific community, and 3) the quality and ease of use of the ACME toolbox itself.

- 1) I found this manuscript to be easy to read, and it was clear what the tool is meant for. I have several relatively minor suggestions for improvements.
 - a. First, would it be possible to list at least a few of the metrics in the abstract? This will be how people search out this paper, and by putting the most important metrics in the abstract, people will have a better chance of finding it. The abstract now specifically list some of the key metrics.
 - b. The authors should also consider moving the “Application of the metrics” section to the Introduction... this is the section which describes why these metrics are important, and set the stage nicely for the descriptions that come in the toolbox descriptions. Up until that point, the manuscript reads a lot like, “here are things we can measure in cirques because we can.” This has been done.
 - c. Regarding the figures, is there some way to combine the information in Figures 1 and 2? They both show the operating window, one with the toolboxes open and one without. It seems like with some rearranging, the cirques could still be seen in a window with all the toolboxes open. Figure 1 and 2 were largely showing the same things, as also highlighted by Clare Boston. Thus, we have decided to combine them and use Figure 1 for a clearer representation of how a cirque could be mapped and to illustrate the basic requirements for the tools to operate.
 - d. Figure 3 is the most important figure, showing what the metric measurements actually are. I don't know if Figure 4 is as effective—a figure that showed more of a comparison between ACME and a manual measurement of one of the metrics might be better. We agree that Figure 4 is not crucial but, unless there is a limitation as to the number of figures we must use, we would rather keep it, as it is a reminder that we are not simply dealing with numbers and statistics but with actual landforms. The idea of adding an

extra figure that further stresses the differences between ACME results and those from the Barr and Spagnolo (2013) paper is good. However, differences between ACME and Barr and Spagnolo (2013) are minimal (typically in the order of 10s of metres), and we can't think of any easy way to represent this in a figure. For this reason, we prefer not to implement this suggestion.

- e. [Some minor editing comments: there was at least one minor typo \(line 253\)](#). This has been fixed.
 - f. [and the authors need to define DTM at first use](#). DTM is now defined in the introduction.
- 2) [This will be a useful ArcGIS toolbox for people who have already digitized their cirques](#). These are useful metrics and having a way to quickly generate them will be helpful to the community. What this paper provides that most user-generated online ArcGIS toolboxes do not is a test of the validity. I was hoping that this toolbox would include a “cirque finder,” because systematically and consistently identifying and then delineating cirques is surprisingly difficult, ambiguous, and time consuming. More detailed instructions or at least some advice on how to identify and delineate a cirque and a threshold midpoint would help researchers generate reproducible results. We would also like to provide a cirque finder tool, but this is something that would require some years of dedicated work, and we remain unsure as to whether this is feasible at all. We agree though that a little more description on how cirques can be identified is necessary, and a few sentences have now been added to section 3.1 along with a dedicated new Figure 1, also following comments by other reviewers.
- 3) [I was able to download ACME from the EVISE journal reviewer page and have spent an afternoon playing around with it](#). The toolbox was easy to download and install and load in ArcGIS. It looks just like it does in Figure 2. This toolbox was simple and straightforward to use; I would feel comfortable asking undergraduates to use it either in research projects or as part of a GIS-based lab activity. I did run into a couple of issues, however.
- a. [First, while I don't have time to run all of the statistics “from scratch” for my own test cirque file, but I was curious about the results I got for the length and width tool \(1\)](#). For one of my three cirques, the tool seemed to calculate an unreasonably high width, about 10 times higher than what it should be. I digitized my test file of cirques and their midpoints very quickly, and this particular cirque was highly elongated, so it is possible there is something funky about the shapefiles I fed the program. I don't suppose there is any possibility of the program letting the user see the length and width lines on top of the cirque? This failure to accurately calculate one of the widths is my biggest concern about the toolbox. As explained in section 3.2. ... *“Both length and width lines are stored as separate shapefiles (‘cirque_length’ and ‘cirque_width’) in a user-defined destination folder.”* Users can therefore easily check odd values. We have now used the tool with thousands of cirques and haven't encountered any issue. In order to obtain a width that is 10 times higher than the length we suspect the user has been experimenting with a cirque that was not only very elongated, but also curving. Realistically, cirques should always be relatively circular in shape and certainly not curving. In our experience, we cannot recall a single cirque with such a shape. However, we have now specified this ‘limitation’ when describing the length and width tool: ... *“The tool is designed to work with features that agree with the classic definition of cirques, i.e., features with a sub-circular or semi-circular plan shape, that encompasses an arcuate headwall and an open down-valley extent (Evans and Cox, 1974). The tool will work with more complex shapes, but should not be relied upon for*

curving, elongated features, though given the definition above, such features are unlikely to be cirques.”

- b. Second, for two of the tools (2 and 3), I had to run the tool twice... the first time I ran these tools, the new fields in the cirque shapefile attribute table were populated with zeros. It worked properly on the second time in both situations. I'm not sure if it just took an extra few seconds to load the data into the attribute table, or if it would have worked if I had closed and reopened the attribute table window, but this happened twice. We have now added the following sentences in section 3.1: ... *“If the attribute table is open when the tools run, the values are not updated on the screen. The tools either need to run with the attribute table closed, or the table needs to be closed after the tool has finished working and then re-opened.”*
- c. Finally, for their description of the slope tool, they should also specify that the Z units must be the same as the map units or else a conversion is necessary (I occasionally work with DEMs with decimeter Z units... this allows for 0.1 m accuracy in an integer grid). We have now stated upfront in section 3.1 that, when a metric has a unit, this is the same as that of the map units.
- d. Or, perhaps there could be both a percent and a degree output for slope (it's just a little easier to convert a percent). In the literature, cirque slope is always/usually described and discussed in degrees. We therefore prefer to keep the outcome of slope calculation in this conventional unit.

My overall recommendation is to accept this paper with moderate revisions. Most importantly, they need to test the length-width tool and ensure it is working properly, even with oddly shaped cirques. I also have provided relatively minor suggestions for organization and figures.

Finally, we have recently (and successfully) run ACME over a very large number of mapped cirques. While we have verified that the tool can run smoothly even when applied to large databases, we have also discovered a minor issue in relation to the calculation of the Area_3D. For this reason, we have added the following to the description of the Area_3D metric: ... *“The tool is based on an ArcGIS functionality (called ‘Surface Volume’) that will calculate the area only for pixels that are at least 50% within the boundary of the cirque polygon. Thus, a number of boundary pixels might not be included in the calculation, meaning that the tool would underestimate the real Area_3D. This is an issue of some relevance when the resolution of the DTM is coarse (e.g. 30 m) and cirques are very small (e.g. <100,000 m²), because the relative number and size of boundary pixels that might be disregarded is large. In exceptional circumstances, the underestimated Area_3D could (erroneously) be lower than Area_2D, the calculation of which is exact and not affected by this boundary pixels issue. When high resolution DTMs are not available, ACME users could consider resampling the coarse-resolution DTM to a higher resolution (e.g. 5 m).”*

ACME, a GIS tool for Automated Cirque Metric Extraction

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Keywords: glacial geomorphology; glacial cirque; morphometry; GIS; hypsometry; metrics

Abstract

Regional scale studies of glacial cirque metrics provide key insights on the (palaeo)environment related to the formation of these erosional landforms. The growing availability of high resolution terrain models means that more glacial cirques can be identified and mapped in the future. However, the extraction of their metrics still largely relies on time consuming manual techniques or the combination of, more or less obsolete, GIS tools. In this paper, a newly coded toolbox is provided for the automated, and comparatively quick, extraction of 16 key glacial cirque metrics; including length, width, circularity, planar and 3D area, elevation, slope, aspect, plan closure and hypsometry. The set of tools, named ACME (Automated Cirque Metric Extraction), is coded in Python, runs in one of the most commonly used GIS packages (ArcGIS) and has a user friendly interface. A polygon layer of mapped cirques is required for all metrics, while a Digital Terrain Model and a point layer of cirque threshold midpoints are needed to run some of the tools. Results from ACME are comparable to those from other techniques and can be obtained rapidly, allowing large cirque datasets to be analysed and potentially important regional trends highlighted.

1. Introduction

Glacial cirques are armchair-shaped hollows, open down-valley and bounded up-valley by a steep slope (Evans and Cox, 1974). Cirques are carved by relatively small glaciers, usually confined to the uppermost elevations of a landscape and are typical of alpine landscapes (Gastaldi, 1873). Cirque

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62 sizes and shapes have been proved to reveal important clues regarding the palaeoenvironment
63 these landforms developed in, and they can shed light on the dynamics of glacier-bed interaction in
64 alpine settings (Barr and Spagnolo, 2015 and references therein). For example, cirque aspect
65 provides information about the extent and magnitude of past glaciations as well as past variations in
66 solar radiation and prevailing wind directions (Derbyshire and Evans, 1976; Nelson and Jackson,
67 2003; Evans, 2006). However, the study of individual landform metrics is not particularly insightful
68 and only the analysis of large populations reveals meaningful patterns (e.g. Evans, 1977; Mindrescu
69 et al., 2010; Mitchell and Humphries, 2015), but these are hampered by the limited availability of
70 time-efficient tools able to cope with large databases.

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76 The history of publications on cirque metrics, a term used here to describe both shape and size, is
77 many decades long (e.g. Evans, 1977) and the literature is vast (see Table 4 in Barr and Spagnolo,
78 2015). From the days when scientists used rulers and protractors on topographic maps (e.g. Temple,
79 1965), and likely spent hours measuring the size and shape of a single glacial cirque, spatial analysis
80 technology has advanced considerably. Many recent papers, in particular, have started to take full
81 advantage of high resolution Digital Terrain Models (DTM) and Geographical Information Systems
82 (GIS), allowing for rapid and improved analyses of cirque size and shape from large datasets (e.g.
83 Anders et al., 2010; Principato and Lee, 2014). However, each metric analysed often requires a
84 separate tool, or a combination of tools, that are not necessarily easy to find, implement, and
85 combine for non-GIS experts. Most importantly, a number of metrics recommended for, and
86 traditionally used in, the study of glacial cirques cannot be calculated in a GIS environment because,
87 until now, a GIS tool specific for the task had not been developed.

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96 In this paper, we consider the most fundamental cirque metrics and present GIS tools designed for
97 their automatic calculation, provided a minimum number of inputs are available. The tools are all
98 packaged within a single toolbox, ACME (Automated Cirque Metric Extraction). The use of ACME
99 improves the speed and quality of studies on cirque metrics, allowing very large populations of
100 mapped cirques to be analysed and important regional-, and perhaps continental-scale, patterns to
101 be discovered.

102 103 104 105 106 107 108 **2. Application of cirque metrics analyses**

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110 All output metrics derived from ACME, which will be described in detail in section 3, can be, and
111 have been, used to understand the temporal evolution of cirques and the glaciers that formed them.
112 Importantly, these metrics and their spatial/geographical variability can help identify the dominant
113 processes that have contributed to the formation of these landforms and decipher
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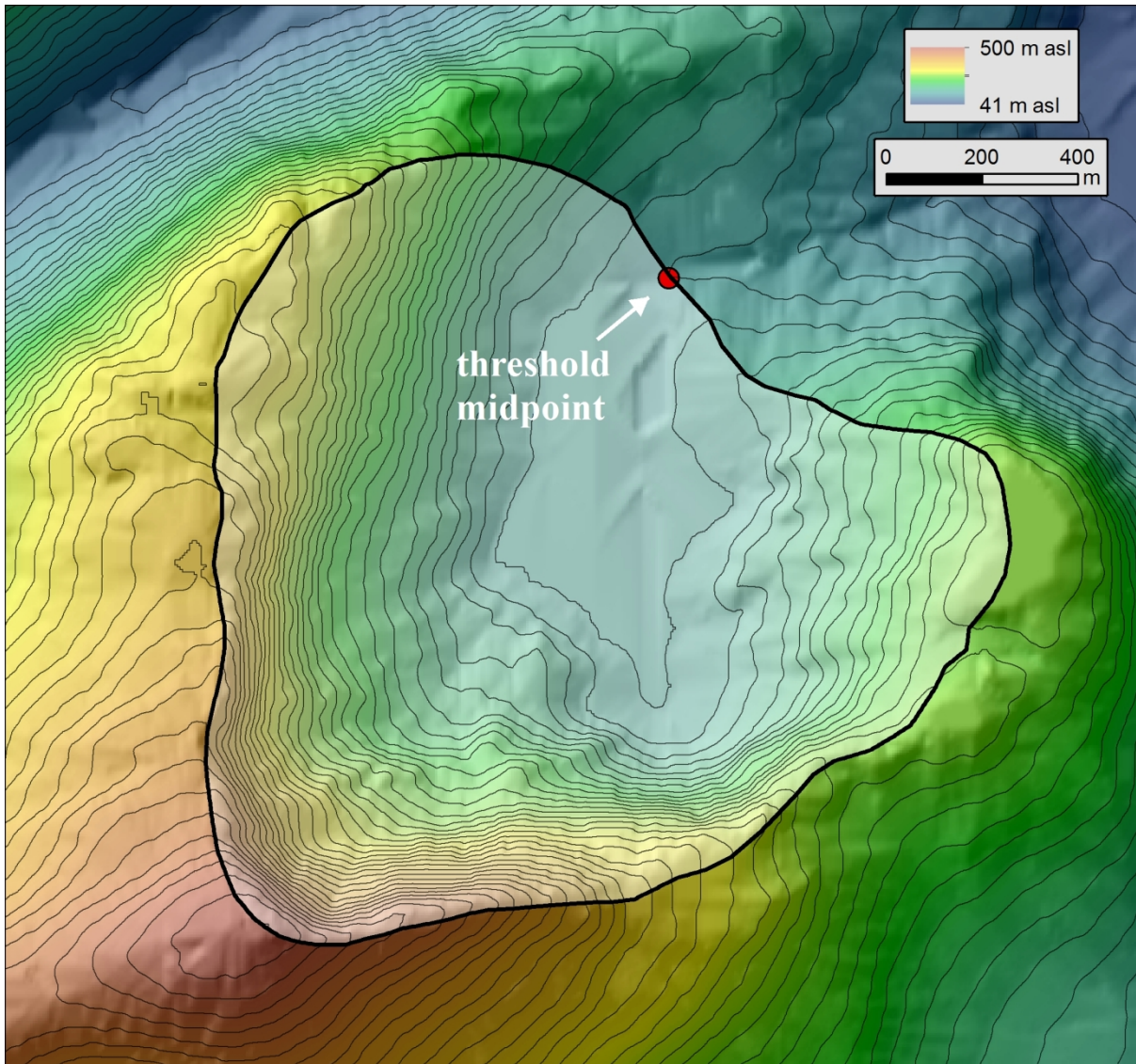
119 (palaeo)environmental, including climatic, factors that have affected the glacial history of specific
120 regions.
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124 For example, cirque length, width, height, perimeter, area and circularity are used to measure
125 different stages of cirque development (Bathrellos et al., 2014) or whether cirques have been mostly
126 occupied by cirque glaciers rather than valley glaciers (Damiani and Panuzzi, 1987). The geographical
127 variations of these metrics in relation to aspect have also been used to infer different styles of glacial
128 activity (Barr and Spagnolo, 2013) as well as the influence of periglacial processes on cirque
129 development (Delmas, 2015). Aspect in itself can be analysed to understand past patterns in solar
130 radiation and, specifically, differential cloudiness between morning and afternoon (Evans, 1977,
131 2006). It is also an important metric to understand the impact of prevailing wind directions (Křížek
132 and Mida, 2013) and the extent of former glaciations (Nelson and Jackson, 2003). Plan closure
133 (Plan_clos) can be used to evaluate cirque development, with the assumption that a less enclosed
134 cirque (i.e. smaller plan closure) might indicate an early stage of development (Mîndrescu and Evans,
135 2014). Studies on the spatial variability in cirque elevation metrics can reveal a number of
136 palaeoenvironmental aspect, including past precipitation gradients (Peterson and Robinson, 1969).
137 Spatial trends in any of the ACME output metrics in relation to lithology, structure and tectonics can
138 also be used to understand geological controls on cirque development and post-glacial modifications
139 (Principato and Lee, 2014). Finally, the study of hypsometric variables, when compared to former
140 equilibrium line altitudes, has been used to test feedbacks between glacial erosion and uplift in
141 mountainous regions worldwide (Foster et al., 2008, Egholm et al., 2009, Barr and Spagnolo, 2014).
142 An in-depth review of previous studies on cirque metrics and a full list of pertinent references can be
143 found in Barr and Spagnolo (2015).
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156 157 **3. Description of the tools** 158

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160 ACME is subdivided into four tools: (1) length and width; (2) perimeter, area and circularity; (3) 3D
161 statistics; and (4) hypsometry (Fig. 1). This subdivision allows users to derive specific metrics
162 separately, as the more metrics that are analysed together the longer a single tool will take to run.
163 The tools require different inputs and extensions and operate with scripts of various levels of
164 complexity. Tools (1) and (2) can be used to study any cirque, while tools (3) and (4), for which
165 ArcGIS Spatial Analyst and 3D Analyst extensions are required, are best suited for unglaciated
166 cirques or those where the subglacial topography is known. Once downloaded, ACME can be added
167 as a new Toolbox to the ArcToolbox list within an ArcGIS session (ArcMap). All tools are coded in
168 Python and their use is described in detail below, after a short introduction of the required inputs.
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180 The tools can be freely downloaded from the journal webpage through the link provided at the end
181 of this paper.
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220 Fig. 1. An example of a cirque in Ireland showing the inputs required for ACME to work. All tools need cirques to be
221 mapped as polygons (in this example the cirque polygon is delimited by the thick black line). The length and width tool
222 requires cirque threshold midpoints (the red dot in this example), while a terrain model is needed in the 3D statistics and
223 hypsometry tools. In this figure, contours are every 10 m of elevation.
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226 227 228 3.1. Input requirements

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230 Users might apply different techniques and map cirques from varying sources (e.g. a DTM or a
231 satellite image) using different GIS software. For ACME to work, all cirques, for which the metrics are
232 sought, need to be mapped as polygons and saved as an ESRI polygon feature class (either shapefile
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239 or geodatabase polygon feature class) (Fig. 1). Cirques are typically characterised by an
240 overdeepened floor and a steep headwall. The perimeter of the cirque polygon will pass through: (i)
241 the break of slope that delimits a cirque's downvalley extent, i.e. the cirque threshold; (ii) the spurs
242 that delimit a cirque laterally and which are often curving inward downvalley; and (iii) the break of
243 slope that could be present on the upper portion of the cirque headwall, upvalley. As (iii) is often
244 difficult to identify, an easier approach, and one that can guarantee more consistency in a large
245 cirque mapping exercise, is to delimit the cirque upvalley along the crestline above the headwall (Fig.
246 1). The four ACME tools will generate and populate the following fields in the attribute table of the
247 cirque polygon feature class: 'L', 'W' and 'L/W' from tool (1); 'Perimeter', 'Area_2D' and 'Circular'
248 from tool (2), 'Z_min', 'Z_max', 'Z_range', 'Z_mean', 'Area_3D', 'Slope_mean', 'Aspect_mean' and
249 'Plan_closure' from tool (3); 'hypso_max' and 'HI' from tool (4). These metrics are described in detail
250 in sections 2.2 to 2.5. If the attribute table is open when the tools run, the values are not updated on
251 the screen. The tools either needs to run with the attribute table closed, or the table needs to be
252 closed and re-opened after the tool has finished working. When these metrics have a unit, this is
253 always the same as that of the ArcMap project and can be checked in the Data Frame Properties.
254 The only exceptions are slope, aspect and plan closure metrics which are in degrees.
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265 In order to obtain cirque length and width, an ESRI point feature class (either shapefile or
266 geodatabase point feature class) of cirque threshold midpoints must also be provided (Fig. 1). A
267 glacial cirque threshold usually corresponds to the cirque frontal moraine or the rock lip or edge (i.e.
268 break of slope) that separates the cirque overdeepening upvalley from the glacial valley below. The
269 threshold midpoint of a cirque can be identified manually by roughly estimating its location half way
270 along the frontal moraine or bedrock sill that typically delimits the cirque down-valley (Fig.1 and Fig.
271 3a). It can also be automatically extracted using a GIS tool, such as the ArcGIS Feature to Point
272 (imposing 'inside' as an option), if the moraine or bedrock sill has been previously mapped as a line.
273 A terrain model in raster format, such as a DTM, DEM or DSM, is required in order to run the 3D
274 metrics statistics and hypsometry tools. All three inputs need to be in the same, projected,
275 coordinate system.
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285 3.2 Length & Width tool

286 This tool calculates the length of cirques, 'L', as the length of the line within the cirque polygon that
287 intersects the cirque threshold midpoint and splits the polygon into two equal halves (Fig. 3b). It also
288 calculates the width of cirques, 'W', as the length of the line perpendicular to the length line and
289 intersecting the length line midpoint (half way through the length line) (Fig. 3b). The elongation,
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'L/W', is derived from 'L' and 'W'. Both length and width lines are stored as separate shapefiles ('cirque_length' and 'cirque_width') in a user-defined destination folder. Users are required to specify a polygon and a point feature class that corresponds to the mapped cirques and the threshold midpoint respectively (Fig. 2). Users must also specify the folder where the resulting length and width line shapefiles should be saved (Fig. 2).

In principle, a threshold midpoint should intersect the cirque boundary. Given the possibility that some digitising errors may occur, the tool will work when a threshold midpoint is within the cirque polygon, whether or not at (i.e. snapped to) the exact cirque boundary. However, it will not work when the point is outside the cirque. Should the tool not find a corresponding threshold midpoint within a mapped cirque, or more than one threshold midpoint (for example in the case of a compound cirque), it will return a warning message "cirque X does not have a threshold or has two or more thresholds (e.g. is part of two or more nested cirques)", X being the cirque's ID number. A value of 0 will be added in the L, W and L/W fields for that specific cirque. Users are recommended to run the tool separately for compound cirques, once for the outer cirques, and a second time for the inner cirques.

The tool is designed to work with features that agree with the classic definition of cirques, i.e., features with a sub-circular or semi-circular plan shape, that encompasses an arcuate headwall and an open down-valley extent (Evans and Cox, 1974). The tool will work with more complex shapes, but should not be relied upon for curving, elongated features, though given the definition above, such features are unlikely to be cirques.

3.3 *Perimeter, Area & Circularity tool*

This tool calculates the perimeter ('Perimeter'), area ('Area_2D') and circularity ('Circular') of the mapped cirques (Fig. 3c). Circularity is defined as the ratio between the cirque perimeter and the perimeter of a circle of the same area (Aniya and Welch, 1981). Large values indicate low circularity while values closer to 1 indicate high circularity. Perimeter, area and circularity are stored in the attribute table of the cirque polygon layer. Perimeter and area are returned in the same units (squared for the area) as the ArcMap project (Data Frame Properties). The only required input for this tool is the polygon layer (shapefile or geodatabase feature class) of the mapped cirques.

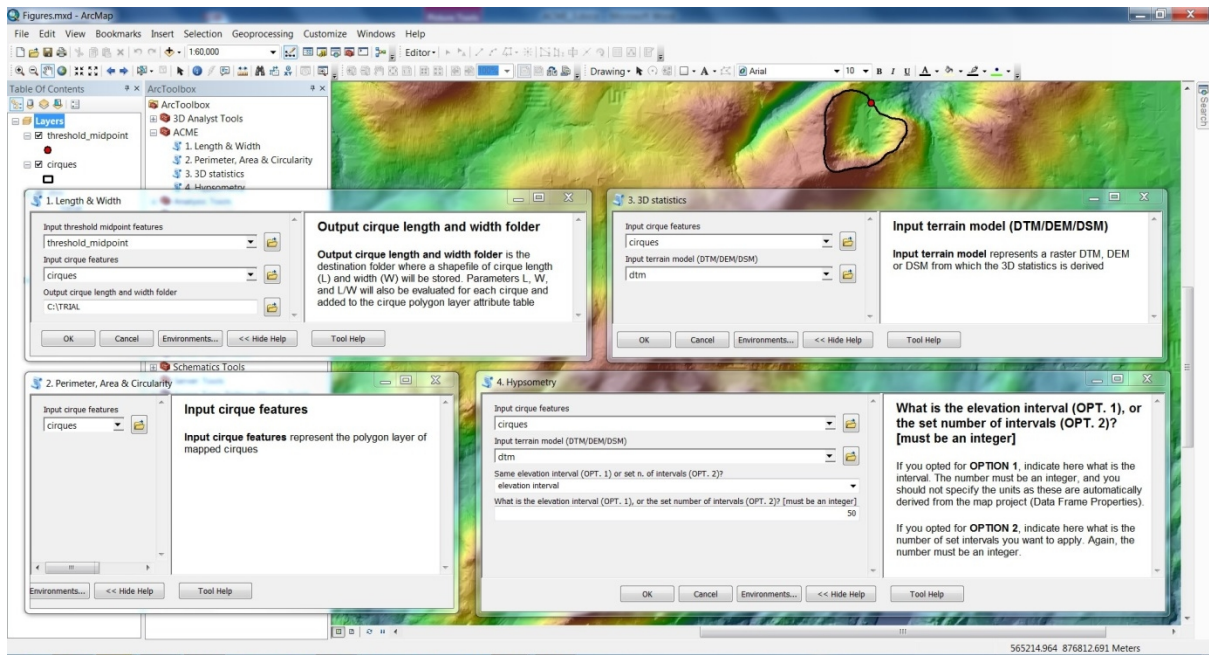


Fig. 2. The interface of ACME. When launched, each tool generates a new pop-up window (1 to 4). All tools require a polygon (shapefile or geodatabase feature class) of mapped cirques (input cirque features). The Length & Width tool also requires a point layer of cirque threshold midpoints (Input threshold midpoint features) which must be located within the boundary of the cirque polygon. Output cirque length and width folder is the destination folder where a shapefile of cirque length and width will be stored. The 3D statistics and Hypsometry tools require a terrain model (Input terrain model), which can be a DTM, DEM or DSM, as an input. Two options are provided for determining elevation intervals within which to calculate the hypsometry metrics. OPT 1 uses the same elevation interval for all cirques, which must be specified in the bottom box. OPT 2 uses the same number of intervals per cirque, also specified in the bottom box. Results from all tools are stored in the attribute table of the cirque polygon layer.

3.4 3D statistics tool

The 3D statistics tool produces a number of outputs and requires both the mapped cirque boundaries and a terrain model, e.g. a DTM, as inputs. For each cirque, the following metrics will be calculated:

- Z_{min} , Z_{max} , Z_{range} and Z_{mean} , corresponding to the minimum and maximum elevation (altitude), the range of elevations (max - min) and the mean elevation (Fig. 3d). Units are the same as the ArcMap project (Data Frame properties).
- $Area_{3D}$, corresponding to the 3D (non-planar) surface area of the cirque (Fig. 3c). Units are the same as the ArcMap project (Data Frame properties). The tool is based on an ArcGIS functionality (called 'Surface Volume') that will calculate the area only for pixels that are at least 50% within the boundary of the cirque polygon. Thus, a number of boundary pixels might not be included in the calculation, meaning that the tool would underestimate the real $Area_{3D}$. This is an issue of

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416 some relevance when the resolution of the DTM is coarse (e.g. 30 m) and cirques are very small
417 (e.g. $<100,000 \text{ m}^2$), because the relative number and size of boundary pixels that might be
418 disregarded is large. In exceptional circumstances, the underestimated Area_3D could
419 (erroneously) be lower than Area_2D, the calculation of which is exact and not affected by this
420 boundary pixels issue. When high resolution DTMs are not available, ACME users could consider
421 resampling the coarse-resolution DTM to a higher resolution (e.g. 5 m).
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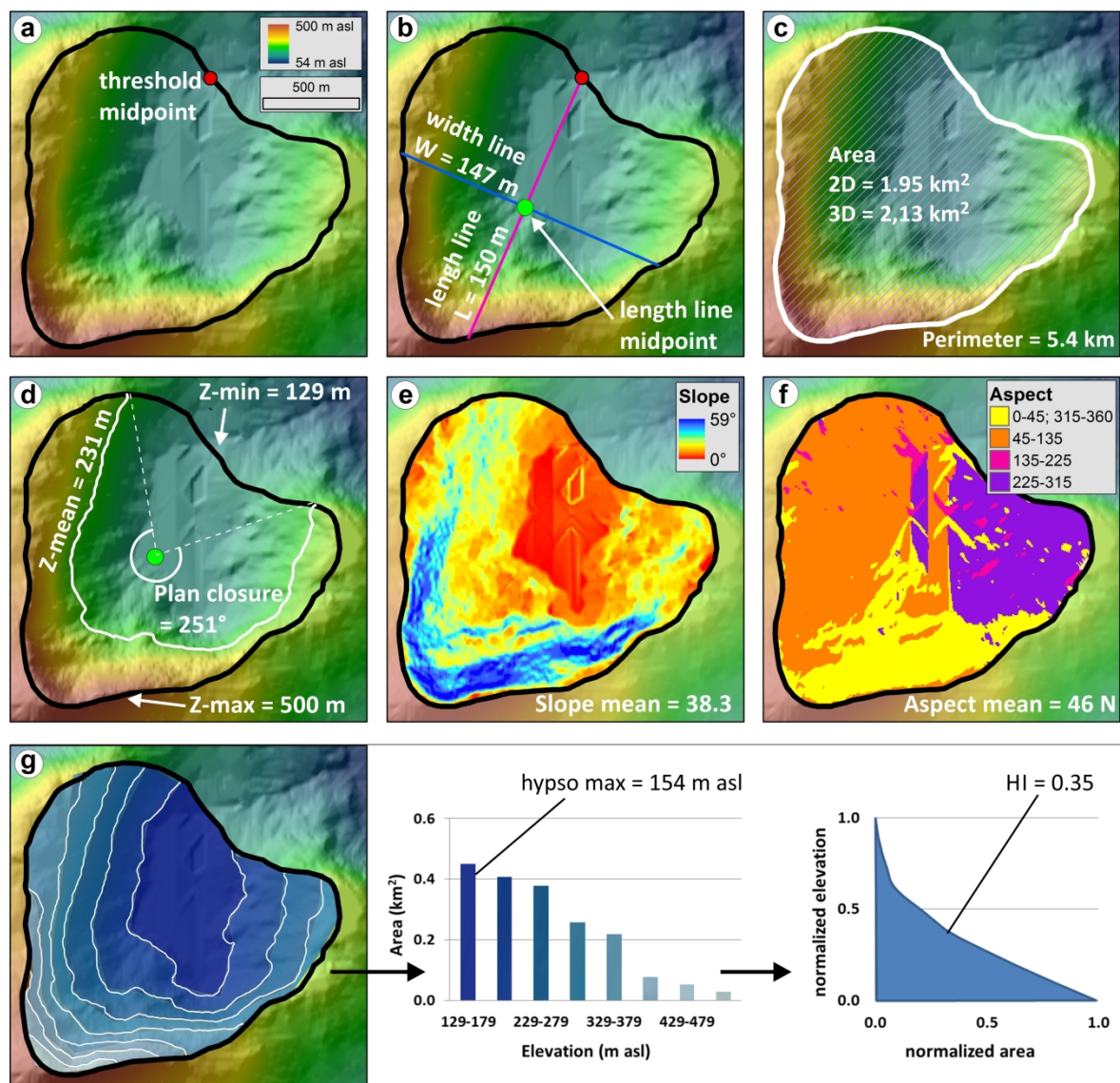
- 425 • Slope_mean, providing the mean value of slopes, in degrees (Fig. 3e). Each cirque comprises a
426 certain number of terrain model pixels, for which slope can be measured. Slope_mean calculates
427 the average of all pixels' slope.
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- 429 • Aspect_mean, corresponding to the mean value of aspects, in degrees north (within the 0-360°
430 interval) (Fig. 3f). The tool returns the mean of all pixel aspects by converting these into radians,
431 extracting the mean sine and cosine of these values, calculating the arctangent of the ratio
432 between mean sine and mean cosine, then finally converting this back into degrees. Mean aspect
433 is calculated by averaging all values across the entire surface of a cirque. This is a much preferred
434 metric to the cirque length line's azimuth when it comes to evaluate the total effect of solar
435 radiation and wind direction on cirque distribution.
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- 438 • Plan_closure, which provides a quantitative evaluation of the planar shape of cirques (Gordon,
439 1977). Values are also in degrees (within the 0-360° interval). It is calculated as 360° minus the
440 angle between the cirque midpoint (so called "centre of gravity" or "centroid") and start and end
441 points along the mid-elevation (half Z_range) contour (Fig. 3d).
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450 3.5 Hypsometry tool

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452 The Hypsometry tool calculates the hypsometric maximum ('hypso_max') and integral ('HI') of each
453 cirque (Fig. 3g). These metrics can be used to evaluate the interplay between glacial erosion,
454 topography and climate (Barr and Spagnolo, 2014). Hypsometric analyses are based on the
455 calculation of the area within a specified elevation interval. The Hypsometry tool works by specifying
456 either a same interval (OPTION 1) or a set number of intervals (OPTION 2) for all cirques. For
457 example, if OPTION 1 is selected and a value of 50 (m) is specified, the hypsometry statistics will be
458 based on areas calculated every 50 m of elevation, regardless of the cirque elevation range. This
459 means that the hypsometric statistics on 'shallow' cirques will be based on few area calculations (i.e.
460 few bins/class intervals), whilst results on 'deep' cirques will be based on many calculations. Users
461 should also keep in mind that when selecting an elevation interval, this should be below the
462 minimum elevation (altitudinal) range of the cirques. If this is not the case, a warning message "The
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selected elevation interval is higher than the elevation range of cirque X, hypso_max and HI will be returned as -9999", X being the ID number of the cirque, will be shown in the result window. If OPTION 2 is selected and a value of 12 is specified, the hypsometry statistics will be based on areas calculated for 12 elevation intervals distributed evenly along the elevation range of all cirques under investigation, therefore the elevation interval will vary depending on the cirque elevation (altitude) range. For instance, a cirque that spans 1200 m, will be sampled every 100 m, while one that spans 600 m, will be sampled every 50 m. Regardless of the chosen option, and the elevation interval adopted, the returned hypsometric maximum value corresponds to the mid elevation of the elevation interval where the area is highest. For example, if the elevation interval is 50 m, and the area is highest in the 2350-2400 m elevation interval bin, then a value of 2375 is populated in the hypso_max field.



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534 Fig. 3 A summary of key measured metrics. (a) Illustrates a cirque mapped as a polygon, with a black outline and a
535 threshold midpoint (red dot). Panel (b) shows the length line, derived as the line passing through the threshold midpoint
536 and splitting the cirque into two equal-area halves; the width line is perpendicular to the length line and passes through its
537 midpoint (half way through the length line). Panel (c) shows the perimeter (white line) and area (the hatched area enclosed
538 by the white line). Panel (d) indicates the minimum, mean and maximum cirque elevations. It shows the mean elevation
539 contour (white), the end points of which, along with the cirque centroid (green dot), are used to derive the plan closure
540 angle. In (e) the slope of each pixel (for this specific DTM the pixel size is 25 m²) comprised by the cirque surface has been
541 extracted and the mean slope calculated. Similarly, in (f) the aspect (in degrees, from 0 to 360 N) of each pixel has been
542 extracted, converted to radians and the mean aspect calculated and returned as degrees north. Panel (g) illustrates how
543 the hypsometric parameters are derived. In this case, areas were calculated every 50 m (white contours); the hypsometric
544 maximum is the elevation bin for which the land surface area is highest, while the hypsometric integral is the area below
545 the curve of the normalised, cumulative plot of area vs. elevation. All parameters shown in this figure are added to the
546 cirque's feature class attribute table and populated once the tools are run.
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556 4. Tools test

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558 To demonstrate its utility, ACME is here used to analyse the morphometry of 3520 cirques on the
559 Kamchatka Peninsula (Eastern Russia), mapped from ASTER GDEM by Barr and Spagnolo (2013).
560 Cirque metrics for this dataset, calculated using ACME, are provided in Table 1 along with those
561 presented in the original paper. The latter were calculated using a combination of GIS techniques
562 (e.g. Pérez-Peña et al., 2009), some of which use an interface in Italian (Federici and Spagnolo, 2004)
563 and are no longer compatible with recent versions of ArcGIS. Table 1 demonstrates that ACME
564 values are very similar to those published before and the differences between the two are not
565 statistically significant, with the exception of cirque width. However, the comparison on this latter
566 parameter is undermined by the fact that Barr and Spagnolo (2013) calculated cirque width using a
567 slightly different method (i.e. as the longest line within the cirque polygon perpendicular to the
568 cirque length line). This means that their width measurements are consistently greater than those
569 calculated using ACME (based on the line perpendicular to the length line and intersecting the length
570 line midpoint). There is currently no consensus on how best to measure cirque width (Barr and
571 Spagnolo, 2015), but given that differences between estimates are typically in the order of 10s of
572 meters (when cirques are 100s of meters wide), this has little impact on interpretations made from
573 the cirque record. Overall, ACME returns metrics comparable to those obtained in the past, with the
574 advantage that ACME (i) contains all relevant tools within a same toolbox, (ii) works on the most
575 recent software version of one of the most commonly used GIS packages, (iii) is in English and (iv)
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contains new GIS implementations of techniques that were originally developed for a topographic, manual approach and were not available to GIS users (e.g. plan closure).

To further test ACME, the minimum and maximum elevations, along with the elevation range, of 51 cirques are compared to those derived from a (much more time consuming) topographic approach, where minimum and maximum elevations were measured on orthorectified topographic maps (with the cirques shapefile used as an overlay) (Fig. 4) (Table 2). Differences between results from the two approaches are minimal and not statistically significant, but ACME is much faster and calculates a number of other metrics that a topographic approach would be unable to return (e.g. average aspect) or would require many hours of work per cirque (hypsometric integral).

In ACME, the only circumstance where the user has discretion over the choice of measurement method is when analysing cirque hypsometry. Specifically, the user can opt to analyse hypsometry using fixed elevation intervals or using the same number of intervals for each cirque and is prompted to select a method. The impact that this choice has on resulting hypsometric data from the Kamchatkan cirque database is highlighted in Fig. 5. This reveals that as the elevation interval increases or the set number of intervals decreases, both hypso_max and hypso_intr increase. With a low elevation interval or high number of intervals, the data will be more precise but the computational time could be considerably longer. Therefore, users must balance their required precision versus processing time.

Table 1. Summary metrics for cirques on the Kamchatka Peninsula. In each case, values reflect the mean of the entire cirque population (n = 3520). Results from a two-tail z-Test (without equal variances) are shown in the last column.

Metric	ACME	Barr and Spagnolo (2013)	z-test results
L (m)	866	868	Not stat. sig. (p = 0.638)
W (m)	964	992	Stat. sig. (p < 0.001)
Perimeter (m)	3082	Not calculated	n/a
Area_2D (km ²)	0.73	0.73	Not stat. sig. (p = 0.994)
Circularity	1.05	1.05	Not stat. sig. (p = 0.951)
Z_min (m)	988	988	Not stat. sig. (p = 0.929)
Z_max (m)	1410	1408	Not stat. sig. (p = 0.843)
Z_range (m)	422	421	Not stat. sig. (p = 0.759)
Z_mean (m)	1180	1177	Not stat. sig. (p = 0.657)
Area_3D (km ²)	0.84	Not calculated	n/a
Slope_mean (°)	27	28	Not stat. sig. (p = 0.236)
Aspect mean (°)	006	006	Not stat. sig. (p = 0.300)
Plan_clos (°)	151	Not calculated	n/a
Hypso_max (1 m elevation interval) (m)	1159	Not calculated	n/a
Hypso_max (50 intervals) (m)	1160	Not calculated	n/a

Hypso_intr (1 m elevation interval) (m)	0.46	Not calculated	n/a
Hypso_intr (50 intervals) (m)	0.47	Not calculated	n/a

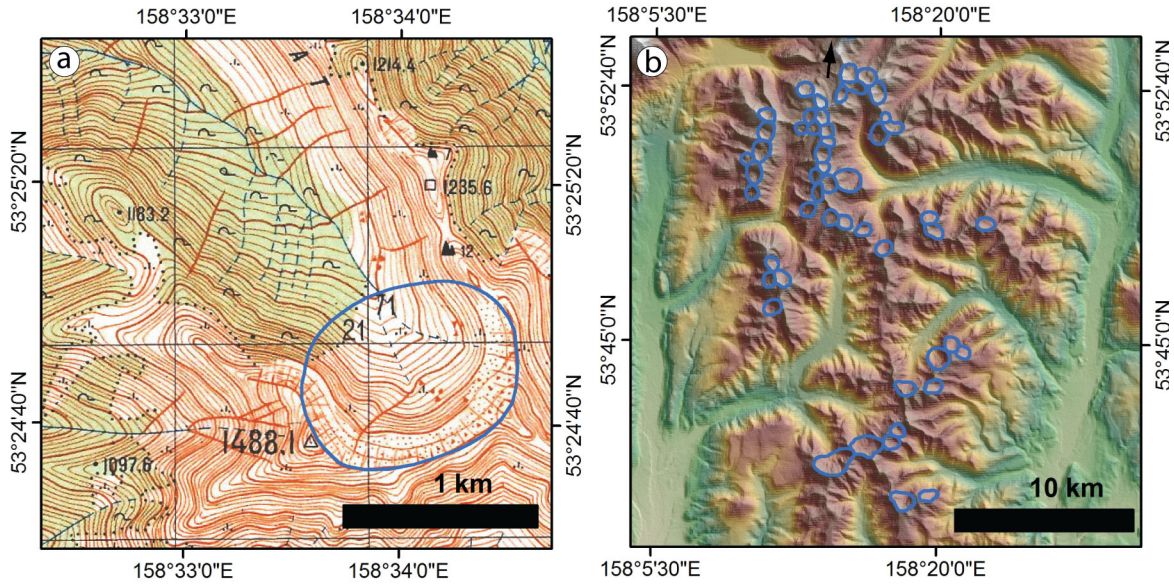


Fig. 4. Example cirques (blue polygons) on the Kamchatka peninsula, shown against (a) a (1:50,000) topographic map and (b) SRTM DEM. Altitudinal data for these cirques are shown in table 2.

Table 2. Altitudinal data for a group of 51 cirques (shown in Fig. 4) on the Kamchatka Peninsula. Values are calculated using the GIS tool presented here (ACME) and from topographic maps (Topographic (manual) approach).

Cirque number	ACME	Topographic (manual) approach	z-test results
Mean_Z_min (m)	1220	1214	Not stat. sig. (p = 0.855)
Mean_Z_max (m)	1632	1628	Not stat. sig. (p = 0.876)
Mean_Z_range (m)	412	414	Not stat. sig. (p = 0.927)

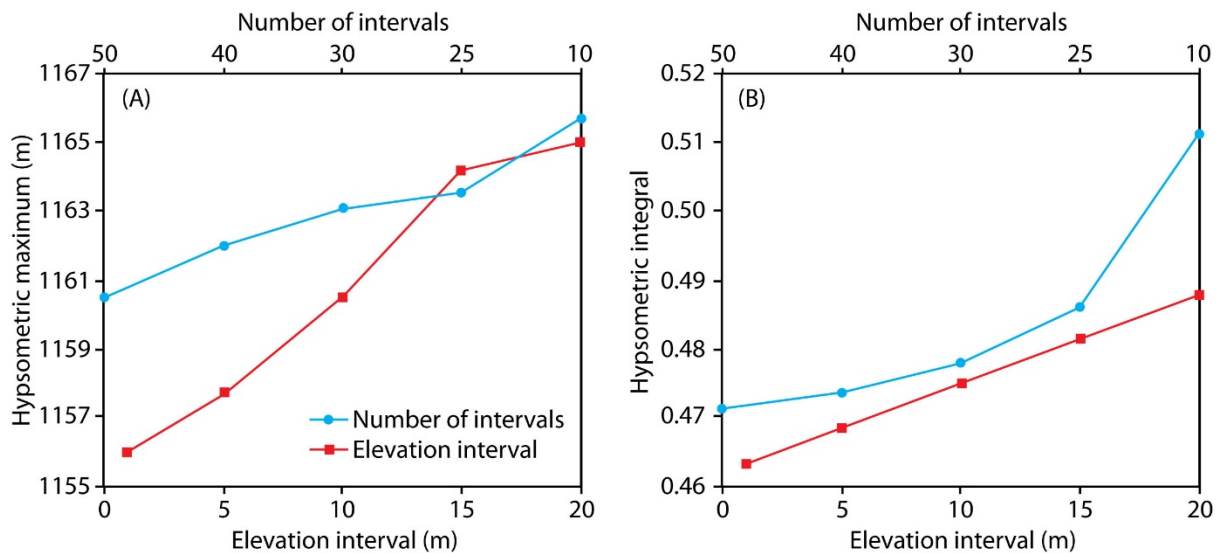


Fig. 5. Mean (A) Hypsometric maximum and (B) hypsometric integral for cirques ($n = 3520$) on the Kamchatka Peninsula, calculated using different numbers of intervals and different elevation intervals. Both the hypsometric maximum (in A) and the hypsometric integral (in B) increase with the elevation intervals and decrease with the number of intervals.

5. Conclusions

Morphometric studies on glacial cirques have revealed how their metrics can provide important insights about past and present environmental conditions (Barr and Spagnolo, 2015 and references therein). These studies are often limited to relatively small sample sizes or numbers of parameters analysed, because the extraction of the metrics is very time consuming. With the growing availability of high resolution terrain models, new regions can be studied and more cirques can be identified and mapped than ever before. To facilitate the analyses of their size and shape characteristics, ACME, a new GIS toolbox, has been developed. ACME automatically extracts 16 glacial cirques metrics. Some of these metrics require only a polygon layer of mapped cirques as an input; others also need a DTM and/or a point layer of mapped cirque threshold midpoints. The 16 metrics are the length, width, elongation, perimeter, planar area, circularity, minimum, mean and maximum elevations, elevation range, 3D area, mean slope, mean aspect, plan closure, hypsometric maximum and hypsometric integral. The interpretation of these metrics can reveal important insights into the environmental conditions under which cirques are formed, including climate. Some of these metrics (e.g. minimum elevation) are routinely discussed in glacial cirque morphometry studies; others (e.g. plan closure) have been seldom used because their calculation, until now, could only be done via a time consuming topographic approach (Barr and Spagnolo, 2015). ACME is now able to quickly and efficiently extract all these parameters automatically. Importantly, ACME results are comparable to those from previous studies based on a combination of other, more or less obsolete, GIS applications and to those manually extracted via a topographic approach.

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772 **Weblink:** ACME can be downloaded here: [link to be provided by the Editor once the manuscript is
773 accepted]. Once downloaded, it can be added to the list of ArcToolbox(es) in ArcMap by right
774 clicking on the ArcToolbox icon and selecting Add Toolbox.
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779 **Acknowledgement:** This paper is dedicated to Ian Evans. His passion for the analyses of glacial
780 cirque metrics, along with his productivity and generosity, has not only allowed these landforms to
781 be now recognised as key indicators of palaeoenvironmental conditions, but has also been an
782 inspiration to many young researchers. We are also thankful to Clare Boston and 3 anonymous
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