

A GIS tool for automatic calculation of glacier equilibrium-line altitudes



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ABSTRACT

A toolbox for the automated calculation of glacier equilibrium-line altitudes (ELAs) using the Accumulation Area Ratio, Area-Altitude Balance Ratio, Area-Altitude and Kurowski methods is presented. These are the most commonly-used methods of ELA calculation in palaeo-glacier reconstructions. The toolbox has been coded in Python and runs in ArcGIS requiring only the reconstructed surface of the palaeo-glacier (a DEM) as input. Through fast and automatic calculation this toolbox simplifies the process of ELA determination and can successfully work both for a single glacier and for large datasets of multiple glaciers.

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1. Introduction

The Equilibrium Line Altitude (ELA) is the average elevation where, over a one-year time interval, accumulation equals ablation so the mass balance at this line is zero (Cogley et al., 2011). The ELA is significant for the understanding of both present-day and past climates and changes in ELA elevation can be used to track changes in climate. It is important to note that palaeoglacier reconstructions determine the ELA assuming the glacier is in equilibrium with climate. This is equivalent to the zero net balance ELA for extant glaciers, whereas annually the ELA can be highly variable. The ELA is coupled with the climate mainly through winter precipitation, which correlates with accumulation (although this also is impacted by windblown snow accumulation and avalanching), and summer air temperature, which correlates with ablation (although other factors such as incoming shortwave and longwave radiation, sensible heat fluxes and snowpack warming from refreezing can play a significant role). To a first order, variations in the ELA are commonly attributed to changes in one or both of these climatic variables.

Relationships have been established between precipitation and temperature at the ELA (Ahlmann, 1924, 1948; Loewe, 1971; Kottlyakov and Krenke, 1982; Braithwaite, 1985; Ohmura et al., 1992; Braithwaite, 2008) which makes it possible to determine one of the two parameters provided the other (usually the temperature) is known. Reconstruction of former glaciers and their ELAs can therefore yield a quantitative measure of palaeo-precipitation which is difficult to determine using other palaeoclimate proxies.

The ELA has not only been successfully used to assess the climate during former glaciations (Bakke et al., 2005; Benn and Ballantyne, 2005; Lukas and Bradwell, 2010; Hughes et al., 2010), but also the mass balance of extant glaciers where no such data are available (Hughes, 2009a).

Despite the importance of the ELA, some calculation methods are laborious, thus leading to the use of simplified approaches and making comparison across methods difficult. In order to minimize calculation time, this paper presents a GIS toolbox that automates the process for multiple techniques. These are summarized in Section 2, while Section 3 describes the tool in detail.

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2. Methods for ELA calculation

MELM, CFA and HM – Various methods have been developed and applied to calculate palaeoglacier ELAs. These can be divided into two groups; those which are solely based on the position (specifically the elevation) of glacial landforms and those which also require the geometry of the reconstructed palaeoglacier surface. Examples of the former are the Maximum Elevation of Lateral Moraines (Lichtenecker, 1938), Cirque Floor Altitudes (CFA; Pewé and Reger, 1972) or the concentration of land-surface area (Hypsometric Maxima, HM; Egholm et al., 2009). These are theoretically correct ELA estimates, but they suffer from potentially significant errors. For example: CFA is only applicable to specific types of glaciers which have formed over multiple glaciations, and the hypsometric maxima are dependent on the dynamics of the glacier and the geological history of the area where the glacier develops (Barr and Spagnolo, 2014). These shortcomings make landform-based ELA estimates useful for first-order (and rapid in the case of MELM and CFA) estimates, but ideally palaeoclimatic reconstructions should not be based on these palaeo-ELAs. More reliable methods require part or all of the reconstructed geometry of the palaeoglacier, derived from the position of glacial landforms and the palaeoglacier bed topography; examples of these are the Toe to Headwall Altitude Ratio (THAR), the Accumulation Area Ratio (AAR), the Median Glacier Elevation (MGE or Kurowski) and the Area-Altitude Balance Ratio (AABR).

THAR – The THAR assumes that the ELA lies at some fixed proportion of the vertical distance (i.e. altitudinal range) between the lowest and highest point of the palaeoglacier, usually in the range 0.35–0.5. It can provide a rapid and simple method for a first approximation of the ELA, but it may have large errors when the glacier geometry is complex (Benn and Lehmkuhl, 2000) and is only suitable for topographically constrained glaciers.

AAR – The AAR is the most widely applied technique for ELA estimation, and it has been used for glacier-climate reconstructions in mountain ranges across the world (e.g. Kerschner et al., 2000; Porter, 2001; Benn and Ballantyne, 2005; Lukas, 2007; Stansell et al., 2007; Pellitero, 2013). The AAR method assumes that the ratio between the accumulation area and the ablation area is constant if glaciers are in steady state (Fig. 1). However, this ratio does not take into account the mass balance gradient, which critically is controlled, to the first order, by the regional climate and further modified by local topoclimatic conditions. The mass balance gradient is a proxy for overall ice flux and it is typically steeper (higher accumulation and higher ablation) on warm, wet, maritime glaciers and shallower for cold, dry polar and continental glaciers. The AAR method also fails to account for the hypsometry, i.e. the area-altitude distribution of the reconstructed glacier surface (Osmaston, 2005).

The main input needed for calculation of the AAR is the reconstructed 3D glacier-surface. The planar surface area is sometimes used (Rea et al., 1999), although it can be significantly less accurate. 3D ice surface reconstructions are normally derived by either interpolation and extrapolation of mapped glacier limits (i.e. freehand drawing of glacier margins and surface contours onto a base map) here referred to as the cartographic method (e.g. Ballantyne, 1989; Benn and Ballantyne, 2005; Lukas and Bradwell, 2010) or from numerical reconstructions based on glacier physics (e.g. Rea and Evans, 2007; Benn and Hulton, 2010).

Knowledge of mass-balance gradients is not required for the AAR method but the ratio of the accumulation area to total area for the reconstructed glacier is. This ratio should ideally be determined from measurements of extant, similar glaciers in the region (Benn and Lehmkuhl, 2000), but this is often impossible where glaciers no longer exist. Hughes et al. (2007) and Hughes et al. (2010) attempted to get around this issue for palaeoglaciers

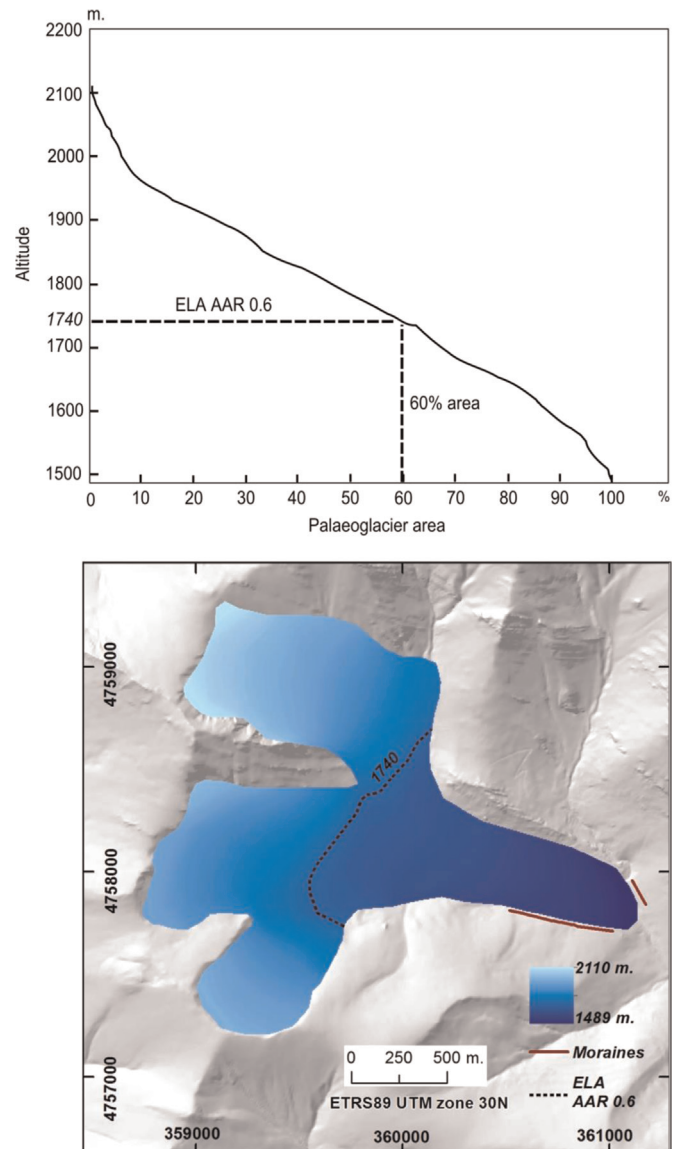


Fig. 1. Visualization of the ELA AAR applied to the Valdenievas palaeoglacier in N Spain, with an AAR of 0.6. (a) Shows the altitude range plotted against the cumulative percentage area of the glacier surface. (b) Shows the reconstructed palaeoglacier and the contour corresponding to the ELA (Pellitero, 2012).

in Greece and Montenegro by applying a range of AARs to populations of reconstructed glaciers following Osmaston (2002). This involves taking the altitudes corresponding to 11 evenly-spaced accumulation area ratios of between 0 and 1 (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0). The standard deviation of each AAR for the group of glaciers was calculated and the AAR with the lowest standard deviation was chosen. Various authors have suggested different ratios depending on the type, size and location of glaciers (Table 1).

Kurowski or MGE – An alternative and simpler method to the AAR is that proposed by Kurowski (1891). This is based on the assumption that, for a glacier in equilibrium where mass balance is a linear function of altitude, the ELA is situated at the mean glacier elevation (Braithwaite and Raper, 2007). The Kurowski method was adopted by Drygalski (1942) but then fell out of use (Osmaston, 2005). However, it became re-established during the 1960s and 1970s when it was applied by Osmaston (1965, 1975) working in East Africa and later for reconstructing Loch Lomond Stadial (Younger Dryas) glaciers in Great Britain (Sissons, 1974;

Table 1

AAR ratios suggested in the scientific literature.

Paper	Type of glacier (location)	Ratio
Bakke and Nesje (2011)	Cirque and valley	0.6 ± 0.05
Ignéczi and Nagy (2013)	Outlet	0.58
Gross et al. (1977)	Cirque, valley and icefields (Alps)	0.67
Braithwaite and Müller (1980)	(Arctic, Alpine and Asian) (North America and Scandinavia) (Extremely high relief areas such as Andes or Himalayas)	0.67 0.5 < 0.5
Clark et al. (1994)	Debris covered glaciers	0.2–0.1
Kern and László (2010)	0.1–1 km ² extension 1–4 km ² extension Larger than 4 km ²	0.44 ± 0.07 0.54 ± 0.07 0.64 ± 0.04
Leonard (1984) and Hughes et al. (2010)	All glaciers (World Glacier Inventory) Ice caps	0.559 ± 0.09 Up to 0.8

Gray, 1982; Sutherland, 1984; Ballantyne, 1989; Hughes, 2002, 2009b). For a glacier with a symmetrical distribution of area with altitude the mean elevation is approximately equal to the median elevation of the glacier, which is equivalent to an AAR of 0.5 (Braithwaite and Raper, 2007). The median glacier elevation has been used in the World Glacier Inventory since the late 1970s (Müller et al., 1977; despite being mistakenly called the “mean” in Müller et al. (1977); an error corrected in Braithwaite and Müller, 1980). Braithwaite and Raper (2007, 2009) found a very high correlation (0.998) between the ELA and MGE, based on a dataset of 144 glaciers with mass balance records of ≥ 5 years.

AABR (and AA) – The second-most widely used ELA calculation technique is the AABR method (Osmaston, 1975; Furbish and Andrews, 1984). This is recognized to be more robust than the AAR and MGE methods because it takes into account both the glacier hypsometry (Osmaston, 2005) and the mass balance gradients (Benn and Lehmkuhl, 2000). The AABR method is based on three assumptions: (a) the accumulation and ablation gradients are approximately linear; (b) the net ratio between ablation and accumulation is known and remains fixed through time (Benn and Lehmkuhl, 2000; Rea, 2009); and (c) the topography is assumed to constrain the glacier, so a change in climate (mass balance) is reflected in a change in the elevation of the terminus. This is not the case for piedmont glaciers that extend onto lowland plains. This method also recognizes that any given unit area of the glacier surface that is altitudinally further away from the ELA (either positive or negative) has a greater contribution to overall mass balance than a unit area that is located closer to the ELA. The AABR method is best suited to snow-fed, clean glaciers, and strictly speaking should not be applied to: glaciers that receive a significant mass inputs from avalanching; glaciers where either, or both, mass balance gradients are not linear; glaciers where extensive debris cover exerts a strong influence on the ablation gradient (Benn and Lehmkuhl, 2000; Osmaston, 2005). These criteria can be assessed where there is an extant glacier but are essentially impossible to ascertain for palaeoglaciers. The AABR method requires the glacier hypsometry and the Balance Ratio (BR). The latter is a crucial element of the AABR method, as it accounts for the differences between the accumulation and ablation gradients and their respective contribution to the glacier mass balance. It can be calculated from the glacier hypsometry using the following equation (Furbish and Andrews (1984)):

$$BR = \frac{\bar{Z}_{ac} A_{ac}}{\bar{Z}_{ab} A_{ab}}$$

Where:

 \bar{Z}_{ac} = Area-weighted mean altitude of the accumulation area. A_{ac} = Area of accumulation. \bar{Z}_{ab} = Area-weighted mean altitude of the ablation area. A_{ab} = Area of ablation.

If there is an extant glacier with a record of measured mass balance, the BR can be determined. Then, based on assumption (b) above, this is applied to the hypsometry of the reconstructed palaeoglacier to calculate the palaeo-ELA. This can only be done if the extant glacier is believed to have similar characteristics to the palaeoglacier (e.g. Rea and Evans, 2007). The next-best alternative is, provided there are the necessary data, to derive a BR from a nearby glacier and assume the mass balance is controlled by similar climatic and glaciological boundary conditions. Often neither is possible because many glacier reconstructions are undertaken in regions that are no longer glacierized. In these instances, a ‘representative’ BR has to be chosen, with careful consideration of additional information, for example, data derived from paleoecological proxies or perhaps climate model output, though caution is required here to avoid circularity. Rea (2009) calculated a series of BRs for a range of glacier types and settings from a global dataset of glaciers which had mass balance records > 7 years. The “representative” BRs are: a global value = 1.75 ± 0.71 ; mid-latitude maritime = 1.9 ± 0.81 ; high-latitude = 2.24 ± 0.85 ; North America – West Coast = 2.09 ± 0.93 ; North America – Eastern Rockies = 1.11 ± 0.1 ; Canadian Arctic = 2.91 ± 0.35 ; Svalbard = 2.13 ± 0.52 ; Western Norway = 1.5 ± 0.4 ; European Alps = 1.59 ± 0.6 ; Central Asia = 1.75 ± 0.56 ; Kamchatka = 3.18 ± 0.16 . Given a population of multiple glaciers within the same region, Osmaston (2005) alternatively suggested performing the calculation for a range of BR’s, and then choosing the one with the lowest ELA standard deviation.

The AABR calculation is implemented in two steps. First, the glacier surface is divided into contour belts using a reasonable contour interval, and then for each belt the area is multiplied by the mid-point elevation. The sum of these values, derived from all contour belts, is then divided by the total glacier area. This produces the ELA Area-Altitude (AA), which is equivalent to an AABR of 1. For any other BR ratio the second step estimates the ELA by calculating multiple palaeoglacier mass balances, for all possible ELAs, starting at the mid elevation of the lowest contour belt. For each iteration, the trial ELA is subtracted from the mean belt altitude and the result is multiplied by the contour belt area. If the result of the multiplication is negative, then it is multiplied by the BR (i.e. it is in the ablation zone). This is repeated for all contour belts and the results summed to give the glacier net mass balance, which can be either positive or negative. The contour belt where the net balance changes sign, from positive to negative (or vice versa if calculated from the top down), is the ELA for the chosen BR. A new BR value necessitates a new calculation (see Fig. 2). For full details of the method see Furbish and Andrews (1984), Benn and Gemmel (1997), Osmaston (2005) and Rea (2009).

Various approaches have been used in the past to perform computer-based ELA calculations. Kaser and Osmaston (2002) developed a program to calculate the ELA using the AABR method, which was coded in ALGOL. Later, another spreadsheet was made available for the calculation of the AABR (Osmaston, 2005). Benn and Gemmel (1997) published an Excel spreadsheet program that also calculated the ELA using the AABR method, but this is unsuitable for glaciers with more extreme hypsometry i.e. large areas towards the top and/or bottom of the accumulation and/or ablation zones respectively (Osmaston, 2005; Rea and Evans, 2007). None of these approaches fully automated the calculation procedure and none used a Geographic Information System (GIS) framework. As a consequence, hypsometry measurements had to be derived separately and imported into a spreadsheet to perform the ELA calculations.

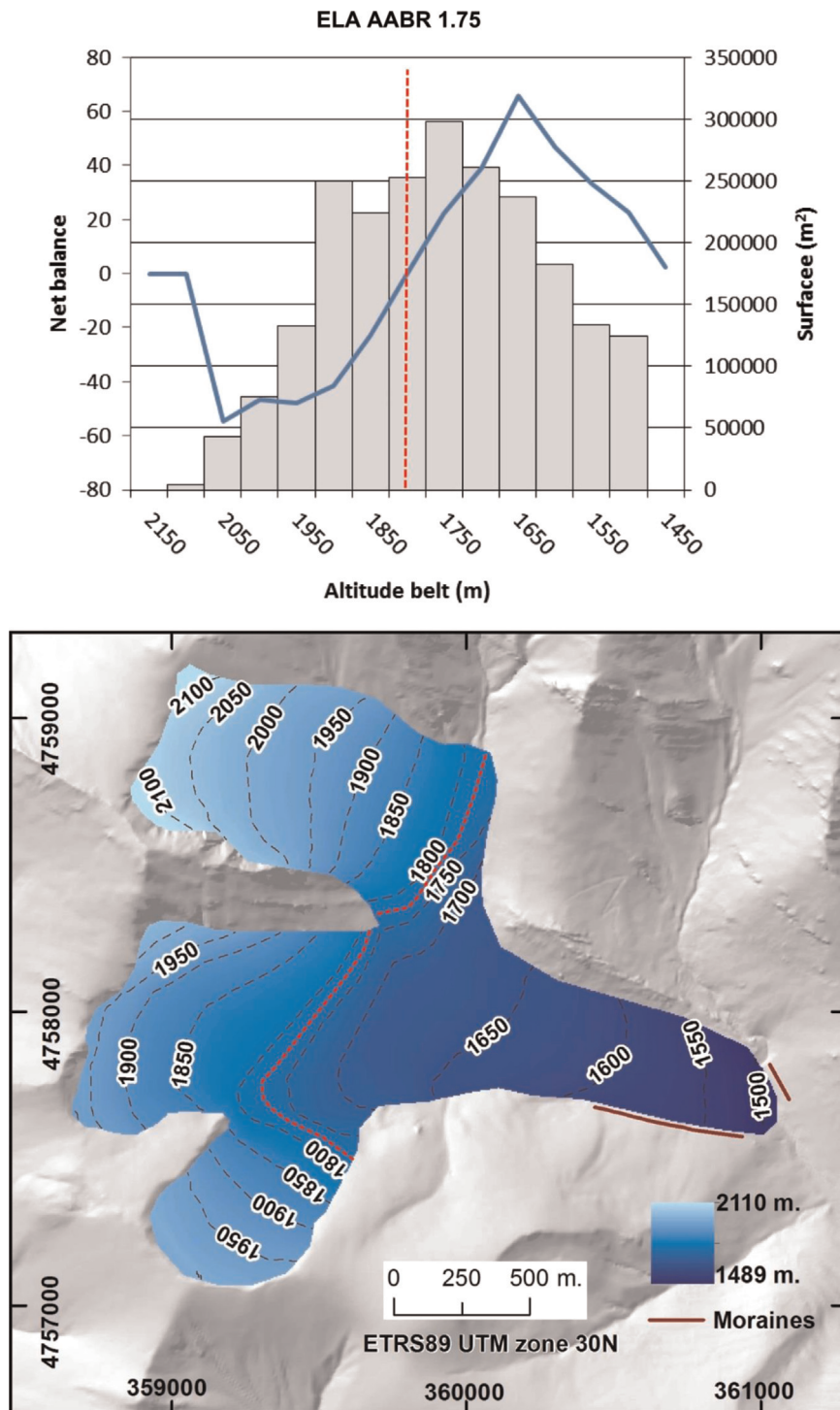


Fig. 2. Mass balance calculated using the AABR method using a BR ratio of 1.75 for the same palaeoglacier as in Fig. 1. The ELA is located where negative and positive net balances are equal. The vertical bars in the top graphic show the distribution of the glacier area with altitude (the hypsometry), the solid line for its net balance (taking into account the BR) and the dotted line is the ELA contour, situated at 1775 m (Pellitero, 2012).

3. The toolbox

This paper presents an ArcGIS toolbox, with Python coded tools, for the automated calculation of the ELA on palaeoglaciers using the four main methods currently in use: the AA (determined as $AABR=1$), AAR, AABR and MGE (determined as $AAR=0.5$). Computational speed is a function of the contour interval, which is user defined, and the glacier size. The tools follow the Osmaston (2005) procedure for the AABR and the González Trueba and

Serrano (2004) approach for the AAR calculation. The toolbox needs to be added to the general ArcToolbox folder prior to use.

3.1. Toolbox operation, scripts and inputs

The ELA calculation toolbox requires a Digital Elevation Model (DEM) of the glacier surface as the main input and a folder to store the outputs. The DEM can use any of the raster formats supported by ArcGIS 10.1. The toolbox includes four Python coded tools and

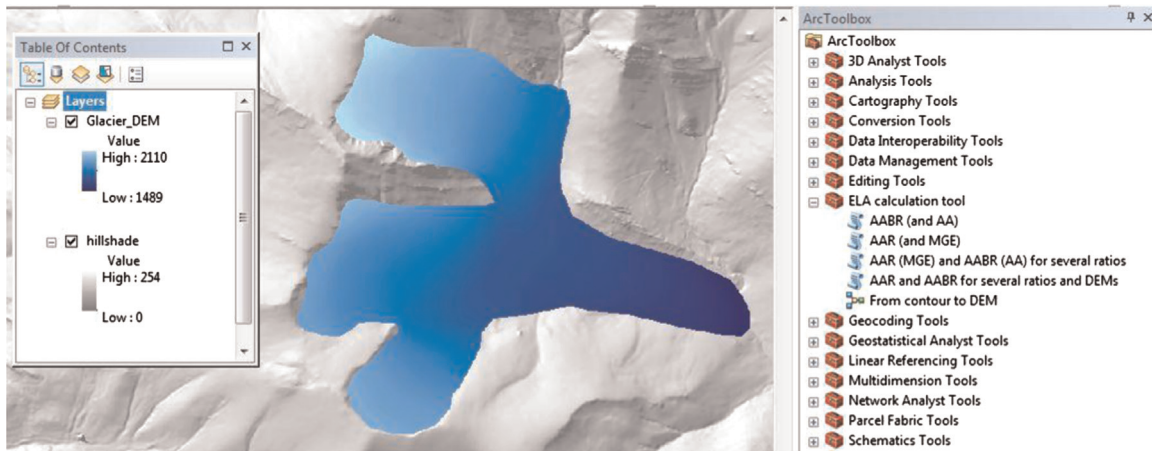


Fig. 3. A screenshot of the Toolbox as it appears embedded in ArcGIS.

one model for the creation of the DEM from contour lines (Fig. 3). The tools require also two additional parameters. The first is the contour interval for the glacier area calculation. The default is set to 50 m, but this can be changed according to user preference. Note it is also dependent on the vertical resolution of the DEM and the size of the glacier; (e.g. Chandler, 2013). However, a larger contour interval will reduce the vertical accuracy, because the calculation error (i.e. the minimum error) is equal to the chosen contour interval. For example, if the interval is set to 10 m, the resultant ELA calculation error will be ± 5 m. The second key parameter is the ratio for the AAR and AABR methods. Default values of 0.67 for AAR and 1.75 for AABR have been set, following the aforementioned literature, but users are again free to modify this ratio (Fig. 4). Once all information is input, results are returned in a pop-up window that also contains additional information about the script run (Fig. 5). A shapefile is created with the contour that corresponds to the ELA. Its name is the same as that of the DEM plus AAR or AABR depending on the tool used.

Gonzalez Trueba and Serrano (2004) suggest introducing a ± 0.05 error in the AAR, which accounts for technical errors in the calculation process. Alternatively, calculating ranges of ELAs is easily implemented using the “AAR and AABR (AA) for several ratios” tool. The tool works in the same way as the previous ones, but two further parameters are added “AAR ratios and interval” and “AABR ratios and interval”. Users can define the range and interval entered thus; *minimum ratio maximum ratio interval* (with space between each value). For example, to calculate AAR-ELAs

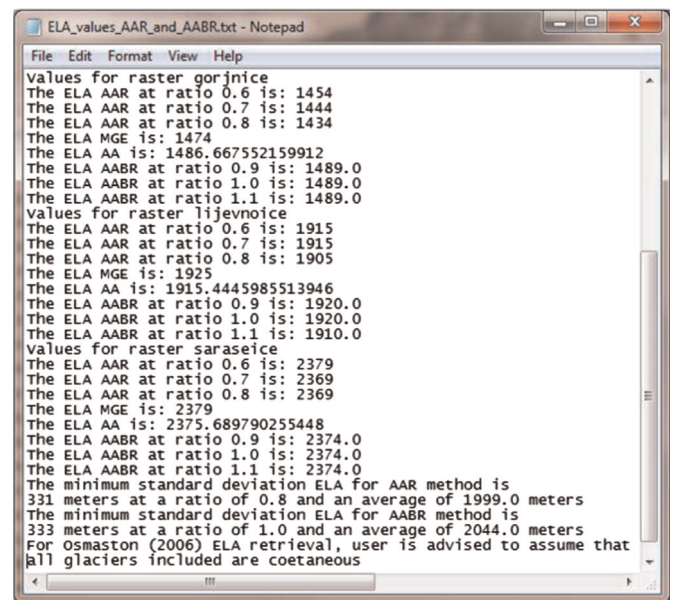


Fig. 5. Example output for “AAR and AABR (AA) several ratios and DEMs” script.

between the ratios 0.4 and 0.7, with 0.05 ratio unit steps, the following is typed “0.4 0.7 0.05”. Default ratio ranges have been set from 0.4 to 0.8 with a 0.05 interval for AAR, and from 0.9 to

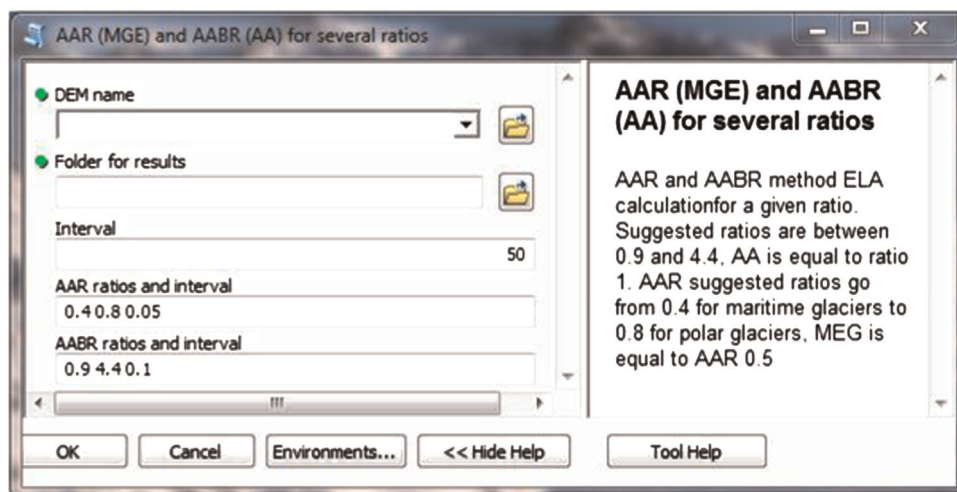


Fig. 4. An example screenshot of the “AAR and AABR (AA) for several ratios” tool as it appears when opened from the toolbox.

```

valden.txt - Notepad
File Edit Format View Help
Start Time: Mon May 12 16:22:53 2014
Completed Surface Volume: 2D Area=120300.36610729 3D Area=124645.51231079 volume=2817719.7328275
Succeeded at Mon May 12 16:22:53 2014 (Elapsed Time: 0.00 seconds)
Executing: SurfaceVolume valden # BELOW 1604 1 0
Start Time: Mon May 12 16:22:53 2014
Completed Surface Volume: 2D Area=250722.46997744 3D Area=258023.36709206 volume=11960580.189045
Succeeded at Mon May 12 16:22:53 2014 (Elapsed Time: 0.00 seconds)
Executing: SurfaceVolume valden # BELOW 1654 1 0
Start Time: Mon May 12 16:22:53 2014
Completed Surface Volume: 2D Area=427343.90730126 3D Area=440568.88621752 volume=28482190.926757
Succeeded at Mon May 12 16:22:53 2014 (Elapsed Time: 0.00 seconds)
Executing: SurfaceVolume valden # BELOW 1704 1 0
Start Time: Mon May 12 16:22:53 2014
Completed Surface Volume: 2D Area=656903.11657683 3D Area=677861.71322529 volume=55631646.074549
Succeeded at Mon May 12 16:22:53 2014 (Elapsed Time: 0.00 seconds)
Executing: SurfaceVolume valden # BELOW 1754 1 0

```

Fig. 6. Results from the SurfaceVolume_3D tool. Reference altitude (1604 m) and 3D area below this altitude (258,023 m²) values have been outlined. These are the values that the script uses for performing the ELA calculations.

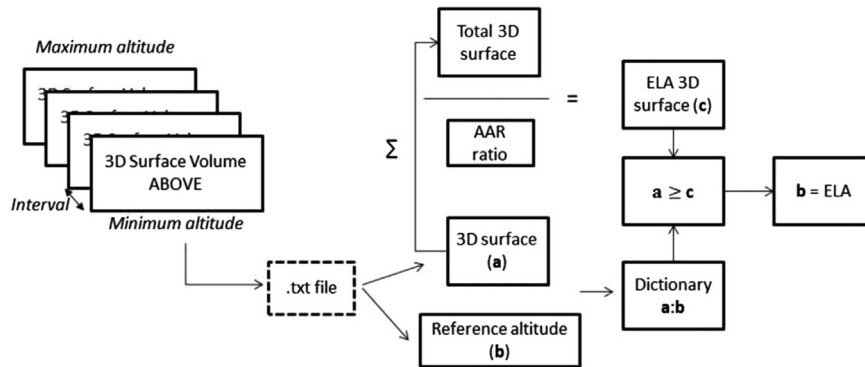


Fig. 7. Flow-diagram illustrating the steps in ELA calculation using the AAR method.

4.4 with a 0.1 interval for AABR, following the proposed ranges for AAR in Kern and László (2010) and for AABR in Rea (2009) (Fig. 4). An AAR of 0.5 (MGE method) is also included as a default. Results are outputted to a *.txt file, saved in the “Workspace” folder, whose name is the same as the DEM plus “_output.txt” and a shapefile taking the DEM name plus “ELAs.shp”.

The tool “AAR and AABR (AA) multiple ratios and DEMs” allows ELA calculations for multiple DEMs stored in the same folder, using multiple ratios for both the AAR and AABR methods. The only required inputs are the relevant folder (named as “Workspace” in the tool) where the DEMs are stored (and where results will be eventually output too), the contour interval for the glacier contour belt areas and the ratio ranges for AAR and AABR. Results are saved in a text file called “ELA_values_AAR_and_AABR.txt”. Finally, the best ELA for the group of glaciers, determined using the lowest standard deviation approach proposed by Osmaston (2005), is provided at the end of the results text file (Fig. 5). Note that if the tool is re-run in the same folder, results are appended at the end of the text file already created. An ELA shapefile is also created for each DEM, which is named following the same convention as above.

In addition, there is a model for the creation of a DEM from contours, which may be useful for users who are unfamiliar with spatial analysis in ArcGIS. This is not coded in Python, but built through the Model Builder directly in ArcGIS. The model uses the “Topo to Raster” tool and requires three inputs: the glacier contours shapefile, the glacier outline and the name and location for the resulting DEM. The first input must be a POLYLINE shapefile or feature class with a field named “CONTOUR”, populated with the elevation of each contour (in m above sea level). The second input is the glacier outline, which can be either, a POLYLINE or, a POLYGON. The third input is the name and location for the output DEM.

3.2. Script execution

All scripts are coded in Python 2.7 and use *arcpy* (ESRI toolset for Python), *os*, *numpy* and *operator* libraries. They mainly utilize

the SurfaceVolume_3D tool, which is embedded in the 3D Analyst package. This tool calculates the 3D area ABOVE or BELOW a given altitude in a DEM. The script first runs the tool to calculate the area ABOVE (for AAR) and BELOW (for AA and AABR) the “trial” altitudes as many times as needed given the glacier altitudinal range (which is automatically calculated) and the desired contour interval. Results are recorded in a .txt file which is named from the DEM and stored in the chosen folder. Then, the script reads the relevant information from the text file and calculates the ELA. Two values are used for the calculation: the reference altitude and the area value for that altitude (Fig. 6).

For the AAR both values are stored in a dictionary, and then the accumulation area (the area above the ELA which is relevant for the given ratio) is calculated from the total area and the chosen ratio. Finally the script goes through the dictionary and finds the contour above which the cumulative area value is immediately higher than the accumulation area, and determines the mean value between this contour altitude and the one below. This yields an altitude value whose ELA calculation error is half the contour interval used (Fig. 7).

For the AABR the glacier is split into contour belts, so the distribution of surface area with elevation above and below the ELA is taken into account (the strength of this method). First the script calculates the total area BELOW each contour, and then creates a list of the mean altitude value for each contour belt. The surface area for each belt is calculated by iteratively subtracting the area below the upper contour from the area below the contour directly below, and the result is multiplied by the mean altitude of the belt. All results are summed and then divided by the total area of the glacier. The result is the AA value, which is equivalent to the AABR for a BR of 1.

In order to calculate ELAs using BRs other than unity, the script performs some further calculations, following Osmaston (2005): a trial ELA is created and is then subtracted from the mean contour belt altitude for all belts (i.e. the elevation of each contour belt from the trial ELA is determined – negative for contour belts below

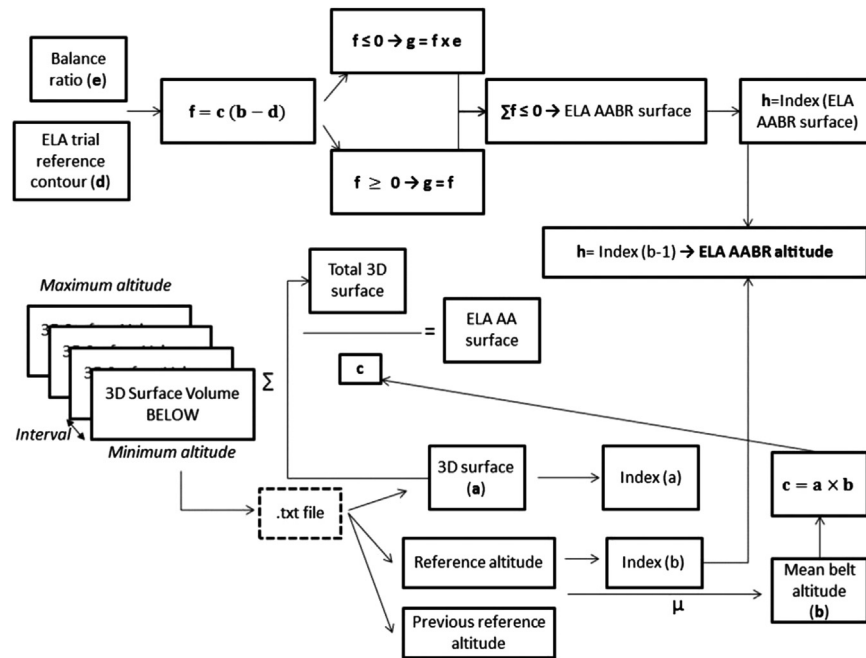


Fig. 8. Schematic flow-diagram showing the steps taken in ELA calculation procedure for the AA/AABR method.

the trial ELA and positive above) and multiplied by each contour belt area. Negative values are multiplied by the chosen BR (i.e. they are in the ablation zone). All belt area-altitude-BR products are added, yielding a result which is initially positive, but decreases on iterating upwards. The first time the result becomes negative means that the zero net balance ELA is situated in the belt below the trial ELA (Fig. 8). The script outputs the ELA as the mean altitude of this belt, so again the calculation error is, at most, equal to half the contour interval.

The scripts are commented, so users can follow their rationale and, should they wish, adapt them to their needs.

3.3. Software requirements and availability

This toolbox is intended to work within ArcGIS 10.1 and subsequent versions. A 3D Analyst and Spatial Analyst license is also required.

The toolbox can be downloaded from the Computers and Geosciences GitHub repository at <https://github.com/cageo/Pellitero-2015> or from the Younger Dryas group website in the University of Aberdeen <http://www.abdn.ac.uk/geosciences/departments/geography-environment/outcomes-442.php>

4. Some tips for glacier reconstruction

The “accuracy” of the ELA calculation can be quantified but the overall “quality” is highly dependent on the palaeoglacier surface reconstruction. There are two main methods used to generate a glacier surface using landform evidence. The first is achieved by reconstructing the ice thickness along a flowline using an equation for ice rheology, following Nye (1952), which was adapted by Schilling and Hollin (1981) and Benn and Hulton (2010), with the latter authors producing a useful Excel spreadsheet. An automated approach for this, implemented in ArcGIS, is currently in preparation. The alternative is the cartographic approach, which relies on the “skill and knowledge” of the scientist to interpret a glacier surface using geomorphological evidence by drawing contours

which replicate “typical ice surfaces” observed today. The latter option becomes problematic where landform evidence disappears and where no topographical constraint limits the ice thickness e.g. for icecaps and icefields (Rea et al., 1999). In such cases the physical based modeling provides the only constraint on the palaeoglacier geometry.

5. Conclusions

This tool provides a method for the calculation of zero net balance/equilibrium ELAs using the four most used methods in palaeoglaciology and provides rapid calculations for single or multiple glacier datasets. It is intended to be useable by both those familiar with ArcGIS and novices alike. The Tool and source code can be downloaded with the paper and so can be modified to meet other end-user needs.

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Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.cageo.2015.05.005](https://doi.org/10.1016/j.cageo.2015.05.005).

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