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Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers

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Abstract

Past fluctuations of tropical and sub-tropical glaciers provide important palaeoclimate proxies for regions where other forms of evidence are rare. However, published equilibrium-line altitude (ELA) estimates for tropical and sub-tropical glaciers at the LGM vary widely, reflecting the diversity of methods and approaches employed by different research groups. This complicates regional and global comparisons of ELA estimates, and emphasises the need for standardised methods. The distinctive character of tropical and sub-tropical glaciers, however, means that standard methods for reconstructing former glacier limits, ELAs, and palaeoclimate need to be adapted for local conditions. Many methods of ELA reconstruction explicitly or implicitly make assumptions about glacier mass balance gradients, and care needs to be taken that the choice of accumulation area ratios (AARs), balance ratios (BRs) and terminus-to-head ratios (THARs) is appropriate, as such indices are influenced by climatic regime, debris cover and other factors. ELA reconstructions should employ multiple methods, and should be cross-checked and fully reported, to allow assessment of the accuracy of ELA estimates. Reliable glacier chronologies are equally important. Dating should be based on multiple radiometric techniques wherever possible, and method of dating, the type of material dated, and the context of the date must all be reported.

1. Introduction

Glaciers of the tropics and sub-tropics occur at high altitudes, and differ in important ways from mid- and high-latitude glaciers in lower topographic settings. First, the tropical and sub-tropical climatic environment results in distinctive glacier mass balance characteristics. Second, high-altitude tropical and sub-tropical glaciers produce glacial landsystems and sedimentary lithofacies associations that contrast with those of valley glaciers in mid- and high-latitudes. Third, in contrast to glacial systems in higher latitude regions, dating glacial landforms and sediments in tropical and sub-tropical settings is more problematic because the standard technique of radiocarbon dating can rarely be applied due to the scarcity of suitable organic deposits. Consequently, the methods used to reconstruct and interpret former glacier equilibrium-line altitudes (ELAs) in low-latitude regions need to be tailored to local conditions, as methods and protocols developed for other settings may not be appropriate. Problems associated with reconstructing ELAs of low-latitude glaciers have been discussed in some detail in recent reviews (Benn and Lehmkuhl,

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2000; Porter, 2001; Kaser and Osmaston, 2002). In this paper, we focus on the climatic and topographic characteristics of tropical and sub-tropical glaciers, the accurate reconstruction of former extent and timing of glaciation, and the implications for ELA reconstruction.

2. Climatic settings

Within the astronomical tropics, the mid-day sun is overhead at least once a year, and is never less than 43° above the horizon. This results in high solar radiation receipts throughout the year; consequently, annual variations in mean daily temperatures are smaller than diurnal temperature ranges (Hastenrath, 1985; McGregor and Nieuwolt, 1998; Kaser and Osmaston, 2002). The thermal homogeneity of the tropics is in sharp contrast to the mid- and high latitudes, where annual temperature fluctuations are larger than diurnal variations. The constancy of mean daily temperatures in the tropics means that the 0 °C atmospheric isotherm maintains a fairly constant altitude, and ablation occurs on the lower parts of glaciers all year. Accumulation cycles reflect the annual migration of the Intertropical Convergence Zone (ITCZ). In the humid inner tropics (e.g. the mountains of East Africa), precipitation occurs all year, but with two maxima in the spring and autumn as the ITCZ passes north and south, respectively. Further from the Equator (e.g. the Peruvian and Bolivian Andes), there tend to be distinct wet (summer) and dry (winter) seasons, the relative durations of which vary spatially and year to year (Fig. 1).

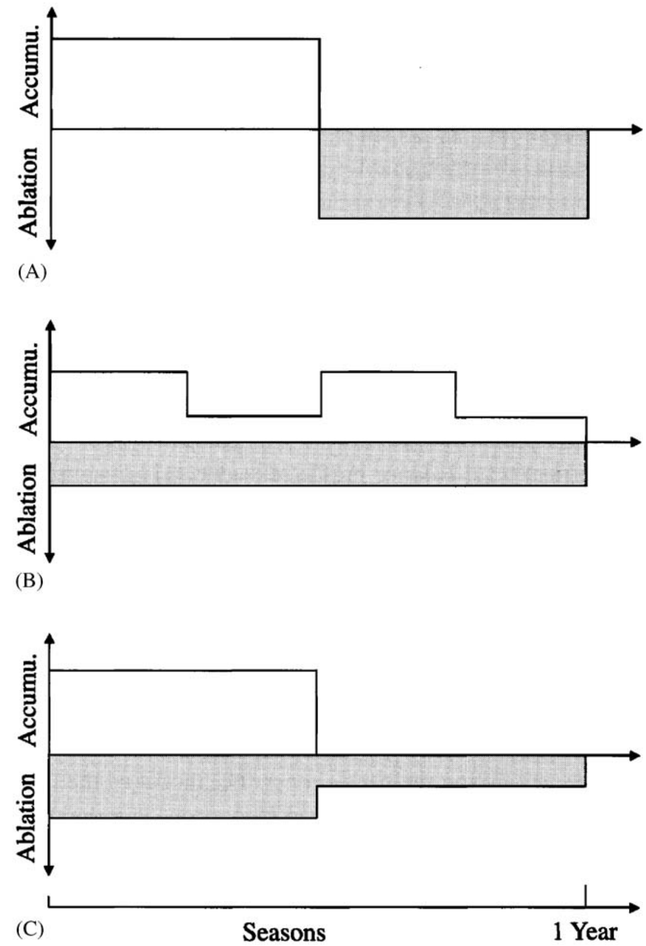

Fig. 1. Idealised annual mass balance cycles for glaciers in (A) mid latitudes, (B) inner tropics, and (C) outer tropics (from Kaser and Osmaston, 2002).

The range of influence of the ITCZ is not coincident with the astronomical tropics, however. Some parts of the tropics are permanently arid or semi-arid (e.g. the central Andes), whereas in parts of the Himalaya, the ITCZ extends as far as ~30°N in the summer months. Consequently, glaciers in the eastern and central parts of the main Himalayan chain (Bhutan, Nepal, Garhwal) receive most snowfall during the summer monsoon (Benn and Owen, 1998). Precipitation totals decline rapidly northward onto and across the Tibetan Plateau. In contrast, the more western parts of the Himalaya (Ladakh, Karakoram, Hindu Kush) have winter precipitation maxima, and are climatically similar to mid-latitude mountain ranges. All parts of the Himalaya experience pronounced annual temperature variations, with cold winters and a distinct ablation season during the warmer months (April–October). The annual mass balance cycles of tropical and sub-tropical glaciers are thus highly variable (Kaser, 1995; Kaser and Osmaston, 2002; Fig. 1).

Vertical mass balance profiles are also influenced by climatic setting (Fig. 2). In the humid tropics, ablation gradients tend to be steeper than in drier environments, due to altitudinal variations in the amount of snow, sleet, and rain falling on the ablation zone during the wet months. In contrast, ablation gradients in the arid sub-tropics are expected to be less steep than in mid-latitudes, because of the importance of solar radiation in glacier energy budgets in cold, high-altitude environments (Kaser, 2001).

Accumulation gradients tend to be small in the tropics, because most snow accumulation is associated with large convective systems. Where mountain summits extend higher than the general height of free convection, accumulation totals may decline at the highest altitudes. In the mid- and high latitudes (including the western Himalayan chain) most snow accumulation occurs in association with travelling depressions, and tends to increase approximately linearly with altitude. Thus, the mass–balance profiles of tropical glaciers tend to exhibit a sharper inflection at the equilibrium line than those of mid-latitude glaciers (Fig. 2). This characteristic can be quantified using the balance ratio (BR),

$$BR = b_a/b_c,$$

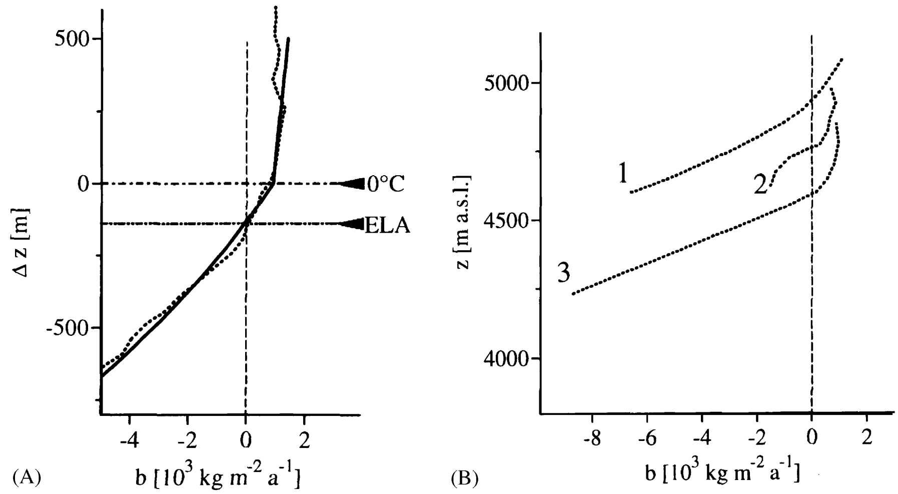

Fig. 2. Vertical mass balance profiles for (A) A mid-latitude glacier (Hintereisferner) and (B) Tropical glaciers (1: Glaciar Yanamarey, Peru, 2: Lewis Glacier, Kenya, 3: Meren and Carstensz Glacier, Irian Jaya). The curves for Hintereisferner show observed (dashed) and theoretical (bold) curves (from Kaser and Osmaston, 2002).

where b_a is the ablation gradient, and b_c is the accumulation gradient (Furbish and Andrews, 1984). For non-debris covered glaciers, BR is typically 1.8–2.0 in the mid-latitudes and >3 in the tropics (Kaser and Osmaston, 2002). Variations in the BR are associated with variations in the relative sizes of the accumulation and ablation areas; glaciers with high BRs have relatively large accumulation areas and small ablation areas. Such variations have important implications for the reconstruction of glacier ELAs from morphometric data, as discussed in Section 6.

3. Glacier types

At present, a very wide range of glacier types exists in the tropics and Himalaya. The types include (1) plateau ice caps (e.g. Irian Jaya); (2) volcano ice caps with radial outlet glaciers (e.g. Mexico, Ecuador, Bolivia); (3) niche and cirque glaciers on dissected mountains or volcanic edifices (e.g. Mt Kenya, the high Andes and Himalaya); (4) valley glaciers (e.g. Himalaya, Andes); and (5) interconnected transection complexes (e.g. Karakoram). Glacier type has important implications for mass balance, and consequently must be considered in ELA reconstructions (Benn and Lehmkuhl, 2000; Kaser and Osmaston, 2002). First, glaciers that are fed entirely or predominantly by direct snowfall (e.g. ice caps) tend to exhibit predictable accumulation gradients, whereas those that receive substantial inputs from avalanches can have accumulation focused in narrow altitudinal zones at the foot of headwalls, and are less amenable to analysis and monitoring. Second, the geometry and mass balance of cirque and valley glaciers are more influenced by local factors such as snow drifting and shading than are ice caps. Third, glaciers with steep valley sides and/or headwalls may have extensive debris mantles on their ablation zones (Clark et al., 1994; Benn and Lehmkuhl, 2000). Debris cover profoundly influences ablation and its spatial variations: very thin debris cover tends to accelerate ablation by lowering albedo, whereas debris thicker than a few cm tends to insulate the underlying ice and inhibits ablation (Østrem, 1959; Nakawo and Young, 1982). Consequently, glaciers with thick debris cover tend to have relatively large ablation zones, with reversed ablation gradients in their lower reaches. Taken together, these factors introduce large local and regional variations in mass–balance characteristics, and the location of glacier ELAs relative to glacier geometry.

Former glaciers had a similar diversity. The glacier type can generally be determined by detailed mapping of geomorphological evidence (e.g. moraines, trimlines) in the field or from aerial photographs or satellite images. Former debris-mantled glaciers can be recognised on the basis of glacial landsystems, particularly the presence of large lateral-frontal moraine ridges or ramps (Owen and Derbyshire, 1989; Benn and Owen, 2002; Benn et al., 2003).

4. Equilibrium-line altitudes

The concept of the glacier ELA requires some clarification. Traditional definitions of the ELA refer to the altitude where $b_n = 0$, where b_n is the net balance at the end of the (summer) ablation season (Paterson, 1994). This definition was developed for mid- and high-latitude glaciers, but is less obviously applicable to tropical glaciers where there is year-round ablation.

Where there is a distinct dry season, the end of the dry season provides a convenient end point for the balance year. The altitude of the equilibrium line is rarely constant across a glacier, but varies with patterns of snow accumulation, shading, and other factors. Annual ELAs reflect transient climatic conditions, and the glacier as a whole may have gained or lost mass over the preceding year. The *steady-state ELA* is the average altitude at which $b_n = 0$, for a glacier with zero net balance as a whole, and thus represents a glacier with a particular geometry that is in equilibrium with climate. This definition of the ELA most closely corresponds to the "theoretical ELAs" calculated for former glaciers.

Steady-state ELAs have been established for some tropical and Himalayan glaciers where mass balance records are available. For example, Kulkarni (1992) and Wagnon et al. (2001) plotted net glacier mass balance (b_n) against annual ELA for multiple years, and the ELA for which $b_n = 0$ was found by interpolation. This procedure is useful where both positive and negative balance years have occurred, but where glaciers are in constant retreat, the modern steady-state ELA is not a particularly useful concept, since it invokes some hypothetical climate for which a glacier of a given size would be at equilibrium. At times of rapid climate change, such a hypothetical steady state is meaningless. Therefore, "present day" ELA must be defined with reference to one particular year or group of years. Needless to say, "present-day" ELAs cited in the literature are not standardised to a common time period, and frequently the year or years for which the ELA applies is not stated. Standardisation of procedures for determining modern ELAs is a very important goal, and will require dedicated research effort. Ideally, ELAs should be established for a "standard decade", to minimise the influence of anomalous years, because tropical and sub-tropical glaciers commonly have large inter-annual variations in the length of the ablation season. In the monsoonal Himalaya, for example, autumn cyclonic snowfalls may shorten the ablation season by a month or more (Benn et al., 2001).

Establishing theoretical modern ELAs in regions with no modern glaciers presents a different set of problems. A commonly used approach is to assume that, in the tropics, the ELA coincides with the 0° mean July (or mean annual) isotherm, which can be determined from radiosonde data (e.g. Porter, 1979, 2001). This assumption is broadly true for the humid inner tropics, but is unlikely to be so in the outer tropics and sub-tropics, where significant ablation can occur during the dry season and the ELA may lie substantially higher than the 0 °C isotherm. For such regions, estimates of the modern ELA can be made by projecting meteorological data up temperature and precipitation gradients in the atmosphere, to levels where the paired variables satisfy established relationships between ablation season temperatures and snow accumulation at glacier ELAs. Such relationships can be determined using empirical curves (e.g. Ohmura et al., 1992) or analytical models (e.g. Seltzer, 1994; Kaser, 2001). It must be emphasised, however, that individual glacier ELAs may deviate significantly from climatic ideals due, for example, to patterns of shading, and snow redistribution by wind and avalanching.

5. Glacier reconstruction and dating

The accurate reconstruction of past ELAs requires that the extent and morphology of the former glaciers can be accurately determined. Furthermore, the age of the reconstructed glacier needs to be determined to enable researchers to use the ELAs as proxies for past climatic conditions. The relative morphostratigraphic context of glacial deposits provides an essential first order chronological framework. Yet without absolute dates to constrain the precise age of the deposits, it is impossible to make regional and global comparisons. Both landform identification and dating present particular challenges in these environments, and adhering to a critical evaluation of field evidence and methodological assumptions is vital to the climatic interpretation of reconstructed ELAs.

Reconstructing the former extent of glaciers requires detailed geomorphic mapping and the analysis of landforms and sediments. The most accurate methods also require that there is sufficient geomorphic evidence, usually lateral-terminal moraines and trimlines, to allow the shape of the former glacier to be reconstructed. However, glacial moraine evidence is by nature discontinuous; and relatively younger and larger advances of a glacier will destroy moraines deposited in older, less-extensive advances, leaving an incomplete geomorphic record. Lake sediments down-valley from the moraines may provide an important source of data to help reconstruct glacier front oscillations, but it cannot automatically be assumed that clastic sediment peaks in lacustrine records correspond to glacial maxima, rather than paraglacial sediment reworking during deglaciation (Ballantyne, 2002).

Careful consideration of the evidence is critical for evaluating the timing and extent of glacier advances. This is frequently challenging in high-energy tropical and sub-tropical settings where denudation is intense, glacial landforms are easily destroyed and sediments are rapidly redeposited or transferred within and/or out of the mountains. Furthermore, many tropical and sub-tropical glacial environments are characterised by abundant debris produced by mass movement processes from steep, long valley slopes. As a consequence, mass movement and glacial landforms and sediments in these regions may be easily misinterpreted because the sediments and landforms produced by mass movement and glacial processes can look very similar. In particular, misinterpretations commonly arise because intense fluvial and glacial erosion often destroys diagnostic morphologies of glacial and mass movement landforms, making their identification difficult. In addition, the diamictons that comprise mass movement and glacial landforms have very similar sedimentary structures and have similar particle size distributions and particle shapes. Furthermore, there are few published data for contemporary glacial and mass movement environments to provide analogues and aid comparisons (Benn and Owen, 2002). Many researchers have highlighted the problem of misinterpretation of glacial and non-glacial landforms and sediments, and have described situations where the reconstructions of the former extent of glaciers may be erroneous because of little detailed geomorphic and sedimentological analysis (Derbyshire, 1983, 1996; Fort, 1986, 1988, 1989, 1995; Fort and Derbyshire, 1988; Derbyshire and Owen, 1990, 1997; Lehmkuhl and Pörtge, 1991; Hewitt, 1999). Clearly, to make accurate reconstructions of former ELAs there should be no ambiguity about the extent of past glaciers and there should be sufficient evidence for a former glacier to be reconstructed in detail.

Defining the age of landforms and sediments used to reconstruct former Late Quaternary glaciers in tropical and sub-tropical settings is difficult because of the lack of suitable organic material for radiocarbon dating. The majority of studies have relied on estimates of the timing of glaciation by comparison with chronologies in higher latitude regions and/or using relative dating techniques such as comparison of soil chronosequences and weathering characteristics (e.g. Burbank and Kang, 1991; Bäumler et al., 1997; Guggenberger et al., 1998). Newly developing techniques that include luminescence and cosmogenic radionuclide (CRN) surface exposure dating are beginning to allow glacial successions throughout the tropics and sub-tropics to be dated and regional correlations are being attempted (Phillips et al., 2000; Richards et al., 2000a, b; Owen et al., 2001, 2002; Smith et al., 2001, 2002; Tsukamoto et al., 2002).

Brigham-Grette (1996) provides a useful summary of the various numerical dating methods that may be used to date glacial landforms. Included are discussions of tephrochronology, lichenometry, and dendrochronology, which are widely used methods for dating Holocene moraines. Benn and Owen (2002) describe the applicability and the application of luminescence and CRN techniques to dating glacial landforms in high-altitude environments with specific reference to the Himalaya. A useful summary of the methods and problems of applying luminescence techniques in Himalayan environments is provided by Richards (2000).

Many of the high glaciated mountain peaks in the tropics and sub-tropics are Quaternary volcanoes, the eruptive products of which may be interstratified with glacial deposits. Limiting and constraining ages for glacial units can be obtained by dating associated lava flows or pyroclastic units. In Hawaii, for example, the ages of moraines and related drifts of three Middle and Late Pleistocene glaciations have been bracketed by K/Ar ages of basaltic and alkalic lavas (Wolfe et al., 1997). The latter lithologies have higher K contents, and therefore provide ages with smaller standard errors. Under favourable conditions, such radiometric ages can overlap the range of radiocarbon dating (Porter, 1979). Zircon fission-track dates can also provide limiting ages for pyroclastic units of early Late Pleistocene age and older (e.g. Herd and Naeser, 1974). Unrealised opportunities for dating Pleistocene volcanic rocks associated with moraines on recently active low-latitude volcanoes exist in Mexico and the northern and central Andes.

Most studies that have applied numerical dating techniques present rather limited data sets and in most cases only one dating method is applied. This makes it difficult to assess the validity of the numerical dating. In particular, where radiocarbon methods have been used, the limited number of dates does not permit testing whether the organic material (often charcoal) is in situ and is a true reflection of the age of the sediment and/or landform. Similarly, in studies where only a few CRN ages have been undertaken on moraine boulders it is not always possible to determine whether these ages are influenced by the inheritance of CRN on derived boulders and/or if weathering or exhumation has resulted in ages significantly younger than the true age of the moraine (Phillips et al., 2000). Owen et al. (2002) discuss some of these problems and provide an example of a sampling strategy for CRN dating of high-altitude glacial landforms in their study of the glacial succession in the Karakoram Range.

The validity and quality of luminescence dating is difficult to assess, especially if full location, sampling methods and analytical data are not presented (Richards et al., 2001). Richards et al. (2000a, b) provide a useful model for applying luminescence methods to date glacial landforms in the Himalaya. In particular, different luminescence techniques on different mineralogies and particle sizes within the same sample are used to provide confidence in the dating.

There are few studies that have attempted to test previous numerical dating or assess the validity of the methods. Finkel et al. (2003) provide an example of a study that tests luminescence and radiocarbon dates in the Khumbu Himal. In their study, they apply CRN methods to redate moraines and successfully confirm the previous dating. Given the uncertainty inherent in most numerical dating techniques, it is important to use multiple dating techniques and to produce large datasets to provide confidence in the dating and hence provide a reliable age on the landform and reconstructed ELA. Overall, it is valuable to consider the quality of dating control in terms of both the relative precision, and methodology used on a valley-specific basis. If moraines are assigned ages on the basis of morphostratigraphic correlations, it is important to consider the distance from directly dated features. Morphostratigraphy is a valid technique within limited geographical areas, but becomes much less certain with increasing distance, particularly where climatic gradients are large.

The main geochronological techniques used to date Late Quaternary age moraines in the tropics and subtropics are summarised in Table 1, which describes the types of material, problems encountered and the data needed to adequately evaluate the validity of the dating.

6. Methods of ELA reconstruction

The range of methods for reconstructing former glacier ELAs has been the subject of several extensive reviews (e.g. Meierding, 1982; Torsnes et al., 1993; Porter, 2001; Kaser and Osmaston, 2002), and details of each method are not repeated here. Methods in common use are: (1) Accumulation Area Ratios (AAR); (2) Area–Altitude Balance Ratios (AABR); (3) Maximum Elevation of Lateral Moraines (MELM); (4) Terminus to Head Altitude Ratios (THAR); and (5) gross morphological indices such as glaciation threshold and cirque floor altitudes. The first two methods are based on assumed forms of the glacier mass–balance gradient, and are therefore broadly compatible with the concept of the steady-state ELA as defined above. MELM makes use of the fact that formation of moraines only occurs below the contemporary ELA, and therefore gives a minimum altitude. THAR invokes general relationships between glaciers and basin relief, but without reference to assumed mass–balance curves. Each method is discussed in turn below.

6.1. AAR method

This method assumes that, under steady-state conditions, the accumulation area of the glacier occupies some fixed proportion of the glacier area. Steady-state AARs for mid- and high-latitude glaciers lie in the range 0.5–0.8 (Meier and Post, 1962; Hawkins, 1985), with typical values around 0.55–0.65 (Porter, 1975). Because glaciers in the humid tropics have steeper ablation gradients and less steep accumulation gradients than mid- and high-latitude glaciers, they tend to have higher steady-state AARs ($\sim$0.8; Kaser and Osmaston, 2002). However, the effect of extensive debris cover lowers the steady-state AAR, because a larger ablation area is required to balance accumulation. Values for modern debris-covered glaciers in the Himalaya are around 0.2–0.4 (Müller, 1980; Kulkarni, 1992), so it is important to determine whether former glaciers had a debris cover (Clark et al., 1994; Benn and Lehmkuhl, 2000; Kaser and Osmaston, 2002). Former steady-state AARs may have differed substantially from modern values in the same region, due to changes in climatic regime, debris cover, or glacier hypsometry, so care is required to choose the most suitable ratio. An interesting solution to this problem has been developed by Kaser and Osmaston (2002). Former ELAs are calculated for homogeneous groups of glaciers using a range of AARs. The AAR that results in the lowest variance of calculated ELAs is then assumed to be the most appropriate value. Applying this method to former glaciers in the Rwenzori, Kaser and Osmaston (2002) determined an "optimum" AAR of 0.65–0.70, lower than that expected for clean tropical glaciers, but compatible with tropical debris-covered glaciers. Geomorphological evidence also indicates that the glaciers had extensive debris covers, supporting this approach to the AAR method.

Traditionally, the AAR method has been used to calculate glacier ELAs using the map area of glacier surfaces, excluding valley sides. However, where avalanching provides an important source of snow accumulation, glacier mass balance is strongly influenced by the form and altitude of valley sides, and AAR methods need to be modified accordingly. Owen and Benn (2005) provide an example of AAR methods based on whole-catchment hypsometry, and highlight the need for further research into methods of ELA reconstruction in high-relief catchments.

6.2. AABR methods

AABR methods (Kaser and Osmaston, 2002; also known as Balance Ratio or BR methods: Furbish and Andrews, 1984; Benn and Gemmell, 1997; Benn and Evans, 1998) takes account of both mass balance gradients and reconstructed glacier hypsometry. Where good topographic maps and air photograph coverage are available, this method is more rigorous than any other, but where they are not available, it offers no particular advantages.

An Excel spreadsheet for the calculation of ELAs using the method of Furbish and Andrews (1984) was published by Benn and Gemmell (1997). However, Osmaston (2005) has shown that this is prone to systematic errors, and overestimates the ELA by a small amount. An improved method of calculation, and a useful review of AABR methods is provided by Osmaston (2005).

Table 1
Summary of the main numerical dating techniques for defining the ages of Late Quaternary moraines in the Tropics and Subtropics

Dating method	Materials dated	Problems	Preferred number of samples	Data needed to objectively evaluate the dating	Precision and accuracy	Key references
Radiocarbon dating: conventional	Organic material (mainly charcoal, palaeosols, and wood) and carbonate precipitates (tufa and cements)	Mixing different organic compounds of different ages; erroneous ages on carbonates if they are not closed systems	Multiple samples in the same stratigraphic horizon and from younger and older sediments within a succession to test for inheritance and bioturbation	Type of material dated, sampling location, stratigraphic relationship, laboratory where samples were dated. Uncalibrated ^{14}C date should be provided together with ^{13}C data.	Precision is high and accuracy is high providing material has not been derived or later incorporated into the moraine. Calibration of radiocarbon dates marginally reduces accuracy.	Trumbore (2000), Röthlisberger and Geyh (1985),Lehmkuhl (1997), Mark et al. (2002), Rodbell and Seltzer (2000)
AMS	Organic material (mainly charcoal, plant remains, shells and calcareous microfossils) and carbonates (tufa and cements)	Old ages due to derived material, young ages due to bioturbation; erroneous ages on carbonates if they are not closed systems				
Cosmogenic radionuclides: ^{10}Be, ^{26}Al	Quartz-rich rocks and sediment	Old ages due to inherited CRNs if boulders and sediment is derived boulders, young ages due weathering and/or exhumation, and errors due to uncertainties in production rates	Multiple samples (at least 3 dates per moraine and from several morpho-stratigraphically similar moraines) to test for inheritance, weathering and exhumation. The use of multiple CRNs is preferred as this helps test for inheritance.	Location of specific sampling sites, descriptions of sampling site and boulder and/or surface that was dated. Details on the sample preparation, the laboratory where the AMS measurements were made. CRN concentrations should be provided with details of the age calculation methods, including what production rates were used in determining the age.	The precision of the AMS measurement is high, but the accuracy is relatively low because of the uncertainty in the geologic stability of the surface and/or derivation of boulders and sediments. Accuracy is further reduced because of the uncertainty in production rates	Gosse and Phillips (2001), Putkonen and Swanson (2003), Owen et al. (2001), Schäfer et al. (2001), Owen et al. (2002), Finkel et al. (2003)
^{36}Cl	Mafic rocks and sediment	Old ages due to inherited CRNs if boulders and sediment is derived boulders, young ages due weathering and/or exhumation, and errors due to uncertainties in production rates. Leaching of Cl due to problematic mineralogies.				

^{21}Ne	Mafic rocks and sediment	Old ages due to inherited CRNs if boulders and sediment is derived boulders, young ages due weathering and/or exhumation, and errors due to uncertainties in production rates				
Ca	Carbonates and sediment	Old ages due to inherited CRNs if boulders and sediment is derived boulders, young ages due weathering and/or exhumation, and errors due to uncertainties in production rates				
In situ ^{14}C	Quartz-rich rocks and sediment	Experimental problems in measuring ^{14}C concentrations				
Luminescence dating: *T*	Burnt flints, pottery and sediment	Rare to find artifacts on LGM moraines, and changes in environmental dose rate through time	Duplicate samples from the same stratigraphic horizon and several samples from different stratigraphic horizons to test for stratigraphic coherence	Location of sampling site and graphic sedimentary logs showing sampling positions and stratigraphic locations. Method of environmental dose rate determination and when applicable radioisotope concentrations. Methods of determining equivalent doses (D_E) including D_E data.	Precision is relatively low because of the variability of the behavior of sediments and determination of environmental dose rates. Accuracy can be high because, with the exception of partial bleaching problems, there are no problems of inheritance	Aitken (1998), Richards (2000), Richards et al. (2000a, b), Tsukamoto et al. (2002)
GLSL/BLSL	Quartz-rich terrestrial sediments	Partial bleaching problems, low luminescence signal, and changes in the environmental dose rates through time				
IRSL	Feldspar-rich terrestrial sediments	Partial bleaching problems, anomalous fading, and changes in the environmental dose rates through time				
Electron spin resonance	Sediment, carbonate precipitates, bones and teeth	Rare to find bones and teeth in moraines. Carbonate precipitates are not necessarily closed systems and may therefore provide erroneous ages.	Duplicate samples from the same stratigraphic horizon and or from the bone or	Location of sampling site and graphic sedimentary logs showing sampling positions and stratigraphic locations. Method of environmental	Precision is relatively low because of the variability of the behavior of materials dated and determination of environmental dose rates.	Grün (1997), Yi et al. (2002)

Table 1 (*continued*)

Dating method	Materials dated	Problems	Preferred number of samples	Data needed to objectively evaluate the dating	Precision and accuracy	Key references
		Problems related to the behavior of the material being dated. Changes in the environmental dose rates through time	tooth. When applicable several samples from different stratigraphic horizons should be dated to test for stratigraphic coherence	dose rate determination and when applicable radioisotope concentrations. Methods of determining equivalent doses (D_E) including D_E data.	Accuracy can be high because there are no problems of inheritance	
Dendrochronology	Tree rings	Generally limited to dating Little Ice Age moraines	Variable; attempt to locate oldest tree growing on moraine or tree tilted by glacier	Ecesis interval (time lag for establishment of tree seedlings on moraine)	Generally datable to nearest decade or less	Brigham-Grette (1996)
Lichenometry	Crustose lichens	Limited to mid- to late-Holocene moraines	Largest lichen on moraine or mean of 5 largest	Development of reliable lichen growth curve	Date to nearest decade (youngest moraines) or century	Brigham-Grette (1996)
K–Ar and Ar–Ar dating	Lava flows and pyroclastic layers	Large potential errors for low-K lithologies	Multiple samples	Relationship of dated unit to moraine or drift body. Replication of ages for same unit.	Accuracy and precision depend on lithology	Renne (2000), Lanphere (2000), Porter (1979), Mahaney (1990)
Tephrochronology	Tephra layers	Ages of young tephra layers usually based on ^{14}C dating of adjacent organic-rich sediments.	One, if correctly identified or dated	Dating of tephra at moraine site, or reliable correlation, based on geochemistry, with samples dated elsewhere	Accuracy and precision is high when ash is correlated with a well-dated ash	Porter (1981), Sarna-Wojcicki (2000), Rodbell et al. (2002)

6.3. MELM

The maximum altitude of lateral moraines provides a secure means of determining the minimum altitude of former glacier ELAs. However, where moraine preservation potential is low, as is often the case in high-relief, high-altitude catchments, this altitude may lie considerably below the true value. The maximum altitude of lateral moraines may also lie well below glacier ELAs where the only moraines are frontal rather than lateral (e.g. as on plateau or volcano ice caps) and partly or completely encircle the ice mass. However, in basins where moraines are well preserved, MELM can be more reliable than other methods, particularly where AARs or BRs are poorly constrained (Richards et al., 2000a).

6.4. THAR

Terminus-to-head altitude ratio methods assume that the glacier ELA can be approximated by some constant ratio between the altitude of the terminus and the head of the glacier. As for AAR methods, this depends crucially on the choice of the correct ratio, which may differ for modern and ancient glaciers in the same region. Meierding (1982) found that THARs of 0.35–0.40 yielded the best results in his study of glaciers in the Colorado Front Range. In middle and northern latitudes the Median Altitude Method has often been employed, which uses THAR = 0.5. However, the appropriate THAR is strongly influenced by glacier shape; Osmaston (1965, 1975) found that for tropical piedmont glaciers and volcano icecaps the optimum THARs were 0.5 and 0.3, respectively. Kaser and Osmaston (2002) introduced a graphical method for determining the most appropriate THAR, in which the terminus and head altitude of a group of glaciers are plotted on a biaxial graph (Fig. 3). The slope of the best-fit line indicates the optimum THAR, and the point at which the line intersects a diagonal drawn through the origin gives the best estimate of the ELA for the group. For three groups of glaciers in the Rwenzori, this method yields THARs of 0.46, 0.50 and 0.55; the corresponding estimates of the ELA are almost identical to those derived by more rigorous methods. THAR methods are less appropriate in very high relief catchments where avalanching forms an important component of the accumulation, and where the position of the "head" of the glacier is more ambiguous.

6.5. Glaciation threshold and cirque-floor altitudes

These methods are the least accurate means of estimating the altitudes of former glaciers. First, such measures give only an approximate position of former ELAs, and second, it is difficult to assign these altitudes to any particular glacial stage. They have proved useful in the past as a general indication of glacier altitudes over large and inaccessible regions.

No one method is ideal in all situations, and the best method depends on glacier type, catchment topography and climatic environment. The best approach is to use multiple methods wherever possible, with a range of values for the relevant ratios. In a comparative study of the ELAs of 75 former glaciers in the Rwenzori, Kaser and Osmaston (2002) found that the root mean squared

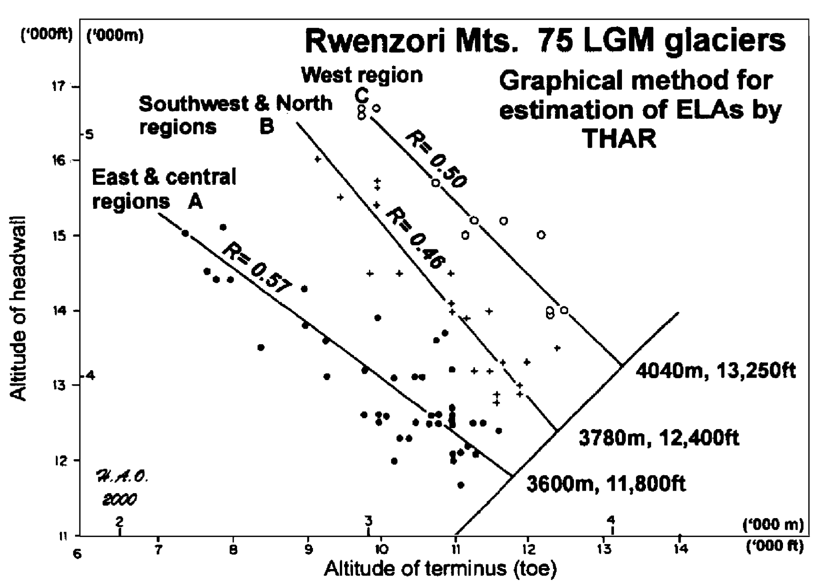

Fig. 3. Graphical estimation of ELA by THAR method for grouped glaciers in the Rwenzori. For explanation see text (from Kaser and Osmaston, 2002).

(RMS) deviation of the individual ELA estimates by AAR (0.67) from the population mean was 200 m. By grouping them into four homogeneous groups based on aspect and location, the deviations from the differing group means were reduced to c.100 m, by both AAR (0.67) and AABR methods, thus yielding more precise estimates of the mean ELA at the locations of these groups. By taking the ELAs of individual glaciers estimated by AABR and using these to derive a symmetrical domed ELA trend surface, computed with a cubic regression, the RMS deviations from it were reduced to 86 m. However, a surface fitted manually to the same points, taking into account its departure from symmetry, reduced the RMS deviations to a mere 35 m. Where sufficient glaciers are available, precision and interpretation will almost always be improved by dividing them into groups, or by deriving ELA profiles across a mountain range, or best by deriving an ELA trend surface.

7. Should former ELAS be corrected for sea level change?

Broecker (1997) argued that, because global sea level during the last glaciation was at least 100 m lower than it is today, former glacier ELAs should be adjusted accordingly, because the glaciers were effectively at higher altitudes. Furthermore, this appears to imply that calculated temperature changes relative to the present should be adjusted correspondingly, since part of the temperature change is attributable to the altitude effect, rather than global climate change (Porter, 2001). However, Osmaston (submitted for publication) has shown that temperatures are not significantly depressed at altitude due to a reduction in glacio-eustatic sea level. This is because the volume vacated by falling sea level is close to that displaced by ice sheets, when density changes are taken into account. Therefore, the atmosphere as a whole does not fall to a lower level due to glacio-eustatic sea level fall. In the absence of external climatic change, temperatures at any given level will remain constant, because the mass of the overlying atmosphere is unchanged. Conversely, temperature at the new, lowered sea level will be higher than that at the ‘old’ sea level, due to higher atmospheric pressure and adiabatic warming.

In contrast, in a cooler world, some additional temperature changes will occur at a given level due to thermal contraction of the oceans, because the atmosphere as a whole does move closer to the centre of the Earth in this case. The effect, however, is small, and is well within the errors associated with ELA estimates, and hence can safely be ignored. Climatic cooling also results in thermal contraction of the atmosphere, resulting in steeper adiabatic lapse rates and additional cooling at altitude. Although significant, this effect will be spatially and temporally variable, and does not appear to justify “correcting” ELA estimates.

8. Meaning of changes in ELA

The difference in altitude between modern and former ELAs (ΔELA) has been widely used to estimate climate change. A factor that is often not considered when calculating ΔELA is that modern and former ELAs are commonly determined for different points in space. Where ELA surfaces are sloping, as is usually the case, this introduces a source of error in ΔELA over and above that associated with the modern and former ELA estimates (Osmaston, 1965, 1975; Porter, 2001; Kaser and Osmaston, 2002). Where possible, trend surfaces of present and former ELAs should be calculated to obtain the most accurate estimates of ΔELA.

The simplest assumption is that all ΔELA can be attributed to changes in temperature, which can be estimated by using an assumed average environmental lapse rate in the atmosphere. However, if there were associated changes in precipitation, the estimated temperature change would be different. This point applies even in the humid tropics. For example, Kaser and Osmaston (2002) found that 20th century changes in the ELAs of glaciers in the Cordillera Blanca cannot be explained by temperature changes alone, but were also influenced by changes in humidity. The meaning of ΔELA is clearest where independent temperature or precipitation proxies are available, although this is commonly not the case. However, the difficulty of separating out the temperature and precipitation signals need not negate the usefulness of ΔELA in providing palaeoclimatic information. Currently available atmospheric general circulation models commonly yield differing climatic scenarios for a given region. These models can be tested against ΔELA data to determine which models yield temperature/precipitation combinations compatible with former glacier distributions, and limnological, palaeobotanical, geochemical, and sedimentological evidence.

9. Summary and recommendations

The determination of ΔELAs for a glaciated region in the tropics, subs-tropics, and Himalaya should follow these basic guidelines:

1. Careful mapping and dating should be conducted in order to determine the past extent of a glacier and the chronology of glaciation. In terms of chronology, the method of dating, the type of material dated, and the context of the date (e.g. does it date glacier advance, retreat, or something else) must all be

reported (see Table 1). Sampling strategy and laboratory methods and assumptions should be recorded in full.

2. Modern ELA needs to be determined for the valley or area where the ΔELA estimate will be made. Again, the method must be reported so that the accuracy of the modern ELA estimate can be assessed.
3. The determination of the palaeo-ELA should ideally incorporate several of the methods mentioned in Section 5. By this means a more accurate palaeo-ELA may be approached.
4. Climatic interpretation of ΔELA should provide a range of possible scenarios that include, among the principal factors, changes in temperature, snowfall, humidity, radiation balance, and wind speed. In the absence of close control on past climatic variations, any climatic assessment of ΔELA for a region should be considered provisional.

It is our hope that by following these guidelines, sufficient rigor will be introduced to ΔELA calculations and their climatic interpretation that such studies will be useful for comparison with other proxies for late-Quaternary climatic change and the outcome of experiments with atmospheric general circulation models.

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