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EQUILIBRIUM LINE ALTITUDE FLUCTUATION ON THE SOUTH WEST SLOPE OF NEVADO COROPUNA SINCE THE LAST GLACIAL MAXIMUM (CORDILLERA AMPATO, PERÚ)

Fluctuación altitudinal de la línea de equilibrio glaciar en la vertiente Suroeste del Nevado Coropuna desde el Último Máximo Glaciar (Cordillera Ampato, Perú)

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ABSTRACT: The main aim of this research was to reconstruct the LLGM (local last glacial maximum), 1955 and 2007 glacial phases on the South West slope of Nevado Coropuna to obtain valuable information on the changes that have occurred and analyze the glacier evolution. For this purpose the ELA (Equilibrium Line Altitude) indicator has been used as a reference, with the AABR (Area x Altitude Balance Ratio) method, based on the principle of weighting the mass balance according to the distance above or below the ELA of that area. An ELA of 4762 m was obtained for the LLGM, 5779 m for 1955 and 5850 m for 2007, implying a vertical shift of 1088 m from the LLGM to 2007 and of 71 m from 1955 to 2007. The total glaciated surface was reduced by 21.5% between 1955 and 2007 and the temperature shift from LLGM to 2007 was 9.13 ºC (0.0091ºC/m). The ice of glaciers makes them valuable for climate research, this method offers quantitative information and the analysis of this data may contribute to research into climate change and climatic trends for future predictions.

KEYWORDS: Glaciers; climate; ELA; AABR; tropical glaciers; Coropuna.

RESUMEN: El principal objetivo de esta investigación es reconstruir las fases glaciares del Último Máximo Glaciar Local (LLGM), 1955 y 2007 en la vertiente Suroeste del Nevado Coropuna para obtener información sobre los cambios ocurridos y analizar la evolución glaciar. Para este propósito el indicador de la altitud de la línea de equilibrio glaciar (ELA) ha sido utilizado como referencia, calculado con el método AABR (Area x Altitude Balance Ratio), basado en el principio de ponderación del balance de masa en función de la distancia por encima o debajo de la ELA de esa área. Se obtuvo una ELA de 4762 m para el LLGM, 5779 m para 1955 y 5850 m para 2007, lo que implica una variación de 1088 m desde el LLGM hasta el 2007 y 71 m desde 1955 hasta 2007. La superficie total glaciada se redujo un 21,5% entre 1955 y 2007 y la variación de temperatura desde el LLGM hasta 2007 fue de 9,13 ºC (0,0091ºC/m). El hielo de los glaciares los convierte en un elemento importante para estudios climáticos, este método ofrece información cuantitativa y el análisis de los datos puede contribuir a investigaciones sobre el cambio climático y tendencias climáticas para predicciones futuras.

PALABRAS CLAVE: Glaciares; clima, ELA; AABR; glaciares tropicales; Coropuna.

1. Introduction

High mountain glaciers in the tropics are very sensitive to temperature variations and are a key factor in climate research. As good indicators of climate change, glaciers can provide climate records. Resolving the exact timing, structure and geographic extent of late-glacial climate events is fundamental to our understanding of the causes of abrupt climate change and poses a key problem in palaeoclimate research (Denton *et al.*, 2005). The ice mass of Nevado Coropuna has decreased from past glacial phases to the present day. Racoviteanu *et al.* (2007) suggested approximately 26% reduction of the ice cover between 1962 and 2000. Úbeda & Palacios (2009) calculated a reduction of ~18% of the glacial system surface for the entire Nevado Coropuna in the 52 years from 1955 to 2007.

To observe glacier and paleoglacier in different phases, the ice mass must be characterized using indicators to show the changes in glacial chronology and magnitude. The best indicator for this purpose is the Equilibrium Line Altitude (ELA) (Ubeda *et al.*, 2012). According to Benn *et al.* (2005) the altitude of the equilibrium line is rarely constant throughout a glacier, but varies with patterns of snow accumulation, shading, and other factors. Therefore the concept of steady-state ELA has used, which is the average altitude at which the net balance at the end of the ablation season is equal to zero. Alcalá *et al.* (2011) reported an LLGM (local last glacial maximum) ELA in the Huayuray valley of 4980 m with AA (Area x Altitude) method. Bromley *et al.* (2011b) used the MELM (Maximum Elevation of Lateral Moraines) and THAR (Terminus Headwall Altitude Ratio) methods to calculate LLGM ELAs for the Pucuncho peaks. The results reported using the MELM method were an average of 4887 ± 77 m for the Western slope and 4745 ± 66 m for the South slope, the results using the THAR method (with ratio 0.28), were an average of 5059 ± 68 m for the West and 4728 ± 228 m for the South slope. For the 1955 glacial phase, Alcalá (2015) calculated an ELA of 5850 m in the Huayuray valley using the AAR method with a ratio of 0.67.

In the Coropuna volcanic complex, research by Úbeda (2011) on the northeast and southeast slopes found that the ELA AABR on the SE slope was 5844 m in 2007, and modern ELAs calculated by Bromley *et al.* (2011b) show average results of 5850 ± 54 m for the West slope and 5580 ± 54 m for the South slope. For tropical glaciers, Kaser & Osmaston (2002) consider the AAR (Accumulation Area Ratio) value = 0.67 to be the most appropriate. Úbeda (2011) obtained a mean AAR value of 0.58 for the glaciers in the Coropuna complex and a temperature shift with an average result of 8.4ºC/km (0.0084ºC/m).

The aim of this research is to analyze glacier evolution on the SW slope of Nevado Coropuna through reconstruction of LLGM, 1955 and 2007 glacial phases using the AABR method for ELA calculation, to obtain valuable information about all the changes that have occurred in order to study climatic trends and observe the glacier response to changes in climate.

2. General settings

The Central Andes are characterized by high altitudes and low temperatures, according to Ammann *et al.* (2001), Quaternary landscapes are often well preserved and are valuable archives for paleoenvironmental reconstruction. Nevado Coropuna (6426 m, 15º 33’S, 72º 39’ W) is located 150 km northwest of Arequipa and is the highest peak of the Cordillera Ampato and the highest volcano in Peru (Figure 1). According to Bromley *et al.* (2011a) the Nevado Coropuna comprises four andesite domes separated by broad saddles and rises ~2000 m above the surrounding puna on all but the south side. Here, incision of the underlying ignimbrite by the Rio Llacllaja, a tributary of the Colca Canyon, has resulted in relief of more than 3500 m. Although andesitic eruptions at Coropuna began during the late Miocene, the mountain’s present structure is attributed to prolonged Quaternary volcanism (Venturelli *et al.*, 1978; Weibel *et al.*, 1978). The main source of precipitation for the tropical Andes of the southern hemisphere lies to the east in the Atlantic Ocean and the Amazon Basin, and the primary transport mechanism is seasonal easterly winds (Johnson, 1976; Vuille & Keimig, 2004). The persistent inversion over the Pacific coast and strong Andean rain shadow effect combine to maintain a semi-arid climate at Coropuna (Bromley *et al.*, 2011a). The tropical Andes of Peru have a wet season during the austral summer and a dry season during the austral winter (Johnson, 1976). Herreros *et al.* (2009) pointed out that 70-90% of annual precipitation occurs from December to March. During the wet season, prevailing easterlies deliver moisture from the Amazon lowlands, while the dry season is dominated by moisture-deficient westerlies from the Pacific Ocean (Garreaud *et al.*, 2003). As a result there is an east–west precipitation gradient across the Andes, with more precipitation typically falling on the east-facing slopes of the eastern cordillera than on any of the slopes further to the west (Kessler & Monheim, 1968; Johnson, 1976). Due to aridity, glaciers are restricted to elevations significantly higher (5100– 5500 m) than the local zero-degree isotherm (~4900 m) Dornbusch (1998). Lahars are relatively common on Nevado Coropuna as shown in slope studies (Úbeda, 2011), and actual glaciers can cause ice falls and dangerous lake formations (Greminger, 2003).

3. Methodology

The GIS software used for the analysis was ESRI ArcGIS10 in its ArcMap environment. The materials used for the analysis were aerial photographs from 1955 obtained from IGN[1], ASTER image (2007), contour lines, Excel

[1] National Geographic Institute, Peru.

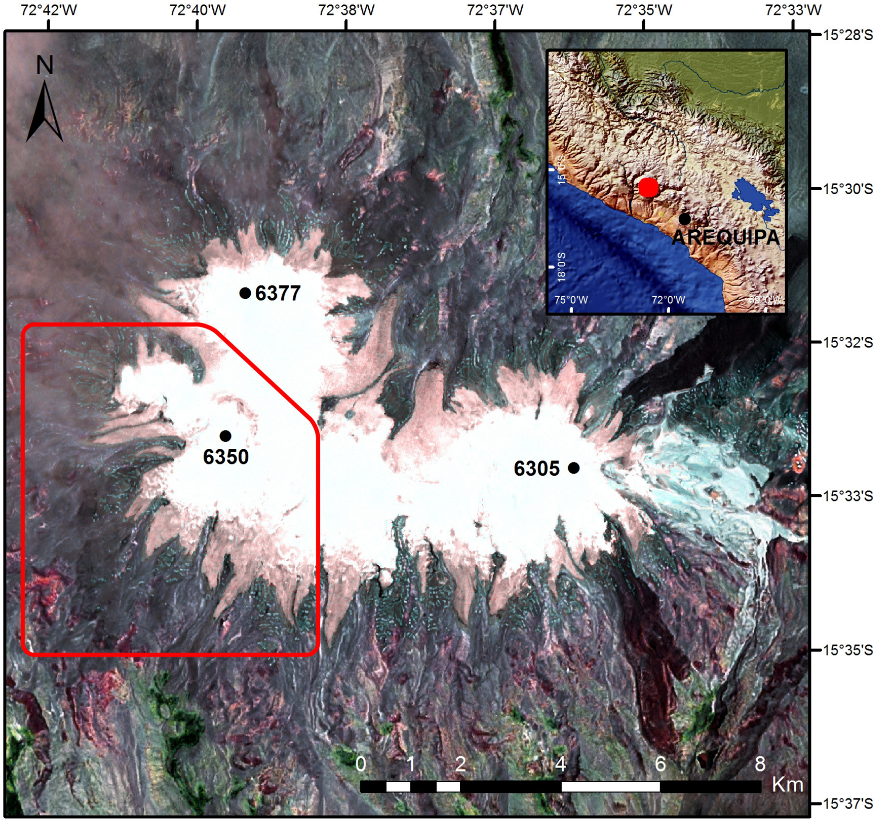

Figure 1: Satellite images (Aster and Landsat) showing location of study area in Nevado Coropuna.
Figura 1: Imágenes de satélite (Aster y Landsat) mostrando la localización del área de estudio en el Nevado Coropuna.

spreadsheet and a map of moraine locations from GFAM[2]-GEM[3] and a satellite image mosaic. The following steps were required to complete all the methodological phases: georeferencing, moraine mapping, glacier and paleoglacier delimitation, surface calculation, ELA and paleoELA calculation.

3.1. Georeferencing

All the images were georeferenced to establish comparisons with GIS software, the georeferencing was the basis of all the subsequent work. The aerial photographs from 1955 were scanned in high resolution and converted to raster files before the georeferencing process. Coordinates were assigned to points on the image of known locations that were distinguished on a georeferenced image used as control layer. These control points help to "fit" the image to the coordinates in the "Rectify" step of the georeferencing. At the end of this process a georeferenced image was obtained. The accuracy of the transformation was evaluated using the Root Mean Square error (RMS), which measures the accuracy of control points and can be used to find and delete inaccurate entries. Once at least four control points had been added, RMS error was calculated for each entry. Basically, the residual error is measures the goodness between the true and transformed locations of the control points (Campos, 2012).

3.2. Moraine Mapping

In order to delimit paleoglaciers of the LLGM glacial phase the moraines were digitized following traces left by these glaciers. The moraines were mapped using photointerpretation techniques with a stereoscope with aerial photographs, Google Earth software was used to assist in this process to improve the interpretation of moraines which did not appear clearly in the photographs. Once the moraines had been identified, they were digitized using both Google Earth and GIS software.

[2] Research Group "Geografía Física de Alta Montaña", Universidad Complutense de Madrid.

[3] NGO "Guías de Espeleología y Montaña", Madrid.

3.3. *Glacier and paleoglacier delimitation and surface calculation*

Interpretation of the satellite and aerial photographs was required to establish the limits of the 1955 and 2007 glaciers. In the case of paleoglaciers the reconstruction of the limits was established starting from moraine mapping. This process is based on the interpretation of aerial photographs through a stereoscope combined with the interpretation of the Google Earth mosaic and Google maps of the study zone. Moraine mapping was also used to delimit the paleoglaciers. Images of the dry season were used wherever possible, as then there is no snow cover on the ice and the glaciers are clearly visible. For the glacier delimitation of 1955 a careful interpretation was carried out as the aerial photographs were not taken in the dry season and the ice was therefore partially covered with snow. For the 2007 glacier delimitation, the ASTER image was taken in the dry season and the glacier ice was clear of snow. The paleoglacier reconstruction was obtained using Google Earth mosaic observation combined with aerial photographs and also using the topographic contour lines.

3.4. *ELA reconstruction*

The ELA (Equilibrium Line Altitude) is an imaginary line separating the ablation zone and the accumulation zone. At this altitude, the amount of new snow gained by accumulation is equal to the amount of ice lost through ablation. There are several methods for reconstructing former glacier ELAs, the most used 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 are based on assumed forms of the glacier mass–balance gradient, and are broadly compatible with the concept of the steady-state ELA. MELM method makes use of the fact that moraine formation 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 (Benn *et al.*, 2005). The AABR method was chosen for the ELAs and paleo-ELAs calculation because is considered to be rigorous and reliable (Osmaston, 2005). According to the explanation given by Osmaston (2005) the AABR method is based on the principle of weighting the mass balance in areas far above or below the ELA by more than in those close to it.

3.5. *ELAs AABR for 1955 and 2007 glaciers*

For the AABR method calculation, the glacier delimitation and contour data (contour lines with 50 m resolution transformed into contour belts) for its surface were required. A contour belt is the area between two contour lines. These contour belts have to be contained in a polygon shapefile in order to calculate each surface area. ArcGIS software was used to create the contour belts. This phase of the process consists of three steps: (1): A shapefile with the contour lines of the study area was obtained. (2): Once a shape with the contour lines had been created, the contour belts of the study area were found. (3): Obtain the contour belts individually for each single glacier.

After completing these steps, the attribute tables of the glaciers contour belts shapefiles were exported as a .dbf archive an opened in a programed spreadsheet for complete the AABR method. This method was developed by Osmaston (2005) refining the AA method by providing for different linear slopes of the mass balance/altitude curve above and below the ELA. The next step was an ELA calculation using the AA method used by Sissons (1974, 1980): ELA = Z * A / A, where Z is the average altitude of the contour belts and A is the area of the contour belts. Then, a series of BR values (e.g. 1, 1.5, 2.0, 2.5, 3.0) were entered and the ELA for each recorded. The ratios were selected with a priori knowledge of what is likely; most glaciers are likely to have a BR of 1.5–3.5, though on a debris-covered glacier it may be less than 1 Osmaston (2005). These steps were repeated for all glaciers and the results were transferred to a second spreadsheet to obtain the mean and the standard deviation of the estimated ELAs for each value of BR. After obtaining these parameters the BR with lowest standard deviation was selected, indicating the ELA with the highest statistical probability of being correct.

3.6. *Paleoglaciers reconstruction and paleoELAs AABR*

A step was added at the beginning of the process to calculate the paleoELAs with the AABR method, but the rest of the procedure is the same. Because the paleoglaciers were non-existent when the contour lines were created, the actual contour lines were modified to represent the paleoglaciers topography, each line should be modified to a hypothetical reconstruction of the ice surface and volume.

For the modification of the contour lines these steps were followed using ArcGIS software:

(1): Obtain paleoglaciers limits using the moraine mapping (Figure 2).
(2): Obtain the contour lines of the study area without the inside contour lines of the paleoglacier.
(3): Reconstruct the contour lines inside the paleoglacier limits with manual digitizing, starting each paleocontour line at the end of the contour line cut in the previous step and finishing it in the continuation of the contour line.

After creating the paleotopography, the contour belts have to be created for each paleoglacier.

At this point, ELA AABR calculations were completed on the spreadsheet and the mean and standard deviations were calculated, obtaining the weighted ELAs using different Balance Ratio values as shown above.

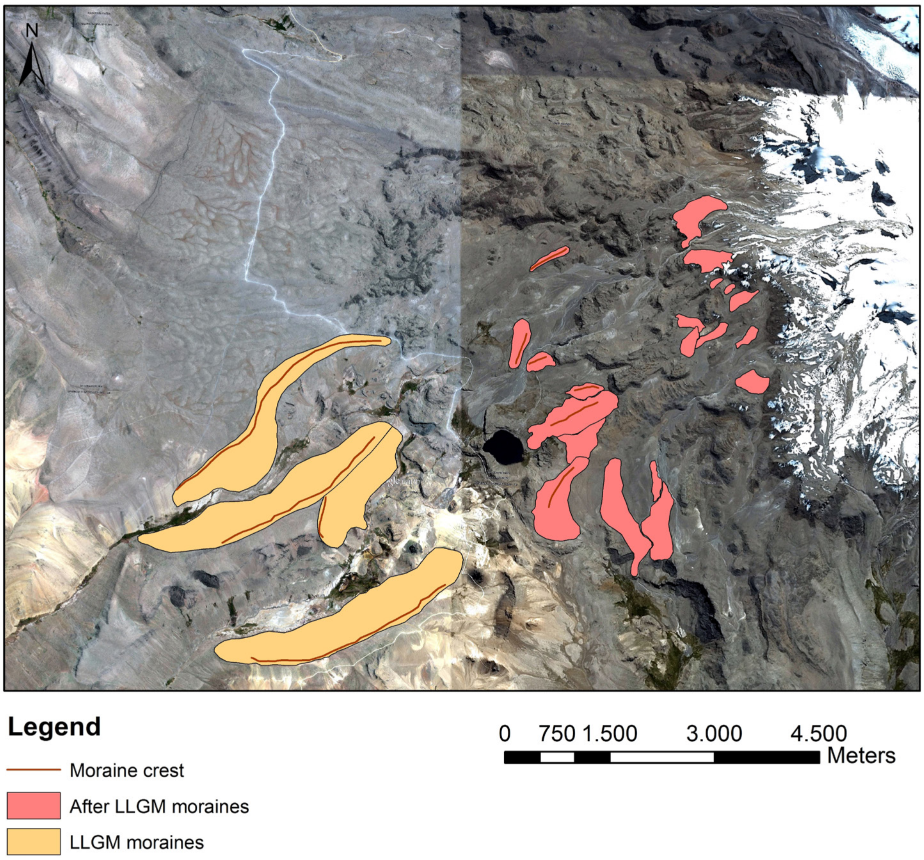

Figure 2: Moraine mapping of the zone of the paleoglaciers calculated in this work over satellite image mosaic.
Figura 2: Mapeo de morrenas de la zona de los paleoglaciares calculados en este trabajo sobre un mosaico de imágenes de satélite.

3.7. Spatial model of ELAs and accumulation and ablation zones

A homogeneous group of glaciers should react similarly to the climate they experience. Therefore their ELAs should be closely similar, differentiated only by such local individual factors as shading by valley-side precipices. In statistical terms the standard deviation of these individual ELAs from the group mean value will be less than that of other possible sets of ELA estimates from their means. Therefore for each input value of the ratio or index set we should calculate the standard deviation of its predictions (or the standard error of the mean), and select the value which has the smallest standard deviation (Osmaston, 2005).

3.8. ELAs spatial model

To calculate the ELA in each glacial phase (LLGM, 1955, 2007), the following operations were carried out:

(1): Obtain the outermost limits of glaciers.
(2): Create a model with 50 m resolution contour line.
(3): Obtain a contour line layer with 1 m resolution from the 50 m resolution layer obtained previously.
(4): Map the ELAs in each glacial phase (LLGM, 1955, 2007).

3.9. Accumulation and ablation spatial zones

The accumulation and ablation zones were deduced dividing the polygon forming the outermost glacier limits into two different polygons along the ELA line.

(1): The outermost glacier limits polygon was converted into poly-line.
(2): The glacier poly-lines were cut over the intersection with the ELA.
(3): A single poly-line layer was obtained combining the glacier poly-lines over the intersection of the ELA and the ELA poly-line.
(4): Obtain the accumulation and ablation spatial model by creating a polygon from the single poly-line layer with selected accumulation lines. The same process was carried out to create the ablation spatial model. This process had to be repeated for each glacial phase (LLGM, 1955, 2007).

3.10. Surface calculation

To calculate the accumulation and ablation zone surfaces, a new field was added in the attribute tables of the single polygons, in this field the surfaces were calculated (in km^2).

3.11. Temperature shift

The vertical shifts of the ELAs are caused by changes in temperatures and analyzing these shifts is possible to study the variation of the climate. The differing ELAs of present and former glaciers are the most important indicators we have of the possible contemporary climatic change (Kaser & Osmaston 2002). Úbeda (2011) uses an equation which obtains the temperature shift from the product of ATLR (Atmospheric Temperature Lapse Rate) and the shift of the ELA.

$$\Delta T = ATLR * \Delta ELA$$

The overall average estimated ATLR is 6.5ºC/km (0.0065ºC/m) (Kaser & Osmaston 2002), and the ATLR on the NE slope of Nevado Coropuna is 0.0084ºC/m Úbeda (2011), this slope was selected because of the geographic location of the study area, with data provided by a set of data loggers situated in NE slope of Coropuna since 2007. This ATLR is close to the ATLR dry limit of 0.0098ºC/m (Kaser & Osmaston 2002).

4. Results

4.1. Moraine mapping

Figure 2 presents a morainic cartography of the study area over a LANDSAT image. The moraines after LLGM were mapped between 4750 and 5000 m and LLGM moraines between 4450 and 4700 m.

4.2. Glacier delimitation and surface calculation

Two phases were established to delimit the glaciers on the SW slope of Nevado Coropuna: 1955 and 2007. The glaciers were delimited using aerial photographs for 1955 and Google Earth mosaic for 2007.

Figures 3 and 4 shows the total glaciated surface in the years 1955 and 2007, 10.7 km^2 and 8.4 km^2 respectively. That means a reduction of 21.5% of the total glaciated surface existing in 1955.

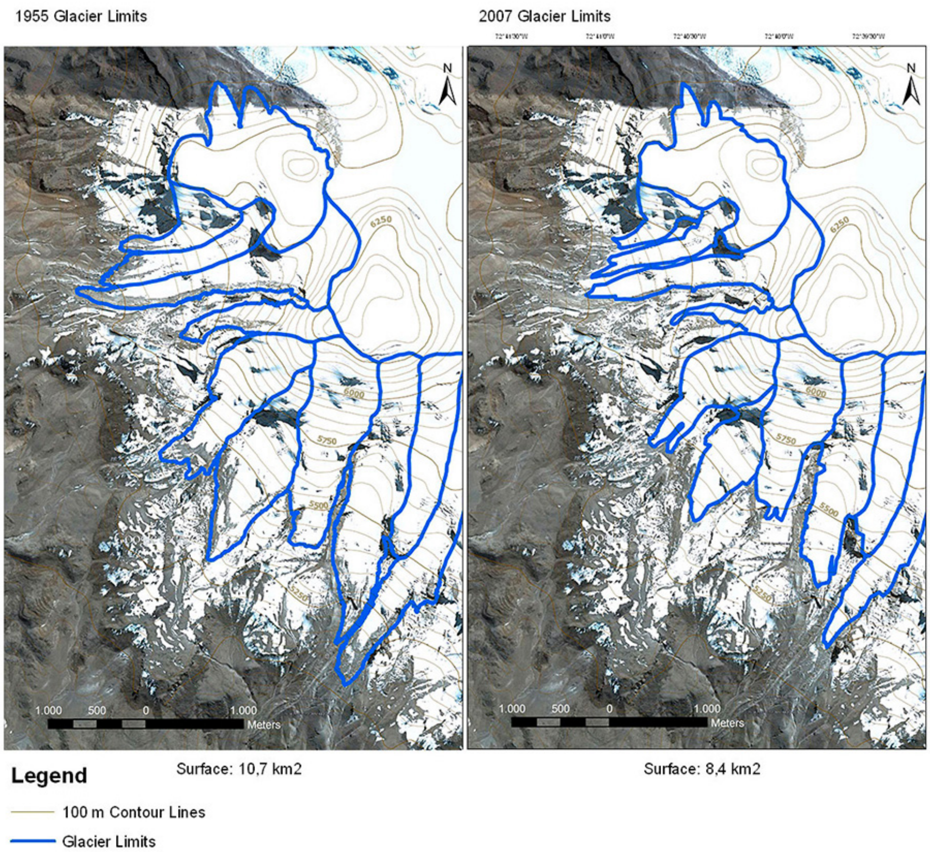

Figure 3: 1955 and 2007 glacier limits over Google Earth mosaic.
Figura 3: Límites glaciares de 1955 y 2007 sobre un mosaico de Google Earth

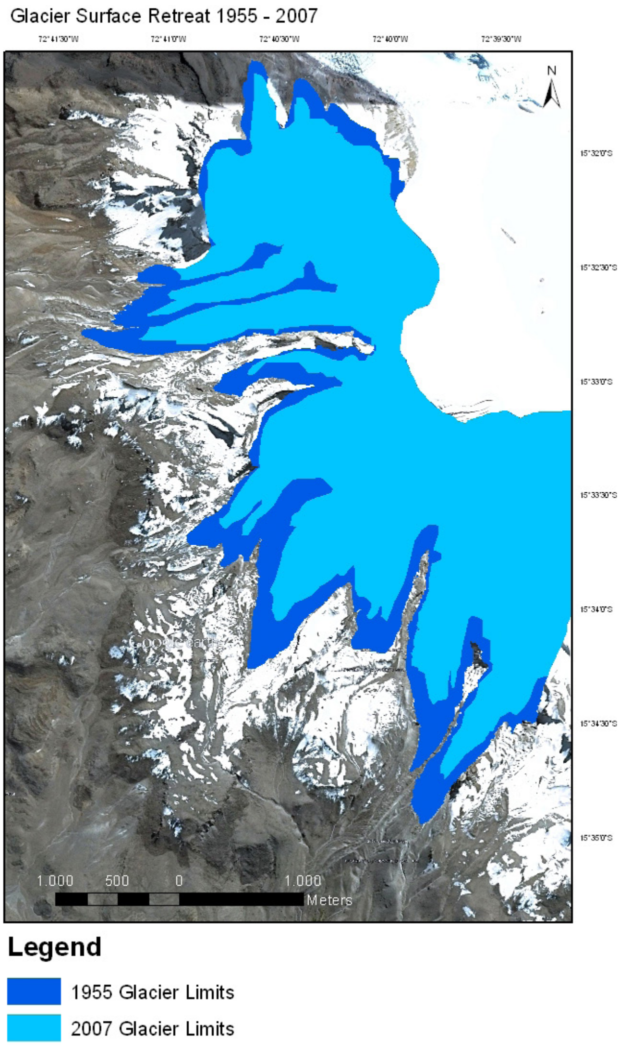

Figure 4: Comparison of the glaciated area between 1955 and 2007.
Figura 4: Comparación del área glaciada entre 1955 y 2007.

In 1955 the upper glacier limits were above 6350 m for Rio Blanco 1 and the lower glacier limit was 5050 m for Tuialqui 1. In 2007, for the same glaciers, the upper limits were above 6350 m and lower glacier limit was 5150 m (Campos, 2012).

The glaciated area retreat of each glacier is shown in table 1. The glacier with the maximum retreat of glaciated area is Tuialqui 5 with a retreat of 46.39%, with Tuialqui 2 showing the least regression, 2.56%. In all the glaciers the glaciated surface has decreased (in some more than others), in 2007 there was a glaciated area surface of 78.5% (8.4 km^2) of the total glaciated area in 1955 (10.7 km^2).

4.3. ELAs AABR

The difference in altitude between modern and former ELAs (ΔELA) has been widely used to estimate climate change (Benn *et al.*, 2005). The glacier delimitation and contour data were required to apply AABR method, and Osmaston's spreadsheet was used to calculate the ELAs and paleoELAs (with previously reconstructed paleotopography). Figure 5 shows the topographical reconstructions for the paleoELA calculation.

Table 1. Glaciated area retreated in each glacier in 2007 regarding 1955.
Tabla 1. Retroceso del área glaciada de cada glaciar en 2007 y 1955.

Glacier Name	1955	2007	Glacier retreat (Km^2)	%	% of 1955
Tuialqui 1	1.63	1.39	0.24	14.72	85.28
Tuialqui 2	0.78	0.76	0.02	2.56	97.44
Tuialqui 3	1.3	1.02	0.28	21.54	78.46
Tuialqui 4	1.17	0.98	0.19	16.24	83.76
Tuialqui 5	0.97	0.52	0.45	46.39	53.61
Tuialqui 6	0.92	0.73	0.19	20.65	79.35
Rio Blanco 1	0.42	0.24	0.18	42.86	57.14
Rio Blanco 2	1.07	0.87	0.2	18.69	81.31
Rio Blanco 3	0.49	0.33	0.16	32.65	67.35
Azufrioc 1	0.39	0.26	0.13	33.33	66.67
Azufrioc 2	1.56	1.3	0.26	16.67	83.33
Total	10.7	8.4	2.3	21.5	78.5

The first calculation in Osmaston's spreadsheet is the ELA AA, which is then weighted by different BR values, where the BR with the lowest standard deviation indicates the ELA with the best statistical probability of being correct. The tables 2, 3 and 4 present the AABR calculations for 1955, 2007 and LLGM glacial phases. The selected ELAs values are those with the lowest standard deviation.

Figure 6 shows the ELAs altitude values in LLGM, 1955 and 2007 glacial phases, the results show an ELA vertical shift of 1088 m from LLGM to 2007, and 71 m from 1955 to 2007.

4.4. Spatial model of ELAs and accumulation and ablation zones

As the ELA is an imaginary line separating the ablation zone and the accumulation zone, at this altitude the amount of new snow gained by accumulation is equal to the amount of ice lost through ablation. In figures 7 and 8 the ELAs were plotted on the Google Earth mosaic.

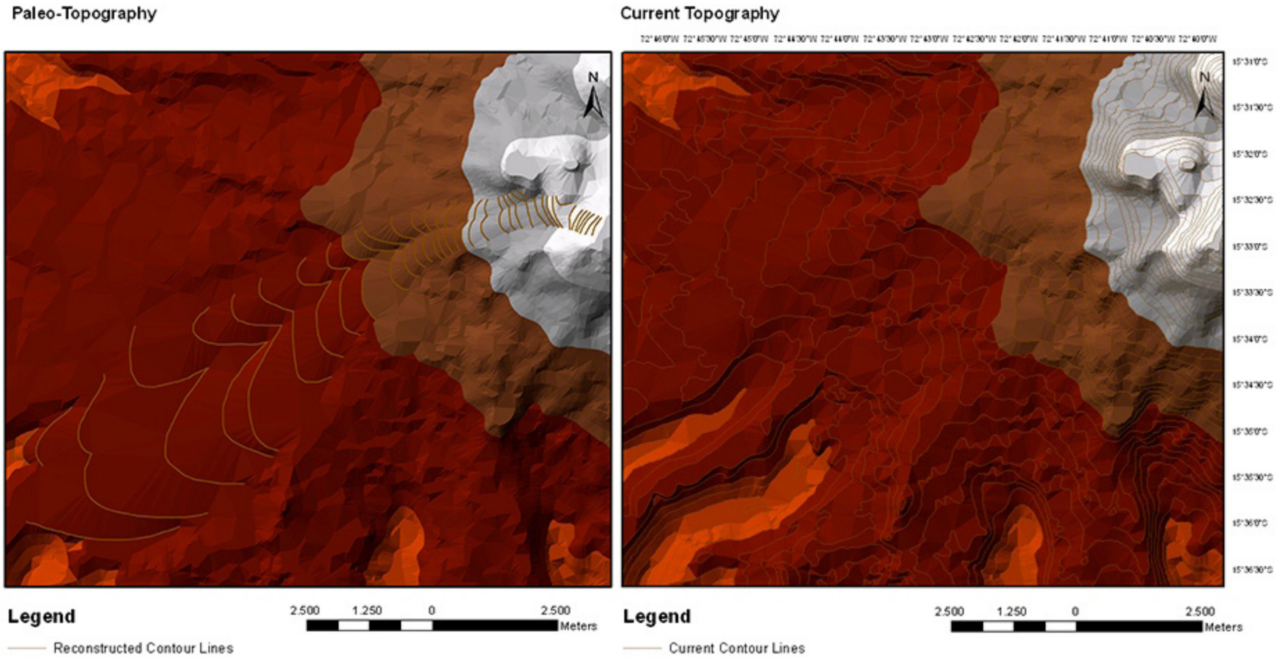

Figure 5: Reconstruction of the topography for the paleoELA calculation compared with the actual topography.
Figura 5: Reconstrucción de la topografía para el cálculo de la paleoELA comparada con la topografía actual.

Table 2. AABR calculations for 1955.
Tabla 2. Cálculos AABR para 1955.

Tuialqui valley	**BR=1**	**BR=1.5**	**BR=2.0**	**BR=2.5**	**BR=3**
Tuialqui 1	5672	5621	5584	5555	5532
Tuialqui 2	5812	5783	5764	5750	5737
Tuialqui 3	5634	5590	5561	5539	5522
Tuialqui 4	5829	5787	5757	5735	5717
Tuialqui 5	5556	5529	5511	5499	5488
Tuialqui 6	5724	5685	5659	5639	5624
Mean	5705	5666	5639	5620	5603
Standard deviation	105.4	105.1	105.3	106	106
Rio Blanco valley	BR=1	BR=1.5	BR=2.0	BR=2.5	BR=3
Rio Blanco 1	5988	5952	5926	5907	5892
Rio Blanco 2	5858	5818	5790	5768	5751
Rio Blanco 3	5704	5678	5661	5648	5637
Mean	5850	5816	5792	5774	5760
Standard deviation	142	137	133	130	128
Azufrioc valley	BR=1	BR=1,5	BR=2,0	BR=2,5	BR=3
Azufrioc 1	5776	5752	5734	5720	5710
Azufrioc 2	6013	6000	5990	5982	5975
Mean	5895	5876	5862	5851	5843
Standard deviation	168	175	181	185	187
General SW slope	BR=1	BR=1.5	BR=2.0	BR=2.5	BR=3
Mean	5779	5745	5722	5704	5690
Standard deviation	141	145	148	150	152

Table 3. AABR calculations for 2007.
Tabla 3. Cálculos AABR para 2007.

Tuialqui valley	**BR=1**	**BR=1.5**	**BR=2.0**	**BR=2.5**	**BR=3**
Tuialqui 1	5746	5706	5675	5651	5631
Tuialqui 2	5819	5791	5772	5758	5747
Tuialqui 3	5699	5659	5633	5613	5598
Tuialqui 4	5900	5861	5835	5815	5799
Tuialqui 5	5615	5589	5572	5560	5551
Tuialqui 6	5831	5795	5769	5750	5734
Mean	5768	5734	5709	5691	5677
Standard deviation	103	101	99	98	97
Rio Blanco valley	BR=1	BR=1.5	BR=2.0	BR=2.5	BR=3
Rio Blanco 1	6116	6085	6062	6044	6029
Rio Blanco 2	5917	5879	5852	5831	5815
Rio Blanco 3	5807	5779	5760	5746	5734
Mean	5947	5914	5891	5874	5859
Standard deviation	157	156	155	154	152
Azufrioc valley	BR=1	BR=1.5	BR=2.0	BR=2.5	BR=3
Azufrioc 1	5867	5841	5822	5808	5797
Azufrioc 2	6029	6018	6009	6003	5998
Mean	5948	5930	5916	5906	5898
Standard deviation	115	125	132	138	142
General SW slope	BR=1	BR=1.5	BR=2.0	BR=2.5	BR=3
Mean	5850	5818	5796	5780	5767
Standard deviation	142	145	147	148	149

Table 4. AABR calculations for LLGM.
Tabla 4. Cálculos AABR para LLGM.

General SW slope	**BR=1**	**BR=1.5**	**BR=2.0**	**BR=2.5**	**BR=3**
Paleo-glacier 1	4867	4826	4801	4783	4770
Paleo-glacier 2	4832	4799	4778	4763	4753
Mean	4850	4813	4790	4773	4762
Standard deviation	25	19	16	14	12

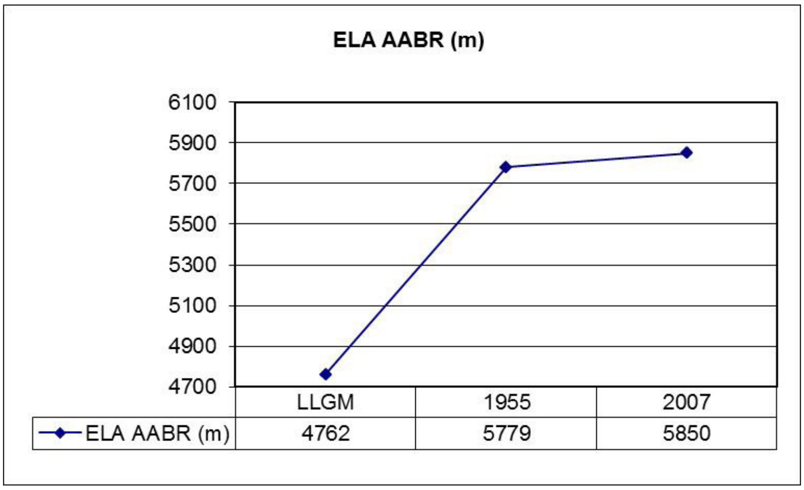

Figure 6: Values of ELA in LLGM, 1955 and 2007 glacial phases.
Figura 6: Valores de la ELA en las fases glaciares LLGM, 1955 y 2007.

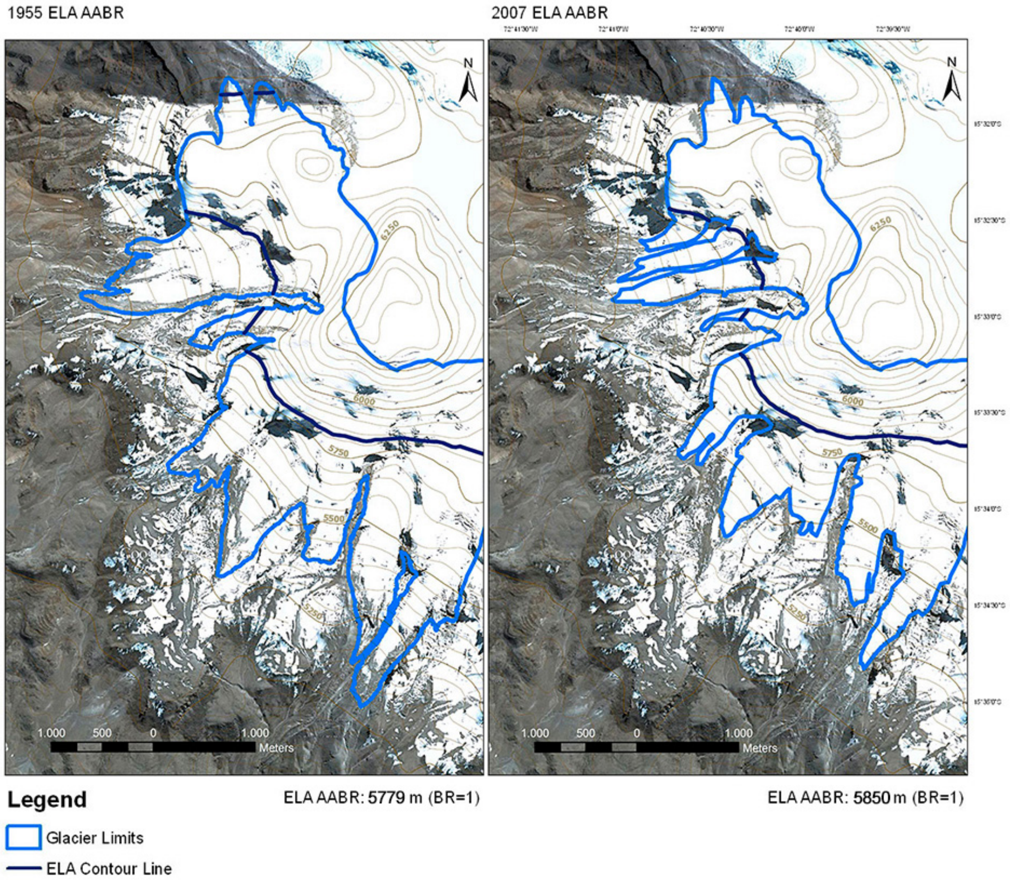

Figure 7: 1955 and 2007 ELAs over Google Earth mosaic.
Figura 7: ELAs de 1955 y 2007 sobre un mosaico de Google Earth.

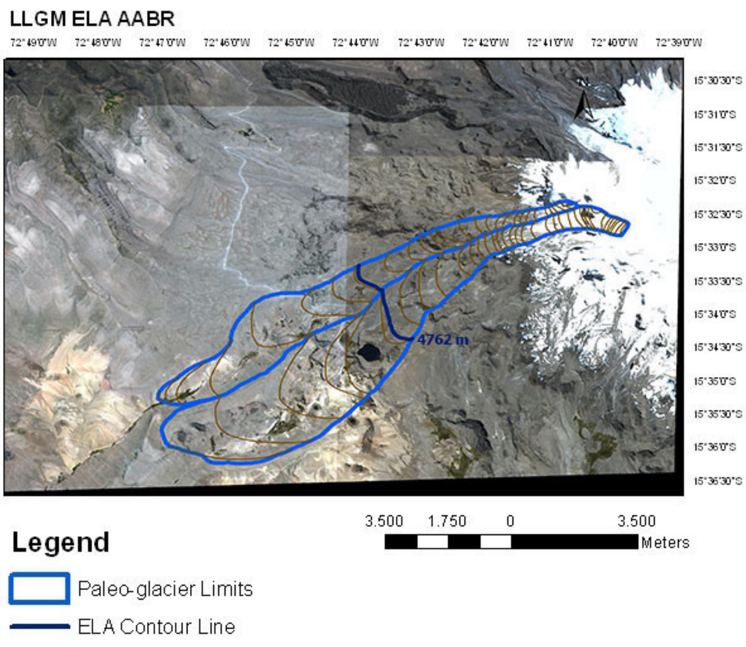

Figure 8: LLGM paleoELA over Google Earth mosaic.
Figura 8: PaleoELA LLGM sobre un mosaico de Google Earth.

The accumulation and ablation surfaces have decreased due to glacial regression. Table 5 shows the accumulation and ablation surfaces in the 1955 and 2007 glacial phases. Figure 9 presents the data for the total glacier surface in both glacial phases, where the accumulation area has decreased from 5.02 km^2 in 1955 to 4.5 km^2 in 2007 (10.36%), and the ablation area also has decreased from 5.67 km^2 in 1955 to 3.9 km^2 in 2007 (31.22%).

With the same balance ratio for both phases (1955 and 2007), the total glaciated surface area has decreased in the accumulation and ablation zones and the mass loss percentage from 1955 to 2007 is higher in the ablation zone. This means that the ice in the ablation zone is melted rapidly during this period. The AAR (Accumulation Area Ratio) is the ratio of the accumulation area to the total glacier area: AAR = AC/TS, where AC is the accumulation area and TS is the total surface. The AAR indicator increased from 0.47 in 1955 to 0.54 in 2007. This indicates that the glaciers in 1955 had a larger percentage of ablation area and in 2007 had a larger percentage of accumulation area. In the case of the paleoglaciers, the ablation zone (71.67%) was larger than the accumulation zone (28.33%), and the AAR was 0.28. There seems to be a clear trend in which each glacial phase grows the accumulation area.

4.5. ELAs vertical shifts

The ELA vertical shift from LLGM glacial phase to 2007 was 1088 m and the result of the equation (ΔT = ATLR * ΔELA) gives a temperature shift of 9.13 ºC (0.0091ºC/m) from LLGM to 2007 for the SW slope of Nevado Coropuna.

Table 5. Accumulation and ablation surfaces in the 1955 and 2007 glacial phases.
Tabla 5. Superficies de acumulación y ablación en las fases glaciales de 1955 y 2007.

	1955	**2007**	**% total 1955**	**% total 2007**
Accumulation	5.02	4.5	46.92	53.57
Ablation	5.67	3.9	52.99	46.43
Total	10.7	8.4		

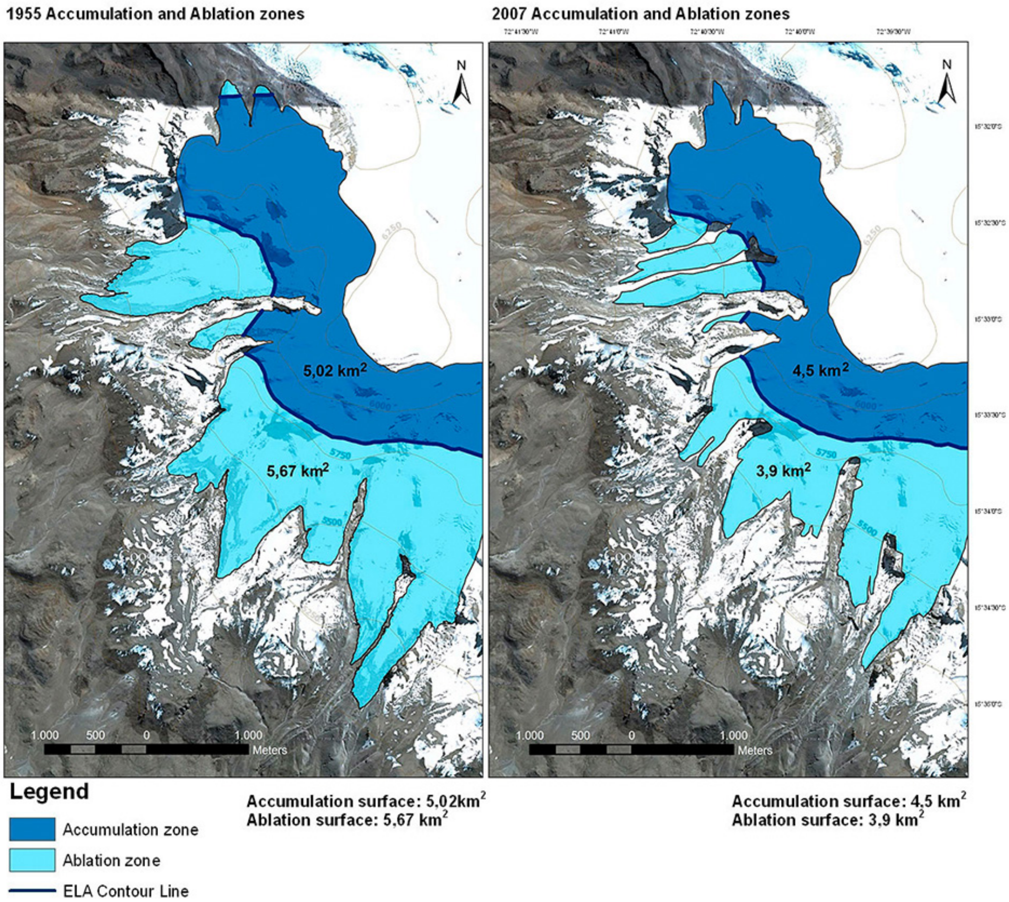

Figure 9: Accumulation and ablation surfaces in 1955 and 2007.
Figura 9: Superficies de acumulación y ablación en 1955 y 2007.

5. Discussion

5.1. Moraine mapping

The moraine mapping of the study zone shows that the LLGM moraines were located between 4450 and 4700 m. Alcalá *et al.* (2011) suggest a minimum elevation of the moraines of 4270 m during the LGMA (last glacial maximum advance) in the Ampato volcanic complex. During the most important re-advance phase the glacier front reached 4520 m. On Sabancaya, in one of the valleys of the Western slope (the rest was covered by recent lava flows) the moraines show a minimum altitude of 4430 m for the LGMA Alcalá *et al.* (2011). Alcalá (2015) reported morainic complexes in HualcaHualca from the LLGMA (local last glacial maximum advance) between 3650 and 4100 m. On the South West slope of Nevado Coropuna LLGM moraines were higher than in those studies Úbeda (2011). Smith *et al.* (2005) pointed out that in some regions the glacial advances of the LLGM are relatively minor compared to older advances and that differences in valley hypsometry and maximum peak altitudes seem likely to have played a role in these regional variations. Studies of Early Holocene and Little Ice Age glacial phases are pending. The differences between the moraine mapping in this study and in other research are probably the result of the different volcanic evolution of each stratovolcano, causing differences in topography and glacier location.

5.2. Glacier delimitation and surface calculation

The glacier limits in 1955 obtained from a reconstruction using satellite images range from the lower limit at 5050 m (Tuialqui 1) to the upper limit at 6350 m (Rio Blanco 1). In the 2007 reconstruction, the limits for the same glaciers were 5150 m (Tuialqui 1) and 6350 m (Rio Blanco 1). The glaciated area had retreated in all the glaciers in the study zone, the glacier with the highest glaciated area retreat percentage was Tuialqui 5 (46.39%) and the lowest percentage was found in Tuialqui 2 (only 2.56%). The total glaciated surface of the study zone was 10.7 km^2 in 1955 and 8.4 km^2 in 2007, this means that the total glaciated surface has been reduced by 21.5% from 1955 to 2007. This result is similar to those obtained by Racoviteanu *et al.* (2007), who suggested a reduction of the ice cover on Nevado Coropuna of approximately 26% between 1962 and 2000, and by Vuille *et al.* (2008), who calculated a retreat of 20% in Nevado Astesonraju (Cordillera Blanca) from 1962 to 2003. The reduction of the glacial system surface calculated by Úbeda & Palacios (2009) for the entire Nevado Coropuna is also similar, with results indicating a reduction of ~18% in 52 years (from 1955 to 2007), and they pointed out that the process appeared to have accelerated over recent decades (~13% in only 21 years). Similar results are obtained by Racoviteanu *et al.* (2008), showing a reduction of 22.5% in Cordillera Blanca from 1970 to 2003. However Alcalá (2015) suggested a 32% reduction of the glaciated area in Pujro Huayjo valley, 35% in Mollebaya valley and 50% in Huayuray valley from 1955 to 2000, higher than the results of this present study, probably due to the glaciers size, the glaciers resistance to changes is directly proportional to its size. Alcalá (2015) considers that the glaciers size seems to be a determining factor in this case. Racoviteanu *et al.* (2008) detected in Cordillera Blanca that small low-lying glaciers with a large proportion of their area in the ablation zone lost ice at higher rates than larger glaciers.

5.3. ELAs AABR

ELA values are highest on north-flowing glaciers and lowest on south-flowing glaciers. The ELA AABR for LLGM obtained in this present study was 4762 m, this result is close to those reported by Úbeda (2011) with the AABR method obtaining an ELA of 4951 m for the SE slope of Nevado Coropuna and Bromley *et al.* (2011b) with the MELM (Maximum Elevation of Lateral Moraines) and THAR (Terminus Headwall Altitude Ratio) methods for the calculation of LLGM ELAs for the Pucuncho peaks, reporting an average of 4887 ± 77 m for the Western slope and 4745 ± 66 m for the South slope (using the MELM method), and an average of 5059 ± 68 m for West and 4728 ± 228 for the South (using the THAR method with a ratio of 0.28). The results reported by Alcalá *et al.* (2011) for the LLGM ELA in the Huayuray valley is 4980 m with AA method and the result reported by Alcalá (2015) on HualcaHualca is 5006 m using the AABR method. The differences between these results and those obtained in this paper could be due to the different location of the glaciers for the result in the Huayuray valley and the use of a different method to calculate the ELA on HualcaHualca. These reasons probably also explain the differences found in Dornbusch (2002) research, that suggested an ELA of ~ 4700 to 4750 m using the THAR and AAR methods in south to southwest facing glaciers on Nevado Coropuna.

The results of calculating ELAs with the AABR method show altitudes of 5779 m in 1955 and 5850 m in 2007. The LLGM paleoELA of the studied paleoglaciers obtained a result of 4762 m, implying an altitude shift of 71 m between 1955 and 2007 and of 1088 m between LLGM and 2007. Úbeda (2011) research on the southeastern slope of the Coropuna volcanic complex found that the ELA AABR was 5787 m in 1955 and 5862 m in 2007, similar to the result obtained in this present study on the SW slope with the same method. Nevertheless, the vertical shift is lower in this study, this may be because of the different topography of both slopes. The modern ELAs for the Coropuna glaciers calculated by Bromley *et al.* (2011b) show average results of 5850 ± 54 m for the West slope and 5580 ± 54 m for the South slope, the mean obtained in the present study is close to the West slope results of Bromley *et al.* (2011b), this may be because of the geographic position of the analyzed glaciers (more in

West than in South). Alcalá (2015) obtained similar results in the Huayuray valley, where the ELAs were 5850 m calculated with AAR method (ratio 0.67) for the 1955 glacial phase and 5890 m calculated with AAR and AA methods in 2000. The value AAR= 0.67 was considered by Kaser & Osmaston (2002) as the most appropriate for tropical glaciers. Úbeda (2011) obtained a mean AAR ratio value of 0.58 for the glaciers in the Coropuna complex. In this present study the AAR (Accumulation Area Ratio) value obtained was 0.54 in 2007 for the SW slope of Nevado Coropuna, similar to the results of the authors mentioned above.

The result obtained for the temperature shift was 9.13ºC/km (0.0091ºC/m) from LLGM to 2007 for the SW slope of Coropuna. This result is close to that obtained by Úbeda (2011) for Coropuna with an average result of 8.4ºC/km (0.0084ºC/m). Alcalá (2015) obtained a temperature shift of 5ºC/km (0.005ºC/m) on HualcaHualca, this result differs because ELAs shift (calculated with AABR method) on HualcaHualca was 765 m, lower than the 984 m calculated here, and the ATLR used by Alcalá (2015) was 6.5ºC/Km (0.0065ºC/m) instead of 8.4ºC/Km (0.0084ºC/m) chosen by the author of this paper.

6. Conclusions

The reconstruction of the LLGM, 1955 and 2007 glacial phases produced in this paper starting from moraine delimitation and using satellite images has allowed us to determine the retreat of the glaciated surface area from 1955 to 2007, obtaining similar results to those of other authors and indicating a 21.5% reduction of the total glaciated surface. From the delimitation of the glaciers, the results obtained for the calculated ELA: 4762 m for LLGM, 5779 m for 1955 and 5850 m for 2007, and their similarity with results reported by other authors show that the AABR method used in this study is valid for indicating the ELA in tropical glaciers. The differences between the results obtained in this study and those obtained in other areas of the Andes are probably because of the different methods used for ELA calculation or different topography of the slopes. This analysis of the temperature shift on the SW slope from LLGM to 2007 indicates a very similar increase to those reported by other authors for the Central Andes.

This research, together with other studies of glacier evolution in the Central Andes, provides an important contribution to climate studies and the work has demonstrated that tropical glaciers are sensitive indicators of climate change and that their delimitation helps to study the evolution of the ELAs. The AABR method applied to calculate the ELA has been shown to be reliable and consistent, obtaining notable results for the analyzed glaciers. The next step in this research is to study the ELA in the Little Ice Age glacial phase, using higher resolution satellite images, with the purpose of analyze changes in more glacial phases from Upper Pleistocene to Holocene.

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