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Reconstruction of mass balance of Nevado Coropuna glaciers (Southern Peru) for Late Pleistocene, Little Ice Age and the present.

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The Nevado Coropuna volcanic complex (15th 31'S-72 º 39 º W) is the quaternary stratovolcano northernmost of the central volcanic zone (CVZ) in the western flank of the Central Andes (Southern Peru). This consists in four adjacent volcanic buildings that are occupied over 5.100-5.700 masl by a system of glaciers covering an area of 47 Km^2 in 2007 (Ubeda et al, 2008). The maximum expansion of glaciers during the Pleistocene affected an area of ∼449 Km^2, dropping to altitudes around 3.600-4800 m (Ubeda et al, 2007). In this work were mapped several hundreds of moraines which constitute a record of climate change since the last glacial maximum (LGM). Current glacier system is formed by dozen of glaciers descending slope down in all directions. Coropuna complex is an excellent laboratory for to investigate the control that climate change, tectonics and volcanism exert on the dynamics of glaciers, a scale of tens of years (by studying current glaciers) and also of tens of thousands of years (by analyzing the geomorphological evidence of its evolution in the past). Ubeda et al. (2008) analyzed the evolution of eighteen glaciers of Nevado Coropuna using indicators as surfaces and Equilibrium Line Altitudes (ELAs) of ice masses in 2007, 1986, 1955, Little the Ice Age (LIA) and Last Glacial Maximum (LGM). The glaciers were grouped into two sets: NE group (seven glaciers) and SE group (eleven glaciers). The work included statistical series of ELAs in each phase, estimates by Area x Altitud Balance Ratio (AABR) method, which was proposed by Osmaston (2005), in addition with estimates of timing (∼$17Cl_{36}$ Ka) and magnitude (∼ 782-911 m) of ELA depression during LGM. The work included statistical series of ELAs in each phase, estimates by the method Area x Altitud Balance Ratio (AABR) proposed by Osmaston (2005), and in addition estimates of the timing (∼$17Cl_{36}$ Ka) and magnitude (∼ 782-911 m) of ELA depression during LGM.

The objective of this work is to estimate the current and past mass balance of glaciers in these phases (2007, 1986, 1955, LIA and LGM) in order to assess the current state of glaciers and deduct the regimes of temperature and precipitation for present and for LGM. To achieve this target were installed in 2007 in the gorge of Queñua Ranra (NE quadrant of Coropuna complex) four stations, that are respectively at 4886 m (E1), 5564 m (E2), 5694 (E3) m and 5822 m (E4). The stations consist of a sensor in air and one (E3) or two sensors in ground (E1).

The sensors record temperature at intervals of 30 minutes (sensors 12, 13, 22 and 32) or 45 minutes (11, 21, 31 and 41), with precision of tenths of a degree Celsius (º C). The first digit of the name of the sensors referred to the station (arranged in increasing altitude) and the second at his position (eg 11-air, 12-ground and 13-deep ground, in the station E1). The records of Ta and Ts have allowed to define homogeneous data sets of 365 days (12-11-2007/11-11-2008). With these data have been calculated for each day and each sensor the average temperatures, and the minimum and maximum temperature variations and was used to estimate the vertical thermal gradient ($\delta T/\delta Z$) between the stations. In E1, Ta = 3.9 º C and Ts =6.8ºC. At E3, Ta=-2.9ºC and Ts=1.3ºC. The rain has been extrapolated from the average of the 1965-2003 series (39 years) from the station of Andahua (15 ˚ 29'36 "S-72 ˚ 20'56" W, 3587 m), 20 km to NE of the eastern summit of Coropuna, resulting in the level E1 (4886 m) a value of P = 494 mm.

The availability of the temperature series has allowed develop the model of mass balance using an adaptation of the method Klein et al. (1999) developed from an earlier proposal (Kaser 1995). The method is to solve two equations. Equation 1: $a=\tau m/Lm[(Qr+\alpha(Ta-Ts)]$, where a is the value of the ablation (mm), τm duration of ablation (days), Lm the latent heat of fusion ($3.34x10^5$J/kg), Qr heat available for melting in the form of net radiation (MJ/day/m), α a coefficient of mass transferred by heat sensitive (0864 MJ/day), and Ta and Ts air and soil temperature,

respectively. Equation 2: b=c–a, where b is the mass balance (mm) and a the ablation (mm). Using the equation 1, maintaining constant Lm, and α, the values of Ta, Ts, τm, a, c and Qr in each altitude has been estimated as follows: The values of Ta, Ts have been deducted respectively of the data from the sensors 11-31 and 12-32, using the linear temperature gradients (δT/δZ) previously deducted. c values have been deducted from the data of Andahua using the linear gradient of accumulation used by Klein et al (1999): δc/δZ=0,1 mm/m. The values of τm and Qr have been deducted from the value of Ta, whereas at the level Za where Ta=0, τm=0 and Qr =0, and applying from that altitude gradients linear $\delta\tau$m/δZ=0,4day/m y δQr/δZ=0,1ºC/m (Klein et al, 1999), positive if $\Delta Z>0$ and negative if $\Delta Z<0$. The development of the model has allowed to define several levels: Za (altitude of the annual isotherm 0ºC, in air temperature), Zs (altitude of the annual isotherm 0ºC, in soil temperature) and altitudinal level $Z_{b=0}$ where mass balance profile is equilibrated. Za, Zs and $Z_{b=0}$ levels shows the state in each phase of climatic variables that control glaciers evolution, and the magnitude and direction of the difference in altitude (ΔZ) between $Z_{b=0}$and ELA levels, the response of the glacier to environmental conditions. The ELAS AABR in 2007, 1986, 1955, LIA and LGM of seven glaciers of the group NE have been analyzed in conjunction with the values of $Z_{b=0}$for all phases. The group NE (Ubeda et al, 2008) consists in two glaciers channelled by the gorge Santiago (S1 and S2) and five glaciers that are channelled by the gorge Queñua Ranra (QR1-QR5). Cosmogenic ages obtained recently suggest a chronology of $\sim$ 17Cl_{36}Ka (Ubeda et al 2008) for the last maximum advance of glaciers in Queñua Ranra. The modelling of mass balance has allowed assess the current status of glaciers and deduce the temperature and precipitation regimes during the last maximum advance (LGM). In gorge Santiago the difference in altitude of the ELA AABR 2007 (6013 m) respect to $Z_{b=0}$ level on that date has a positive value (ΔZ=+39m). However, in gorge Queñua Ranra this value is negative (ΔZ=-53m). The gaps in altitudes between a $Z_{b=0}$and ELAs AABR explains the differing realities of glaciers, which have been observed in the field. In gorge Queñua Ranra ($\Delta Z>0$) ELA AABBR and climate are in disequilibrium and the loss of volume, the effect of ablation, is evident across the surface of the glaciers below the level $Z_{b=0}$. In gorge Santiago ($\Delta Z<0$) ELA AABR is in equilibrium with climate and the fronts of the glaciers descend to the altitude that determines the mass balance, where it is produced mostly ablation, but above that level have not been detected loss of volume as those seen in Queñua Ranra. Furthermore, the development of the model has allowed the estimation of temperature depression ($\downarrow$Ta y $\downarrow$Ts) during LGM in gorge Queñua Ranra. Furthermore, the development of the model has allowed the estimation of depression of temperature ($\downarrow$Ta and $\downarrow$Ts) in Queñua Ranra during the LGM, as well as the values of precipitation (P) needed to explain ELA depression in this stage. During the LGM, with ELA=5186m and $\downarrow$ELA=782m, $\downarrow$Ta=6,580ºC and $\downarrow$Ts=4,393ºC, with estimate values of P=675-676mm (ΔP=37%) at E1 level (4886 m).

The values of ELA depression are within the ranges proposed for the region (Klein et al, 1999). The magnitude and timing of the of temperature depression are consistent with recent estimates in central Pacific (Blard et al., 2007) and in eastern bolivian Andes (Kull et al., 2008).

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