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Mountain Permafrost in the Tropical Andes of Peru: The 0°C Isotherm as a Potential Indicator

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ABSTRACT

In the tropical Andes of Peru very little is known about the occurrence and extent of mountain permafrost. Only recently systematic studies have been carried out on the high elevation sites of the mountain ranges (cordilleras). In the framework of the first pioneering studies, and with the objective to improve the understanding of characteristics of mountain permafrost and rock glaciers, we analyze how mountain permafrost in the Peruvian Andes is correlated with the altitude of the 0°C isotherm (ZIA). Climate change has generated an increase in air temperature and in the ZIA in the past decades. These temperature changes could lead to impact the state of the mountain permafrost. In this research, we focus on two mountain regions: The Cordillera Central (CC) and the Cordillera Volcánica (CV), the first located in the central zone and the second in the south zone of Peru. The study used air temperature data from 20 weather stations (2002–2016) to calculate the mean annual air temperature (MAAT), interpolated using a multiple linear regression model (MLRM) and digital elevation model (MERIT DEM). Occurrence and extent of 46 intact rock glaciers (IRG) and the global model of permafrost (Permafrost Zonation Index) were used to validate the results. The MAAT of CC has a minimum value around -4.1°C ($R^2 = 0.8$) and a ZIA average of ~5152 m a.s.l. None of the IRGs are located above the ZIA. The MAAT of CV has a minimum value around of -5.5°C ($R^2 = 0.8$), a ZIA average of ~4861 m a.s.l., and 60% of the IRGs are located above of the ZIA. The results show a greater variation of the position of the ZIA in CC in comparison to CV, which could indicate a possible degradation of mountain permafrost in these mountain ranges.

1. INTRODUCCIÓN

Mountain regions create conditions for the existence of permafrost (Arenson et al., 2011). Dominant factors such as elevation and its derivatives (aspect and slope), incidence of solar radiation, snow cover and the ground conditions influence on the ground temperatures (Gruber and Haeberli, 2009). In the Peruvian Tropical Andes, permafrost is expected to be found on all slopes above the ZIA and some studies (for example, Gorbunov, 1978; Guodong and Dramis, 1992; Haeberli et al., 1993) state that the mountain permafrost is at a minimum altitude of

approximately 5000 m a.s.l. In these mountain ranges, periglacial features such as intact rock glaciers (IRG) are geomorphological indicators of the occurrence of permafrost and therefore they can be used to approximate the regional lower limit of the mountain permafrost belt (Delaloye and Echelard, 2020). Based on this, it was estimated that the occurrence of isolated permafrost in a small sector of the cordilleras of southern Peru (Chachani Volcano, Arequipa) is above 5050 m a.s.l., between 5250 to 5420 m a.s.l. there is discontinuous permafrost, and at higher elevations permafrost tends to be continuous (Andrés et al., 2011; Yoshikawa et al., 2020). However, these geomorphological approaches are usually complex and require fieldwork. The ZIA is an indicator that has been used to estimate areas that are at negative temperatures levels and may host mountain permafrost (Carey et al., 2012; Haeberli et al., 2017), as well as, the changes that may occur in the permafrost due to its location in or outside the ZIA (Azócar et al., 2017). According Bradley et al. (2009) the ZIA is located within 4800 m a.s.l. $\pm$ 300 m for regions ranging from 20°N to 20°S that corresponds also to the lower limit of the permafrost estimated for the mountainous regions of Peru (~5050 m a.s.l.), therefore, ZIA could indicate the possible distribution of mountain permafrost in Peru. The variation of ZIA would also be used to evaluate the existing changes in these areas that potentially contain permafrost, since currently and as a result of climate change, there has been an increase of $\sim 0.2^\circ\text{C}/\text{decade}$ in the global average temperature during the last 30 years (IPCC, 2019).

This increase is also evident in mountainous areas. In the Alps the increase is of $0.5^\circ\text{C}/\text{decade}$ (EEA, 2009) and in the Andes it is $0.11^\circ\text{C}/\text{decade}$ (Vuille et al., 2015). According to these trends, the ZIA will increase its altitude as time passes, in some projections it is estimated that the current altitude of the ZIA for tropical mountain ranges would experience an increase of 230 m by the end of the 21st century (Schauwecker et al., 2017). The relationship between the ZIA and the lower limit of the permafrost (delimited using intact rock glaciers) will help us to estimate how it behaves as a function of time.

Finally, this research used ZIA data from two pilot mountain ranges in the Peruvian Andes to infer mountain permafrost. As well as studying its variation to identify areas where the permafrost is possibly changing as a result of the increase in temperature.

2. DATA AND METHODS

2.1. Study area

The study area comprises the central and southern sector of the tropical Andes of Peru, covering the areas of the Cordillera Central (CC) in the center and the Cordillera Volcánica (CV) in the southern part of Peru. The CC cover an area of 11,574 km² and is located between the parallels 13.0° and 11.4° S between the meridians 76.7° and 75.2° W. CV has an area of influence of 5805 km² and is located between 15.6° a 16.9° S and 70.5° and 71.8° W. In terms of altitudinal distribution, CC has an average altitude of 4,162 m a.s.l, with the highest point located at Pariacaca glacier (5750 m a.s.l.) Meanwhile, CV has an average altitude of 4368 m a.s.l, with the highest site located at Chachani Volcano (6057 m a.s.l; Figure 1).

Rainfall is concentrated in the northeastern area of the CC, where there is an average annual rainfall greater than 800 mm during the austral summer (Aybar et al., 2019; INAIGEM, 2018). A semi-frigid climate predominates, with an average annual temperature around 6 °C above 4500 m a.s.l. (Vicente-serrano et al., 2017). The climatic conditions in the CV are characterized by having precipitation that is concentrated in the eastern flank of the mountain range with annual mean values of 400 mm, with temperatures below 5 °C above 4500 m a.s.l. which favors the presence

of moderate frosts during the dry autumn (INAIGEM, 2018; Vicente-serrano et al., 2017). The climatic characteristics, high altitude, and increase in latitude allows greater possibilities of finding permafrost in the CV compared to the CC.

Figure 1. Location map of the study area using the MERIT digital elevation model (90 m). Elevation ranges are shown in the legend; yellow dots indicate the location of intact rock glaciers.

2.2. Data

2.2.1. Air temperature data

The maximum and minimum monthly mean temperature data (T_{max} and T_{min}) were provided by the National Service of Meteorology and Hydrology of Peru (SENAMHI-Peru). The T_{max} and T_{min} are calculated by the average of the maximum and minimum daily air temperatures records in a given month. Then, Mean Annual Air Temperatures (MAATs) were calculated for 20 weather stations located above 3000 m a.s.l. for a fifteen-year meteorological period (2002 to 2016; Table 1).

2.2.2. Rock glacier inventory

The regional inventory of rock glaciers was prepared using Microsoft's Bing Maps imagery accessible through QGIS 3.12. Rock glaciers were identified following the criteria of classification proposed by Humlum (1982), Barsch (1996) and Pereyra et al. (2010). Frequently, active and inactive rock glaciers (grouped together as intact forms in this study) have a steep front with visual

unstable rocks with ridges and furrows on their surface that are indicative of their present deformation (Azócar et al., 2017). In contrast, an irregular and collapsed surface due to thawing of ice commonly indicates that rock glacier is in its fossil or relict condition (Colucci et al., 2016; Rangecroft et al., 2015).

Table 1. Location of the weather stations and number of years between 2002 and 2016 with observations.

Weather station name	Cordillera	Region	Record <i>n</i> years	Longitude	Latitude	Elevation (m)	MAAT (°C)
Huancalpi	CC	Huancavelica	15	-75.237	-12.539	3450	9.0
Jauja	CC	Junin	15	-75.487	-11.787	3378	11.3
San Juan de Jarpa	CC	Junin	15	-75.432	-12.125	3600	9.2
La Oroya	CC	Junin	15	-75.959	-11.569	3910	8.5
Huayao	CC	Junin	15	-75.338	-12.038	3360	12.2
Laive	CC	Junin	15	-75.355	-12.252	3860	6.5
Huaro-chiri	CC	Lima	15	-76.234	-12.139	3120	9.8
San Lázaro de Escomarca	CC	Lima	12	-76.352	-12.181	3758	7.2
Carania	CC	Lima	14	-75.872	-12.344	3820	7.6
Vilca	CC	Lima	14	-75.826	-12.115	3832	7.2
Patahuasi	CV	Arequipa	7	-71.415	-16.055	4035	6.4
Pampa de Arrieros	CV	Arequipa	15	-71.589	-16.063	3715	8.6
Pillones	CV	Arequipa	14	-71.213	-15.979	4455	3.5
Las Salinas	CV	Arequipa	14	-71.148	-16.318	4378	4.5
Imata	CV	Arequipa	15	-71.091	-15.843	4475	3.7
El Frayle	CV	Arequipa	15	-71.189	-16.155	4131	8.1
Huanca	CV	Arequipa	15	-71.881	-16.035	3065	12.7
Puquina	CV	Moquegua	15	-71.169	-16.627	3284	12.7
Ubinas	CV	Moquegua	15	-70.854	-16.372	3380	10.5
Crucero Alto	CV	Puno	15	-70.912	-15.764	4521	4.1

For this research, we grouped active and inactive rock glaciers as intact forms, due to uncertainties in their classification (Azócar et al., 2017). Rock glaciers were digitized as point marks located at the end of the rock glacier front using an on-screen map scale of 1:5000.

2.2.3. Digital elevation model

The MERIT (Multiple Error Elimination Enhanced Terrain) digital elevation model was developed by removing multiple error components (absolute bias, stripe noise, speckle noise, and tree height bias) from the existing spaceborne DEMs (SRTM3 v2.1 and AW3D-30m v1). It represents the terrain elevations at a 3 arc sec resolution (~90m at the equator), and covers land areas between 90N-60S, referenced to EGM96 geoid (Yamazaki et al., 2017).

2.3. Methodology

2.3.1. Regionalization of Mean Annual Air Temperature (MAAT)

To estimate the ZIA, the MAAT was first calculated using data from meteorological stations over a 15-year time period (2002-2016) and additional data was obtained from the PISCOt grid

(Peruvian Interpolation data of the SENAMHI's Climatological and hydrological Observations) for different points within the whole study area (Aybar et al., 2019). The MAAT for a particular year was calculated as the arithmetic average of the monthly mean temperatures for that year. To have a better representation of the mountain climate, all meteorological stations are located above 3000 m a.s.l. and are far away from the coast to avoid the moderating effect of the ocean on the air temperature (Hiebl et al., 2009, Azócar, 2013).

The temperature data underwent quality control based on the standard deviation of the data, in order to eliminate errors in the time series caused by changes in the temperature sensor, station location or poor data capture (Hunziker et al., 2018). The elevation (meters), latitude (coordinate in degrees) and longitude (coordinate in degrees) were used, taken from the MERIT Digital Elevation Model (MERITDEM) with a resolution of 90 m and a vertical precision of around 4 m (Yamazaki et al., 2017). Multiple Linear Regression models (MLRM), unlike ordinary linear regression models, can explain the dependency between observations and estimated values (Alzate et al., 2018; Azócar et al., 2017).

To predict the spatial variability of MAAT, the annual residual variation was also considered. To calculate the MAAT at any location X with known elevation, latitude and longitude within the study region, the following model equation was used:

$$\text{MAAT}(x) = a_1 \text{elevation}(x) + a_2 \text{latitude}(x) + a_3 \text{longitude}(x) + \text{residual} \quad (10)$$

The overall fit of the MM was evaluated by examining the mean absolute error (MAE) in °C, coefficient of determination (R^2) and root-mean-square error (RMSE). This model was applied in the R programming language, using the *Reggie* package (Rauthe et al., 2013).

2.3.2. Estimation and validation of ZIA

We used the 0 °C MAAT threshold to illustrate the extent of conditions suitable for permafrost under present day conditions (2002-2016) similar to Rangecroft et al. (2016). For this purpose, we extracted the MAAT pixel values that are at a temperature ≤ 0 °C. In this way new value were assigned to each pixel: 0 being a pixel with a temperature higher than 0 °C and 1 pixels with lower temperature. Thus, images with binary values were obtained, and all those areas that had temperatures higher than 0 °C were eliminated. Finally, the remaining areas were displayed in a GIS, to obtain the altitude of the ZIA.

This estimate was discussed and compared with the lower limit of permafrost assuming that above this threshold discontinuous permafrost could be found. This limit is given by the minimum altitude of active and inactive rock glaciers (Barsch, 1996). In addition, the lower limit of fossil rock glaciers is used as an indicator of past permafrost conditions (Kerschner, 1978). It is assumed that changes in the altitudinal distribution reflect changes in climatic conditions, especially mean annual air temperatures (Lambiel and Reynard, 2001). Also, a qualitative analysis was performed between the ZIA and the global permafrost zonation developed by Gruber (2012).

3. RESULTS AND DISCUSSION

3.1. Mean Annual Air Temperature

The temperature distribution model indicated a current ZIA (2002-2016 mean) at ~5152 m a.s.l. in CC, and at ~4861 m a.s.l. in CV. The result cannot be directly compared with other studies, because they were carried out in places close to our study settings and on a different time scale (SENAMHI, 2016; ZIA~5100 m at Cordillera Huaytapallana near CC, Schauwecker et al., 2017;

~5010 m at Cordillera Vilcanota near CV). The rate of temperature decrease with altitude obtained in this study (-0.55°C per 100 m) is reasonably close to the average temperature decrease in the free atmosphere ($\sim -0.6^{\circ}\text{C}$ per 100 m; Beniston, 2006). The minimum temperatures identified in CC reach values of -4.1°C with a standard deviation of 3.2°C , while in CV the lowest temperature corresponds to -5.5°C with a standard deviation of 2.2°C (Figure 2).

Figure 2. The maps illustrate current annual mean air temperature (MAAT) areas for CC and CV using a suitability threshold of 0°C and -2°C as an approximation of the extent of mountain permafrost. Rock glaciers distribution are shown as red and green dots.

The precision (MAE) of the MAAT distribution model is between 1.1 - 1.4°C for CC and 0.9 - 1.3°C for in CV highlighting uncertainties in this key predictor of permafrost preference in this region.

The analysis carried out to the values of the MAAT model yielded R^2 values close to 1 (0.8) for both mountain ranges, showing a good correlation between the observed and the estimated values. However, the values obtained in the RMSE (1.7°C and 1.2°C , for CC and CV respectively) indicate that there may be uncertainties in these predictions.

The estimated MAAT values agree with MAAT models used as explanatory variable to estimate the distribution of permafrost in the Chilean Andes (RMSE $< 0.96^{\circ}\text{C}$ in Azócar et al., 2017) and on a global scale (RMSE $\approx 1^{\circ}\text{C}$ in Gruber, 2012). These comparisons can only provide a very general guidance. The lack of air temperature records and the spatial distribution of weather station could increase the residual standard errors and affect possible interpretation on permafrost

distribution. Therefore, MAAT obtained in the study could be warmer than reality and permafrost distribution may be underestimated at higher elevations.

3.2. Rock Glacier Inventory

85 rock glaciers were inventoried in the study area (Figure 2). Of these, 44 were classified as intact and 41 as fossils or relicts forms. The number of rock glaciers differs by 74 between CC and CV. Furthermore, the distribution of rock glaciers by dynamic status within each mountain range was uneven, ranging from 44% intact forms in CV to 8% intact forms in CC.

Figure 3. The figure shows the aspect as a function of the minimum altitude where intact rock glaciers are located. This is the lower limit of current permafrost based on an inventory of rock glaciers in CC and CV.

Rock glaciers have predominant orientations towards the south, similar finding have been indicated by Loarte et al., (2019) that indicate that rock glaciers located above 4,700 tend to have west-southwest aspects and rock glacier located above 5200 m a.s.l have mainly eastern orientations (Figure 3). Intact rock glaciers with north aspects were not identified possibly due to higher radiation rates on slopes with this orientation. On the other hand, we observed an uneven distribution of rock glaciers in each zone due to climate conditions. In CC, rock glaciers are scarce in comparison to white glaciers and wet conditions are more predominant (Marcer et al., 2017). Meanwhile, in CV, climate conditions are drier and rock glaciers are abundant thanks to the absence of white glaciers, a lithology prone to rock erosion, and the production of talus (Matsuoka & Ikeda, 2001). The existence of abundant fossil or relict forms in both mountain ranges suggests that favorable conditions existed for generalized permafrost in late glacial cold events. These findings were also found by previous studies (Guodong & Dramis, 1992; Lambiel & Reynard, 2001; Deluigi et al., 2017). Most intact rock glaciers occur in a MAAT below the ZIA, 60% (24) are below this threshold in CV, while in CC all the intact rock glaciers are below the ZIA limit (Figure 4). Brenning (2005) and Rangecroft et al., (2015) also reported active rock glaciers with positive MAAT in mountain ranges such as CC.

Figure 4. Proportion of intact and fossil rock glaciers located below (+MAAT) and above (–MAAT) the isothermal altitude of 0 ° C MAAT (ZIA) for CC and CV.

Figure 5. Annual ZIA (from 2002-2016) for CC and CV estimated with data from SENAMHI meteorological stations using the MAAT model: the x-shaped symbols represent the median, the boxes represent the 25th and 75th percentiles, the whiskers represent standard deviations and outliers are represented by points.

3.3. Calculated and Variation of Zero Isotherm Altitude (ZIA)

Figure 5 shows the mean elevation of the ZIA over a 15-year period. The CV shows a decline in the ZIA during the years 2002-2008, also reported by SENAMHI (2016), influenced by local effects that occurred in the climate of this area. However, as of 2010, an altitude peak is shown that follows a positive trend during the rest of the years for both CC and CV (Harris et al., 2000). The higher altitude found in CC with respect to CV is explained by the climatic difference between the two zones, CV is further from the equator, where drier and colder climates predominate

(Schauwecker et al., 2017). This is due to the nature of the annual air temperature cycle with cooler mean air temperature in dry areas (see, for example, Schauwecker et al., 2014). The highest ZIA in CC is in agreement with that observed by Bradley et al. (2009) for tropical areas.

In general, the air temperature and estimation of the ZIA is affected by several factors (for example, katabatic winds, aspect and insolation) that can influence the local climate conditions. Therefore, the regional estimate of the ZIA presented here is associated with a bias that increases significantly when temperature extrapolation is carried out for periods with few weather stations available (Schauwecker et al., 2017). However, because the stations used in this study have similar information periods in the 15 years evaluated, it allows us to identify the variations experienced by the ZIA during this period. In CC there have been variations in the ZIA between the 5000 at 5500 m asl, while in CV there are changes between 4800 and 5000 m a.s.l. These changes evidenced in the ZIA could be related to past events of rock falls and slope collapses registered in the Peruvian Andes (Evans & Clague, 1994). For example, in Arequipa (area of the CV) areas potentially exposed to sliding slopes and rock falls have been identified due to some triggering factor, such as temperature. Rock collapses could impact and travel considerable distances in the valleys (Vela, 2018).

3.4. ZIA and Lower Limit of Permafrost

The results indicate of this research indicate that the lower limit of mountain permafrost based on rock glacier distribution could be located in CV at 4655 m and at 4767 m in CC (Figure 3). Meanwhile, the estimated position of ZIA is at 4861 m a.s.l. and 5152 m a.s.l. for CV and CC respectively (± 4 m, error inherited from DEM). The difference between the two altitudes is because intact rock glaciers can exist below the ZIA due to local favorable conditions (i.e. lower radiation, geomorphological position and sources of debris material).

Similar findings have been found for the European Alps (Marcer et al., 2017) and for Chilean, Argentine and Bolivian Andes (Azócar et al., 2017; Esper Angillieri, 2017; Rangelcroft et al., 2015). When we comparison the results of global Permafrost Zonation Index (PZI) values (Gruber, 2012) with the ZIA obtained in this study the PZI values greater than 0.4 are found below the ZIA or in colder conditions.

As found in CV, the highest probability of finding permafrost is above 4712 m a.s.l. and near the ZIA (4861 m a.s.l.), values that are close to the one obtained by Andrés et al., (2011), which shows us a lower limit of 4900 m a.s.l. for CV. Gorbunov (1978) also estimated that the permafrost could be above 5000 m a.s.l. in tropical mountain ranges.

4. CONCLUSION

The results show that statistical models can be used as first approaches to estimate MAAT and ZIA position, however, the lack of measurements over 5000 m a.s.l. and the effects of some local factors (temperature circulation and complex topography) could affect the prediction of temperature in higher elevations. In general, the linear multiple regression model is useful for general approaches to the estimation of MAAT and ZIA. However, for more suitable statistical approaches, it is highly recommended to use Mixed Effect Models due to these models account for the non-independence of data.

The aspect of rock glaciers affects the position of the lower limit of permafrost, which generates the altitudinal differences with the ZIA. However, it is observed that the majority of IRG are within the ZIA limit in CV, while the opposite occurs in CC. Therefore, the ZIA can be used as an indirect indicator of the initial estimated distribution of mountain permafrost. In addition, the

altitudinal difference between the ZIA and the lower limit of the permafrost, can generate changes in the local landscape, a problem that will increase as time progresses, since a positive trend was observed in the ZIA, which means that the ZIA will retreat to higher ground, exposing new areas to landslides.

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