Journal of South American Earth Sciences 73 (2017) 42–49

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Permafrost distribution map of San Juan Dry Andes (Argentina) based on rock glacier sites

María Yanina Esper Angillieri

CONICET, CIGEOBIO, UNSJ, Av. José I. de la Roza y Meglioli, Rivadavia, San Juan, 5400, Argentina

A R T I C L E I N F O

Article history:
Received 17 July 2016
Received in revised form
17 November 2016
Accepted 1 December 2016
Available online 3 December 2016

Keywords:
Rock glacier
Mountain permafrost
Logistic regression
Dry Andes of San Juan

A B S T R A C T

Rock glaciers are frozen water reservoirs in mountainous areas. Water resources are important for the local populations and economies. The presence of rock glaciers is commonly used as a direct indicator of mountain permafrost conditions. Over 500 active rock glaciers have been identified, showing that elevations between 3500 and 4500 m asl., a south-facing or east-facing aspect, areas with relatively low solar radiation and low mean annual air temperature (−4 to 0 °C) favour the existence of rock glaciers in this region. The permafrost probability model, for Dry Andes of San Juan Province between latitudes 28°30′S and 32°30′S, have been analyzed by logistic regression models based on the active rock glaciers occurrence in relation to some topoclimatic variables such as altitude, aspect, mean annual temperature, mean annual precipitation and solar radiation, using optical remote sensing techniques in a GIS environment. The predictive performances of the model have been estimated by known rock glaciers locations and by the area under the receiver operating characteristic curve (AUROC). This regional permafrost map can be applied by the Argentinean Government for their recent initiatives which include creating inventories, monitoring and studying ice masses along the Argentinean Andes. Further, this generated map provides valuable input data for permafrost scenarios and contributes to a better understanding of our geosystem.

1. Introduction

The Argentinian Andes have abundant mineral resources that attract mining. Many deposits are in remote locations and at high elevations characteristics periglacial environments. An important debate generated by a recent federal regulation in Argentina, places mountain permafrost distribution and the potential of ground ice for as a store of water at the center of the scene. These regulations protect glaciers and rock glaciers as strategic fresh water resources for the future, prohibiting human activity on or close them that could change their natural behavior (Ruiz and Trombotto Liaudat, 2012).

As permafrost is in essence invisible, its occurrence can only be proved by direct and continuous records of the ground temperature requiring boreholes drilling (van Everdingen, 1998). Without private sector support, this types of operations in a site such as San Juan Dry Andes is currently unaffordable because of complex logistics and high costs. Nevertheless, the probability of permafrost can be modeled (Riseborough et al., 2008). The lack of enough and reliable data for calibration and validation probably is one of the most important limitations for permafrost modeling and it is important to devise strategies for the efficient use of existing data (Boeckli et al., 2012). In this context, estimates of permafrost distribution in the Argentine Andes are important. This article provides a first-order assessment of permafrost distribution in the San Juan Dry Andes region based on the mapping of rock glaciers. Rock glaciers conform one of the most salient features of the periglacial zone of this region. Barsch (1996) characterized rock glaciers as geomorphological expressions of creeping mountain permafrost (Fujii and Higuchi, 1978), and they serve as indicators of past and present mountain permafrost (Haeberli et al., 2006). Additionally, the role of these periglacial features is of critical importance in arid mountain ranges because act as potential long-term reservoirs for water (Brenning, 2005; Azócar and Brenning, 2010). Water resources in many of the world's arid mountain ranges would be threatened primarily by human perturbation including mining, land cover change, pollution, and destructive recreation, and in parts of the South American Andes could be exacerbated by glacier recession. Alternative sources of water, such as more resilient

E-mail address: yaninaesper@gmail.com.

http://dx.doi.org/10.1016/j.jsames.2016.12.002
0895-9811/

permafrost features (e.g. rock glaciers), are expected to become increasingly important as current warming continues (Rangecroft et al., 2016).

Permafrost mapping and modeling have been initiated in major mountain regions all over the world, (Gruber, 2012; Boeckli et al., 2012; Li et al., 2008; Ridefelt et al., 2008; Bonnaventure and Lewkowicz, 2008; Arenson and Jakob, 2010; Janke et al., 2011; Bonnanventure et al., 2012; Ruiz and Trombotto Liaudat, 2012, among others). Active rock glaciers have been used for modeling permafrost extents and changes in the North American Rocky Mountains (Janke, 2005), in the Maritime Southern Alps, New Zealand (Sattler et al., 2016).

There is little precise information about permafrost distribution in San Juan Dry Andes (Fig. 1). Only studies of Schreiber (2015), who modeling the distribution of mountain permafrost in a little sector of the central Andes of San Juan, and a permafrost map are available digitally that cover the San Juan Dry Andes region and provide estimates of permafrost extent, the Global Permafrost Zonation Index, based on a computer model (Gruber, 2012). This model run with an air temperatures based on the NCAR-NCEP reanalysis and CRU TS 2.0. Studies examined its local distribution (Schrott, 1996, 1998; Croce and Milana, 2002; Perucca and Esper Angillieri, 2008, 2011; Esper Angillieri, 2009, 2010). Since these investigations have been restricted in area, an attempt was made to model the probability of permafrost distribution for entire San Juan Dry Andes using geographic information system (GIS) techniques and topoclimatic data (elevation, aspect, solar radiation, mean annual precipitation and mean annual temperature) from active rock glaciers inventory.

2. Regional setting

The study area is in the middle west of Argentina and the west of San Juan Province, between 28°30′S-32°30′S latitudes (Fig. 1). The steep relief, low mean annual air temperature (MAAT), intensive weathering (frost shattering) and enough debris supply promote the rock glaciers develop (Schrott et al., 2012). Active rock glaciers indicate the presence of discontinuous permafrost (Barsch, 1996).

Dry Andes have semi-arid conditions with short-lived summers and rigorous winters with low temperatures (−18 °C to 0 °C), scarce precipitation (150–200 mm) and strong winds. From 3500 to 4000 m asl, temperatures range between −18 °C and 10 °C, rain is scarce and very irregular; snow precipitations are small and decrease considerably from south to north. Between 4000 and 6000 m asl, the precipitations are mainly snow (Lliboutry, 1998) and hail. MAAT is 1.9 °C at ~3400 m asl., and the mean zero degree isotherm altitude (ZIA) at this latitude of the Andes around ~3600 m asl. Recent winters have been particularly dry, with very little snow cover remaining into the summer field season.

At this latitude, the Andes are divided into Principal Cordillera and Frontal Cordillera. The Frontal Cordillera contains a Paleozoic basement constituted by sedimentary, metamorphic and igneous rocks (Ramos, 1988) and it is intruded by Upper Paleozoic granitoids. An Andean cover lies unconformably over the Paleozoic

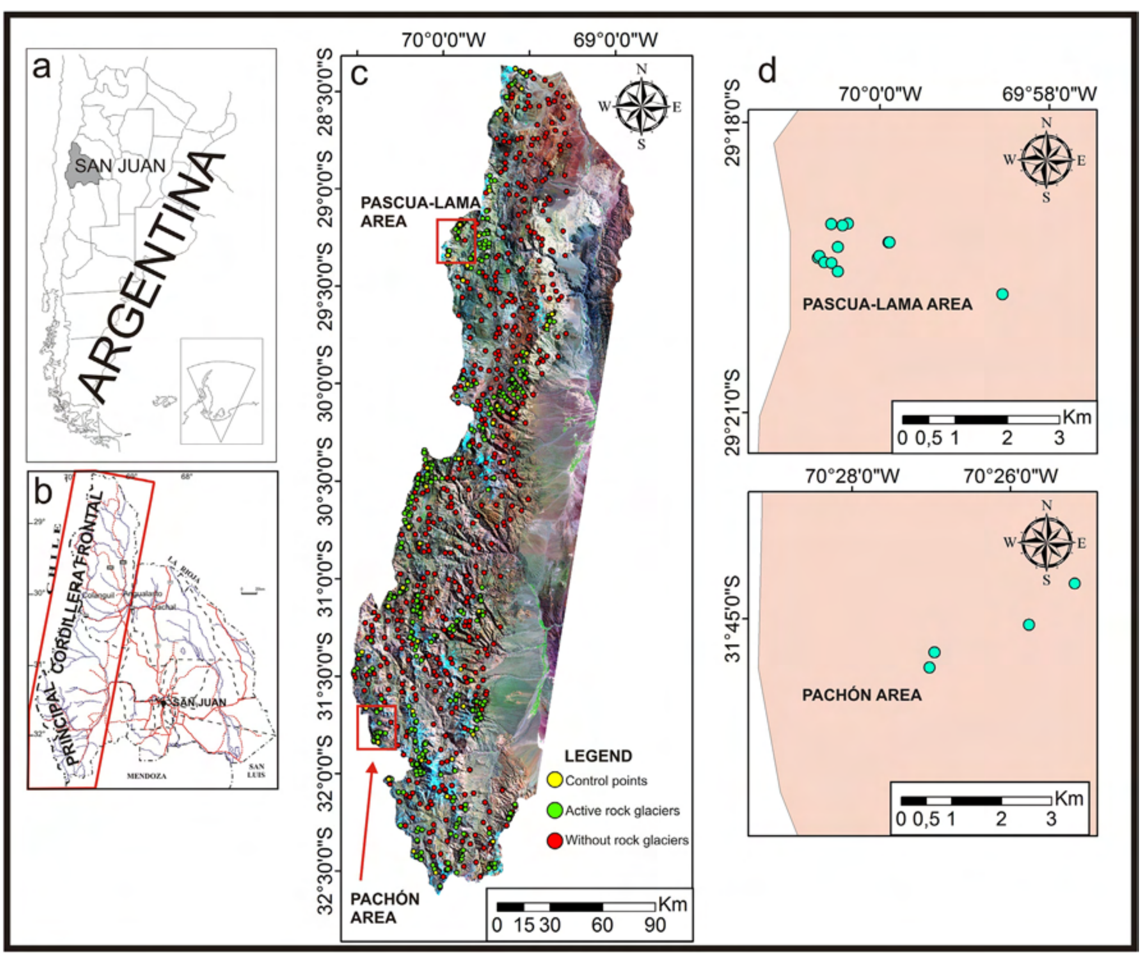

Fig. 1. Geographic location of the study area. (a) San Juan Province, Argentina, (b) Iglesia Department, the rectangle represents the specific study area, (c) location of control point, active rock glaciers, and points without rock glaciers, (d) points with checked occurrence of permafrost.

basement, and is constituted by Permo-Triassic and Cenozoic sedimentary, volcanic and volcaniclastic rocks, intruded by Mesozoic and Cenozoic granitoids (Rabassa and Clapperton, 1990). Principal Cordillera is characterized by a deformed belt of Mesozoic and Cenozoic sedimentary and volcanic rocks (conglomerates, sandstones and shales with ignimbrites and pyroclastic deposits) that overlie the Permo-Triassic volcanic and igneous complex, at these latitudes. The deformation style of this basement and the sedimentary cover are very different. Their contrasting rheological properties are one of the factors that contribute to the complex structure of the region (Cristallini and Ramos, 2000). The modern deposits, gravels, sands, marls, and clay, occupy the valleys and river beds.

3. Materials and methods

Active rock glaciers are a diagnostic and well visible geomorphological feature to detect the existence of permafrost. Based on an interpretation of Google Earth™ high resolution satellite imagery (SPOT 5 with a 2.5 m spatial resolution, and IKONOS with a 4 m spatial resolution) and ArcGis 10.3, an inventory of active rock glaciers in the area was created, following the morphological criteria of Wahrhaftig and Cox (1959) and Martin and Whalley (1987). In general, active rock glaciers have a steep (>35°) frontal slope and a well-developed flow-like morphology defined by sets of parallel and curved ridges separated by long V-shaped furrows (Barsch, 1996; Roer and Nyenhuis, 2007). The landforms were mapped as point features in ArcMap 10.3 at the base of the toe of the each rock glacier. By mapping a single point, is avoided redundant information biasing the statistical evaluation of the relationship between permafrost presence and the topoclimatic variables (Sattler et al., 2016).

Identifying points of active rock glaciers were recorded. The active status of rock glaciers was estimated based on the visibility of a front with the appearance of fresh material exposed as well as an overall convex and full shape (Schmid et al., 2015).

The permafrost probability was modeled, using a logistic regression model and some topoclimatic variables. The model, similar to the one proposed by Janke (2005) and Sattler et al. (2016), estimates the relation between the permafrost probability attributed to rock glaciers occurrence, the altitude, aspect, mean annual air temperature, mean annual precipitation and the potential incoming solar radiation.

Elevations (Fig. 2.1) were obtained from topographical information obtained from ASTER GDEM V2 with a 30 m spatial resolution (NASA, 2011). Therefore, a digital elevation model (DEM) was made for the region. Using the DEM, slope aspect (Fig. 2.2) and the amount of solar radiation (Fig. 2.5) were calculated. Solar radiation (in WH/m^2; equal to 0.001 h of sun), for 2012 year, was estimated using the hemispherical viewshed algorithm developed by Rich et al. (1994), Fu and Rich (2002).

Uncertainty exists in the choice of a suitable regional air temperature and precipitation model. Measurements of air temperature and precipitation, in the San Juan Dry Andes, are rare, impeded by the low density of long-term climate stations at elevations of ~1000 m asl and the absolute absence of stations at summit height. Therefore, the air temperature (Fig. 2.3) and precipitation (Fig. 2.4) maps were carried out from information collected by Hijmans et al. (2005), who compiled monthly climate averages, data at 30 arc sec (~1 km) horizontal resolution, measured at weather stations from a large number of global, regional, national, and local sources, mostly for the 1950–2000 period (precipitation records from 47,554 locations and mean temperature from 24,542 locations, from the entire world).

Logistic regression allows the formation of multivariate regression relation between a dependent variable and several independent variables (Hosmer and Lemeshow, 1989; Atkinson and Massari, 1998). Dependent data are made up of 0 and 1 values which show the absence and presence of rock glaciers respectively. In the current situation, the binary dependent variable represents the presence or absence of an active rock glacier. In a logistic regression analysis, the number of points representing areas with an occurrence and that without it should be the same (e.g., Ayalew and Yamagishi, 2005). 484 points represent the active rock glaciers and they are considered as indicators of permafrost. Therefore, 484 points without rock glaciers but with similar characteristics of occurrence were randomly selected. Factors were treated as categorical variable (Fig. 1c).

In logistic regression, multicollinearity checking is necessary to check the correlation of independent variables (Hosmer and Lemeshow, 1989). Multicollinearity is a statistical situation in which two or more predictor variables are highly correlated, meaning that one can be linearly predicted from the others with a non-trivial degree of accuracy. Tolerance (TOL) and the variance inflation factor are two important indexes that are widely used for multicollinearity checking. According to Menard (1995), a TOL value less than 0.2 is one indicator for multicollinearity, and serious multicollinearity occurs between independent variables when the TOL values are smaller than 0.1. The variance inflation factor (VIF) is calculated by 1/tolerance. If VIF value exceeds 10, it is often regarded as indicating multicollinearity. Additionally, the Pearson correlation was also used to test the correlation between variables.

Finally, the resulting probability map, with a 30 m spatial resolution, was verified and compared using known rock glaciers locations that were randomly selected and had not been previously used in the calculation of the model. Additionally to assess the accuracy of the probability model, the area under the receiver-operating characteristics curve, which is known as AUROC, was calculated. This value ranges between 0.5 (random model behavior) and 1.0 (perfect model; Hosmer and Lemeshow, 2000). Further verification was carried out by another 16 points with checked occurrence of permafrost, 12 points from Pascua-Lama area (BGC Engineering, 2009) and 4 points from Pachón area (Trombotto Liaudat, 2014).

4. Results and discussion

4.1. Rock glacier characteristics

526 active rock glaciers were identified from interpretation of Google Earth satellite imagery. 484 points represent the active rock glaciers for model construction and 42 were reserved for model validation. The majority of them (308) are talus glaciers; only 218 are tongue-shaped glaciers. Rock glaciers were used as a proxy, because they are visual indicators of permafrost, can occur near the lowermost regional occurrence of permafrost in mountains, and can be delineated based on high-resolution remote sensing imagery freely available on Google Earth (Schmid et al., 2015).

The area was divided into four elevation classes (Table 1). The elevation map (Fig. 2.1) reveals that elevation ranges from 1200 to 6694 m asl. Active rock glaciers mapped occur from 3284 m asl. at 30°30′S to 4928 m asl. at 29°18′S, conforming with the global trend of increasing elevational permafrost limits with decreasing latitude (Cheng and Dramis, 1992). More than 89% of them develop between 3500 and 4500 m asl. Most mountain permafrost in South America is found at high elevations in the Andes. Permafrost mostly appears in groups of rock glaciers. Between 15° and 22°S Rangecroft et al. (2014) reported the lower limit of permafrost to be at 4700 m asl. in the Bolivian Andes; between 22° and 28°S Ahumada (2002) recognized the presence of rock glaciers between 4500 and

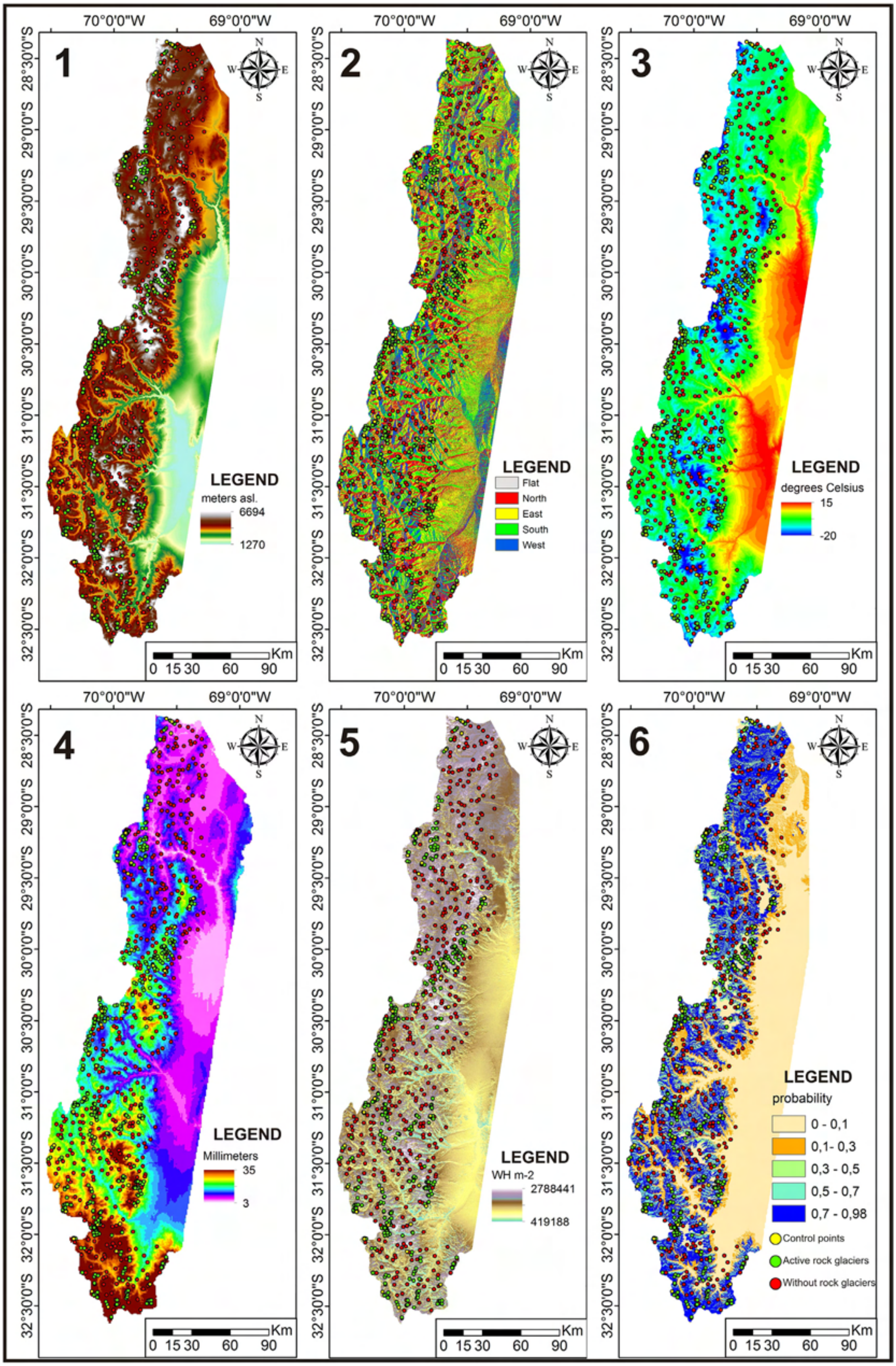

Fig. 2. Variables maps: 1) altitude; 2) aspect; 3) mean annual air temperature; 4) mean annual precipitation; 5) solar radiation and 6) Spatial model, based on logistic regression of the permafrost probability Dry Andes of San Juan.

5000 m asl.; at about 28°S, the lower limit of Andean permafrost is restricted by a type of discontinuous permafrost, with abundant rock glaciers (Barsch, 1978); at an elevation of 4300–4500 m asl. Perucca and Esper Angillieri (2008) recognized the limit of approximately discontinuous permafrost to be at about 5000 m asl.; at 30°S for Schrott (1994), the continuous permafrost is found

Table 1
Logistic regression coefficients and frequency classes for different variables.

Variable	Class	Points showing rock glaciers occurrence	% Rock glaciers occurrence	All point for modeling	% All point for modeling	Coefficients of logistic regression
Elevation [m. asl]	2000–3000	0	0	17	2	3.631
	3000–4000	433	44	433	45	21.084
	4000–5000	273	56	491	51	21.327
	5000–6000	0	0	27	2	1
Aspect [degree]	N (315–45)	34	7	174	18	−0.380
	E (45–135)	145	30	270	28	0.728
	S (135–225)	235	47	358	37	1.053
	W (225–315)	70	14	166	17	1
Temperature [°C]	−14–−5	53	11	144	15	20.004
	−4–0	423	87	696	72	20.480
	1–4	8	2	109	11	17.427
	5–8	0	0	19	2	1
Precipitation [mm]	7–18	300	62	674	70	−0.911
	19–25	155	32	244	25	−0.509
	26–33	29	6	50	2	1
Solar Radiation [WH/m^2]	0895929–1,500,000	8	2	48	5	−1.530
	1,500,000–2,000,000	333	69	496	51	1.255
	2,000,000–2,500,000	143	29	424	44	1

between 4000 and 4800 m asl., at 33°S, Brenning (2005) indicated that between 3500 and 3800 m asl.; the baseline of the discontinuous permafrost is found; at 34°S, this limit reaches 3500–3600 m asl. (Trombotto et al., 1999); and at 44°S, an altitude of 2060 m asl. (Trombotto, 2002); at 51°30′S, permafrost was reported at an altitude of 980–1100 m asl. (Roig, 1986).

Aspect regions (Fig. 2.2) were classified according to the aspect class as flat (−1°), north (315°–360°, 0°–45°), east (45°–135°), south (135°–225°) and west (225°–315°). Most active rock glaciers occur on south-facing (48.55%) and east-facing (29.96%) slopes (Table 1). Esper Angillieri (2010); Martini et al. (2013): Rangecroft et al. (2014) obtained similar results.

All active rock glaciers occur between MAAT of −9 and 4 °C (Fig. 2.3), the average MAAT for rock glaciers in the region is the −2 °C. Only the 1,6% (8) are situated below the mean annual 0 °C isotherm. More than 87% (423) of them develop at temperatures at or below zero (−4 to 0 °C). Active rock glaciers with positive MAAT have been reported by Brenning (2005) and Rangecroft et al. (2014). The mean annual precipitation (MAP) ranges from 6 mm to 37 mm (Fig. 2.4). The average MAP for rock glaciers in the region is the 17 mm.

Anderson-Teixeira et al. (2015) testing WorldClim data by comparison of available weather station data and revealed close correlation for MAAT (R2 >97%). However, these authors concluded that WorldClim data tested to systematically underestimate MAP at sites with high MAP. An independent cross-validation of Worldclim indicated temperature deviations of <0.3 °C and precipitation deviations of <10 mm mo^{-1} in most locations, and comparison with a similar gridded dataset indicated the greatest uncertainty occurs in mountainous and data-sparse regions (Hijmans et al., 2005).

The active rock glaciers in the study area receive solar radiation (Fig. 2.5) amounts between 1,310,494 and 2,347,750 W H m^{-2} corresponding to 1310.5–2347.7 h (low solar radiation). In contrast, the San Juan Province received an average solar radiation of 12.3 h per day during 2012, which is equivalent to a total of 4432.28 h (hi solar radiation).

4.2. Model validation and uncertainties

The observed distribution of active rock glaciers and logistic regression coefficients are shown in Table 1. With, all the factors treated as categorical variable, the system constructed were found to be valid; with 75.3% of the pixels used being correctly predicted (80.6% of the active rock glaciers pixels and 70.0% of non-rock glaciers).

From the analysis of the obtained permafrost model (Fig. 2.6) and considering a probability greater than 70% for the occurrence of rock glacier indicating permafrost, currently, permafrost covers about 28.9% (10772.4 km^2) of the entire study area (37276.1 km^2).

The test showed that the goodness of fit of the equation could be accepted because the values of Cox and Snell R2 (0.328) and Nagelkerke R2 (0.437) are greater than 0.2 (Clark and Hosking, 1986). The TOL, VIF values and Pearson correlations in this study are showed in Table 2. It reveals that there is no multicolinearity among any of the variables and weakly correlated with each other. Pearson correlations (Table 2) show that the variables used in the present study are only weakly correlated with each other. The highest correlation was found between elevation and MAAT (−0.611) but its value is below the risk level of 0.7 (Clark and Hosking, 1986).

The testing validation performed by comparing known rock glacier location data, which were not included in the model, indicated good fit with an accuracy of 85.71%. Also, the ROC curve of the training set, shows an AUC value of 0.802 which exhibit the robustness and the good reliability of the model. Further verification was carried out by another 16 points locations with checked

Table 2
Multicollinearity checking and Pearson's correlation coefficients between variables.

	Tolerance (TOL)	Variance inflation factor (VIF)	Elevation	Aspect	Temperature	Precipitation	Solar radiation
Elevation	0.587	1.702	1.000	−0.008	−0.611	0.038	0.302
Aspect	0.802	1.247	−0,008	1.000	−0,043	0032	−0.417
Temperature	0.566	1.767	−0.611	−0,043	1.000	−0.249	−0,220
Precipitation	0.899	1.113	0.038	0,032	−0,249	1.000	−0.098
Solar radiation	0.717	1.395	0.302	−0.417	−0,220	−0.098	1.000

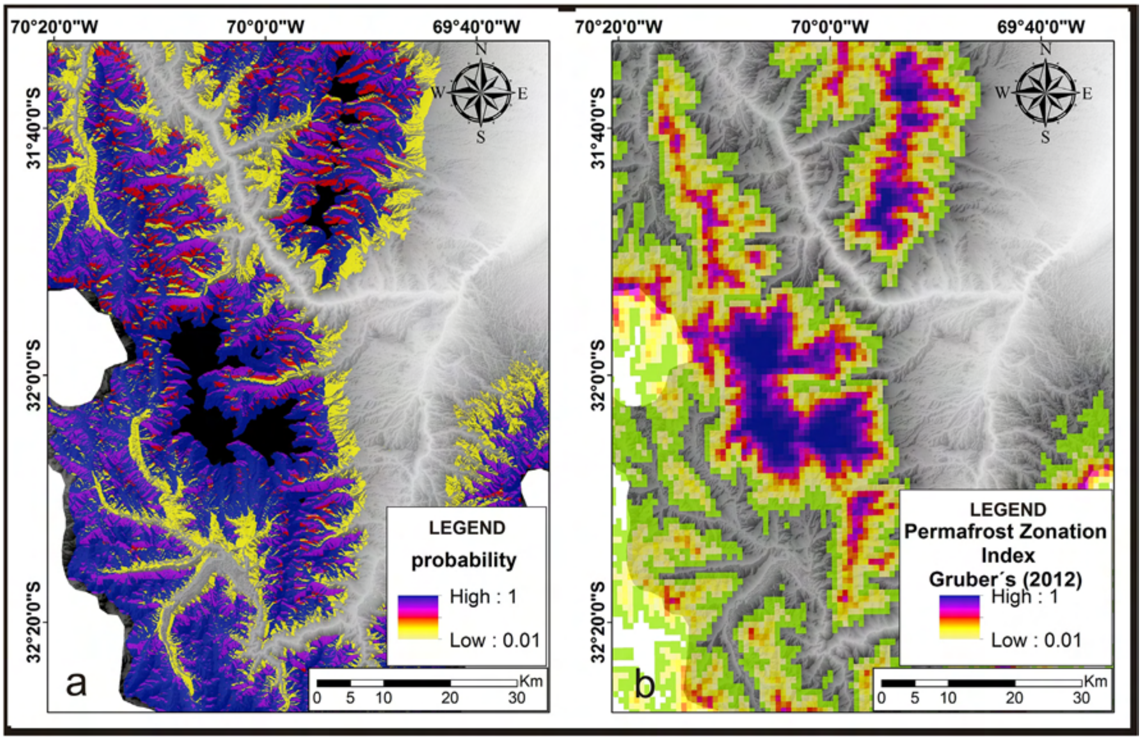

Fig. 3. Comparison of models: a) present permafrost distribution map, with a 30 m spatial resolution; b) PZI model of Gruber (2012).

occurrence of permafrost, 12 points from Pascua-Lama area (BGC Engineering, 2009) and 4 points from Pachón area (Trombotto Liaudat, 2014), these points indicate a 75% accuracy (Fig. 1d).

Despite differences in methodologies and spatial resolution between the regional (~1 km) Global Permafrost Zonation Index of Gruber (2012) and the of the present study (30 m), a simple visual comparison between a portion of the present local permafrost distribution model of Andes of San Juan with the PZI, exposed strong similarities (Fig. 3). Nevertheless, despite its limitation over small areas, Ardelean et al. (2015) consider the PZI model a very useful approach that practically confirms the possibility of permafrost occurrence within the study area and also enables the comparison amongst mountain ranges of similar scale.

Nevertheless, the lack of reliable and appropriate data (continuous records of the ground temperature) for calibration and validation probably is one of the most important limitations for permafrost modeling in dry Andes. However, if there were point (borehole) measurements, due to the heterogeneity, it is not enough to describe the regional conditions of the area, making it difficult to use for model validation (Gruber, 2012).

Since, the statistical model is calibrated based on rock glacier occurrence as a binary variable, the precision of the map is related to correct identification of the active periglacial features and while this model combination results in probabilities sensu strictu, their application to areas that are not rock glaciers or steep bedrock is difficult. Furthermore, micro-topography can also influence local-variations in permafrost distribution and associated terrain attributes (Lara et al., 2015; Wainwright et al., 2015), but fine-scale topographical datasets are currently unavailable for all Dry Andes of San Juan.

The obtained permafrost model in this region primarily serves as an indication map at a regional scale, indicates the areas that can be protected or investigated further, it can assists planners in permafrost related constructions, infrastructure route planning and the establishment of guidelines for hazard assessment but does not substitute local investigations if detailed knowledge concerning permafrost occurrence is required. The map provides valuable input data for permafrost scenarios and contributes to a better understanding of our geosystem.

Finally, the possibility of mapping rock glaciers from high-resolution remote sensing imagery freely available makes this an attractive and unique data source. However, an estimation of permafrost distribution based on rock glacier activity generally results in an overestimation of the amount of permafrost below surfaces that are not rock glaciers (Boeckli et al., 2012).

5. Conclusions

For the first time a regional permafrost distribution map, with a 30 m spatial resolution, based on the mapping of rock glaciers, is available for the region of the all Dry Andes of San Juan, a map which is of use to local and national authorities. Present permafrost occurrence is still a widespread phenomenon estimated to cover 10772.4 km^2 (~28.9% of the entire area). Logistic regression analysis revealed that all active rock glaciers lie above 3284 m asl., pointing to the possible minimum elevation for rock glacier formation. MAAT, slope, and MAP are important factors, with south-facing and east-facing slopes and air temperatures between −4 and 0 °C being the main conditions for their occurrence. The validation results showed satisfactory agreement between the permafrost distribution generated map and the known active rock glaciers locations; over 82% of the validation set are correctly classified falling in high probability of permafrost areas. Also, the ROC curve had shown an area under curve (AUC) value of 0.802 which demonstrates the robustness and good reliability of the model. The results obtained in this study were in alignments with those from other parts of the Andes and have provided an advanced knowledge of the of rock glaciers and current permafrost distribution in San Juan Dry Andes. Furthermore, the methodology presented here is easy to reproduce and may be applied to other mountainous regions, as a useful tool to assess periglacial environments in relation to gemorphic and topoclimatic setting. However, the models should be used cautiously for specific site development due to the scale of the analysis. Therefore, the models used in such study are valid for general planning and assessment purpose but may be less useful at site-specific scale, where local geological and geographic heterogeneities may prevail.

Acknowledgements

The author thanks especially the anonymous reviewer for his helpful comments. CONICET (National Council of Scientific and Technological Research) has provided funding for research and CIGEOBIO provided funds for ArcGIS 10.3 software license.

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