Mountain Permafrost Distribution in the Andes of Chubut (Argentina) Based on a Statistical Model

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Abstract

An important debate generated by a new federal regulation in Argentina places mountain permafrost distribution and the potential of ground ice for water storage at the center of the scene. The main problem is related to the lack of field data on a regional scale. With the aim of solving this problem, in the Precordillera of Chubut, Argentina, a statistical model of mountain permafrost distribution based on measured BTS (Bottom Temperature of Snow cover) was presented. A multiple linear regression analysis was used to reproduce BTS distribution with elevation and potential short-wave radiation as independent variables. A threshold classification was then applied to BTS distribution in order to discriminate between probable, possible, and no possible permafrost zones. The model results suggest that mountain permafrost may exist, and is related to high-elevation south-facing slopes or highly cast shadow zones. Although the model was statistically significant, it is necessary to confirm the presence of permafrost by ground validation.

Keywords: BTS; Andes of Patagonia; statistical modeled permafrost distribution; ground ice.

Introduction

Mountain permafrost distribution and its response to climate change has become an area of major importance during recent years in Argentina and other countries with mountain environments. The main issues are (1) the occurrence of ice in mountain permafrost as water storage, especially in arid mountain regions, and (2) the risk of natural hazards related to mountain permafrost degradation in populated regions.

In Argentina, mountain permafrost and glacier distribution has been the focus of an intense social, political, and scientific debate in relation to the recently approved Federal Glacier and Periglacial Protection Law (Ley 26.639, 2010), most commonly called “Glacial Law.” This law protects glaciers and rock glaciers as strategic fresh water resources for the future, prohibiting any human activity on or close to them that could modify their natural behavior. Another important aspect of the “Glacial Law” is the creation of a National Inventory of Glaciers and Rock Glaciers using remote sensing.

One concern of the scientific community is the problem of mapping the distribution of mountain permafrost using satellite imagery. In this context, mountain permafrost distribution models based on indirect information such as the BTS (Bottom Temperature of Snow cover) method (Haeberli 1973) could help identify the zones where permafrost is developed and also indicate zones where rock glaciers or ice-rich permafrost landforms may exist.

In this paper, we present modeled permafrost distribution for the Andes of Northern Patagonia, based on BTS data and topoclimatic factors.

Background

Permafrost in Patagonia

Permafrost in Patagonia is mainly associated with fossil cryogenic sedimentary structures related to cold episodes associated with the Pleistocene Glaciations (Trombotto 2008). Garleff & Stingl (1998) describe different periglacial features for the Patagonian Andes and point to temperature as the most important cryogenic factor. Trombotto (2000) indicates that it is possible to find continuous permafrost above 2,000 m a.s.l. at a regional scale in North Patagonia. Ruiz & Trombotto (2011) present a detailed periglacial geomorphology map of Cordón Leleque and they recognize, among other landforms, relict rock glaciers, active protalus lobes, and protalus ramparts; the latter are related to present permafrost.

BTS

First introduced by Haeberli (1973), BTS consists of measuring the temperature at the base of the mid-winter snow cover. It is based on two assumptions: (1) BTS remains constant in mid-winter below a snow cover of at least 0.8 m thickness, and (2) the BTS value is determined by the heat flux from the subsurface and serves as proxy of subsurface thermal conditions. Haeberli (1978) empirically established BTS thresholds of -3°C and -2°C for discrimination between likely permafrost, possible permafrost, and no permafrost.

Although the method was developed for the Swiss Alps (Hoelzle 1992, Gruber & Hoelzle 2001), it has been tested and used in other mountain ranges of the world with positive results (Brenning et al. 2005). However, data do not yet exist to date that would prove its validity for application in the Andes.

Mountain permafrost distribution models

Different types of models have been used to simulate and predict mountain permafrost distribution, based on topoclimatic parameters, BTS, and morphological terrain expressions (Gruber & Hoelzle 2001, Brenning & Trombotto 2006, Arenson & Jakob 2010, and others). In this study, we used the multiple linear regression approach presented by Gruber & Hoelzle (2001). These authors demonstrated that mountain permafrost distribution in the Swiss Alps could be replicated using a model distribution of BTS and Haeberli’s (1978) thresholds.
Brenning et al. (2005) present the typical problems with BTS and statistical models of permafrost. These authors suggest that common errors are associated with (1) the distribution and distances between each measurement; (2) early or late snow cover; (3) early snow melting, both local and regional; and (4) operational errors associated with observer and instrumental bias.

Study Area

The study was carried out in the Precordillera of Chubut (42°–43°S, 71°–71.5°W) (Figs. 1A, 1B). At this latitude, the Andes can be separated in two main mountain ranges: the Lake Region Andes where, due to high precipitation, it is possible to find valley glaciers terminating close to 1,000 m a.s.l., and an east mountain range, informally called Precordillera, which is similar in elevation to the Lake Region Andes but receives much less precipitation. The Andes constitute a massive barrier to the atmospheric westerly flow, generating steep west-east precipitation gradients (Prohaska 1976). According to Condom et al. (2005), the climatic Equilibrium Line Altitude for glaciers (~2,200 m a.s.l.) is higher than the 0°C isotherm (~1,980 m a.s.l.) at the Precordillera, favoring the development of mountain permafrost (Haebelri 1985) (Fig. 1B).

The Rivadavia Range (RIV) (Z1, Fig. 1C) at the western margin of Precordillera, Esquel Range (ESQ) (Z2, Fig. 1C) and the Leleque Range (LEL) (Z3, Fig. 1C) at the eastern margin, were the areas selected for the BTS measurements. Although all three ranges reach 2,100 m a.s.l., ESQ is the one with the largest area above the treeline (~1,500 m a.s.l.).

With the exception of ESQ, where the ski resort of La Hoya is located, these mountain ranges are extremely remote, without road access. The only human activities are forestry and/or livestock.

These ranges are located within the watersheds of very important rivers in the region. RIV (eastern margin), LEL (western margin), and ESQ (western margin) are the watersheds of the Percey and Esquel. These rivers deliver water to the communities of Esquel and Trevelin, the most important towns in the west of the Chubut province. LEL (eastern margin) and ESQ (eastern margin) are part of the watershed of the Chubut River, the most important river in the province. This allochthonous river is the water source for the main agricultural activity of Chubut province, located more than 400 km from its source area.

Method

The model

The theory behind this model is presented in Gruber & Hoelzle (2001) and will be discussed only briefly here. Permafrost is a thermal phenomenon that can be described in terms of energy balance and heat transfer capacity. The most important incoming sources of energy are turbulent heat (i.e., air temperature) and radiation (both short and long wave). It has been shown that air temperature and solar radiation are closely related to the presence or absence of permafrost (Hoelzle 1994). Gruber & Hoelzle (2001) propose elevation as proxy of temperature, and potential short-wave radiation (PSWR) during summer as model parameters. They also use a vegetation index (Soil Adjusted Vegetation Index, SAVI) as proxy of vegetation cover to tune the model. Brenning et al. (2005) have shown that the importance of SAVI, as a normal explanatory variable, does not improve the predictability of the model. In this study, we were dealing with an area above the tree line where vegetation is largely absent, so we also discard this parameter.

For the model, the SRTM Digital Elevation Model (DEM) was used. Although it is a medium spatial resolution source, it reproduces the terrain with great fidelity and has a global accuracy of 20 m (Jarvis et al. 2008). The DEM with a 95-m grid cell in Universal Transversal Mercator (Zone 19S) projection and WGS 84 Datum formed the common basis on which all other data have been entered and processed in a GIS environment (SAGA GIS 2.07). The PSWR for each grid cell was calculated using the Potential Incoming Solar Radiation module of SAGA GIS (Wilson et al. 2000). It takes into account the effects of topography and shading for every grid cell. It is possible to use different parameters to tune the model, primarily related to atmospheric conditions. Here the total PSWR for “summer” (December 1 to April 30) was calculated using an incremental period of 1 hr with an arbitrary Lumped Atmosphere Transmittance of 70%. Total PSW was divided by the number of days in order to obtain a mean daily PSWR, expressed in mega joule by square meter per day (MJ/m² d).

BTS measurements

For this study, a total of 80 BTS readings during the winters of 2009, 2010, and 2011 were used. Measurements were conducted with a snow probe of 2-m length with a Grant temperature sensor at its tip and a digital tester (precision 0.8%). Resistivity was measured in the field and then converted to temperature. Locations in the field were determined using a handheld GPS, and the altitude for each point was extracted from the DEM in the GIS environment for consistency in the model tuning. A description of the 80 BTS measurements is presented in Figures 2 and Figure 3. Two different biases were detected. The first was related to the slope of the BTS point, where no slope greater than 35° was detected. This is related to two causes: (1) because of the coarse cell size of the DEM and the algorithm used to calculate the slope angle, only a huge steep face could achieve high values, and (2) on steep slopes there is no possibility for a thick snow cover to accumulate (Fig. 2). The second bias is related to the aspect of the BTS point, where a deficit in south-facing slopes was observed. This was mainly related to the difficulties of accessing the study zone; in general, the approach to the mountain areas was from the east (Fig. 3).

Of the 80 BTS, 15 were excluded from the model validation. The remaining 65 were used to run the model. In order to eliminate the possibility for pseudo replication and autocorrelation (Brenning et al. 2005), BTS were resampled to the spatial size of the DEM. If more than one BTS was located in the same grid cell, the mean value was used. With this
approach, the number of BTS to make the model decreases to 36.

Based on the 36 driving points, a multiple linear regression analysis was performed in order to predict the BTS, using elevation (Z) and PSWR as independent variables.

The regression yields a relation of the form:

\[ BTS = a + b \times Z + c \times PSWR \]  \hspace{1cm} (1)

where \( a, b, \) and \( c \) are coefficients obtained from the analysis.

In order to assess whether the BTS remains constant throughout winter, a simple experiment was conducted in LEL (Fig. 1B). A miniature temperature logger (UTL-2), measuring temperature every 4 hours throughout the year, was introduced at the interface between the air and blocky surfaces to monitor BTS. The sensor was located in a protalus lobe that could be active (frontal slope angle >45°).

In order to test the model, BTS and the permafrost distribution model output were compared with a recent periglacial map of Cordón Leleque (Ruiz & Trombotto 2011). The correlation between the landform distribution and the permafrost distribution model was analyzed using zonal statistics and visual inspection on a screen.

Finally, the importance of permafrost areas as water storage was analyzed. This property is related to the ice content, which is largely correlated to ground porosity. Rock glaciers, as ice-rich creeping permafrost landforms (Barsch 1996), are where ground ice is concentrated in a mountain permafrost environment. A simple slope analysis was conducted to assess
how much of the area that was detected as possible permafrost (PP) and as likely permafrost (LP) could indeed have ground ice. In general, debris-covered surfaces and rock glacier surfaces had slopes from 0 to 25°, and it is possible to assume that slopes of more than 25° could be related to rocky outcrops (totally impermeable) or high slope screes (low ground ice content). In this respect, PP and LP areas for each mountain zone were subdivided between two categories: potential to contain ground ice (PGI) (slope < 25°), and no potential to contain ground ice (NPGI) (slope > 25°). It is important to note that this simple analysis does not take into account two important factors related to the generation and behavior of rock glaciers: (1) debris supply, without which it is not possible to form rock glaciers, and (2) creep phenomena that allow rock glaciers to transport ground ice downslope from its source zone.

Results

Significance of BTS measurements

In Figure 4, the mean daily temperatures at the ground surface in LEL are shown. Throughout the year, four different periods of time could be distinguished: (1) Dry snow cover less than 1 m. Although there was some variation, temperature was attenuated by an increasing snow cover; (2) Dry snow cover more than 1 m. During winter (mid July to mid October) the temperature reached a stable value around -2.7±0.1°C and indicates likely permafrost conditions; (3) Snow melting, a temperature-stable period, close to 0°C, was detected in spring and is related to melting of the snow cover. At the end of this period the temperature decreased below zero because of a very cold day which refroze and cooled the snow; (4) Bare surface. During summer all the snow melted, and the temperature was free to oscillate with air temperature. The difference between the measured BTS during winter (16/08/2010) and the temperature of the miniature data logger (-0.3°C) could be related to the accuracy of the thermistors.

Permafrost distribution model

After running the multiple regression analysis, two outliers were identified in the residual plot (Fig. 5A). They were discarded and a new regression analysis was conducted. The coefficients obtained were a=2.6, b=-0.0049, and c=0.24. The overall R²=0.48, with a P-value of 0.000062 (α=0.001), indicates the result is statistically significant (i.e., the relation is unlikely to have occurred by chance). Nevertheless, these coefficients should not be used in other areas without new analysis (Gruber & Hoelzle 2001). The RMSE (root mean square error) between the BTS measurement and the BTS modeled was 1.0°C.

The regression was then applied to the entire project area, generating a continuous field of simulated BTS, and subsequently grouped into classes to obtain a permafrost distribution model for the study area:

- <-3°C likely permafrost (LP)
- -3 to -2°C possible permafrost (PP)
- >-2°C no permafrost (NP)

Testing the significance of the model

Fifteen BTS data points were not used in the regression analysis and used for cross-validation. The RMSE of modeled and BTS used for cross validation is 1.01°C. The agreement between the model and the measured BTS is shown in Figure 5B. Although the residual could exceed ±2°C, the model fails in only one case to reproduce the permafrost class (Fig. 5B). In this case, the model overestimates the presence of permafrost.

Permafrost distribution in Precordillera of Chubut and its comparison with periglacial landforms

The statistical permafrost distribution obtained in this study is presented in Figures 5C and 5D and Table 1. Although the area covered by PP and LP was small (~16% and ~2% of the area above tree line, respectively), the model indicates permafrost conditions for all the highest zones in the study area.

An example of the periglacial landform map of Ruiz and Trombotto (2011) is shown in Figure 5E. In general, the distribution of active permafrost landforms (protalus ramparts and lobes) coincided with the LP area (Figs. 5D and 5E). The zonal statistics by landforms indicate that active protalus ramparts and lobes have a mean BTS of -3.1±0.1°C and -2.9±0.4°C, respectively. In contrast, relict rock glaciers have a mean BTS of -1.3±0.5°C. This also indicates a good agreement.

Potential of permafrost areas as water storage

Results of the threshold classification (PGI) are shown in Figure 5D and Table 1. More than 60% of LP area in ESQ and
LEL, and only 38% of LP area in RIV, could be PGI. Although the classification selected with good agreement the active protalus distribution (Fig. 5E), it also includes some of the little cliffs on arêtes (Fig. 5D) and over-estimated the actual distribution. The misclassification is highly dependent on the MDE resolution.

**Discussion**

Combined BTS surveys using both mapping and monitoring have shown significant differences in the evolution of BTS values throughout the winter, depending on the thermal characteristics of surface material and annual snow cover history at a site (Brenning et al. 2005).

Since no attempt has been undertaken to map the permafrost distribution in North Patagonia by means of BTS or other methods, the spatial and temporal characteristics of BTS values, and thus their applicability to map permafrost distribution, is unclear.

The only independent result came from the periglacial landforms map of Ruiz & Trombotto (2011). We found good agreement between the LP and active landform distribution in LEL, which indicates that at least in this range the model is a good approximation.

The difference between the total area of PP and LP between mountain ranges (Fig. 5C, Table 1) is related to the parameters (elevation, solar radiation) used in the model and the hypsometry of each range. ESQ, which has more area distribution above 1,600 m a.s.l., is also the one with more PP and LP. The threshold classification used to identify PGI zones overestimated the actual distribution mainly because the MDE used to derive the slope is too coarse to resolve small cliffs or outcrops.

The $R^2$ of $\sim 0.5$ indicates that only half of the variability is explained by the model. In order to improve the model, it is necessary to (1) increase the number of independent BTS measurements, (2) improve the PSWR calculation, (3) take into consideration the transient effects of ground temperature, and (4) improve the resolution of the DEM.

**Conclusions**

In this work, the first BTS measurements conducted in North Patagonia were presented. With a multiple linear regression, the measurements were used to model the distribution of mountain permafrost in the Precordillera of Chubut. The model indicates that although not aerially extensive, permafrost conditions are related to high-altitude zones (mainly between 1,750 m a.s.l. and 2,100 m a.s.l.) that received low radiation (i.e., southwest facing slopes or highly shaded areas). In order to estimate how much of this area could have ground ice and be considered as a long-term water storage reservoir, a simple slope classification approach was conducted. This approach overestimates the presence of ground ice and does not provide any information on permafrost thicknesses.

The presence of permafrost and ground ice content in the Precordillera of Chubut must be confirmed by ground verification before the permafrost distribution obtained here can be used for legislative and binding actions.
Acknowledgments

Thanks to Jose Hernández (Técnico Principal IANIGLA-CONICET) for constructing the probes. The research was funded by CONICET (PIP 114-200801-00156) and Agencia de Promoción Científica (PICT 2007-0379). Thanks to Andres Errasti, Lucas Bianchi, Gabriel Rocamora, and Gabriel Moretta for their help during the fieldwork. The manuscript was improved by the comments of Lukas Arenson and another anonymous referee.

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