The permafrost environment of northwest Hurd Peninsula (Livingston island, maritime Antarctic): Preliminary results

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Summary The permafrost spatial distribution in Hurd Peninsula (Livingston Island, Antarctic) and its thermal state are the focus of the ongoing research. A multidisciplinary approach that includes meteorological and ground temperature monitoring, geomorphological mapping and geophysical surveying has been used. The results from this research indicate that ice-cored moraines and active rockglaciers are present down to sea-level. Permafrost in bedrock is more difficult to assess. It is present at 275m ASL in Reina Sofia Hill, with an active layer ca. 1m deep. At 100m the Electrical Tomography Resistivity data suggests that permafrost is present, at least under snow patches. At 35m ASL in bedrock permafrost hasn't been found. However, more research is needed for assessing the spatial distribution of permafrost. Drilling and borehole temperature monitoring are the main objectives of the next Antarctic campaigns.

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Introduction

Little is known about the distribution, thickness and properties of Antarctic permafrost. The main reason for this is the scarce network of permafrost temperature monitoring boreholes and the short number of active layer monitoring sites. There is also a general lack of exposures and a need for observation by drilling (Bockheim, 1995).

There are 10 GTN-P permafrost temperature monitoring boreholes in the Antarctic, but only 4 are deeper than 19 m. This is a small number for a continent with *ca.* 14 million sq. km, when compared with over 600 GTN-P candidate boreholes in the Arctic. From the Antarctic boreholes, only 2 are in the Antarctic Peninsula region and both are less than 2.5 m deep. Fourteen active layer monitoring sites exist in the Antarctic, a very small number when compared to more than 100 in the Arctic (Brown et al. 2000). In the Antarctic Peninsula region only 3 preliminary sites exist, which were installed by our research group in Deception and Livingston Islands in 2006 and 2007.

In order to increase the number of GTN-P sites in the Antarctic two IPY core projects were implemented (Bockheim, 2005): a) Thermal State of Permafrost (TSP); and b) Antarctic and sub-Antarctic Permafrost, Soils and Periglacial Environments (ANTPAS). TSP focus on obtaining a "snapshot" of permafrost temperatures at a Global scale during the IPY and includes drilling new boreholes in the Antarctic, which will be part of the WMO/FAO/IPA GTN-P. ANTPAS focus on the installation of active layer monitoring sites to include in the Circum-polar Active Layer Monitoring Network (CALM-S) and on the installation of geomorphodynamics monitoring sites.

Study area

Hurd Peninsula is a mountainous area located in the south coast of Livingston Island, South Shetlands, Antarctic (62º39'S, 60º21'W). Climate at sea-level is cold-oceanic with frequent summer rainfall and moderate annual temperature range. Data from meteorological stations in the South Shetlands show mean annual air temperature of -1 to -2ºC at sea level. The summer meteorological conditions are dominated by the influence of polar frontal systems. About 90% of the island is glaciated with ice-free areas occurring at low altitude, generally in small and rugged relief peninsulas. The study focuses on the ice-free areas of the northwestern part of Hurd Peninsula in the vicinity of the Spanish Antarctic Station Juan Carlos I (SAS). The bedrock is a low-grade metamorphic turbidite sequence with alternating layers of quartzite and shales, with conglomerates and breccias in some areas (Miers Bluff Formation - Arche et al., 1992). Dolerite dykes and quartz veins are frequent (Arche et al., 1992). The surficial lithology is very heterogeneous.

Methods

Permafrost distribution in mountainous terrain is very complex. This is related to the high variability of ground properties, aspect, altitude and snow cover. Furthermore, due to the rocky characteristics of the ground, it is difficult to make direct permafrost observations. In order to characterize the permafrost environment, we have been using an interdisciplinary approach: (i) geomorphological mapping, (ii) meteorological monitoring, (iii) ground temperature monitoring, (iv) geophysics and (v) spatial modelling. This approach widens the breadth of the available data, and allows a stronger insight into the permafrost distribution problem.

Geomorphological mapping

Geomorphological mapping has been conducted at a 1:5,000 scale in the vicinity of the SAS with a focus on identifying periglacial landforms and deposits. The aim was to identify and use those geomorphic processes linked to the active layer and permafrost dynamics as indicators of permafrost presence or absence. We have used the traditional field geomorphological approach for mapping landform/deposit limits, together with a detailed survey using a RTK GPS (Vieira et al., 2000). The main forms and deposits used as indicators of frost activity are: (i) stone-banked lobes (seasonal frost or active-layer dynamics), (ii) stone circles (seasonal frost or active-layer dynamics), (iii) protalus rockglaciers (permafrost creep), (iv) frost-shattered debris (freeze-thaw), (v) debris-flows (possible permafrost degradation) and (vi) talus slopes (freeze-thaw).

Meteorological monitoring

Livingston Island lacks a continuous time-series of meteorological data. Meteorological monitoring has been conducted for: (i) the detailed study of the summer seasons of 1998-99, 1999-00 and 2000-01 with a focus on the radiation balance; (ii) the study of the air temperature regime at different altitudes. The former intends to characterize the radiation regime during the thaw season and the meteorological controls on active layer development. The later focuses on the vertical lapse rates and their temporal variability. Snow thickness is monitored at different sites.

Ground temperature monitoring

The temperature regime of the ground is a core issue in permafrost research. The objective is to understand the effects of climate change on ground temperatures, but also to use the ground temperature data as ground truth and input values for the spatial and temporal modelling of permafrost.

Ground temperatures are monitored using: (i) active layer boreholes with measurements at different depths, and (ii) ground surface temperatures.

(i) Two boreholes have been drilled in 2000 in Hurd Peninsula. In Reina Sofia hill the borehole is 1.1 m deep and in Incinerador point is 2.3 m. Temperatures are monitored hourly at 5, 15, 40 cm in both boreholes and also at 80 cm in Reina Sofia, and at 90, 150 and 210 cm in Incinerador Point. Drilling of a new 20 m depth borehole and several 5-7m boreholes in Livingston are planned for 2007-08.

(ii) Ground surface temperatures were monitored in different sites to evaluate the ground-atmosphere coupling using the n-factor index. Ground surface temperatures are monitored in two CALM-S grids once a year, to evaluate the spatial variation and microclimatic controls. In the next seasons the CALM-S grid nodes will start to be monitored at 1 hour intervals for the whole year.

Geophysics

Two complementary techniques were used: Electrical Resistivity Tomography (ERT) and Refraction Seismic Tomography (RST). Since a marked increase of the electrical resistivity occurs at the freezing point, electrical methods are suitable to detect and characterize structures containing frozen material. This phenomenon has been recognized in several field and laboratory studies (e.g. Hoekstra et al., 1975) and electrical methods have been widely applied in permafrost studies. Electrical resistivity tomography is probably the most universally applicable method. As for most geophysical techniques the obtained resistivity model is not unambiguous and depends on data quality, measurement geometry and the choice of inversion parameters (Hauck and Vonder Mühll, 2003).

The application of refraction seismics has a long tradition in permafrost studies (e.g. Zimmerman and King, 1986; King et al., 1988). An observed sharp increase of P-wave velocity at the freezing point is used to differentiate between frozen and unfrozen material. The P-wave velocity distribution can be used as a complementary indicator to specific electrical resistivity for the presence of frozen material. Differentiation between frozen and unfrozen bedrock with low ice content is difficult (Hauck et al. 2004).

Results and discussion

Geomorphology

Frost-shattered debris is widespread and covers about 21% of the ice-free terrain. Clast size is closely related to the lithology. Greywacke and fine sandstone result in larger clasts. Shale layers produce smaller, frequently matrix-supported clasts. No dominant geographical control on the spatial distribution of angular debris has been found.

Talus slopes occupy ca. 6% of the ice-free area. Their preferential location is below large free-faces where rockfall activity is intense. The significance of coastal cliff locations is evident in the altitudinal analysis which shows that 58% of the talus area is below 75 m ASL (above sea-level). The rest is scattered in the other altitude classes. Low values of summer net radiation seem to favour the development of talus deposits (Vieira and Ramos, 2003).

Stone-banked lobes (SBL) are widespread and form in frost-shattered debris or till. Frontal heights of lobes are generally around 0.5 m but can reach over 2 m. These values suggest that they are related to annual freeze-thaw cycles

(Matsuoka, 2001) and probably involve most of the active layer. Although SBL are not necessarily indicators of permafrost, features of the observed type develop frequently in the warm permafrost zone (Matsuoka 2001).

Rockglaciers are the most visible expression of the presence of mountain permafrost (King et al. 1992, King and Åkerman, 1993). Protalus rockglaciers are found at the south slope of Johnsons Ridge. They are small features. An important control on their presence seems to be the high rockfall activity. Other rockglaciers were identified in Livingston Island outside the study area by Serrano and López-Martínez (2000). Our observations in the False Bay area enabled the identification of widespread rock glaciers near the sea-level, lying directly on the raised beaches. The geophysical investigations conducted at the moraine at the Holocene beach terrace close to the SAS shows that the moraine is ice-cored. Open fractures were observed in the moraine surface, revealing active deformation. This moraine has been dated from 300 to 700 years BP (Pallàs, 1996).

Patterned ground is the most frequent periglacial phenomenon in the South Shetlands (Serrano and López Martínez, 1998). In the study sector it is restricted to few sites. This is probably due to the steep nature of the terrain. The altitudes of non-sorted circles are closely related to the levels of the erosional surfaces. The spatial significance of stone circles increases with altitude.

Permafrost degradation features are relatively scarce, probably due to the rocky and boulderly characteristics of the terrain. Detachment slides have been observed in the fronto-lateral moraine of the Argentine Lobe (Hurd Glacier) and in the south slope of Johnsons Ridge, debris-flows occur. These features may be linked to a warming of the ground surface, but a more detailed study is still lacking.

Meteorological monitoring

Meteorological monitoring has been conducted in Reina Sofia Hill during 3 summers. The most interesting result is the importance of the incoming diffuse radiation when compared to the direct short-wave component. Data from 1999-2000 shows that the former accounts for 77% of the total incoming radiation. This fact may be responsible for the lack of control of aspect on the distribution of periglacial features. Meteorological data, especially the radiation balance components are being analysed using a GIS for spatial modelling of the summer radiation budget. We expect that the results will provide a significant input into the pattern of solar radiation induced ground warming during the summer, allowing a better understanding of the spatial variations of active layer thickness.

Ground temperature monitoring

Active layer temperatures have been monitored continuously since 2000 in 2 boreholes. The data shows no significant trend for the period 2000-07. Differences in mean annual ground temperatures have been interpreted by Ramos and Vieira (2003) as the result of differences in snow cover. This is supported by Enthalpy exchange modelling. N-factor analysis from different sites in Livingston Island also supports the important role of snow cover on the ground temperature regime (Ramos et al. 2002).

Geophysics

Geophysical surveying using electrical resistivity tomography and refraction seismics was conducted for studying the spatial distribution of permafrost. The surveys were planned in order to focus on the altitudinal and ground control on permafrost distribution. The surveying results show that ice-cored moraines occur down to sea-level, even in sites that were deglaciated 300 to 700 years ago. In the bedrock of the Myers Bluff formation a general increase in resistivity was found with increasing altitudes. The sites that were surveyed at 35 m ASL showed low resistivity seeming to indicate that frozen bedrock may be absent. Ramos col, a site at 115 m ASL shows conditions that are probably transitional between continuous and sporadic permafrost. The resistivity is low along the flat sector of the profile, but increases significantly near the slopes in the vicinity of snow patches. The results suggest that permafrost may be present near the snow patches, but absent in the flat snow free area. This type of conditions suggests that the insulating effect of snow is especially significant during the thaw season. At the highest site, in Reina Sofia Hill (275 m ASL) a high resistivity zone is present along the profile across the interfluve. In this site drilling has shown that permafrost occurs at 1 m depth and therefore geophysical observations are directly validated.

Conclusions

The multidisciplinary approach used in northwest Hurd Peninsula allows a preliminary insight into permafrost distribution. Cryogenic geomorphodynamics shows no clear control of aspect, a fact that seems to be related to the importance of the diffuse component of the incoming radiation that origins a relatively homogenous thaw, more controlled by site specific conditions. Altitude plays a role in active layer processes. A significant amount of work is lacking in what respects to permafrost distribution, namely in what concerns to snow cover and ground surface temperature monitoring (including BTS). The observations indicate that continuous permafrost is present in bedrock at 275m ASL, but that at 115 m ASL permafrost seems to occur only in some locations, probably controlled by late lying snow patches. The limit between continuous and discontinuous permafrost in bedrock is probably between these two limits. It is however possible, that at 115 m the active layer is thicker than 1m and that the permafrost table lies below this depth. At 35 m ASL results indicate that permafrost may be absent in bedrock, or that the active layer is thicker than 2.3 m. New 5-7m deep drillings to be conducted in 2007/08 will contribute to answer to this problem.

Ice-cored sediments are widely distributed and occur down to sea-level. These should be of glacigenic origin, but in several cases still show active deformation giving origin to rockglaciers, mainly of the protalus or moraine derived types.

The marginal position of Livingston Island in the Maritime Antarctic allows to use the Hurd Peninsula as an excellent laboratory for monitoring environmental change and the dynamics of the Antarctic permafrost environment near its northern margin. Our goal is to continue the ongoing effort, but to strengthen the parameters to be monitored, especially in what concerns to snow cover distribution and energy balance modelling. The models to be developed should offer valuable information for the permafrost dynamics in the rest of the Antarctic Peninsula region.

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