Active layer dynamics in three topographically distinct lake catchments in Byers Peninsula (Livingston Island, Antarctica)

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Abstract

Topography exerts a key role in controlling permafrost distribution in areas where mean annual temperatures are slightly negative. One such case is the low-altitude environments of Maritime Antarctica, where permafrost is sporadic to discontinuous below 20–40 m asl and continuous at higher areas and active layer dynamics are thus strongly conditioned by geomorphological setting. In January 2014 we installed three sites for monitoring active layer temperatures across Byers Peninsula (Livingston Island, South Shetland Islands) at elevations between 45 and 100 m. The sites are situated in lake catchments (lakes Escondido, Cerro Negro, and Domo) that have different geomorphological and topographical conditions. Our objective was to examine the role of topography and microclimatic conditions in determining the active layer thermal regime in order to identify the factors that control geomorphic processes in these lake catchments. At each site a set of loggers was installed to monitor air temperature (AT), snow thickness (SwT) and soil temperature (ST) down to 80 cm depth. Mean annual air temperatures (MAAT) showed similar values in the three sites (−2.7 to −2.6 °C) whereas soil temperatures showed varying active layer thicknesses at the three catchments. The ground thermal regime was strongly controlled by soil properties and snow cover thickness and duration, which is influenced by local topography. Geomorphological processes operating at the lake catchment scale control lacustrine sedimentation processes, and both are dependent on the combination of topographical and climatic conditions. Therefore, the interpretation of lake sediment records from these three lakes requires that soil thermal regime and snow conditions at each site be taken into account in order to properly isolate the geomorphological, environmental and climatic signals preserved in these lake records.

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1. Introduction

Soil thermal regime plays a major role in ice-free terrestrial ecosystems in Maritime Antarctica, influencing edaphic, biological, hydrological and geomorphological processes (Oliva et al., 2014a). Environmental dynamics in these areas is strongly conditioned by the distribution of permafrost and the active layer thermal regime. This is particularly important in ice-free areas of the Antarctic Peninsula (AP) region where permafrost is located near its climatic limits (Vieira et al., 2010; Bockheim et al., 2013). These small variations in soil temperature and moisture conditions can trigger changes in permafrost and active layer state and associated geomorphological processes, although the knowledge of these variations in still is very poor. The warming scenarios forecasted for the next several decades in the AP (IPCC, 2013) will lead to significant changes on permafrost state and geomorphic processes, although the degree and intensity of these changes will be substantially different in continuous and discontinuous permafrost regions. A better understanding of present-day permafrost distribution and active layer dynamics is of major importance for anticipating future environmental responses under changing climate conditions.

Active layer dynamics in ice-free environments of the AP region have been examined from a wide range of perspectives, including the thermal characterization of active layer regimes (Ramos and Vieira, 2003; Ramos et al., 2008; Guglielmin et al., 2008; Guglielmin et al.,
2012; Michel et al., 2012; de Pablo et al., 2014, Hrbáček et al., 2015), the influence of vegetation cover and air temperatures (Cannone et al., 2006, Almeida et al., 2014), thermal properties of the bedrock (Ramos and Vieira, 2003; Correia et al., 2012), as well as the role of snow cover on soil temperatures (Trindade et al., 2010; de Pablo et al., 2013; Hrbáček et al., 2016). The interaction between active layer dynamics and geomorphic activity in the AP region has been little addressed until now (Bockheim et al., 2013), with the few existing studies focusing on the monitoring of both ground temperatures and physical weathering processes (e.g. Guglielmin et al., 2014).

In the case of the polar regions, permafrost and active layer dynamics also control the interaction between lacustrine and terrestrial ecosystems (Izaguirre et al., 2012; Pienitz et al., 2004; Vonk et al., 2015). The study of lake sediment records for paleoenvironmental purposes requires a thorough understanding of present-day ecological dynamics at the lake catchment scale in order to infer past environmental conditions. Limnological processes are influenced by a complex set of feed-back mechanisms driven by climate conditions (e.g. biological productivity or lake ice cover), and other factors directly controlled by permafrost (e.g. hydrological, geomorphological and sedimentological processes). Therefore, permafrost controls geomorphic processes, which in turn influence limnological processes and the patterns of lake sedimentation. However, the interaction between permafrost and limnological processes is still poorly understood (Oliva and Antoniades, 2016). This study focuses on the monitoring of the active layer of the permafrost in three sites at lake catchments in the Byers Peninsula (Livingston Island, Antarctica) with different topographical characteristics, with the purpose of better understanding the interactions between permafrost and limnological processes in the Maritime Antarctic.

The Byers Peninsula constitutes a reference for studies dealing with terrestrial ecosystems in Maritime Antarctic environments (Quesada et al., 2013), with almost one hundred papers published in peer-reviewed journals about a wide range of different topics as of 2013 (Benayas et al., 2013). Many studies focused on geomorphological processes, namely the distribution of glacial and periglacial phenomena (López-Martínez et al., 1996, 2012; Mink et al., 2013), but only a few examined permafrost conditions and active layer dynamics in the area (de Pablo et al., 2013, 2014).

The central objective of this study was to better understand the climatic and environmental controls on subsurface thermal conditions that drive geomorphic processes in lake catchments of permafrost environments at Byers Peninsula. This will provide further insights to the interpretation of past landscape changes inferred from lacustrine records (Liu et al., 2015; Oliva et al., 2016). Our approach involved four principal steps:

- To measure the thermal regimes of the active layer between January 2014 and January 2015 in three topographically contrasted sites in the Byers Peninsula.
- To examine the coupling of air and soil temperatures, together with the evolution of the snow cover.
- To understand how the different factors controlling current soil thermal conditions in the Byers Peninsula may have conditioned sedimentological processes in lake catchments, and therefore conditioned the climatic/environmental signals recorded in lake sediments.
- To determine how future climate scenarios might affect active layer dynamics in an area where permafrost regime is under boundary climate conditions.

2. Study area

2.1. Regional setting

The Byers Peninsula is located in the westernmost part of Livingston Island and constitutes the largest deglaciated environment in the South Shetland Islands (SSI) with an ice-free surface of ca. 60 km² (Fig. 1). The area was designated an Antarctic Specially Protected Area (ASPA No. 126) in order to preserve one of the highest levels of biodiversity in Antarctica (Toro et al., 2007).

Mean Annual Air Temperatures (MAAT) at 70 m asl between 2002 and 2010 were, on average, −2.8 °C and annual precipitation ranged between 500 and 800 mm (Baňoh et al., 2013). Snow cover in Byers Peninsula persists for 8–9 months a year, although its duration has significantly increased over the past decade due to lower summer air temperatures in the SSI (Navarro et al., 2013). Vegetation cover is composed of mainly mosses and grasses mostly concentrated across the Holocene marine terraces and sparse lichens at higher elevations (Vera, 2011). Soils are shallow with very low OC concentrations, in most cases below 2%, except those of ornithogenic origin (Moura et al., 2012). Otero et al. (2013) found total organic carbon concentrations ranging between 0.39% and 0.56% in soils near Limnopolar Lake, in central Byers Peninsula.

The lithology is mainly highly weathered sedimentary, volcanic and volcanoclastic rocks (López-Martínez et al., 1996). The geomorphology of Byers Peninsula is structured by a central plateau (90–140 m asl) surrounded by a sequence of Holocene marine terraces (2–15 m asl) (Fig. 1b). Some volcanic plugs stand out of the plateau, such as Star Hill (265 m asl), Chester Cone (188 m asl) and Cerro Negro (143 m asl).

The eastern ice-free margin of the Byers Peninsula is delimited by the Rotch Dome glacier, which has formed a polygenic moraine extending from the northern to the southern edges of the peninsula. The eastwards retreat of this ice cap during the Holocene has left a bare landscape where periglacial processes are currently dominant (Oliva et al., 2016). Following deglaciation, permafrost controls geomorphodynamics in the new ice-free areas. However, the distribution of permafrost in Byers Peninsula remains unclear, though permafrost-related features are widespread, such as patterned ground, sorted circles, or blockstreams (Ruiz-Fernández and Oliva, 2016). In most of the deglaciated environments of the SSI, the elevation limit between sporadic or discontinuous permafrost and permanently frozen ground is placed above ca. 30 m asl (Serrano et al., 2008). However, recent electrical resistivity measurements in Byers suggest that sporadic permafrost conditions may be also present in the lowest marine terraces at elevations of only 4–6 m asl (Corrales et al., reviewed). The only study that has published soil temperatures in the Byers Peninsula suggests that the permafrost table is at about 1.3 m depth at an altitude of 105 m asl in the central plateau (de Pablo et al., 2014).

2.2. Escondido, Cerro Negro and Domo lakes

This research focuses on three study sites in the central-eastern sector of the Byers Peninsula (Fig. 2, Table 1). In all cases the monitoring sites are located on bare surfaces surrounding lakes that have been the subject of paleolimnological studies (Liu et al., 2015; Oliva et al., 2016). The three sites have coarse textured soils, with abundant gravels and a sandy-silty matrix and low organic matter content. Generally, soils in the Maritime Antarctic have limited water circulation through the soil in summer (Navas et al., 2008). The similarity of the soils in the three sites enables inferences of inter-site differences driven by topographic and/or microclimatic conditions.

The Escondido site is located at an altitude of 92 m asl in a depression surrounded by three hills; the site receives a significant amount of wind-blown snow from the nearby hills. The Cerro Negro site is situated at 100 m asl in a small glacial cirque at the highest part of the Cerro Negro volcanic plug; it is a very windy area, with varying patterns of snow drift according to the prevailing winds. The Domo site is located at 45 m asl in a slightly higher position (~3 m) than the lake; the area is exposed with very strong winds that remobilize the snow cover.

The lithostratigraphy of the sediment cores collected from these lakes revealed the existence of very different patterns of sedimentation in the lakes of the Byers Peninsula during the Holocene (Oliva et al.,...
Escondido Lake sediments showed an alternation between organic-rich moss layers and silty mineral units; Cerro Negro Lake sediments showed very low sedimentation rates with long periods of relatively homogeneous deposition; and Domo Lake sediments were exclusively inorganic with coarse-grained particles (Fig. 3).

3. Materials and methods

In January 2014 we installed a set of temperature loggers at three sites of the Byers Peninsula (Escondido, Cerro Negro and Domo) in order to monitor air, snow, and soil temperatures in boreholes at six depths between 5 and 80 cm. Loggers were installed after an anomalously snowy winter and spring, a fact that must be taken into account when interpreting the results. All loggers were set up on 29 January 2014 and monitored until 5 January 2015. The types of sensors, monitoring intervals and characteristics of the devices are summarized in Table 2.

The shallow boreholes were drilled using a STIHL BT 121 driller in fine-grained sediments. The hole was cased with a PVC pipe with an external diameter of 65 mm and the loggers were inserted at depths shown in Table 2. The air temperature logger consisted of a Tinytag (Plus 2) fitted inside a radiation shield on a mast at 1.5 m above the ground (Fig. 2). Borehole temperatures were monitored with high resolution DS1922L Ibutton single-channel mini-loggers. The loggers at 5 cm depth in Escondido and 10 cm depth at Cerro Negro failed and no data was recorded. Snow thickness was determined taking into account temperatures recorded by DS1921G Ibutton loggers mounted in a vertical array (Lewkowicz, 2008). Temperature differences between loggers placed beneath the snow surface and those exposed in the air above permitted inferences of snow cover to be drawn. This method has already been widely implemented in Maritime Antarctica (e.g. de Pablo et al., 2014, de Pablo et al., this issue). All loggers failed on 18 July 2014 and no data is available after this date.

Data obtained from field measurements were used to calculate mean daily temperatures and visualized using Grapher 9 and Surfer 12 software. The Kriging interpolation method was used for the creation of isopleths plots. Thermal oscillations were calculated using the daily maxima and minima. The soil thermal dynamics were described using

Fig. 1. Location of Byers Peninsula within the South Shetlands Islands (left) and study sites within the peninsula (right).

Fig. 2. Pictures of the monitoring sites together with a panoramic view of each lake catchment.
the parameters proposed by Vieira et al. (2003) and Guglielmin et al. (2008) and used in several studies for the AP region (e.g. de Pablo et al., 2014; Hrbáček et al., 2016):

1) Freezing-degree days (FDD), calculated as the cumulative sum of the mean daily temperatures of days under 0 °C during the freezing season, and thawing-degree days (TDD), the sum of the mean daily temperatures for the days over 0 °C calculated both for air (DDa) and ground (DDg).

2) The sum of freezing days with maximum daily temperature below −0.1 °C and minimum daily temperature below −0.5 °C; the sum of thawing days with minimum daily temperature above +0.1 °C and maximum daily temperature above +0.5 °C.

3) Days with freeze-thaw (FT) cycles, calculated as those days with temperatures both below −0.5 °C and above +0.5 °C.

4) The number of isothermal days with all the hourly measurements ranging between −0.5 and +0.5 °C (zero-curtain effect).

5) Freezing and thawing n-factors determined from the air temperature at 1.5 m and soil temperature at 5 cm depth.

The analyzes of the effect of snow cover (until 18 of July) on daily soil temperature amplitude at 5 cm was studied using data from the Cerro Negro and Domo sites only, as the Escondido logger at the same depth failed.

Lake sediment sequences were retrieved in November 2012 (for further details, see Oliva et al., 2016).

4. Results

4.1. Air temperatures

Air temperatures showed very small inter-site variability during the study period due to limited altitude differences, with mean air temperatures varying between −2.6 °C (Domo) and −2.7 °C (Escondido and Cerro Negro) (Table 3). Similarly, small differences were also recorded for extreme maxima, ranging from 6.1 °C (Domo) to 6.5 °C (Escondido), as well as for extreme minima, ranging from −13.4 °C (Escondido) to −13.9 °C (Cerro Negro) (Fig. 4a).

The seasonal air temperature regime also showed a similar behavior between sites, with differences of only 0.2 °C. Temperatures varied between −1.7 and −1.9 °C in the period between March and May, between −4.6 and −4.8 °C in the period from June to August and −3.1 to 3.3 °C from September to November. Temperatures in Escondido were generally slightly colder than at the Domo and Cerro Negro sites, which recorded similar values. In the summer months (January–February 2014 and December 2015), lower temperatures were recorded at Cerro Negro relative to Escondido (higher by 0.1–0.4 °C) and Domo (higher by 0.3–0.5 °C).

4.2. Soil thermal regime

The evolution of soil thermal regime characteristics at the sites during the study period is shown in Fig. 4 and the main statistics are summarized in Table 3. Mean daily soil temperatures showed lower temporal (annual) and vertical (depth) variability in Escondido (Fig. 4b) (Table 3). Mean temperatures ranged between −0.1 °C (20 to 80 cm) and −0.2 °C (10 cm), with very low daily amplitudes between 0.0 °C (40 to 80 cm) and 0.4 °C (10 cm). Maximum soil temperatures

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**Table 1**

Main geographical characteristics of the study sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Altitude (m asl)</th>
<th>Snow cover catchment January ’14 (%)</th>
<th>Snow cover catchment January ’15 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Escondido</td>
<td>62°37′06.57″ S</td>
<td>61°03′36.50″ W</td>
<td>92</td>
<td>&gt;60</td>
<td>&lt;95</td>
</tr>
<tr>
<td>Cerro Negro</td>
<td>62°37′47.30″ S</td>
<td>61°00′19.99″ W</td>
<td>100</td>
<td>&lt;35</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Domo</td>
<td>62°37′17.49″ S</td>
<td>60°58′32.98″ W</td>
<td>45</td>
<td>&lt;30</td>
<td>&lt;25</td>
</tr>
</tbody>
</table>

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**Fig. 3.** Pictures of the sediment cores collected from each lake (modified from Oliva et al., 2016).
ranged between 6.3 °C (10 cm) and 0.2 °C (80 cm), while minimum soil temperatures oscillated between −2.5 °C (10 cm) and −0.7 °C (80 cm). The active layer remained unfrozen until 14 August 2014 at 80 cm depth, while the 10 cm depth refroze in July 2014. On the other hand, the thawing of the active layer at 10 cm to 50 cm depth started between 14 and 16 December 2014, stabilizing at slightly positive temperatures of 0.1 to 0.2 °C.

The soil thermal regime at Cerro Negro showed more variability than in Escondido during the study period (Fig. 4c). Negative mean temperatures measured at Cerro Negro slightly decreased with depth from −0.7 °C at 5 cm to −0.4 °C at 80 cm (Table 3). At these depths, the maximum temperatures ranged between 13.7 °C and 0.2 °C, while the minimum oscillated between −6.2 °C and −1.5 °C, respectively. The maximum daily amplitudes of soil temperatures followed a similar pattern to the maximum air temperatures, reaching 14.6 °C at 5 cm depth and only 0.1 °C at 80 cm. However, the mean daily amplitude for the whole period was only 1.2 °C at 5 cm and 0.0 °C at both 60 and 80 cm depth. At Cerro Negro, the near surface loggers at 5 and 10 cm depth refroze on 11 May 2014, although deeper layers at ca. 80 cm depth remained unfrozen until 15 June 2014. The thawing of the active layer started on 1 December 2014, but thawed depth reached ca. 25 cm only in early January 2015.

Domo recorded the largest variability of soil temperatures (Fig. 4d). Mean soil temperatures decreased from −1.3 °C at 5 cm depth to −0.7 °C at 80 cm. At the same depths, the maximum soil temperatures reached 17.9 °C and 0.2 °C, respectively, while the minimum varied between −9.9 °C and −2.4 °C. The maximum daily amplitudes also decreased significantly with depth, from 19.8 °C at 5 cm to 0.3 °C at 80 cm. On the other hand, the mean daily amplitude varied between 2.3 °C at 5 cm and 0.0 °C at 80 cm. The active layer at 5 to 20 cm depth refroze on 9 May 2014, and the refreezing also expanded to the rest of the profile relatively quickly: in 18 days (26 May 2014) it reached 80 cm depth. The development of the active layer at the end of 2014 started between late October and early November when the soil thawed down to 10 cm depth. The fastest thawing of the active layer begun later, around 25 November 2014, and reached 80 cm thickness 15 days later.

### 4.3. Thermal characteristic of the active layer

For the Escondido site, FDD and TDD factors were only calculated for the 10 cm-depth logger, as the logger at 5 cm failed. A substantial decrease between 10 cm (−130 °C·day) and 80 cm (−50 °C·day) was observed for FDDg, while FDDa reached −960 °C·day (Table 3, Fig. 5a). A similar decreasing pattern was observed between TDDg at 10 cm (50 °C·day) and 80 cm (25 °C·day), with −38 °C·day for TDDa (Table 3, Fig. 5b). The use of the 10 cm-depth logger as the near-surface reference affected the very low value of the freezing n-factor, 0.11 (Fig. 5a). Isothermal days were the most common daily regime with regards to soil temperatures (Fig. 6a), with their proportion increasing with depth: from 184 days (10 cm) to 317 days (80 cm). On the other hand, the total number of freezing days decreased with depth, from 104 days (10 cm) to 25 days (80 cm), as well as thawing days, which were only observed between 10 cm (24 days) and 40 cm (8 day) with maximum at 20 cm (34 days).

At the Cerro Negro site, the sums of both FDD and TDD showed the same pattern observed for mean temperatures. The total sum of FDDg decreased from −310 °C·day at 5 cm to −150 °C·day at 80 cm depth (Table 3, Fig. 5a). A significant difference was observed between FDDg (−310 °C·day) and FDDa (−930 °C·day). This pattern is suggested also by the very low value of the freezing n-factor 0.03. Comparing to FDD, the total sum of TDDg reached significantly lower values, ranging from 76 °C·day (5 cm) to 13 °C·day (80 cm), with TDDa reaching 31 °C·day (Table 3, Fig. 5b). The daily regime of soil temperatures also reveals an increasing number of isothermal days with depth, oscillating between 62 days at 5 cm and 198 days at 80 cm (Fig. 6b). On the other hand, the frequency of freezing days decreased from 211 at 5 cm to 144 at 80 cm. Thawing days were observed only in the upper 60 cm, ranging from 6 days (60 cm) to 34 days (20 cm).

At the Domo site, the sum of FDDg and TDDg reached their highest values for all depths (Table 3, Fig. 5). Total FDDg decreased with depth from −580 °C·day at 5 cm to −280 °C·day at 80 cm. A remarkable difference was also found between FDDg at 5 cm (−580 °C·day) and FDDa (−910 °C·day). The total freezing n-factor reached 0.64, ranging from 0.75 to 0.78 during the winter season from June to September (Fig. 5a). The decrease of this factor at the end of the freezing season was led by the more pronounced warming of the ground soil with respect to the air.

The total sum of TDDg reached significantly lower values comparing to FDDg, oscillating between 134 °C·day (5 cm) and 27 °C·day (80 cm), while TDDa reached 44 °C·day (Table 3, Fig. 5b). In contrast to the Escondido and Cerro Negro sites, the soil thermal parameters showed a very different pattern along the depth profile (Fig. 6c). Isothermal days increased significantly with depth: from 37 days at 5 cm to 159 days at 80 cm. A similar pattern was observed with freezing days: from 172 at 5 cm to 183 at 80 cm. The increase of freezing days with

### Table 2

Main characteristics of the devices used in this research.

<table>
<thead>
<tr>
<th>Type</th>
<th>Sensor</th>
<th>Height/depth (m)</th>
<th>Resolution (°C)</th>
<th>Accuracy (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperatures</td>
<td>Tinytag (Plus 2)</td>
<td>1.5</td>
<td>0.02</td>
<td>0.25</td>
</tr>
<tr>
<td>Snow depth</td>
<td>Ibutton (DS1921G)</td>
<td>2.5, 5, 10, 20, 40, 80, 120</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Borehole</td>
<td>Ibutton (DS1922L)</td>
<td>5, 10, 20, 40, 60, 80</td>
<td>0.0625</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### Table 3

Main temperature characteristics of the study sites in period 30 Jan.-2014 to 5 Jan.-2015.

<table>
<thead>
<tr>
<th>Site</th>
<th>Parameter</th>
<th>AT</th>
<th>STS</th>
<th>ST10</th>
<th>ST20</th>
<th>ST40</th>
<th>ST60</th>
<th>ST80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Escondido</td>
<td>MEAN</td>
<td>−2.7</td>
<td>N/A</td>
<td>−0.2</td>
<td>−0.1</td>
<td>−0.1</td>
<td>−0.1</td>
<td>−0.1</td>
</tr>
<tr>
<td></td>
<td>MAX</td>
<td>6.5</td>
<td>N/A</td>
<td>6.3</td>
<td>3.2</td>
<td>0.8</td>
<td>0.2</td>
<td>0.2</td>
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<tr>
<td></td>
<td>MIN</td>
<td>−13.4</td>
<td>N/A</td>
<td>−2.5</td>
<td>−1.2</td>
<td>−0.8</td>
<td>−0.7</td>
<td>−0.7</td>
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<tr>
<td></td>
<td>FDD</td>
<td>−958</td>
<td>N/A</td>
<td>−127</td>
<td>−94</td>
<td>−66</td>
<td>−59</td>
<td>−51</td>
</tr>
<tr>
<td></td>
<td>TDD</td>
<td>38</td>
<td>N/A</td>
<td>50</td>
<td>48</td>
<td>26</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Cerro Negro</td>
<td>MEAN</td>
<td>−2.7</td>
<td>N/A</td>
<td>−0.5</td>
<td>−0.4</td>
<td>−0.4</td>
<td>−0.4</td>
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<tr>
<td></td>
<td>MAX</td>
<td>6.2</td>
<td>13.7</td>
<td>N/A</td>
<td>4.4</td>
<td>2.1</td>
<td>0.7</td>
<td>0.2</td>
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<tr>
<td></td>
<td>MIN</td>
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<td>−6.2</td>
<td>N/A</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>TDD</td>
<td>31</td>
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<td>N/A</td>
<td>57</td>
<td>42</td>
<td>19</td>
<td>13</td>
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<tr>
<td>Domo</td>
<td>MEAN</td>
<td>−2.6</td>
<td>1.3</td>
<td>−1.2</td>
<td>−1.1</td>
<td>−0.9</td>
<td>−0.8</td>
<td>−0.7</td>
</tr>
<tr>
<td></td>
<td>MAX</td>
<td>6.1</td>
<td>17.9</td>
<td>7.0</td>
<td>4.6</td>
<td>2.5</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>MIN</td>
<td>−13.5</td>
<td>−9.9</td>
<td>−7.7</td>
<td>−5.5</td>
<td>−3.7</td>
<td>−2.9</td>
<td>−2.4</td>
</tr>
<tr>
<td></td>
<td>FDD</td>
<td>−900</td>
<td>577</td>
<td>507</td>
<td>453</td>
<td>366</td>
<td>312</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>TDD</td>
<td>44</td>
<td>134</td>
<td>82</td>
<td>61</td>
<td>55</td>
<td>42</td>
<td>27</td>
</tr>
</tbody>
</table>
depth was gradual, in contrast with the sudden increase of 86 isothermal days recorded between 5 and 20 cm. The highest number of thawing days was observed between 5 and 40 cm (38 to 45 days), and significantly lower at 60 cm (11 days).

4.4. Freeze-thaw cycles

FT cycles (FT) were calculated and summarized as an FT calendar for each site (Fig. 7). FT were not observed deeper than 10 cm. In total, 4 FT

Fig. 4. Evolution of mean daily temperatures during the measurement period for: (a) air temperatures, (b) soil temperatures at Escondido, (c) Cerro Negro, and (d) Domo sites.

Fig. 5. Development of a) FDD and freezing n-factor and b) TDD and thawing n-factors at each site during the period 30 January 2014 to 5 January 2015.
were observed at 10 cm depth at Escondido (Fig. 7a) during February 2014. A significantly greater number of FT was found at 5 cm depth at Cerro Negro. In total, 29 FT occurred between the end of January and mid-April 2014 (Fig. 7b), with a higher frequency in February (10) and March (12), while none was observed at the end of 2014.

At the Domo site FT were detected at 5 and 10 cm depth (Fig. 7c). Altogether, up to 48 FT were recorded at 5 cm during the control period, with 34 FT concentrated between the end of January and mid-May 2014 and 14 FT between the end of November and December. The highest occurrence of FT was noted in March (14 FT) followed by February (11 FT). Logically, the total number of FT at 10 cm depth was significantly lower relative to 5 cm. Only 6 FT were detected during study period, 5 in February and only 1 in December (Fig. 7c).

4.5. Snow conditions

Snow loggers provided information about snow thickness and its evolution until 18 July 2014 (Fig. 8). Data shows evidence of a significantly thicker snow cover at the Escondido site with respect to Cerro Negro and Domo, where snow cover never exceeded 20 cm during the measurement period. Cerro Negro showed a more stable snow cover than Domo, where snow cover was very thin, even during mid-winter. Only a few short-term events with continuous snow cover were observed before 1 May 2014, between 14 and 22 March at Cerro Negro with 10 cm maximum snow thickness, between 26 March and 10 April at Domo with 10 cm maximum snow thickness, and between 23 and 27 March at Escondido with 20 cm maximum snow thickness. After 1 May 2014 the snow cover at Escondido and Cerro Negro was persistent, while permanent snow cover was observed after 26 May at Domo. It is likely that a heavy snow fall occurred on 26 May, as suggested by the increase of snow thickness: it increased from 20 to...
5. Discussion

The soil thermal regime in the three monitored sites during the study period showed that the annually thawed layer exceeds 0.8 m depth in all the cases. The presence of stable frozen layer conditions was extrapolated to >1 m depth at Escondido and ca. 0.85–0.9 m depth at Domo and Cerro Negro (Fig. 9). These depths are close to the 1.3 m reported for the depth of the permafrost table at the Limnopolar site by de Pablo et al. (2014).

The continuation of monitoring activities during the next several years will provide accurate long-term data about the depth of the permafrost table and its annual variations in these sites. These depths are in agreement with the maximum active layer thickness (ALT) observed across the SSI, which are highly variable depending on the nature of the sediments and of the bedrock. In the case of sediment sites, the ALT oscillates between 0.8 and 2 m depth across different areas of the AP region (e.g. Vieira et al., 2010; Michel et al., 2012; Bockheim et al., 2013; Almeida et al., 2014, de Pablo et al., 2014), with the exception of Deception Island where volcanoclastic sediments result in a thinner active layer ranging between 0.3 and 0.7 m depth (Goyanes et al., 2014). In other localities of the Maritime Antarctica the ALT showed also a high variability, such as on Signy Island where ALT was influenced by vegetation and ranged between 0.8 and 1.8 m (Guglielmin et al., 2012), or in conditions with colder climate on James Ross Island where the ALT reached 0.5 to 0.8 m at sites with different lithological properties (Hrbáček et al., this issue). Varying active layer thicknesses promotes also the existence of different cryoturbic features in the soils of the Maritime Antarctica (Schafer et al., 2008). In all cases, the ALT in bedrock sites may be several meters deep (Ramos et al., 2008; Vieira et al., 2010), as suggested by Wilhelm et al. (2015) and Uxa (2016), from Amsler Island, where ALT in deep borehole exceeded 8–10 m.

5.1. Inter-site variability of air and soil temperatures and snow conditions

Air temperatures did not show significant variations among the three topographically contrasted study sites in Byers Peninsula (−2.6/−2.7 °C), with extreme annual amplitudes of only 20 °C, as expected in this maritime periglacial environment.

By contrast, the monitoring of soil temperatures showed significant differences in terms of average and extreme values (Table 3, Fig. 9). The highest soil temperature amplitude (27.8 °C at 5 cm), observed at Domo, was significantly higher than at Cerro Negro (19.9 °C at 5 cm) and Escondido (8.8 °C at 10 cm). Similarly, the amplitude of soil temperature at Domo at 80 cm (2.6 °C) was higher than those observed at Cerro Negro (1.7 °C) and Escondido (1.4 °C). However, while the highest temperature near-surface (18.9 °C at 5 cm) was recorded at Domo, the highest temperature in the lowest part of the profile (0.2 °C at 80 cm) was similar to all study sites. These differences in soil thermal dynamics are also confirmed by the large variability shown by the thermally defined days between sites (Fig. 6). The thermal regime at Escondido indicated a very high number of isothermal days increasing with depth and a decreasing number of freezing days, which suggests the prevalence of temperatures around 0 °C. This had an effect on the sum of FDDg and TDDg, respectively, which were significantly lower at Escondido. The increasing number of isothermal days with depth was also observed at Cerro Negro and Domo, however the total number of isothermal days at 80 cm was lower by 118 days (Cerro Negro) to 157 days (Domo) than at observed at Escondido. A striking difference was also found when comparing freezing and thawing days at the three sites. While at Cerro Negro the total number of freezing days gradually decreased with depth, at Domo they gently increased. On the other hand, thawing days reached their maximum at 20 cm at Cerro Negro, as opposed to 10 cm at Domo.

The sandy-silty sediments prevailing in these catchments determine high porosity, which favors the presence of high water content mainly from snow melt (Otero et al., 2013), and consequently more ground ice. These conditions would promote more isothermal days (zero curtain effect) during the thaw season. In the case of Byers Peninsula, de Pablo et al. (2013) also supported this idea based on the calculation of the apparent thermal inertia that suggested an important presence of water in the sand, which is therefore consistent with the idea of a long zero curtain period in the ground.

The fact that freezing and thawing days occurred more frequently explains the higher sum of FDDg and TDDg at Cerro Negro and Domo in comparison to Escondido. However, the total sum of FDDg and TDDg at Domo was almost twice as high as at Cerro Negro. Values of FDDg and TDDg found in our study are comparable with those described in the nearby Limnopolar site by de Pablo et al. (2014). However, both FDDg and TDDg were significantly lower compared to other localities in the AP where FDDg can drop below — 2500 °C·day, as in James Ross Island (Hrbáček et al., this issue), while TDDg can exceed 400 °C·day in Signy Island (Guglielmin et al., 2012) or Adelaide Island (Guglielmin et al., 2014).

![Fig. 9. Thermal profiles of the active layer at Escondido, Cerro Negro and Domo sites.](image-url)
Significant variability of snow thickness was found in the three sites during the monitoring period that lasted until late July 2014. While snow thickness reached 80 cm at Escondido, the maximum thickness in Cerro Negro and Domo reached 20 cm. These data confirm the presence of a variable, but thicker and more stable, snow cover during the winter in Byers Peninsula – as already observed in several localities in the western AP region (e.g. de Pablo et al., 2014; Guglielmin et al., 2014) – with respect to the eastern side of the AP (Hrbáček et al., 2016).

The effect of the snow thickness on the daily soil temperature amplitude at 5 cm depth was analyzed both for Domo and Cerro Negro (Fig. 10). The data showed a gradual decrease of mean daily amplitude and its range with increasing snow thickness (Fig. 10). The mean daily amplitude at 5 cm was highest (4.0 °C) together with the highest range of daily amplitude (0.1 to 15.6 °C) in days without snow on the ground. The increase of snow thickness brought a gradual decrease of both mean daily amplitudes and the magnitude of these changes. The mean daily amplitude reached 0.3 °C only on those days with at least ca. 20 cm of snow thickness, while daily amplitudes ranged between 0.0 and 2.0 °C. However, daily amplitude was equal or lower to 0.3 °C in 40 in 54 cases. Although a snow cover exceeding 40 cm thickness is generally considered as the insulating layer necessary for a 0 °C amplitude (Zhang, 2005), our data suggest that even thinner snow covers (around 20 cm) are sufficient insulators in this part of the Maritime Antarctica, due to relatively high and stable winter temperatures and generally smaller air thermal amplitude.

Despite the lack of snow thickness data after 18 July 2014, it is possible to infer approximate snow depths based on changes in daily amplitudes using data from Fig. 10. The daily soil temperature amplitude regime showed significant differences between Domo and Cerro Negro and Escondido (Fig. 11). The daily amplitude at 5 cm depth at Domo after 18 July 2014 ranged from 0.1 to 1.5 °C, which suggests that snow thickness may have reached a maximum of ca. 20 cm. By contrast, the amplitude at 5 cm depth at Cerro Negro and 10 cm depth at Escondido, respectively, rarely exceed 0.1 °C. Such low ranges in soil temperatures suggest the presence of stable snow cover until 5 January 2015 with thicknesses of several decimeters.

Overall insulating effect of snow, described using freezing n-factors, showed significant differences between the sites. Values of the freezing n-factors at Escondido (0.11 for 10 cm) and at Cerro Negro (0.33 for 5 cm) were similar to the n-factor values observed during earlier years with snow persisting during several months at Livingston Island (de Pablo et al., 2013). The higher freezing n-factor at Domo (0.64 for 5 cm) and its increase between June and September suggests irregular occurrence of snow or thinner snow cover conditions comparing to Escondido and Cerro Negro. However, the effect of snow cover on the soil thermal regime is still very significant in comparison to freezing n-factor values around 0.90 for winters with irregular presence of snow in some localities in eastern AP (Hrbáček et al., 2016), where the thermal properties of the rocks are also different (Hrbáček et al., this issue).

5.2. Topographic controls on soil temperatures

The interaction between climate conditions and terrain factors on soil temperatures in permafrost environments has been widely studied over the last several decades (e.g. Brown, 1973; Oliva et al., 2014a). Soil temperatures are strongly influenced by the duration and thickness of snow cover in both permafrost regions and seasonal frost environments (Ishikawa, 2003; Zhang, 2005; Löffler et al., 2006; Gądek and Leszkiewicz, 2010; Magnin et al., 2015). The importance of cryogenic activity as a geomorphic process in permafrost regions is strongly influenced by the intensity of the cold, the moisture conditions and the duration of negative temperatures in the ground, together with sudden variations of air temperatures, may also form cryogenic soil structures (French, 2007). In the case of Byers Peninsula, there was no extreme contrast of daily air temperature values, as generally occurs in the Arctic (Christiansen, 2005) or other regions in continental Antarctica (Raff and Stenni, 2011). The flat relief of the central plateau where the lakes are distributed, together with the prevailing unstable atmospheric conditions typical of the SSI, explains the limited spatial variability of air temperatures.

By contrast, soil temperatures showed very different patterns that were highly influenced by topography. The location of Escondido Lake, in a depression surrounded by several peaks, favors snow accumulation on the gentle slopes of the catchment due to wind redistribution. This site recorded the thickest and longest-lasting snow cover (Fig. 8) – it was still covered by 60 cm of snow in January 2015 – which promoted very stable soil temperatures as shown by the high number of isothermal days close to 0 °C. The snow covering the hillsides limited FT cycles (only 4) and periglacial activity. The thickness of the snow cover insulated the ground from air temperature oscillations and prevented frost penetration, which explains why the frozen layer at this site was several decimeters deeper than at sites with shallower snow cover.

Cerro Negro Lake is located in the bottom of a small cirque in the highest part of Cerro Negro hill, a volcanic plug with columnar jointing (Ruíz-Fernandez & Oliva, 2016). Despite being located at a higher altitude, the area has a moderate snow cover, which is more permanent than in Domo Lake due to shading by the hills surrounding the cirque. This was reflected by the moderately high number of FT cycles relative to Escondido and Domo sites that were concentrated before the stabilization of snow cover in mid April.

The Domo site is located on a windswept hill slightly elevated from the lake, in a location that leads to snow scouring. This explains why the maximum thickness of the snow reached 20 cm (Fig. 8), favoring ground cooling. Despite being the lowest site, at an elevation of only 45 m, the projected depth of the frozen layer was ca. 0.85 m below the surface. The active layer at Domo showed very dynamic behavior, with continuous temperature oscillations, which is also reflected in the larger number of FT cycles.

The soil thermal regime in the Byers Peninsula is strongly dependent on topography, which at the same time determines the duration and thickness of snow cover. The presence of snow cover insulating the ground favors a deeper thawed layer. This is reflected in the fact that at the site with the thickest snow cover (Escondido) the estimated active layer thickness was deeper than 1 m, while at the two sites with less snow cover (Cerro Negro, 0.90 m; Domo, 0.85 m) was ca. 0.85–0.9 m.

Fig. 10. Effect of snow thickness on daily amplitude of ground temperature at 5 cm soil depth.
5.3. Past environmental conditions and geomorphological implications

Snow cover protects the ground from external atmospheric oscillations, stabilizing soil temperatures and limiting frequent FT cycles (Goodrich, 1982). Snow is a major geomorphic agent conditioning biological, hydrological and cryogenic processes in ice-free areas. The thickness and duration of snow cover determines soil thermal oscillations around 0 °C, which in turn increases/decreases the effectiveness of the physical weathering, and therefore enhances/limits the generation of sediment, surficial erosion and the mobilization of particles (French, 2007). The three study sites in Byers Peninsula had very different annual patterns of snow cover evolution that translated to significant changes in the driving factors that trigger landscape change in this periglacial environment, such as variations in the depth of the estimated depth of the permafrost table (Fig. 9) or the number and timing of FT cycles (Fig. 7).

As in other cold climate regions, snow cover controls the thermal regime of the ground, which at the same time plays a crucial role in determining geomorphological processes. Together with runoff and topography, frozen ground conditions control sediment mobilization and the intensity of mass movements in periglacial environments (Matsuoka, 2011). The melting of the snow cover during the thawing season leads to increased surface runoff and the supersaturation of the uppermost soil layer down to the frozen level. During this period mass wasting activity is more intense, since the saturated soil – susceptible to ice segregation – is more easily mobilized downslope (Matthews et al., 2005; Harris et al., 2008; Oliva et al., 2011, 2014b; Oliva and Ruiz-Fernández, 2015).

The thickness and duration of snow cover in the reference sites, as well as the topographic characteristics of the catchments in the relatively homogeneous lithological environment of Byers Peninsula, are decisive factors in explaining the very different lithostratigraphical properties of the lake sedimentary sequences (Fig. 3) (Oliva et al., 2016). Apart from the variations related to the Holocene natural climate variability in the AP (Bentley et al., 2009), some sedimentological patterns may be explained by the geomorphological setting where the lakes are located.

The Escondido Lake catchment receives abundant snow blown by wind from the surrounding peaks. The significant snow coverage on the slopes limits cryogenic activity, sediment production and its mobilization down-slope. During wet and/or cold years the thick snow cover prevents the lake ice cover from melting, reducing sediment input to the lake, while during dry and/or warm years mass wasting on the permafrost slopes is enhanced, which may contribute to an increase of the lake bioproductivity. The influence of climate conditions (i.e. snow cover, presence of ice-cover) on the prevailing depositional processes is interpreted as the main factor promoting the alternation of moss layers and mineral layers in the sediments of Escondido Lake (Oliva et al., 2016).

Cerro Negro Lake has a very small catchment composed of large, angular and heterometric boulders with little fine-grained sediment (Ruiz-Fernández and Oliva, 2016). The snow-free conditions during part of the year favor the effectiveness of intense frost shattering, although this is mitigated by the presence of the massive basalt boulders. The low sediment production generated by physical weathering processes in this very small catchment is reflected by sedimentation rates that during the last 7.5 ka were the lowest of the three examined lakes (Oliva et al., 2016). Consequently, the sedimentological changes observed in Cerro Negro Lake show long-term patterns, with millennial periods of more minerogenic deposition and others with the sedimentation of more organic-rich layers. Therefore, its sediment composition is reflective of the major environmental changes observed in the Cerro Negro area during the Mid-Late Holocene.

Domo Lake is situated in an intramorainic depression of Late Holocene age, surrounded by unconsolidated sediments mostly composed of sands and pebbles. An OSL date of the basal sediments of the lake, together with the inexistence of tephra layers in its sediments, suggests that the lake formed within the last 1.8 ka cal BP (Liu et al., 2015; Oliva et al., 2016). Domo catchment sediments are therefore very susceptible to being remobilized on the moderate to gentle catchment slopes when the upper layers of the active layer begin to thaw and become saturated following snow melt. This process coincides with the period when more FT cycles are recorded, which can also trigger the translocation of particles due to frost-heave activity (Harris et al., 2011). These processes favor the mobilization and transport of sediments downslope to the lake, which may explain the very inorganic sandy sediments observed in the Domo Lake cores. Domo Lake sediments thus record geomorphological activity in the catchment over the past several centuries as a response to prevailing climate conditions and active layer dynamics.

5.4. Future environmental conditions and geomorphic consequences

Present-day climate conditions in the AP region are a consequence of the period of rapid warming recorded during the second half of the 20th century, when temperature increased by ca. 0.5 °C/decade (Turner et al., 2005; Steig et al., 2009) followed by the last decade of stabilization with cool summer conditions, particularly in the SSI (Navarro et al., 2013). By the end of the 21st century, most climate models anticipate a significant warming in many high latitude environments accompanied by an increase in precipitation, mostly concentrated during the warm season (IPCC, 2014).

Terrestrial ecosystems will respond accordingly. It is expected that the recent accelerated and widespread glacier retreat recorded in the AP (Pritchard and Vaughan, 2007; Cook and Vaughan, 2010) will continue in the future. These retreating glaciers will expose new ice-free areas and those already in existence will expand, particularly in the
northern and western AP regions where mean annual temperatures are close to 0 °C. Newly exposed areas and currently ice-free environments will experience significant biological, hydrological and geomorphological changes. The impact of warmer temperatures and higher precipitation – mainly in summer – on soil thermal conditions in the ice-free areas of the SSI may be strongly dependent on the magnitude and rate of change, as well as on the seasonality of these variations.

Warmer conditions will entail an earlier onset of the thawing season, which in turn would produce longer annual snow-free periods. Higher precipitation together with higher temperatures during the summer season would therefore imply increased rainfall and increased runoff. These conditions promote increased soil temperatures: active layers would be expected to thicken and permafrost conditions would be restricted to higher elevations. For our three monitoring sites in the Byers Peninsula, the migration of permafrost to higher altitudes would imply that some sites – where permanent frozen conditions are currently at their climatic limits – might change from being permafrost environments to areas of seasonal frost. Moreover, more water availability on the bare slopes of the Byers Peninsula would enhance periglacial processes and mass wasting activity in the area.

6. Conclusions

We examined the effects of topography and climate on air temperatures, snow thickness and active layer dynamics in three contrasting sites in Byers Peninsula, Livingston Island. The implications derived from soil thermal states are profound, affecting geomorphological processes at the lake catchment scale and lake sedimentation processes. Therefore, a broader perspective of the factors controlling soil thermal dynamics may allow us to: (a) obtain an enhanced comprehension of past environmental changes inferred from lake sediments, and (b) anticipate the environmental impacts that future climate scenarios may have in the terrestrial ecosystems of Maritime Antarctica.

While air temperatures did not record significant variations in the three sites during the measurement period, snow thickness and active layer showed substantial changes both at short and long-term scales. Mean air temperatures ranged from −2.6 to −2.7 °C at elevations between 45 and 100 m asl. The soil thermal profiles suggest that permanent frozen conditions would be found below 0.9 to 1.2 m depth, depending on the locality. The monitoring of active layer temperatures showed significantly different soil thermal dynamics depending on the topographic setting. The relief and the duration and thickness of snow cover played a crucial role in insulating the ground. The different patterns between sites had implications for soil thermal regimes: Escondido recorded very stable (slightly positive or negative) temperatures throughout the year, Cerro Negro showed a similar pattern but with higher thermal oscillations in terms of amplitude and range and Domo recorded large oscillations that reached greater depths in the ground.

The different soil thermal patterns have direct and varied geomorphological implications in surrounding lake catchments, resulting in varying lake sediment records. Escondido Lake sediments reflect changes directly related to climate conditions through snow cover changes; Cerro Negro Lake sediments represent long-term environmental changes; Domo Lake sediments reveal changing mass-wasting processes.

This monitoring experiment in Byers Peninsula will be continued in the future to accurately understand the very different soil patterns and their environmental implications, as well as to provide new insights about the future response of permafrost conditions in an area which may undergo significant climate variations.

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