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Thaw depth spatial and temporal variability at the Limnopolar Lake CALM-S site, Byers Peninsula, Livingston Island, Antarctica

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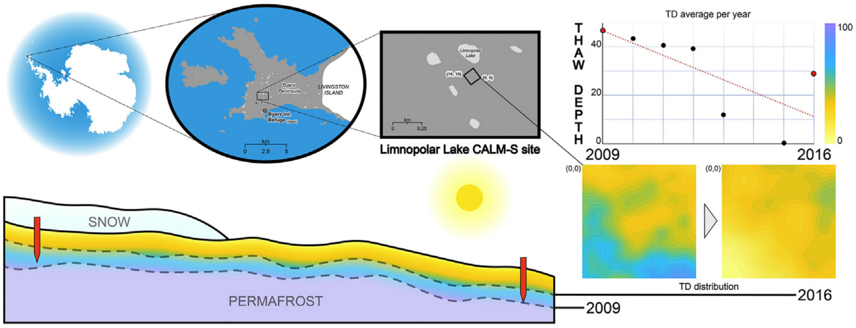
HIGHLIGHTS

- The spatial and temporal evolution of thaw depth in the CALM site from 2009 to 2016 is studied.
- Averaged thaw depth ranges between 47 and 0 cm in the study period.
- The thaw depth was lower where ground snow cover persisted.
- Variability index and parameters reveals a high inner variability in the CALM site.
- The thaw depth decreasing ratio is 16 cm/decade, similar to others Antarctic CALM-S sites.

GRAPHICAL ABSTRACT



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ABSTRACT

A new Circumpolar Active Layer Monitoring (CALM) site was established in 2009 at the Limnopolar Lake watershed in Byers Peninsula, Livingston Island, Antarctica, to provide a node in the western Antarctic Peninsula, one of the regions that recorded the highest air temperature increase in the planet during the last decades. The first detailed analysis of the temporal and spatial evolution of the thaw depth at the Limnopolar Lake CALM-S site is presented here, after eight years of monitoring. The average values range between 48 and 29 cm, decreasing at a ratio of 16 cm/decade. The annual thaw depth observations in the 100 × 100 m CALM grid are variable (Variability Index of 34 to 51%), although both the Variance Coefficient and the Climate Matrix Analysis Residual point to the internal consistency of the data. Those differences could be explained then by the terrain complexity and node-specific variability due to the ground properties. The interannual variability was about 60% during 2009–2012, increasing to 124% due to the presence of snow in 2013, 2015 and 2016. The snow has been proposed here as one of the most important factors controlling the spatial variability of ground thaw depth, since its values correlate with the snow thickness but also with the ground surface temperature and unconfined compression resistance, as measured in 2010. The topography explains the thaw depth spatial distribution pattern, being related to snowmelt water and its accumulation in low-elevation areas (downslope-flow). Patterned grounds and other surface features correlate well with high thaw depth patterns as well. The edaphic factor ($E = 0.05842\ m^2/°C \cdot day$; $R^2 = 0.63$) is in agreement with other permafrost environments, since frozen index ($F > 0.67$) and MAAT ($< -2\ °C$) denote a continuous permafrost existence in the area. All these characteristics provided the basis for further comparative analyses between others nearby CALM sites.

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1. Introduction

The climate change is affecting to the whole Antarctic continent but the highest increase in the mean annual air temperature on the planet has been registered in the western sector of the Antarctic Peninsula. An increase of about 0.56 °C/decade during the last 60 years has been reported (Turner et al., 2005), resulting in one of the planet regions with higher increase in air temperature during the last years (Quayle et al., 2002). Moreover, a positive increase in precipitation and snow accumulation also have been reported or modeled (Van den Broeke et al., 2006; Thomas et al., 2008). This increase in temperatures and precipitations causes a wide variety of effects on the environment, as the glaciers retreat, the increase in their flow velocity, the reduction of the extension of the ice packs (e.g., Vaughan et al., 2003; Cook and Vaughan, 2010; Turner and Marshall, 2011), changes in the ecosystems (e.g., Cannone et al., 2006; Guglielmin et al., 2008, 2014), variations in the snow cover (e.g., de Pablo et al., 2017; Ramos et al., 2017), or changes in the permafrost and active layer thicknesses and their thermal regimes that has been described widely recently (e.g., Vieira et al., 2010, 2016; Guglielmin and Cannone, 2012; Davies et al., 2012; Bockheim et al., 2013; Guglielmin et al., 2014; Ramos et al., 2017). As in the Arctic, the continuous monitoring of permafrost and active layer as part of the Thermal State of Permafrost (TSP) and the Circumpolar Active Layer Monitoring (CALM) networks (e.g., Brown et al., 2000; Matsuoka and Humlum, 2003; Nelson et al., 2004; Bockheim, 2006; Matsuoka, 2006) resulted in a useful tool. Those networks contributed to our understanding of the effect of the global climate warming in the permafrost thermal behavior in Antarctica (e.g., Hinkel, 1997; Harris et al., 2001; Turner et al., 2007; Vieira et al., 2010, 2016; de Pablo et al., 2013, 2014; Bockheim et al., 2013; Ramos et al., 2017), as well as to the climate warming monitoring (e.g., Nelson and Shiklomanov, 2009; Vieira et al., 2010, 2016).

Due to the increase in the air temperature detected in the western sector of the Antarctic Peninsula, few new active layer and permafrost monitoring sites has been established at different latitudes in the last decades at Signy (South Orkney Islands), King George, Livingston, and Deception (South Shetland Archipelago), or Adelaide Island, among others (e.g., Ramos et al., 2007; de Pablo et al., 2010; Vieira et al., 2010; Michel et al., 2014; Almeida et al., 2014; Guglielmin et al., 2012, 2014). They aim to help in our understanding of the effects of the global warming in the thermal regimes of the permafrost and active layer, and the advance ratio of the regional warming. On the other hand, there is a wide variety of environments between both sides of the Antarctic Peninsula, from the cold and dry areas with continuous permafrost in James Ross Island (Fukuda et al., 1992) to the warm and wet areas of discontinuous permafrost in Livingston Island (Ramos and Vieira, 2003). Owing to that, other monitoring sites have also been established in the eastern sector of the peninsula, as in James Ross Island, which results will be useful for comparative purposes (e.g., Hrbáček et al., 2016).

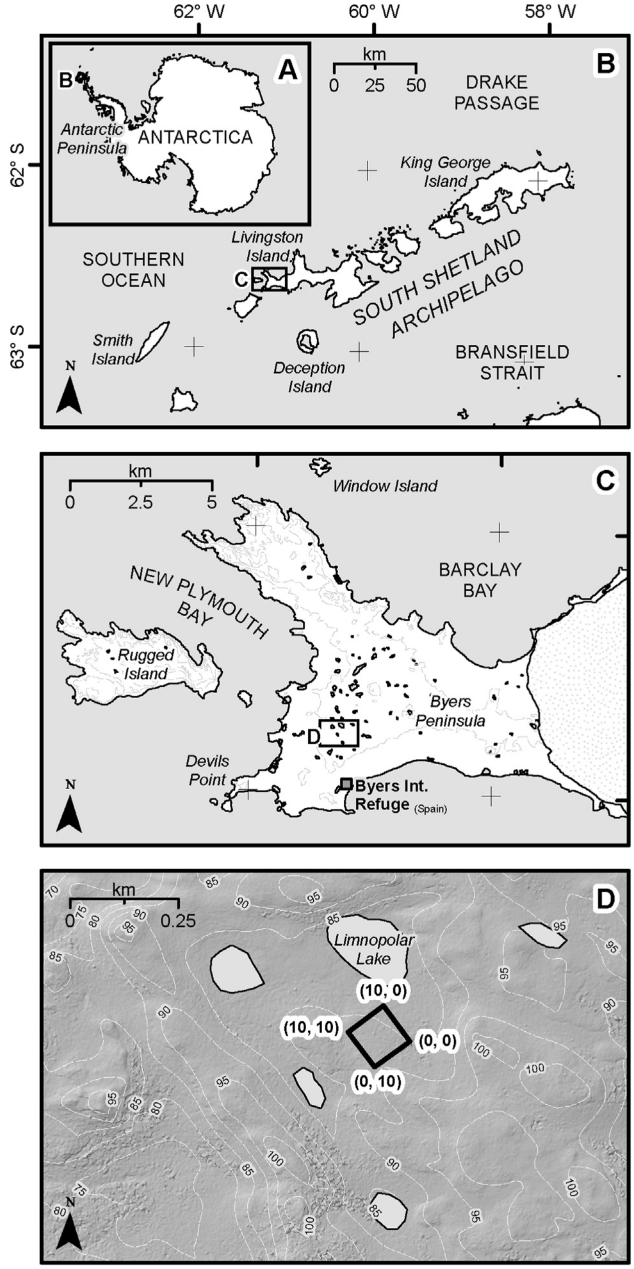

Fig. 1. Location of (D) the Limnopolar Lake CALM-S site in (A) the Antarctic continent, (B) the Livingston Archipelago, and the (C) Byers Peninsula. The CALM-S limits are showed in D, overlaying the shaded relief map. Grey dashed lines are contours each 50 m in C and every 5 m in D.

One of the South Shetland Islands' CALM-S sites was established on the Limnopolar Lake watershed in the Byers Peninsula (Livingston Island) in early February 2009 (de Pablo et al., 2010) (Fig. 1). The first data records from the air, surface and ground temperature, thaw depth probing, and snow thickness made possible establishing an active layer deeper than 120 cm thick over a possible permafrost table, as deduced from the active layer temperatures profile (de Pablo et al., 2014). The thermal regime characterization of the active layer was conducted after few years of continuous monitoring (de Pablo et al., 2014), together with a detailed analysis of the effect of the snow cover on the measured thaw depth and the active layer thermal regime (de Pablo et al., 2017). In this scenario, and inspired by different analyses in other Arctic and Antarctic CALM sites (e.g., Nelson et al., 1998; Hinkel and Nelson, 2003; Watanabe et al., 2003; Guglielmin et al., 2014; Bobrik et al., 2015), this paper aims to perform a detailed analysis of the spatial and temporal evolution of the thaw depth in the Limnopolar Lake CALM site during the 2009–2016 period. The objectives are to 1) complete our understanding of the active layer characteristics (de Pablo et al., 2013, 2014, 2017) and to know how it was changing in the last years, since 2009, 2) to obtain information about the small-scale behavior in that CALM-S site, and 3) to establish the base for future regional comparative analyses between different monitoring sites on both sides of the Antarctic Peninsula (e.g., Michel et al., 2012; Hrbáček et al., 2016; Ramos et al., 2017).

2. Study area

The Limnopolar Lake CALM-S site (A25) is a 100 × 100 m grid (Fig. 2) marked in the perimeter every 10 m by wood stakes, following the CALM protocol (Brown et al., 2000; Matsuoka and Humlum, 2003; Nelson et al., 2004, 2008; Nelson and Shiklomanov, 2009). It was established in early February 2009, together with temperature sensors