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Active layer and permafrost thermal regime in a patterned ground soil in Maritime Antarctica, and relationship with climate variability models

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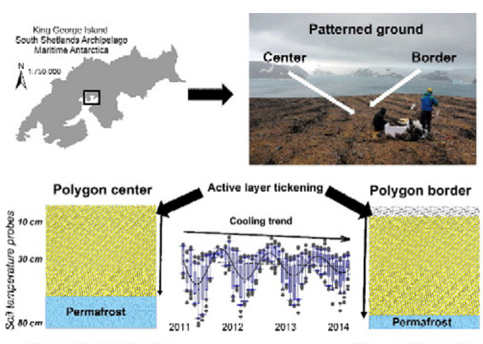
HIGHLIGHTS

- Soil thermal regime in a patterned ground soil was evaluated.
- Summer and winter temperatures are becoming colder and warmer, respectively.
- The border of the patterned ground is more sensitive to energy variation at the surface.
- Air temperature showed a significant correlation with the modes of climate variability (AAO and ENSO).

GRAPHICAL ABSTRACT



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ABSTRACT

Permafrost and active layer studies are important to understand and predict regional climate changes. The objectives of this work were: i) to characterize the soil thermal regime (active layer thickness and permafrost formation) and its interannual variability and ii) to evaluate the influence of different climate variability modes to the observed soil thermal regime in a patterned ground soil in Maritime Antarctica. The study was carried out at Keller Peninsula, King George Island, Maritime Antarctica. Six soil temperatures probes were installed at different depths (10, 30 and 80 cm) in the polygon center (Tc) and border (Tb) of a patterned ground soil. We applied cross-correlation analysis and standardized series were related to the Antarctic Oscillation Index (AAO). The estimated active layer thickness was approximately 0.75 cm in the polygon border and 0.64 cm in the center, indicating the presence of permafrost (within 80 cm). Results indicate that summer and winter temperatures are becoming colder and warmer, respectively. Considering similar active layer thickness, the polygon border presented greater thawing days, resulting in greater vulnerability to warming, cooling faster than the center, due to its lower volumetric heat capacity (Cs). Cross-correlation analysis indicated statistically significant delay of 1 day (at 10 cm depth) in the polygon center, and 5 days (at 80 cm depth) for the thermal response between

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atmosphere and soil. Air temperature showed a delay of 5 months with the climate variability models. The influence of southern winds from high latitudes, in the south facing slopes, favored freeze in the upper soil layers, and also contributed to keep permafrost closer to the surface. The observed cooling trend is linked to the regional climate variability modes influenced by atmospheric circulation, although longer monitoring period is required to reach a more precise scenario.

1. Introduction

Soils have become crucial in addressing current and future global challenges. Broadly speaking, soils are drivers of physical, hydrological, erosional, geochemical and biological cycles, directly affecting human survival (Brevik et al., 2015). Many of the current environmental, social, economic, social, health issues are linked to soils (Keesstra et al., 2012; Brevik et al., 2015; Galati et al., 2016). Also, soils play a key role continuously providing a wide diversity of ecosystem services, such as food, biodiversity, nutrient cycling, carbon sequestration, erosion protection, water storage and quality (Keesstra et al., 2012; Brevik et al., 2015; Galati et al., 2016; Parras-Alcántara et al., 2016). Hence, success of the policies at regional and global scales can be accessed by understanding aspects related to the soil (Brevik et al., 2015). This is particularly relevant in cold regions, where soils are reported to be an important indicator of environmental changes, especially those related to nutrient cycling, carbon storage, as well as hydric and thermal regimes (Bockheim et al., 2013; Almeida et al., 2017; Thomazini et al., 2016).

The cryosphere is one of the most sensitive components of the Earth system to climate change and variability (Turner et al., 2014). Exchanges of energy and mass (water, carbon dioxide, methane and other gases) between the cryosphere and climate system influence regional and global climate through complex feedback processes (IPCC, 2014). In the last decades, the rate of regional warming has varied considerably, profoundly modifying many ecosystem processes, especially in polar regions (Turner et al., 2016; Schaefer et al., 2016). Hence, understanding climate-induced changes are essential for observational studies and numerical modeling (e.g. Global Circulation Models of the atmosphere - MCGA) related to climate change variability (Justino and Peltier, 2008; Michel et al., 2012; IPCC, 2014). In this context, permafrost represents an important terrestrial component due to the large energy and mass transfer capacity between this layer and the Earth surface. Also, permafrost are known to be extremely sensitive to climate warming (Bockheim et al., 2013), with great implications on local and global ecosystem dynamics (Thomazini et al., 2016). Hence, changes in the permafrost will results in many changes in the Earth System.

Permanent or seasonal frozen conditions depends on climate and topography variables, such as snow cover and distribution, soil attributes (i.e. texture, organic matter content, mineralogy), solar radiation, wind speed, precipitation, aspect, slope angle and altitude, cloud cover, type and height of vegetation, moisture and temperature (Vieira et al., 2010; Michel et al., 2014; Pogliotti et al., 2015; Almeida et al., 2017; De Pablo et al., 2017; Schaefer et al., 2016; Ramos et al., 2017). With snow melting, vegetation, erosion, biological activity, chemical and physical soil attributes, as well as the buffering action of the active layer are strongly affected (Schaefer et al., 2016). Seasonal frost may result in great variability of soil temperature and moisture, resulting in an interannual variability of thaw and freeze processes, affecting permafrost and active layer distribution and thickness, respectively (Ramos et al., 2017). These fluctuations will influence frost, soil creep, solifluction, leading to patterned ground formation (Ramos et al., 2017). For this reason, permafrost and active layer thermal regime studies have become highly relevant in view of ongoing climate changes.

The temperature measurements along the soil profile allow, inter alia, to identify the depth of the active layer and permafrost, heat flux, as well as seasonal freezing and thawing regimes. Also, the identification of processes that affect the soil/rock thermal regimes, such as crioclasty and termoclasty, for instance, is possible (Simas et al., 2007; Bockheim et al., 2013; Pereira et al., 2013). The mechanisms of energy exchange among surface and water flow are coupled with the seasonal processes of freezing and thawing, and thereby, directly influence the climate system (IPCC, 2014). In the last years, permafrost warming and increasing active layer thickness has been observed worldwide (Pogliotti et al., 2015). However, recent studies reported reduction of active layer thickness, resulting in higher permafrost table in volcanic soils from Maritime Antarctica (De Pablo et al., 2017), but none monitoring of patterned ground is yet available. Hence, even though the monitoring period may be considered short for yielding long-term trends, the lack of specific information on active patterned-ground thermal regime justify the present work, since these areas represent the most typical periglacial features in this region. Therefore, further studies on patterned-ground from different regional substrates are necessary to confirm the current trend of permafrost and active layer thermal dynamics in this part of Antarctica.

Antarctica is one active component of the climatic Earth system, where changes in surface temperature patterns are influenced by climate variability modes, such as Antarctic Oscillation (also called Southern Annular Mode - SAM) and El Niño Southern Oscillation (ENSO) (Kwok and Comiso, 2002; Lindemann and Justino, 2015; Turner et al., 2016). These modes may overlap the global temperature variation patterns (Turner et al., 2016) and do not explain the same surface temperature variability across the Antarctic region, having low correlation among them (Kwok and Comiso, 2002). In addition, one given mode influences the temperature patterns in the Antarctic Peninsula and continent, differently. For example, SAM defines important rules on atmospheric circulation patterns and spatial distribution of the Antarctic ice sheet, while ENSO particularly affects the sea surface temperature of peripheral Antarctica seas, by complex processes of atmospheric teleconnection (Kwok and Comiso, 2002; Turner et al., 2016). In the southern hemisphere, SAM is responsible for the present-day surface climate conditions (Lindemann and Justino, 2015).

Modes of climate variability may influence the variability on Antarctic climate over the recent years, directly affecting temperature, glacier retreats, ice melt and see level (Russell and McGregor, 2010; Fogt et al., 2011; Abram et al., 2014; Lindemann and Justino, 2015). The understanding of these processes, especially the tendency of high (seasonal) and low (interannual and decadal) frequency, allow the identification of the modes signal. By filtering the signal, the overlapping with global patterns can be avoided (Kwok and Comiso, 2002). With this, trends on degradation or preservation of permafrost in the Antarctic region can be assessed. In this perspective, climate variability will strongly affect local and global hydrology, biological activity and soil development.

Maritime Antarctica is recognized as a key region for monitoring climate changes, in which soil thermal regime (active layer and permafrost dynamics) can be used as a climate change indicator (Almeida et al., 2017). This study described the results of four-years monitoring of permafrost and active layer soil thermal regime in a patterned ground area, with a near-surface permafrost. In this case, small changes on annual or interannual temperature can strongly affect soil thermal regime, being recognized as an important sensitive indicator of warming, still little studied. Hence, the objectives of this work were: i) to characterize the soil thermal regime (active layer thickness and permafrost formation) and its interannual variability and ii) to evaluate the influence of