Permafrost warming and vegetation changes in continental Antarctica

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Abstract
Continental Antarctica represents the last pristine environment on Earth and is one of the most suitable contexts to analyze the relations between climate, active layer and vegetation. In 2000 we started long-term monitoring of the climate, permafrost, active layer and vegetation in Victoria Land, continental Antarctica. Our data confirm the stability of mean annual and summer air temperature, of snow cover, and an increasing trend of summer incoming short wave radiation. The active layer thickness is increasing at a rate of 0.3 cm y\(^{-1}\). The active layer is characterized by large annual and spatial differences. The latter are due to scarce vegetation, a patchy and very thin organic layer and large spatial differences in snow accumulation.

The active layer thickening, probably due to the increase of incoming short wave radiation, produced a general decrease of the ground water content due to the better drainage of the ground. The resultant drying may be responsible for the decline of mosses in xeric sites, while it provided better conditions for mosses in hydric sites, following the species-specific water requirements. An increase of lichen vegetation was observed where the climate drying occurred. This evidence emphasizes that the Antarctic continent is experiencing changes that are in total contrast to the changes reported from maritime Antarctica.

Keywords: climate change, active layer, permafrost, vegetation, Antarctica, mosses, snow, ground water content, incoming radiation

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1. Introduction

The high-latitude areas of both hemispheres are expected to be highly sensitive to the impacts of climate change. Vegetation, the active layer, and the underlying permafrost are key environmental components of terrestrial ecosystems.

Since the 1990s, permafrost has generally warmed across the Northern Hemisphere (Christiansen et al 2012, Romanovsky et al 2011): it exhibited smaller warming rates in warm (close to 0 °C) or ice-rich permafrost, while in other areas (such as the higher altitudes of Central Asia) it has shown a rate of increase of up to 0.5 °C decade\(^{-1}\) since the early 1990s (e.g., Zhao et al 2010). However, since the 1990s, trends have been weak in several sites, including Alaska (e.g. Osterkamp 2008), northern Canada (e.g. Smith et al 2005) and Antarctica (McMurdo Dry Valleys) (Guglielmin et al 2011). Since the 1990s, a progressive increase of the active layer thickness (ALT) has been recorded in all regions, with the exception of northern Alaska, the western Canadian Arctic, and West Siberia (Christiansen et al 2012). In continental Antarctica, in northern Victoria Land, the active layer thickened by 1 cm y\(^{-1}\) from 1996 to 2009 (Guglielmin and Cannone 2012), while in the McMurdo Sound (southern Victoria Land) no clear trend was recognized from 1999 to 2007 (Adlam et al 2010).
Permafrost warming and active layer thickening were mainly attributed to air warming, although in several cases the role of snow cover, soil properties and the overlying vegetation were emphasized (e.g. Osterkamp 2007, Romanovsky et al 2007, Fedorov and Konstantinov 2008, Haeberli et al 2010, Romanovsky et al 2010). In particular, the active layer thickness does not always follow the trend of the underlying permafrost and, in general, appears much more closely related to the trend of summer air temperature (e.g. Osterkamp 2008, Streletskiy et al 2008) or to summer radiation (Guglielmin and Cannone 2012).

Vegetation affects the energy balance of the soil and, therefore, vegetation changes can have feedbacks on the active layer thickness and underlying permafrost temperature (Walker et al 2003, Guglielmin and Cannone 2012). Traditionally in the Arctic, vegetation is considered an important factor that greatly affects the energy balance and, consequently, the active layer (e.g. Klene et al 2001), and also because different vegetation associations produce a different organic layer thickness (Mazhitova et al 2004, Smith et al 2009). In continental Antarctica, despite its scattered coverage, the cryptogamic vegetation provides an insulating effect on the ground surface temperature (GST), with a net cooling. The degree of cooling varies with differences in vegetation type, structure, coverage and thickness (Cannone and Guglielmin 2009).

Conversely, active layer changes can indirectly modify the overlying vegetation through variations of the frost heave, cryoturbation, ice segregation or gelifluction disturbance, or through the different water availability linked to the active layer thickness (Cannone et al 2007, 2014).

Relating to the impacts of recent climate change on vegetation, in maritime Antarctica a large increase of the two native Antarctic vascular plants (Deschampsia antarctica, Colobanthus quitensis) has been documented in the past 30–50 years in response to air warming (Parnikoza et al 2009, Torres Mellado et al 2011) and probably also to increased precipitation and active layer thickening (Cannone et al 2014).

There is a shortage of data available on vegetation changes in continental Antarctica. In Victoria Land the only example of long-term vegetation monitoring, carried out at Cape Hallett (Brabyn et al 2005), showed that, in the period 1960–2004, vegetation expanded (with an increase of algae), although it was not possible to associate this change with long-term temperature increases, while it is likely that it was driven by local alterations of water supply. In other sectors of continental Antarctica, in Wilkes Land, there was a generalized increase of lichen vegetation and a concomitant decrease of bryophytes due to a drying climate (period 1960–1990; Melick and Seppelt 1997). In Dronning Maud, Johansson and Thor (2008) reported an increase in both lichen species density and abundance and a slight increase of lichen taxa of their permanent plots for the period 1992–2002.

In one of the few areas of the world in which air warming does not exist (Victoria Land, Ross sector, continental Antarctica) we aim to: (a) identify the patterns of spatial and temporal active layer variability; (b) analyze the changes of the associated vegetation; (c) identify the climatic forcing factors of active layer and vegetation changes.

2. Material and methods

2.1. Study sites

This work was carried out at four study sites located across a latitudinal gradient from Apostrophe Island (73°30′S 167°50′E) to Prior Island (75°41′S 162°52′E) (figure 1(A)). The sites are ice-free areas located along the coast, with similar altitudinal ranges (50–150 m.a.s.l.), allowing one to achieve comparable data not influenced by differences in elevation. At all sites there is continuous permafrost with an active layer varying in thickness from zero to more than 100 cm depending on the year and the site location. Detailed descriptions of the chemical and physical characteristics of the soils are available in Cannone et al (2008).

The vegetation of Victoria Land is composed exclusively of cryptogams. Previous descriptions of the moss and lichen flora and of the main vegetation communities have been provided (e.g. Kappen 1985, Castello and Nimis 1995, Seppelt et al 1995, 1996, Seppelt and Green 1998, Smith 1999, Cannone 2005, Cannone and Seppelt 2008). At Victoria Land, since 2002, a long-term monitoring network of vegetation was established (Cannone 2006). The vegetation of the Victoria Land monitoring network includes four main vegetation types, dominated by (a) mosses, (b) mosses encrusted by epiphytic lichens, (c) macrolichens, and (d) scattered epilithic lichens and mosses, respectively.

The climate of the area surrounding the Italian Antarctic Research Station ‘Mario Zucchelli’ (MZS) is characterized by a mean annual air temperature of −13.9°C (Frezzotti et al 2001). Precipitation, always in the form of snow, is very low and ranges between 100 and 200 mm (Grigioni et al 1992, Monaghan et al 2006).

The main study site, named unofficially boulder clay, is located close to MZS, in northern Victoria Land. Boulder clay (74°44′45″S 164°01′17″E, 205 m.a.s.l.) is an ice-free area located about 6 km south of the Italian station on a very gentle slope (5°) with southeastern exposure. Lithologically, a Late Glacial ablation till overlies a body of dead glacier (Guglielmin et al 1997). Surface features include perennially ice-covered ponds with icing blisters and frost mounds, frost-fissure polygons and debris islands (Guglielmin et al 1997, French and Guglielmin 1999, 2000). The till matrix is generally silty sand, with small patches of clayey silt. Vegetation is very scarce (less than 5% of the surface is covered by vegetation), composed mainly of patches of mosses and epilithic lichens (Cannone et al 2008). The boulder clay site represents the longest near-continuous data series of permafrost and active layer temperature in Antarctica (Guglielmin 2004, 2006). Since 1999, a 100 × 100 m circumpolar active layer monitoring (CALM) grid (Nelson et al 2008) was established at this site. Details of the active layer and GST spatial variability were given in a previous paper (Guglielmin 2006).

The other three sites (Apostrophe Island, 73°30′S 167°50′E; Edmonson Point, 74°19′S 165°07′E and Prior Island 75°41′S 162°52′E) were selected within a long-term monitoring network (Cannone 2006) for this investigation (figure 1(A)). They represent the most common soil and vegetation types in Victoria Land (see table 1, p. 4 in Cannone et al 2008 for details on soil types and table 4, p. 7 in Cannone and Seppelt 2008 for details on vegetation types).
3. Field surveys

3.1. Active layer

Active layer measurements were performed within the boulder clay CALM grid, which is a 100 m × 100 m grid (figures 1(B) and (C)). The measurements were carried out on each of the 121 grid points marked in the field by a wooden stake, through two different methods: (a) ground probing according to the CALM protocol (Nelson et al. 2008) and (b) measurement of the thermal profiles (down to a depth of 30 cm) according to Guglielmin (2006). In the second case the active layer thickness was then calculated as the 0 °C depth by extrapolating from the two deepest temperature measurements (Guglielmin 2006). Here we used only the data obtained by the second method because, due to the coarse grain size, the data achieved by probing are less consistent (Guglielmin 2006). At the same time also the snow cover (cm) was manually recorded at the same 121 points: these data are referred to the long-lasting snow cover still occurring at the date of the measurements. Due to logistical constraints, it was not possible to perform the active layer, ground temperature at 10 cm depth (GT10) and snow cover measurements every year.

Ground surface temperatures were monitored at 2 cm depth at boulder clay (permafrost station, see Guglielmin 2006, Guglielmin and Cannone 2012), Prior Island, Apostrophe Island and Edmonson Point. The thermistors have an accuracy of 0.1 °C at boulder clay station and 0.2 °C at the other sites, with a resolution of 0.01 °C. Temperatures were measured every 10 min. At boulder clay station uninterrupted monitoring has continued since 1996, while at the other sites a summer monitoring was carried out in the season 2001/2002 and, since December 2009, a continuous monitoring is ongoing. Air temperature and incoming solar radiation were recorded by the PNRA (Progetto Nazionale Ricerche Antartide) AWS Eneide (74°41′S 164°05′E) located in the middle of the coastal latitudinal gradient (data are kindly
3.2. Vegetation survey

The vegetation survey was carried out in the CALM grid at boulder clay in 2002 and 2012/13. In 2002 the survey was carried out in all the 121 nodes of the grid on 50 cm × 50 cm plots. For each plot the total vegetation cover (%), list of species, and percentage cover of each species was recorded. In 2012/13, due to logistical constraints, the survey was carried out on only 25 nodes of the grid selected randomly, using the same method adopted in 2002, in order to provide comparable data.

The permanent plots located at boulder clay (PP10, PP11), Prior Island (PP5, PP6), Edmonson Point (PP1, PP2 and PP3) and Apostrophe Island (PP7) were installed in 2001/2002 (Cannone 2006) and analyzed according to the protocol by Cannone (2004). In 2011/12/13 the permanent plots were re-surveyed to analyze the eventual changes that occurred in more than 10 years.

4. Statistical and GIS analyses

The analyses of the trends with time of the main climatic parameters were carried out by linear regression. To assess which factors affected active layer thickness, snow cover, ground temperature at 10 cm (GT10) and the main vegetation parameters (total coverage, etc) within the boulder clay CALM grid, we carried out general regression models (GRM) with backward stepwise selection. All these computations were carried out using the software Statistica 6.0 produced by StatSoft®. The vegetation changes occurred in the boulder clay CALM grid and their interactions with the main environmental factors were analyzed by means of multivariate analysis (RDA, Redundancy Analysis). In particular, for the RDA the data were log transformed, the standardization by species was centered, and the sample standardization was normal and the significance of the first ordination axis was performed by Monte Carlo test ($p < 0.05$). The vegetation changes occurring in the selected permanent plots were analyzed by means of multivariate analysis (RDA, Redundancy Analysis). In particular, for the RDA the data were square-root transformed, the standardization by species was centered, without standardization by samples, and the significance of the first ordination axis was performed by Monte Carlo test ($p < 0.01$). The multivariate analyses were performed using the software CANOCO for Windows (Ter Braak and Smilauer 1998). A table with the eigenvalues and the percentage of variance was reported for each analysis (Supplementary Table 1 available at stacks.iop.org/ERL/9/045001/mmedia).

To illustrate the spatial variability of snow cover, GT10, active layer thickness and vegetation, maps were prepared using the triangulation with a linear interpolation algorithm (Hinkel and Nelson 2003, Mazhitova et al 2004) available in commercial software (QGis 1.8.0). The normalized index of active layer variability (INV, see figure 6) was determined according to Hinkel and Nelson (2003).

5. Results

5.1. Climate

In the period 1996–2012, the mean annual air temperature (MAAT) (figure 2) ranged between $-15.3 \degree C$ (2008) and $-12.5 \degree C$ (2011), with an almost stable trend ($\beta = +0.035 \degree C \text{ y}^{-1}$), although not statistically significant. In the same period, summer air temperature (DJF-Air) (figure 2) ranged between $-6 \degree C$ (2008) and $-2 \degree C$ (2011), being apparently stable (without any statistically significant trend). Only during fall (MAM_air) was there a statistically significant warming of air temperature ($R = 0.64$, $p < 0.01$; $\beta = +0.16 \degree C \text{ y}^{-1}$), compensated by a decreasing spring air temperature ($\beta = -0.21 \degree C \text{ y}^{-1}$, although not statistically significant).

The total summer incoming short wave radiation (DJF_Radtot) (figure 2) showed a statistically significant increase ($R = 0.61$; $p = 0.013$; $\beta = +9601$), although this
trend is less pronounced than that recorded until 2009 ($p = 0.031; \beta = +12.621$; Guglielmin and Cannone 2012).

The snow cover data are available since 2000 at the boulder clay CALM grid, with only three years lacking (2007–2009). Snow cover showed a relatively large inter-annual variability, both relating to the mean (6–18 cm) as well as the maximum values (<50–130 cm) (figure 3), but showed no apparent trend in the selected period. Snow cover distribution is strongly controlled by the meso-morphological features (figures 1(B) and (C)) and, in particular, by the central E–W oriented depression that acts always as the main accumulation zone (figures 1(B) and 4). The possible spatial variations are related to micro-morphological features (<10 m), such as big boulders, and some small concavities and convexities that produce snow accumulation, mainly N–S or NE–SW oriented, when the prevailing wind blows from the NW, as it did in 2013.

5.2. Active layer

At the boulder clay CALM grid, the active layer thickness showed a large variability (figure 5), both for its mean values (from 2 to 18 cm) and its ranges (maximum values between 23 and 92 cm), with a slight increasing trend (+0.3 cm y$^{-1}$, $p < 0.05$). For all years (with the exception of 2001), at intra-annual level, the active layer thickness was strictly linked to the ground temperature at a depth of 10 cm (data not shown), as tested by linear regression ($p < 0.01$, $\beta$ ranging between +0.11 and +0.3, depending on the specific year).

The linkage of the active layer thickness at boulder clay with the ground temperature is testified also by the summer thawing degree days of the ground surface temperature (DJF soil TDD) recorded at the boulder clay permafrost station, which exhibited a statistically significant increase ($R = 0.75$, $p < 0.01; \beta = +11.45$), although with a less pronounced trend than until 2009 ($p < 0.01; \beta = +13$; Guglielmin and Cannone 2012).

The INV showed a wide variability, with values ranging between 0 and 827%, with an annual mean of 142% (if we include also the nodes never thawed) in the examined period or with a range between 0 and 387% and a mean of 67.8%; considering only the nodes that every year were thawed.

Considering the sites located along the latitudinal transect, the ground surface temperature (GST) and the thawing degree days (TDD) showed contrasting patterns (table 1), with a significant increase in the plots hosting barren ground (PP3, Edmonson Point, PP6, Prior Island), as well as in the plots characterized by the occurrence of moss-dominated vegetation with high coverage and high soil water content (PP1, PP2, Edmonson Point). On the other hand, GST decreased in the plots characterized by the dominance of epilithic lichens, mainly on blocks (PP7, Apostrophe Island, PP11, boulder clay).

At these sites, the soil total organic carbon (TOC) increased since 2002 (table 1). The soil water content showed contrasting patterns, with a slight increase or stability in the driest plots (PP6, Prior Island and PP10, boulder clay) and a strong decrease in the wettest plots (PP1, PP2, PP3, Edmonson Point) (table 1).

5.3. Vegetation

The vegetation of the boulder clay CALM grid was composed exclusively of cryptogams (mosses; epilithic, epiphytic and ubiquitous lichens; cyanobacteria and algae), occurring in discontinuous and scattered patches. According to the survey carried out in 2002, almost all of the 121 nodes of the CALM grid were characterized by the occurrence of communities dominated by mosses with epiphytic lichens and cyanobacteria colonizing the sediments with finer grain size, coupled with communities dominated by epilithic lichens, mainly occurring on pebbles and blocks. In 2002 the dominant moss species were Schistidium antarcticum, followed by Bryum argenteum, while other species such as Syntrichia princeps and Cetrodon purpureus occurred only sporadically across the grid. Several epiphytic lichens were associated with Schistidium antarcticum and other moss species, such as Buellia grimmiae, B. papillata, Candelariella flava and Leproloma spp. Cyanobacteria occurred both associated with the moss-dominated communities, as well as alone as crusts on the finer sediments. The epilithic communities were mainly composed of crustose lichens (dominated by the placodioid Buellia frigida), but included also foliose (mainly Umbilicaria decussata) and fruticose lichens (Usnea antarctica).

Analyzing the vegetation changes in the selected 25 nodes of the CALM grid, since 2002 there was a generalized decline of vegetation, both for the total coverage and for the coverage of the main groups of cryptogams (mosses, cyanobacteria), with the exception of lichens (figure 7).

The spatial distribution of vegetation within the selected 25 CALM grid nodes (figure 8) showed that the vegetated areas almost coincide between 2002 and 2013 and that their coverage was almost stable (although with slight decreases of mosses and increases of lichens).

The multivariate analyses (RDA) (figure 9) emphasized that the floristic composition of vegetation changed slightly comparing 2002 and 2013, with two main groups of species: (a) the community dominated by Schistidium antarcticum is
Table 1. Main vegetation and soil characteristics in 2002 and 2013 at the selected permanent plots at Edmonson Point (PP1, PP2, PP3), Prior Island (PP5, PP6), Apostrophe Island (PP7) and boulder clay (PP10, PP11). Legend: ND = not determined.

|                | PP1 2002 | PP1 2013 | PP2 2002 | PP2 2013 | PP3 2002 | PP3 2013 | PP5 2002 | PP5 2013 | PP6 2002 | PP6 2013 | PP7 2002 | PP7 2013 | PP10 2002 | PP10 2013 | PP11 2002 | PP11 2013 |
|----------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Total coverage (%) | 83.75    | 94.5     | 88.13    | 88.06    | 0        | 0        | 17.8     | 24.3     | 1.8      | 3.8      | 45.4     | 49.5     | 3.6      | 3.2      | 19.5     | 21.5     |
| Mosses (%)      | 58.46    | 73.1     | 82.64    | 79.5     | 0        | 0        | 0.5      | 0.5      | 0.03     | 0.2      | 3        | 3.9      | 1.47     | 1.15     | 0.38     | 0.43     |
| Lichens (%)     | 0        | 0.69     | 5.29     | 5.97     | 0        | 0        | 17.08    | 22.89    | 1.3      | 1.57     | 45.87    | 50.6     | 2.08     | 2.08     | 19.15    | 19.84    |
| Cyanobacteria (%)| 25.94    | 23.5     | 0        | 15.19    | 0        | 0        | 0.007    | 0        | 0        | 0.16     | 0        | 0.11     | 0        | 0        | 0        |
| Algae (%)       | 0        | 3.22     | 0.05     | 0.16     | 0        | 0        | 0.1      | 1.08     | 0.73     | 2.04     | 0        | 0        | 0        | 0        | 0        |
| Water (%)       | 30.3     | 19.0     | 27.6     | 13.7     | 16       | 3.08     | ND       | 4.8      | 0.7      | 0.77     | 7        | 5.2      | 0.9      | 1.46     | ND       | 4.35     |
| TOC (%)         | 1.6      | 2.9      | 0.5      | 1.1      | 0.1      | 0.46     | ND       | 4        | 4        | 7.35     | 0.3      | 1.74     | 0.2      | 0.78     | ND       | 0.56     |
| GST (°C)        | 3.8      | 4.1      | 2.8      | 5.3      | 5.3      | 7.8      | 1.9      | -0.3     | 1.7      | 2.8      | 7.3      | 4.5      | -0.1     | 0.5      | ND       | ND       |
| TDD             | 126      | 135.5    | 134      | 265      | 250.5    | 370.1    | 169.9    | 111.9    | 151.2    | 258.2    | 234.5    | 152.5    | 39       | 119      | ND       | ND       |
preferentially associated with sites with less snow cover, higher topographic position, thicker active layer and higher GT10, (b) the communities of epilithic lichens (*Buellia frigida, Umbilicaria decussata*), are mainly associated with the availability of blocks, larger snow accumulation and thinner active layer. Closer to the origin, the community dominated by *Bryum argenteum* and epiphytic lichens showed wide ecological requirements. The shift between the 2002 and 2012 sites in the site graph (figure 9) emphasized that in the 10-year period the vegetation changed slightly. In most cases these changes depended on the decrease of coverage of one or more species, while the floristic composition within the plot remained relatively stable.

Considering the sites located along the latitudinal transect, vegetation exhibited contrasting patterns too (table 1), although different from those of the environmental abiotic factors. Indeed, both the southernmost plots located at Prior Island (PP5, PP6), the northernmost plots of Apostrophe Island (PP7) and the plot with highest moss coverage and soil water content of Edmonson Point (PP1) were characterized by a large vegetation increase (total vegetation coverage). The intra-plot patterns of mosses and lichens mainly reflected the original vegetation composition of each plot (e.g. lichens increased in

Figure 4. Changes of snow cover (cm), active layer thickness comparing 2002 and 2013 within the boulder clay CALM grid and active layer variability index (INV) computed for the selected period.
plots mainly composed of lichen vegetation, while mosses did the same in plots mainly dominated by mosses). There was also an increase of algae in half of the selected plots, independently of the values of soil water content.

Also the RDA allowed one to emphasize the changes occurring in the selected permanent plots in the period 2002–2013 (figure 10). As could be expected, the higher values of total coverage, mosses and cyanobacteria were associated with higher soil water contents, differently from lichens. The sites were split into two main clusters: one dominated by lichen vegetation (on the left part of the graph) and one mainly dominated by mosses and cyanobacteria (right part of the graph). Moreover, lichens showed a preference for sites with lower GST and TDD, in a similar way to the lichens occurring in the boulder clay CALM grid (figure 9). The shifts of the sites in the graph emphasized the changes occurring since 2002 and due to changes of both the environmental parameters and the vegetation (see also table 1).

5.4. Climate–active layer–vegetation interactions

Among the main environmental and climatic factors affecting the active layer thickness across the entire boulder clay CALM grid were snow cover, summer air temperature and summer incoming short wave radiation (table 2), as tested by GRM. Analyzing the factors affecting snow cover, the most important were slope, and spring and fall air temperature (table 2).

The snow patterns and persistence, especially in the central depression, control the GT10, ALT patterns and INV,
because the ground never thaws when snow persists for all the summer.

Analyzing at intra-annual level which were the most important environmental factors (elevation referred to the origin of the grid, slope, aspect, surface texture, active layer thickness, GT10, snow) affecting vegetation distribution, we found that the only factor exerting a statistically significant influence \( (p < 0.05) \) in 2002 was the occurrence of blocks (total vegetation coverage and lichens), while in 2012 they were sand (total coverage, mosses), blocks and active layer thickness (lichens) (data not shown).

6. Discussion

6.1. Climate

Our data confirm on a longer time span (until 2012/13) the trend of stability of the mean annual air temperature (MAAT) already outlined by Chapman and Walsh (2007) for the period 1958–2002. According to our results, the air temperature trends observed until 2009 in fall (warming) and spring (cooling) are enhanced, while the trends of both summer incoming radiation and summer soil TDD are less pronounced than in 2009 (Guglielmin and Cannone 2012). The trend of
solar radiation increase detected by Doran et al (2002) was further confirmed by Hoffman (2010) in the Dry Valleys and Guglielmin and Cannone (2012) in northern Victoria Land.

The observed air temperature stability despite the increase of short wave summer radiation could be explained at a local scale as an albedo effect (Gardiner 1987). The coastal areas of continental Antarctica (including also our study sites), are characterized by the predominance of snow and ice coverage with high albedo (0.6–0.9) with respect to sediment or bedrock outcrops, as well as by a high-speed wind regime. As a consequence, the influence of incoming short wave radiation on air temperature is negligible, but not on the ground temperature (due to the lower albedo allowing more energy to be absorbed).

Indeed, the effect of differential albedo coupled with the increase of incoming radiation promoted an increase of the melting of buried ice in the past decade also in the McMurdo Valley (Fountain et al 2014) despite a decrease of air temperature.

Moreover, the processes/trends observed at our study site as well as in the McMurdo Dry Valley could be related to a process occurring at a regional scale. Indeed, what is now happening is the opposite of what happened along the coastal areas of Antarctica between 1959 and 1988. In that period a decrease of short wave incoming radiation occurred in association with an increase of air temperature (Stanhill and Cohen 1997).

At our study site, the snow cover showed no trend relating to its mean depth (figure 3), confirming what was reported by Monaghan et al (2006). However, there was a change of the spatial distribution patterns of snow cover within the CALM grid, likely related to a potential change of wind direction (figure 4), as the main part of the snow accumulated in the grid is drifted by the wind.

6.2. Active layer

Our results show that the active layer thickness is increasing, although the data of the monitoring of the boulder clay CALM grid (121 nodes) provide a trend (+0.3 cm y \(^{-1}\)) less pronounced than at the boulder clay permafrost monitoring station (+1 cm y \(^{-1}\)) within the borehole until 2009 (Guglielmin and Cannone 2012). In the other monitoring sites of Victoria Land there are unfortunately insufficient data of active layer thickness dynamics due to logistical constraints.

The active layer increasing trend is a widespread process observed with different rates at several locations in the Northern Hemisphere, from northern Sweden (e.g., +0.7 to −1.3 cm y \(^{-1}\)) in the period 1978–2006, with an acceleration since 1995, according to Åkerman and Johansson (2008) and more recently confirmed by Callaghan et al (2010), in the High Arctic (e.g. Svalbard Islands and Greenland, although not spatially and temporarily uniform, Christiansen et al 2010), in North America (e.g., +0.7–1 cm y \(^{-1}\)) in Yukon, in the period 1985–2008, according to Burn and Zhang (2009), Russia (Drozdov et al 2012, Kaverin et al 2012) and in the north of East Siberia (Fyodorov-Davydov et al 2008). However, long-term observations of changes in ALT are less conclusive because often the active layer thickness exhibits substantial inter-annual fluctuations (e.g. Smith et al 2009, Popova and Shmakin 2009) and in several regions it remained substantially stable (e.g., North Slope of Alaska according to Streletsikiy et al (2008), Shiklomanov et al (2010)). In continental Antarctica, only Adlam et al (2010) reported active layer thickness data at southern Victoria Land and, for the period 1999–2007, they did not recognize any apparent trend.

In terms of spatial variability, the active layer at the boulder clay CALM grid showed values of mean inter-annual INV much higher than those reported for sites with continuous permafrost at Bolvansky in Russia (Mazhitova et al 2004) or at Toolik Lake or Atqasuk in northern Alaska (Hinkel and Nelson 2003). The higher inter-annual variability is mainly concentrated in the upper and more wind exposed relief (SW corner) or on the gentle slope exposed to E–SE. The snow patterns control the INV because this value is lower where snow persists for a longer time. Differently from the Arctic sites, here the scattered vegetation and related scarce underlying organic layer (very thin) do not significantly affect the energy balance and the active layer thickness at the scale of the grid. In addition here the ice content in the ground is very homogeneous and therefore not so important in the INV values.

6.3. Vegetation

Within the boulder clay CALM grid the total vegetation cover decreased (mainly due to the reduction of mosses and cyanobacteria) while lichens increased. The decline of mosses can be related to the active layer thickening, increasing solar radiation and decrease of ground water availability. Indeed, only the xeric Schistidium antarctici persisted in this site,
while the other moss species declined since 2002 (figure 9). Conversely, the epilithic lichens increased slightly because they are mainly located on blocks in sites were the drifted snow accumulates, providing water supply independently of the active layer thickness changes/dynamics (figures 4, 8).

In most of our selected study sites (with the exception of Edmonson Point) lichens exhibited a generalized increase. The lichen increase is mainly associated with a decrease of both GST and TDD (table 1, figure 10). Edmonson Point provides a different trend because this is a special site characterized by a much higher soil water content (about one order of magnitude more than the other sites), being a true ‘oasis’ in the polar desert (Bargagli et al 1999). At this site it is remarkable that mosses increased their coverage significantly where GST and TDD slightly increased, while they decreased their coverage where GST and TDD showed much larger increases.

In continental Antarctica there are very few examples of long-term monitoring of vegetation. In the Ross sector, for northern Victoria Land (Cape Hallett area), Brabyn et al (2005) reported that between 1968 and 2004 the total vegetation expanded (with an increase of algae) and they interpreted this change to be driven by local alterations of water supply, rather than by global warming. A trend of lichen expansion associated with drying conditions was described for Wilkes Land by Melick and Seppelt (1997) in the period 1960–1990. Also for Dronning Maud, another site of continental Antarctica geographically remote from Victoria Land, Johansson and Thor (2008), performing the monitoring of their permanent plots (period 1992–2002), observed that there was an increase of lichens both relating to the abundance, density and number of taxa. Although few, these examples provide evidence that where climate drying is occurring there is an increase of lichens, while there are contrasting patterns on moss responses, depending on their ecological requirements in terms of water availability, as the capability of contrasting water stress events is species-specific (Wasley et al 2006).

In maritime Antarctica, one of the three regions of the planet suffering the fastest climate warming, there are several examples of vegetation changes with evidence of enhanced cryptogamic (mosses and lichens) colonization of recently deglaciated areas; but, above all, vegetation changes concern the large expansion of the two native vascular plant species (Deschampsia antarctica and Colobanthus quitensis) (e.g. Fowbert and Smith 1994, Smith 1994, Parmikoza et al 2009, (Torres Mellado et al 2011), Cannone et al 2014).

In the polar regions of the northern Hemisphere, long-term manipulation experiments showed that warming induced a decrease in non-vascular plant biomass (both mosses and lichens), although the declining trend of non-vascular plants with warming has also been assumed to reflect competition with vascular plants instead of the effect of climatic drivers (e.g. Chapin et al 1995, Hobbie et al 1999, Cornelissen et al 2001, Elmendorf et al 2012).

Therefore, continental Antarctica provides a unique opportunity to assess the natural dynamics and responses of cryptogams without the disturbance effect due to the competition with vascular plants (such as in maritime Antarctica and in the Arctic), as well as the impact of grazing (such as in the Arctic, e.g. Joly et al 2009), or of fur seals and animal disturbance (such as in maritime Antarctica, e.g. Favero-Longo et al 2011).

### 6.4. Climate–active layer–vegetation interactions

Continental Antarctica represents the last pristine and most extreme environment on Earth and one of the most suitable contexts to analyze the relationship between active layer, vegetation and climate, and their dynamics (Cannone and Guglielmin 2009).

Our data showed that the snow distribution is the main driving factor (table 2) of the active layer thickness of the boulder clay CALM grid, with summer air temperature and summer short wave incoming radiation as secondary factors. The role of the snow cover in warming/cooling the ground surface and thickening/thinning of the active layer has been already pointed out in the Arctic (e.g. Osterkamp 2007, Romanovsky et al 2007, Fedorov and Konstantinov 2008). However, here the active layer thickness is increasing despite the substantial stability of snow cover. This could be explained by the increase of short wave incoming radiation, as demonstrated by Guglielmin and Cannone (2012) for the close boulder clay permafrost station (until 2009). In any case, here snow cover also exerts a ‘net warming effect’ due to its thermal insulating effect, as already reported in the Arctic (e.g. Goodrich 1982, Johansson et al 2013). In particular here the warming effect is mainly due to the prevailing negative air temperatures in spring and summer.

Concerning the active layer thickness in the other sites, the available data are not enough to compute trends. However, the increase of GST and TDD at Edmonson Point and in all the barren ground sites suggests that an increase of the active layer thickness is very likely. This trend is indirectly confirmed in all sites (except PP6) by the strong reduction of the ground water content, probably due to the better drainage triggered by the thickening of the active layer.

The buffering effect of the vegetation on GST and TDD and, probably also on the active layer, was observed in the vegetated plots, confirming previous results achieved by Cannone and Guglielmin (2009). Moreover, the better drainage and the decrease of the water content in the soil due to the active layer thickening may have produced the decline of mosses. The apparent paradox of the PP1 at Edmonson Point, in which mosses increased despite the decrease of the ground water content, can be explained considering that this site was water saturated in 2002, while now it is well hydrated but not saturated, being more compatible with the ecological requirements of the mosses.

The observed increase of total organic carbon (TOC) in the soil could affect the C cycle in the future; although, at the moment, its influence on the ground thermal conditions is negligible because the organic layer is too discontinuous and thin.

### 7. Conclusions

Despite the lack of air warming in continental Antarctica our data emphasize that ecosystem changes occurred rapidly, as they are already detectable in only 10 years.

The active layer is thickening at a rate comparable to areas in which air warming is occurring, emphasizing
the role of solar radiation and snow cover. These factors are particularly important in extremely cold areas such as continental Antarctica, where the air temperature seldom exceeds 0°C even in summer and vegetation is exclusively cryptogamic and patchy.

The thickening of the active layer produced a general decrease of the ground water content due to the better drainage of the ground and to the increase of the incoming solar radiation.

The resultant drying may be responsible for the decline of mosses in xeric sites (Prior Island, boulder clay), while they have provided better conditions for mosses in hydric sites (Edmonson Point), following the species-specific water requirements. This evidence emphasizes that the Antarctic continent is experiencing changes (climate, ecosystems) totally different from those of the Antarctic Peninsula and of maritime Antarctica.

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