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Interactions between climate, vegetation and the active layer in soils at two Maritime Antarctic sites

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Abstract: In the summer 2000–01, thermal monitoring of the permafrost active layer within various terrestrial sites covered by lichen, moss or grasses was undertaken at Jubany (King George Island) and Signy Island in the Maritime Antarctic. The results demonstrated the buffering effect of vegetation on ground surface temperature (GST) and the relationship between vegetation and active layer thickness. Vegetation type and coverage influenced the GST in both locations with highest variations and values in the *Deschampsia* and *Usnea* sites and the lowest variations and values in the Jubany moss site. Active layer thickness ranged from 57 cm (Jubany moss site) to 227 cm (Signy *Deschampsia* site). Active layer thickness data from Signy were compared with data collected at the same location four decades earlier. Using a regression equation for air temperature versus ground surface temperatures the patterns of changing air temperature over time suggest that the active layer thickness increased *c.* 30 cm between 1963 and 1990 and then decreased 30 cm between 1990 and 2000. The documented increased rate of warming (2°C ± 1) since 1950 for air temperatures recorded in the South Orkney Islands suggests that the overall trend of active layer thickness increase will be around 1 cm year^{-1}.

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Introduction

Climate is one of the most important factors influencing both permafrost occurrence (Haeberli 1990, French 1996) and vegetation (Ellenberg 1988). Past climate changes have affected vegetation at both species and community level, exerting significant impacts on its characteristics and distribution (Birks 1991, Wick & Tinner 1997). Permafrost has been demonstrated to be highly susceptible to climate change (Osterkamp 2005), particularly where it has a discontinuous distribution (Burgess *et al*. 2000). As climate influences permafrost, active layer thickness, vegetation and soil properties so these environmental components interact through complex mechanisms, activating both positive and negative feedbacks (Walker *et al*. 2003, Chapin *et al*. 2005). Changes in climate are able to affect permafrost and vegetation in different ways depending on various factors, including vegetation types and soil properties. In the Arctic several authors have described the interactions between these systems (e.g. Shiklomanov & Nelson 2003, Walker *et al*. 2003), emphasizing the importance for understanding of climate change impacts, but these topics have, as yet, been poorly addressed in the Antarctic.

Polar regions are potentially highly sensitive systems for studying climate impacts because both their abiotic (Weller 1998) and biotic components (Smith 1990, Hodkinson *et al*. 1998) are highly susceptible to perturbations. The polar areas of both hemispheres are increasingly recognized as key regions for the assessment and monitoring of climate change impacts. The largest and most rapid changes are expected to occur in the polar areas and the first evidence is already being observed in the High Arctic (e.g. Osterkamp 2005, Chapin *et al*. 2005, Hinzman *et al*. 2005) and in the Antarctic Peninsula (e.g. Convey 2001, Cook *et al*. 2005, Turner *et al*. 2005).

The influence of climate on permafrost is expressed by the combination of surface energy balance and the thermal offset. The former determines the ground surface temperature (GST), the latter the permafrost temperature from the input of the GST. The surface energy balance in particular is influenced by factors such as vegetation and snow cover, both acting as a buffering layer between the atmosphere and the ground (Williams & Smith 1989). Land cover, and, above all, vegetation changes are among the more important factors able to modify permafrost distribution and its thermal regime.

Whilst permafrost has long been a major topic in the Arctic, permafrost studies in the Antarctic are still in their infancy. In particular, specific investigations focusing on the relationships between vegetation and permafrost as a sensitive indicator of climate change are still lacking. In most cases vegetation and permafrost have been investigated separately, without significant reference to their interactions. Descriptions of the main characteristics and patterns of vegetation communities are available from different sites throughout Antarctica (e.g. Lindsay 1971, Allison & Smith 1973, Smith 1972, 1988, 1990, 1999, Walton 1990, Gremmen *et al.* 1994, Melick *et al.* 1994, Melick & Seppelt 1997, Cannone 2005, unpublished). Only a few studies have focussed on permafrost and active layer characteristics (i.e. Chambers 1966a, 1966b, 1967, 1970, Guglielmin 2004, Bockheim 2002, Bockheim & Hall 2002, Guglielmin *et al.* 2003) and multidisciplinary approaches to this topic have only now begun to develop (Cannone & Guglielmin 2003, Guglielmin *et al.* 2005).

Because of its climatic and geographical characteristics, the warmer, wetter maritime Antarctic region shows higher sensitivity to climate change than the cold, dry Continental Antarctic (Smith 1984). Evidence of regional climate warming has been recorded in the maritime Antarctic since 1950, and has been accelerating since 1980 (Convey 2001, Vaughan *et al.* 2003, Turner *et al.* 2005). This remarkable warming has been evidenced in major glacial events such as the recent break-up of the Larsen B ice shelf (Rott *et al.* 1996) and substantial glacier recession in the Antarctic Peninsula (Cook *et al.* 2005). At the same time, significant increases in the distribution of two native vascular plants have been observed in different localities of Maritime Antarctica (Smith 1984, Geringhausen *et al.* 2003).

The main aims of this paper are:

1) to demonstrate for the first time in the Maritime Antarctic the buffering effect of vegetation on the ground thermal regime and its role in the energy balance of the surface ground,
2) to assess for northern Maritime sites, the relationship of vegetation with active layer thickness,
3) to provide a preliminary assessment of the active layer changes in the last 40 years comparing our measurements with the data collected by Chambers (1966b) for Signy Island.

Study areas

The study sites are located at Jubany (King George Island, South Shetland Islands) (62°14'15"S, 58°40'00"W); and at Signy Island (South Orkney Islands) (60°43'S, 45°38'W). Both sites lie north of the Antarctic Peninsula in the northern Maritime Antarctic region under similar climatic and biogeographic conditions, but in geographically distinct locations. Long term meteorological records are available for Jubany and Signy Island, with the latter in particular having records dating back to the late 1940s as well as a set of active layer thickness measurements from the early 1960s (Chambers 1966b).

Climate and landscape

King George Island is a large island with a significant ice cap. It has a cold moist maritime climate characterized by mean annual air temperatures of -2°C (Olech 1994) and mean air temperatures above 0°C for at least one month (and up to four) each summer. Precipitation, mainly as rain, falls primarily in summer, ranging between 350 and 500 mm per year (Øvstedal & Smith 2001). Cloud cover averages 6–7 okta in summer. King George Island is almost entirely composed of igneous rocks, mainly basalts, with the subsidiary occurrence of metamorphic rock types. Few permafrost data are available for King George Island though Chen (1993) reported continuous permafrost in a study conducted close to the Chinese Great Wall scientific station, with a thickness ranging between 20 and 100 m and an active layer between 0.5 and 1.8 m. Based on the available climate data for the island and using the methodology of Brown & Pewè (1973), it can be predicted that discontinuous permafrost should occur in the area. Given the widely differing topographic and hydrologic conditions, and varying geological composition and vegetation coverage it would seem more reasonable to assume that permafrost on King George Island, and in the Jubany area, is discontinuous with a very variable active layer (0.5 to more than 2 m).

At Signy Island the cold oceanic climate has a mean annual air temperature of around -3.5ºC, with mean monthly air temperatures above 0°C for at least one (and up to three) months each summer. The island lies south of the much larger and higher Coronation Island which generates regular Föhn winds that bring moist misty air over Signy Island. Comparison of the long term meteorological records for Signy Island and Laurie Island (lying east of Coronation Island) indicates that Signy Island is ~0.5ºC warmer over the past 50 years but shows the same rate of overall warming (Smith 1996). The precipitation regime is primarily rain in summer, with an annual total of around 400 mm, and cloud cover is 6–7 okta year-round. The ice cap covers half this small island and is currently shrinking rapidly. The substrate is mainly quartz-mica-schist with small limestone outcrops. At Signy Island too, the climatic conditions are favourable for the occurrence of discontinuous permafrost, according to the methodology of Brown & Pewè (1973). Studies from the 1960s and 1970s (Chambers 1966a, 1966b, 1967, 1970, Holdgate *et al.* 1967, Collins *et al.* 1975) reported that permafrost was discontinuous, with an active layer ranging from a minimum of 40 cm in the moss covered sites, to a maximum of more than 2 m in well-drained coarse deposits.

Vegetation

Both locations have similar vegetation community types (Allison & Smith 1973, Smith 1996). The most widespread communities are the fruticose and foliose lichen sub-formations and tall moss cushion sub formations, while, for the Antarctic vascular herb tundra, the grass and cushion chamaephyte sub-formation are dominated by *Deschampsia antarctica* Desv. and *Colobanthus quitensis* Bartl. Among the most widespread communities are the *Usnea-Andreaea* association, distributed in the drier and more exposed sites, barren ground colonized by crustose and foliose lichens (with *Caloplaca-Xanthoria* in dry sites and *Leptogium puberulum* in wetter conditions) and the moss turf and cushion sub-formations in the wetter areas. Despite their geographical separation, the two study sites show significant similarities, in relation to both their climate and vegetation.

Methods

Test sites and vegetation

Sites were selected according to the protocol proposed by Cannone & Guglielmin (2003). For the data logger sites replicated measurements of the ground temperature in the first 30 cm indicated a very good correlation between the vegetation type and the ground thermal regime. All the study sites were chosen for similar conditions of altitude, aspect, slope, and distance from sea, along a gradient of vegetation colonization and development. At Signy Island the sites were situated in a location documented by Chambers during his early investigations on permafrost (1966a, 1966b, 1967, 1970). It was not possible to select the exact same site used by Chambers as the site markers were no longer present but care was taken to match the location and vegetation types as closely as possible from Chambers' site descriptions and photographs.

Percentage cover for all species at each site was estimated visually. Species nomenclature followed Øvstedal & Smith (2001) and Redón (1985) for lichens and Ochyra (1998) for bryophytes. The Signy sites were

a) barren ground with scattered mosses (*Andreaea*),

b) macrolichens (predominantly *Usnea antarctica*),

c) short moss cushion and turf sub-formation (*Andraea depressinervis*, *A. regularis*), and

d) *Deschampsia antarctica*.

At Jubany we identified essentially similar representative sites, with the exception of the tall moss cushion sub-formation, dominated by *Sanionia uncinata*, and the selection of two main types of barren ground with

a) fine texture and scattered xeric epilithic lichens (mainly *Caloplaca* spp. and *Xanthoria*), and

b) coarse texture and scattered *Leptogium puberulum*.

A further significant difference was that *Deschampsia-Colobanthus* communities at Signy Island develop primarily on lithosols, whereas at Jubany these communities develop directly on the rock. Growth on rock was not considered appropriate for this study so only the Signy Island grasses data are presented here.

Physical measurements

At each site the active layer thermal regime was measured using four thermistors at different depths. At Jubany the RiSCC protocol was followed, putting the first thermistor 2 cm below the ground surface (that is the topographic surface for all sites except for the *Sanionia* site, where the topographic surface coincided with the moss surface). At Signy it was decided to place the thermistor 1 cm below the surface, to achieve data comparable with those of Chambers. The second thermistor at each site was placed at 30 cm and the last two at different depths, according to the characteristics of the lithosols (down to 82 cm). The thermistors used at Signy and in the sites of epilithic lichens (fine grained barren ground) and mosses in Jubany had an accuracy of 0.4°C and the data were recorded every 10 min with Hobo Pro® dataloggers (Onsett Computing). In the two other Jubany sites the thermistors had an accuracy of 0.2°C and were recorded at 10 minute time intervals on Pico® dataloggers (Micros). Where it was possible, we also installed sensors to measure the incoming solar radiation (Stowaway®) and relative humidity (PICO®) close to the study site surface. The microclimatic data were recorded in the period 27 January–4 March 2001 at Jubany and 10 February–16 March 2001 at Signy.

Additional data for Signy were obtained from the Signy Island long term microclimate monitoring programme.

The thermally defined active layer was computed by both polynomial and linear extrapolation from the maximum measured ground temperatures at the two deepest depths, as suggested by Guglielmin (2006). To check the calculated active layer thickness at each temperature recording site a pit was dug to describe the soil/lithosol structure. Samples for the measurement of ground water content (obtained by the difference between the fresh sample weight and that of the sample dried at 60°C for 24 hours) were collected only at Signy.

Data elaboration

The soil profile temperature and the meteorological data (i.e. air temperature, net radiation, incoming radiation, wind speed, wind direction, air humidity) served as the basis for the calculation of a correlation matrix carried out separately for Jubany and Signy using Statistica® software. The significant values presented are those showing $P < 0.05$.

In addition, the thawing degree days (obtained by the cumulative sum of the mean daily temperatures above 0°C) and the freezing degree days (obtained by the cumulative sum of the mean daily temperatures below 0°C) were

Table I. Main topographic and ecological characteristics of the selected study sites at Jubany and Signy.

Jubany sites	*Deschampsia*	*Usnea*	*Sanionia*	*Leptogium* Barren ground (coarse)	Epilithic lichens Barren ground (fine)
Elevation (m a.s.l.)	12	31	20	29	27
Slope (º)	3	3	2	6	3
Aspect (º)	320	350	340	50	350
Vegetation coverage (%)	67.4	76.7	94.5	3.9	3.6
Community dominants	*D. antarctica*	*U. antarctica*	*S. uncinata*	*L. puberulum*	*Caloplaca* spp. *Xanthoria elegans*
Height of vegetation (cm)	1–8	2–4	2	1–4	1–4
Organic mat (cm)	0	0	6	0	0

Signy sites	*Deschampsia*	*Usnea*	*Andreaea*	*Andreaea* barren ground
Elevation (m a.s.l.)	4	80	80	80
Slope (º)	5	3	3	3
Aspect (º)	270	340	340	340
Vegetation coverage (%)	85	45	65	15
Community dominants	*D. antarctica*	*U. aurantiaco-atra*	*A. depressinervis*	*A. depressinervis*
Height of vegetation (cm)	4	4	2	4
Organic mat (cm)	5	1	0	0
Water content (%) 2–30 cm	15.49	6.42	14.26	11.28
Water content (%) 60–100 cm	13.7	5.57	15.19	13.62

calculated for both sites using the air temperature data for the year 2000.

Results

At Jubany all sites were in relatively close proximity (10–100 m), showing similar conditions of elevation, slope and aspect and characterized by different vegetation types, ranging from scattered pioneer communities to the more evolved stages of both the cryptogam and the vascular Antarctic tundra (Table I). At Signy three sites were located in the same area and in the same conditions previously investigated by Chambers in the 1960s, all of them in very close proximity (10–20 m) and again showing similar conditions of elevation, slope and aspect. However, due to the absence of the grass, *Deschampsia antarctica* in this study area, the nearest *Deschampsia* site located less than 200 m from the other three sites was used. The *Deschampsia* site therefore shows slightly different characteristics, mainly in relation to elevation and aspect (Table I). At Jubany the test sites were subject to environmental gradients of ground moisture, snow thickness/permanence and wind exposure, with the *Usnea* and the *Caloplaca-Xanthoria* communities colonizing the more xeric sites, whilst the *Leptogium* and *Sanionia* communities were found in the more hydric sites.

The climatic data (mainly air temperature, atmospheric pressure and relative humidity) recorded in 2000 do show some differences in temperature between the two stations. At Jubany, the air temperature ranged between -16.4°C and

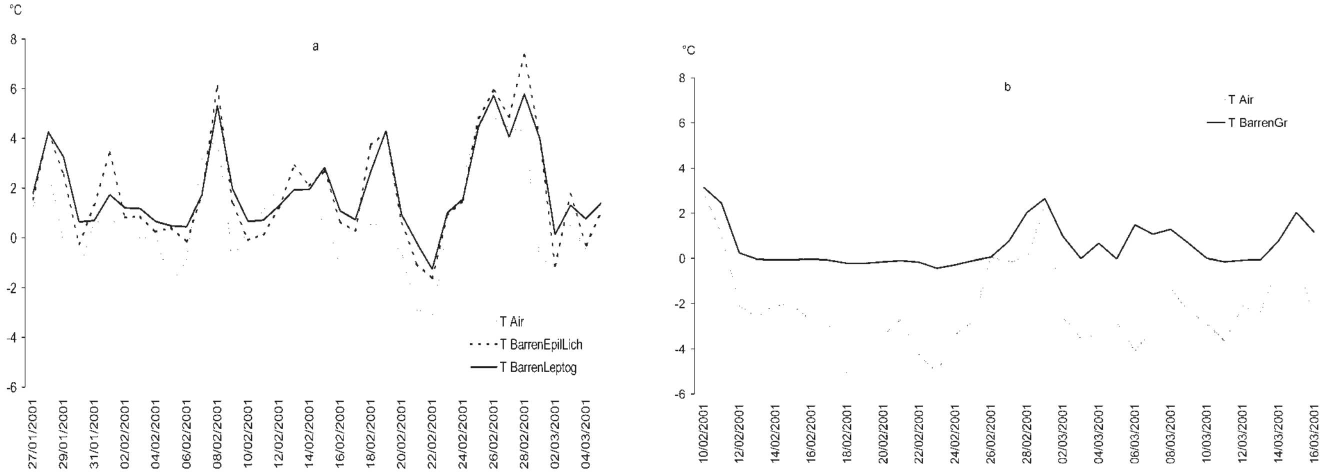

Fig. 1. Daily means of air temperature (T Air) and barren ground surface temperature at **a.** Jubany (respectively, epilithic lichens on barren ground and *Leptogium puberulum* on barren ground), and **b.** Signy Island.

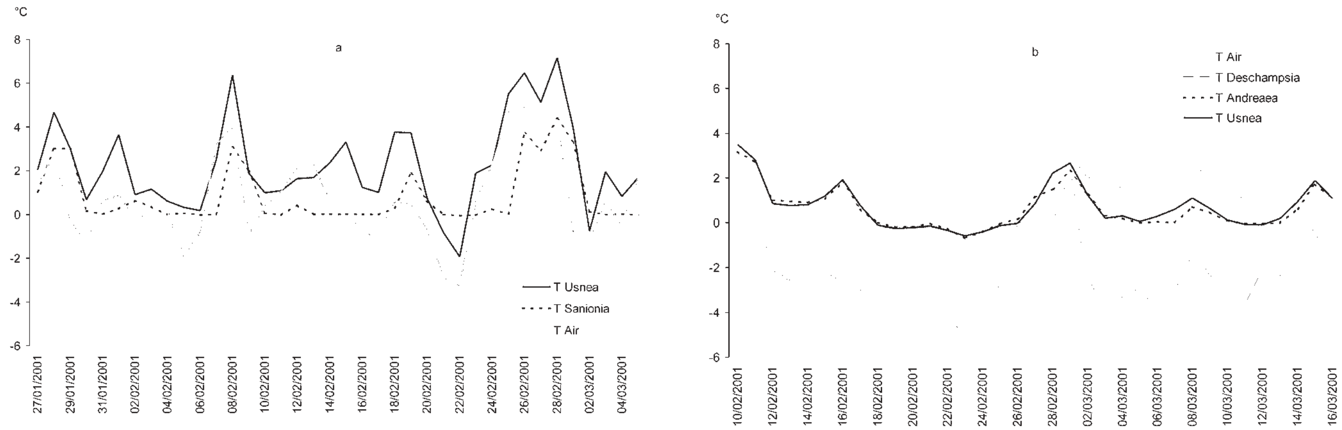

Fig. 2. Average daily ground surface temperature with different types of vegetation cover at **a.** Jubany (at the *Usnea* and the *Sanionia* sites respectively), and **b.** Signy Island (at the *Deschampsia*, *Usnea* and *Andreaea* sites).

5.8°C with a mean of -1.2°C; whereas at Signy, the average temperature was lower (-6°C) with a range of -28.6°C to 4.3°C. Air humidity and atmospheric pressure were reasonably similar with a slightly higher mean atmospheric pressure at Jubany.

The meteorological pattern was similar at both locations with consistent sharp variations in temperature coupled with the stronger pressure changes between May and November (winter period). On both the islands there was a temporal correspondence (in more than 50% of instances) between low pressure events (linked to the passage of frontal systems) and increases in air temperature. However, comparison of the thawing degree days (respectively 285 and 31) and freezing degree days (734 and 2064) at Jubany and Signy Island indicated differing conditions at these two sites with respect to air temperature.

Figure 1 shows the relationships between mean daily air temperature and barren ground surface temperature (GST) at Jubany and Signy respectively. Generally barren ground was subject to radiative heating and warmer than the air temperature, except for three days at Jubany. The pattern for air temperature and GST were similar but with a delay of one day for GST with respect to air temperature. Absolute differences between the two parameters were greater at Signy Island (up to 5°C) than at Jubany (< 2.5°C), probably reflecting the different depth of the surface thermistors, (1 cm and 2 cm respectively). There was also a long period (12 days) at Signy Island where the temperature of the soil remained at the ice melting temperature.

The effects of vegetation cover on the average daily GST are shown in Fig. 2, represented by the moss (*Sanionia uncinata*) and *Usnea* sites at Jubany and the moss (*Andreaea depressinervis*), *Usnea*, and *Deschampsia antarctica* sites at Signy. At Jubany the strong buffering effect exerted by the moss community is particularly striking, with GST being generally lower than air temperature and showing less variation. The GST of the Jubany *Usnea* site was always higher than air temperature, with a similar pattern to the barren ground. The data also emphasized that, at Jubany, GST positive peaks were

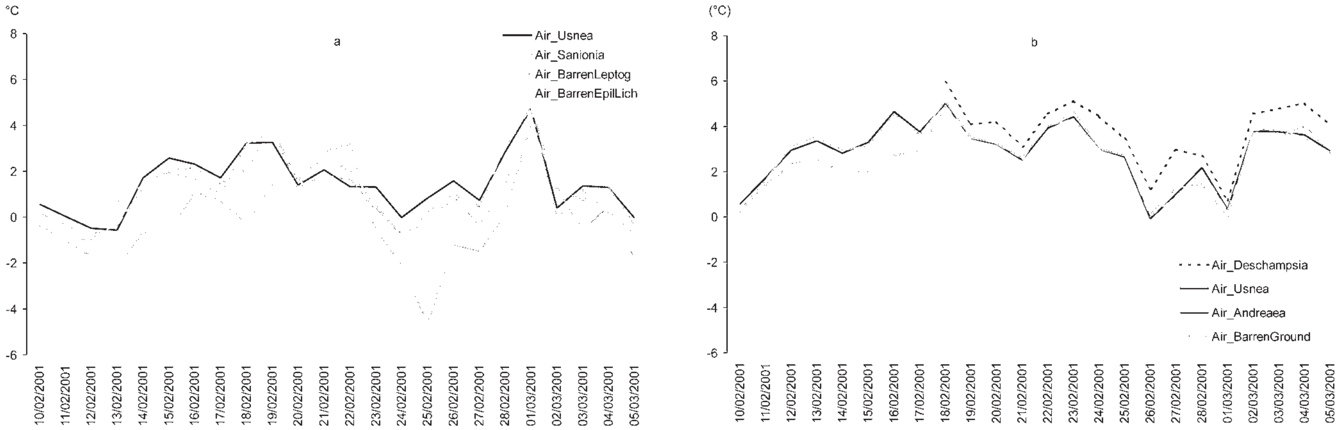

Fig. 3. Differences (ΔT in °C) between air temperature and the ground surface temperature for different vegetation types at **a.** Jubany (respectively, air-*Usnea*, air-*Sanionia*, air-epilithic lichens barren ground, air-*Leptogium puberulum* barren ground), and **b.** Signy (air-*Deschampsia*, air-*Usnea*, air-*Andreaea*, air-barren ground), between 10 February–5 March 2001.

Table II. Correlation matrix showing the relationships between ground temperature of different types of vegetation coverage and climatic parameters measured at Jubany (in bold $P < 0.05$)

	GST *Usnea* (°C)	GST *Sanionia* (°C)	GST *Leptogium* (°C)	GST epilithic lichen (°C)	Air temperature (°C)	Net radiation (Wm^{-2})	Wind speed (msec^{-1})	Wind direction (°)	Air humidity (%)	*Usnea* humidity (%)	Cloudiness (oktas)
GST *Usnea site*	1.00	**0.66**	**0.92**	**0.97**	**0.51**	**0.65**	**-0.24**	0.00	-0.05	**-0.28**	-0.04
GST *Sanionia site*	**0.66**	1.00	**0.76**	**0.66**	**0.32**	**0.24**	-0.09	-0.06	0.09	-0.07	**-0.19**
GST barren *Leptogium*	**0.92**	**0.76**	1.00	**0.92**	**0.44**	**0.55**	**-0.16**	0.01	-0.03	**-0.23**	-0.07
GST barren epilithic lichens	**0.97**	**0.66**	**0.92**	1.00	**0.44**	**0.73**	**-0.21**	-0.01	-0.06	**-0.34**	-0.01
Air temperature	**0.51**	**0.32**	**0.44**	**0.44**	1.00	0.08	**-0.31**	**0.15**	-0.11	-0.03	-0.01
Net radiation	**0.65**	**0.24**	**0.55**	**0.73**	0.08	1.00	-0.02	-0.02	0.00	**-0.37**	-0.02
Wind speed	**-0.24**	-0.09	**-0.16**	**-0.21**	**-0.31**	-0.02	1.00	**0.49**	**0.18**	**0.15**	-0.10
Wind direction	0.00	-0.06	0.01	-0.01	**0.15**	-0.02	**0.49**	1.00	-0.09	0.00	0.03
Air humidity	-0.05	0.09	-0.03	-0.06	-0.11	0.00	**0.18**	-0.09	1.00	**0.22**	**-0.89**
Usnea humidity	**-0.28**	-0.07	**-0.23**	**-0.34**	-0.03	**-0.37**	**0.15**	0.00	**0.22**	1.00	**-0.16**
Cloudiness	-0.04	**-0.19**	-0.07	-0.01	-0.01	-0.02	-0.10	0.03	**-0.89**	**-0.16**	1.00

delayed in the mosses site relative to both the other vegetated sites and the barren ground. At Signy, the *Usnea* and moss (*Andreaea*) sites showed similar GST values almost always higher than air temperature, though slightly lower than the GST of the *Deschampsia* site.

The absolute differences (ΔT) between air temperature and the GST between 10 February and 5 March 2001 have been calculated and compared for each site at both Jubany and Signy Island (Fig. 3). At Jubany the GST of the *Usnea* site showed the highest values with respect to air temperature, with similar values, albeit slightly lower, for the *Leptogium puberulum* and the *Caloplaca-Xanthoria* barren ground sites. The *Sanionia uncinata* community showed the lowest values with respect to air temperature of all the sites at both locations. All the sites at Signy were characterized by GST values warmer than air temperature, ranging from < 1 to almost 6°C. The *Deschampsia* site had the highest ΔT, followed by both the *Usnea* and *Andreaea* sites, which have very similar trends and values. No significant differences were observed between the values of incoming radiation at the surface of the various study sites (data not shown). This factor was therefore unlikely to be responsible for the different GST observed.

The correlation matrix calculated for Jubany data (Table II) indicates how the analysed parameters are linked to each other. The ground temperatures measured in different study sites showed the highest correlations, in particular between the *Usnea*, the epilithic lichens barren ground and the *Leptogium* barren ground sites. All these parameters were positively related to the net radiation (especially the epilithic lichens barren ground site) and to the air temperature, whilst they were weakly related to the humidity recorded within the *Usnea* thalli. The ground temperature of the *Sanionia* site correlated with the other ground temperatures and was more weakly linked to net radiation and air temperature. The climatic parameters, wind speed and wind direction were positively correlated but had a negative correlation with air humidity and cloudiness, whilst air temperature showed a weak positive correlation with wind speed.

At Signy the correlation matrix (Table III) highlighted strong positive correlations between the ground temperatures measured in the four study sites and all positively correlated with air temperature, especially the *Andreaea* and *Usnea* sites. These two sites also had positive correlations with air humidity, whereas both the

Table III. Correlation matrix showing the relations between the ground temperature recorded with different types of vegetation coverage (*Deschampsia*, *Usnea*, *Andreaea*, barren ground with *Andreaea*) and some climatic measured parameters at Signy (in bold $P < 0.05$)

	GST *Deschampsia* (°C)	GST *Usnea* (°C)	GST *Andreaea* (°C)	GST barren ground (°C)	Air temperature (°C)	Incoming radiation (Wm^{-2})	Wind speed (msec^{-1})	Wind direction (°)	Relative humidity (%)	Pressure (HPa)
GST *Deschampsia*	1.00	**0.79**	**0.72**	**0.89**	**0.58**	0.26	-0.29	-0.08	0.24	-0.17
GST *Usnea*	**0.79**	1.00	**0.96**	**0.93**	**0.77**	-0.17	-0.08	0.10	**0.52**	-0.30
GST *Andreaea*	**0.72**	**0.96**	1.00	**0.85**	**0.82**	-0.33	-0.10	0.23	**0.63**	-0.35
GST barren ground	**0.89**	**0.93**	**0.85**	1.00	**0.68**	0.13	-0.20	-0.01	0.28	-0.17
Air temperature	**0.58**	**0.77**	**0.82**	**0.68**	1.00	-0.39	0.08	0.19	**0.46**	0.12
Incoming radiation	0.26	-0.17	–0.33	0.13	-0.39	1.00	-0.34	-0.28	**-0.62**	0.30
Wind speed	-0.29	-0.08	-0.10	–0.20	0.08	-0.34	1.00	0.25	0.13	0.27
Wind direction	-0.08	0.10	0.23	–0.01	0.19	-0.28	0.25	1.00	**0.52**	0.15
Air humidity	0.24	**0.52**	**0.63**	0.28	**0.46**	**-0.62**	0.13	**0.52**	1.00	**-0.44**
Pressure	-0.17	-0.30	-0.35	–0.17	0.12	0.30	0.27	0.15	**-0.44**	1.00

Table IV. Active layer (AL) thickness (cm) (calculated applying respectively the polynomial and linear extrapolations) and ground surface temperature (GST) at Jubany and Signy.

Sites	Jubany AL (cm) poly	 AL (cm) lin	 GST (°C)	Sites	Signy AL (cm) poly	 AL (cm) lin	 GST (°C)
Deschampsia	nd	nd	-	*Deschampsia*	227	173	1.3
Usnea	116	116	2.3	*Usnea*	133	125	0.7
Sanionia	57	57	0.7	*Andreaea*	89	89	0.7
Leptogium barren ground (coarse)	105	91	2	*Andreaea* barren ground	86	68	0.4
Epilithic lichens barren ground (fine)	116	98	1.9				

Deschampsia and barren ground sites showed no correlation with this parameter. Whereas, at Jubany, the ground temperatures of all sites showed positive correlations with net radiation (even stronger than those with air temperature) this correlation was not significant at Signy. There was a positive relationship between Signy air temperature and air humidity, and humidity was negatively related to incoming radiation and atmospheric pressure. In contrast to Jubany, Signy wind speed data were not linked significantly to wind direction, which was correlated positively to air humidity, reflecting the influence of Coronation Island föhn winds.

The calculated active layer thickness varied significantly, depending on the vegetation type (Table IV). In the vegetated sites, with the exception of the Signy *Deschampsia* site, the values of active layer thickness were exactly the same or very similar whether applying linear or second order polynomial extrapolations. The polynomial extrapolation always produced higher values than the linear model. At Signy there was a gradient of decreasing active layer thickness from the *Deschampsia* site, to the *Usnea* (which gave similar values for Jubany and Signy), to the barren grounds and then the moss sites and the same pattern (excluding *Deschampsia*) was seen at Jubany. It was possible to observe at Jubany a difference of active layer thickness between the epilithic lichen barren ground, in xeric conditions on fine textured ground, and the *Leptogium* barren ground, characterized by a wetter environment and coarse ground texture. The thinnest active layer was at the *Sanionia* site and here the permafrost table was around 50 cm. It was not possible to dig the explorative trench further than this depth, because the ground water flow filled the bottom of the pit almost immediately. At Signy the *Deschampsia* site had a much thicker active layer than the *Usnea* site, whilst the *Andreaea* site and the barren ground yielded similar values. This may be due to the fact that the latter two sites are characterized by similar ecological and edaphic conditions that reflect the occurrence of the same vegetation type, although with different coverage.

At Signy we compared our measurements with the data collected by Chambers (1966b). Although the sites are possibly not precisely the same location from photographs, the moss dominated site (65% coverage) seems comparable to the description of the site provided by Chambers (60% coverage of thin moss). In 1963 the active layer measured by Chambers was 120–125 cm, which is 30–40 cm deeper than our data for the *Andreaea* moss site and more comparable to the data calculated for our *Usnea* site.

Results of the interpretive trenches dug at each site revealed similar stratigraphy and substantially homogeneous substrata between sites with a pebbly-gravel and sand matrix deposit in all the sites. The only important difference was the occurrence of a layer 6 cm thick of organic mat underlying the *Sanionia* cover. At Signy the ground water content did not show significant differences (< 5%) when comparing the different sites. Logistical constraints did not allow us to carry out these measurements at Jubany and the only possible observation is that at the *Sanionia* site the ground was clearly more or less saturated.

Discussion

Existing variations

The differences in temperature between sites with differing vegetation and the surrounding barren ground at Jubany demonstrate the strong effect of some types of vegetation cover on the summer soil/lithosol temperature. Previously published data (Cannone & Guglielmin 2003) indicated that the differences are independent of microclimatic conditions. The buffering effect of the different types of vegetation can be attributed to the influence of vegetation on snow distribution, thickness and longevity (Liston 1995, Liston & Sturm 1998, Liston *et al.* 2002), and on the radiative balance of the surface (Chapin *et al.* 2000). Field observations indicate that the snow cover is thinner and melts earlier over the *Usnea* and *Deschampsia* sites than at the *Sanionia* site. All these sites were flat with negligble slope: hence, snow accumulation and melting could not be linked to the effect of microtopography.

These observations are also supported by experimental data collected in the field. Analysing Fig. 1, it can be seen that, after snowfall, the barren ground temperature remained close to 0°C between 13 and 25 February. The GST both of *Andreaea* and *Usnea* fluctuated before 17 February, remained close to 0°C between the 17 and 22, and started to again fluctuate after 22 February. With GST being close to 0°C, the snow cover thickness allowed the underlying surface to be insulated from the inputs of air temperature and of incoming radiation (Hong *et al*. 1992, Granberg

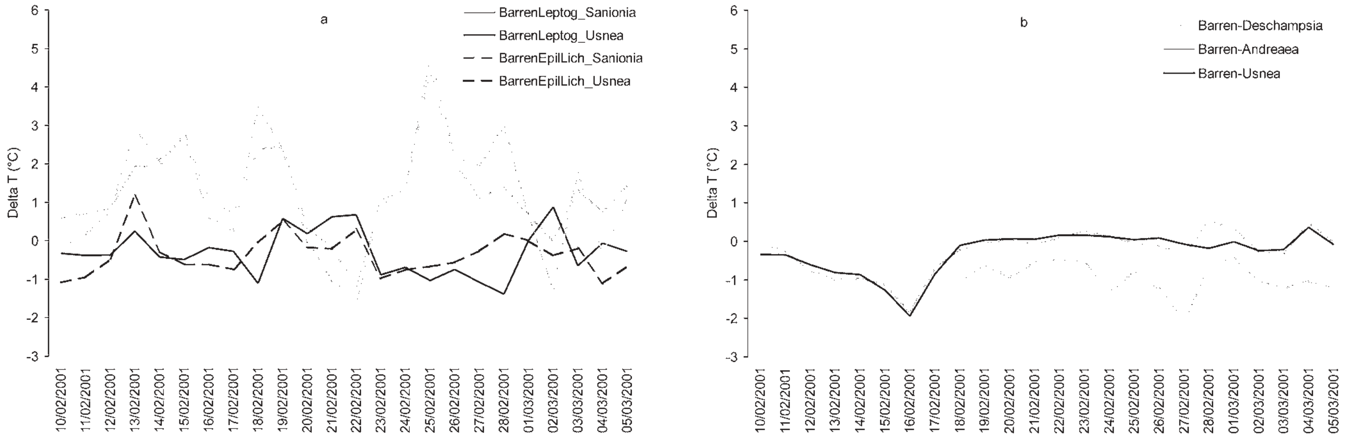

Fig. 4. Temperature differences (ΔT in °C) between barren ground and different types of vegetation cover at **a.** Jubany (*Leptogium* barren ground-*Usnea*, *Leptogium* barren ground-*Sanionia*, epilithic lichens barren ground-*Usnea*, epilithic lichens barren ground-*Sanionia*), and **b.** Signy (barren ground-*Deschampsia*, barren ground-*Usnea*, barren ground-*Andreaea*), between 10 February–5 March 2001.

1988). Preliminary data using optical microprobes have demonstrated that long-wave radiation does not penetrate through snow cover more than 2–3 cm (J.C. Ellis-Evans, unpublished data). Similar trends are visible in Jubany when comparing *Usnea* and *Sanionia* sites (Fig. 1). After the snow fall of 8 February, the GST at both sites stabilized close to 0°C, with the *Usnea* site showing GST fluctuations (similar to the pattern for air temperature) three days earlier than those seen at the *Sanionia* site. These differences have been explained elsewhere by the structure and growth form of the different vegetation types and their albedo (Liston 1995, Chapin *et al.* 2000, Sturm *et al.* 2002).

The occurrence of stratified vegetation with, for example, two cryptogamic layers (crustose lichens; fruticose and foliose lichens) and of vascular plants with different heights within a site makes for a more complex surface 3-D morphometry. The relatively open structure of *Usnea* and *Deschampsia* communities facilitates the creation of funnels and voids in the snow cover, allowing air to flow to the surface. In addition, when the tallest vegetation (*Deschampsia*, *Colobanthus*, *Usnea*, *Cladonia*, etc.) partially outcrop from the snow, the lowered albedo (0.097 vs 0.81 of the snow) leads to faster warming and melting of the snow cover. This matches the effects of vegetation on snow melt reported for Arctic vegetation (Liston 1995). However Sturm *et al.* (2002) demonstrated that this effect is exerted by vegetation where its height matches snow depth, whereas vegetation heights significantly above or below snow depth induce slower rates of snow melting. Although these observations are derived from studies of shrub and forest vegetation in Alaska, the ecological principle is relevant to the Antarctic context, where the amount of snow and the snow depth are significantly lower. However a thinner snow cover is also in agreement with the ecological preference of *Usnea* communities for locations (particularly the tops of ridges) exposed to wind action (Lindsay 1971, Allison & Smith 1973, Gremmen *et al.* 1994).

The substantial differences in temperature between the *Sanionia* site and the surrounding barren ground at Jubany demonstrate the strong effect of this type of vegetation on the summer soil/lithosol temperature. This effect will in part be linked to the structure of this vegetation type but will also be affected by its high water content and its propensity to accumulate an organic layer beneath the growing plant. Figure 1 shows that the GST of the *Sanionia* site also remains close to 0°C during periods without snow cover on the ground, as illustrated by the period 16–21 February. This can be attributed to the dense structure of *Sanionia* and its ability to maintain an high water content inside its canopy and close to the surface. This high water content dissipates absorbed energy as latent heat during water phase changes as temperatures hover around 0ºC. The observed negigible difference in GST between *Usnea* and the barren ground sites at both Signy and Jubany, (Fig. 4), indicated that in the summer the microclimatic conditions, and consequently the surface energy balance of these sites, were comparable on the two islands.

Active layer thickness is related primarily to the GST, as shown in Table IV. Considering only the Signy sites, where ground water content data were obtained, the *Usnea* site showed a substantially lower water content then the other sites. At Jubany the occurrence of a thick organic layer (6 cm) associated with the saturation conditions of the *Sanionia* site enhanced the effect of a lower GST, resulting in the thinnest active layer at all sites. Similar effects on GST, due to the insulating and water-holding capacity of thick organic material, have previously been observed in the Arctic by Kane (1997).

Where the same vegetation type (*Usnea*) can be compared at both Jubany and Signy, the calculated active layer thickness was very similar, indicating the significance of the vegetation type in determining active layer thickness, despite the slight differences in climate evident between the two geographically remote sites. The data also revealed that there is a direct relation between the xericity of the site, reflected in the ecological preference of each vegetation type, and the active layer thickness, but also on the basis of the presence or absence (very low coverage, < 5%) of vegetation. This link between vegetation type and active layer thickness could be related to different drainage of the ground when constrained by the different depths of the permafrost table and, consequently, to a different water content in the soil, as in the case of Jubany where all the sites are characterized by the same microclimatic conditions and substrate but different permafrost table depths.

These data indicate that type and coverage of vegetation influences the active layer thermal regime and its thickness. Even though obtained from vascular tundra, the results published for sites in the Arctic (i.e. Mackay *et al.* 2002) agree with our data, demonstrating that changes of vegetation cover are able to influence ground thermal regime and snow depth and also to induce thickening of the active layer.

Long-term change

The continuous meteorological record from Orcadas Station (Laurie Island) dates back to 1901 and indicates that the South Orkneys have gone through both cooling and warming periods but that overall there has been a steady increase in temperature over the past century. In particular there has been a significant warming of mean summer air temperatures over the past 50 years (Smith 1990). Mapping the Signy Island meteorological records for 1946–89 onto the Orcadas data confirmed that both datasets followed the same trend but Signy proved consistently ~0.5ºC warmer (Ellis-Evans 1990), probably due to föhn winds from nearby Coronation Island in the summer. Laurie Island lies east of Coronation and appears not to be impacted by föhn winds so is more representative of the South Orkneys as a whole.

Since 1990, there has been a downturn in mean annual air temperatures at Signy Island. A linear regression ($GST = 0.8094air + 1.7009$, $R^2 = 0.9244$) was fitted to the mean monthly GST and mean monthly air temperatures from Chambers original data for 1963 (Chambers 1966a, 1996b). Assuming a constant relationship over time the equation was applied to the long term records of air temperature to estimate the changes in GST and, consequently, in the active layer thickness at the *Andreaea* site. The analysis indicated that the active layer thickness increased around 30 cm over the period 1963–90 (a period of warming on Signy Island) but then decreased by 30 cm over the period 1990–2001 when Signy Island endured a series of particularly cold winters. Applying the regression equation to our data for the *Andreaea* site resulted in an active layer thickness estimate the same as we measured at the site. This may be somewhat coincidental as the linear regression describes a simplified relationship, but the result does suggest that the relationship broadly describes the response of the active layer to climatic changes and that the active layer is highly sensitive to climatic change. Applying the warming trend of air temperature (2°C ± 1) for Orcadas over the past century as used by Vaughan *et al.* (2003), the active layer should be increasing on average around 1 cm per year, which suggests that the active layer could provide a useful indicator of climate change.

Conclusions

Our results demonstrate the effect exerted by the cryptogamic vegetation on the ground thermal regime and on the active layer thickness, as well as the potentially relevant impacts of variations in vegetation as a response to climate change inputs. A simple relationship between air temperature and surface temperature potentially offers a means for sensitively monitoring these climate changes. Further investigations of the specific effects of particular communities (e.g. *Sanionia*) on the surface energy balance are still needed, as well as year round monitoring of both the GST and the climatic factors involved. A network of monitoring sites could be usefully deployed along the Antarctic Environmental Gradient (AEG), as proposed by RiSCC, to provide more detailed information on different ecological conditions. The resulting data could interact with current ecological research in international programmes to improve assessment of climate change impacts on the sensitive vegetation-permafrost systems of Antarctica.

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