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Short Communication
Effect of Snow Cover on the Active-Layer Thermal Regime – A Case Study from James Ross Island, Antarctic Peninsula

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ABSTRACT

The response of active-layer thickness and the ground thermal regime to climatic conditions on the Ulu Peninsula (James Ross Island, northeastern Antarctic Peninsula) in 2011–13 is presented. The mean air temperature over this period was –8.0°C and ground temperature at 5 cm depth varied from –6.4°C (2011–12) to –6.7°C (2012–13). The active-layer thickness ranged between 58 cm (January 2012) and 52 cm (February 2013). Correlation analyses indicate that air temperature affects ground temperature more significantly on snow-free days ($R^2 = 0.82$) than on snow cover days ($R^2 = 0.53$). Although the effect of snow cover on the daily amplitude of ground temperature was observable to 20 cm depth, the overall influence of snow depth on ground temperature was negligible (freezing *n*-factor of 0.95–0.97). Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: active-layer; ground temperature; snow cover; air temperature; Antarctic Peninsula; active layer thickness

INTRODUCTION

The Antarctic Peninsula (AP) has experienced the largest atmospheric warming of all regions on Earth over the last 50 years (Turner *et al.*, 2002), with the temperature increase accelerating downwasting of ice sheets on the AP (Vaughan, 2006) and causing the collapse of ice shelves along its eastern coast (Cook and Vaughan, 2010). The response of regional permafrost to this warming remains unknown and represents one of the most important topics in climate modelling, because numerical models suggest that permafrost may become the dominant contributor of CO_2 and CH_4 into the atmosphere in the 21st century (Schaefer *et al.*, 2011). Despite the increasing number of periglacial studies focusing on the AP in the last decade (Vieira *et al.*, 2010; Guglielmin *et al.*, 2014; Bockheim *et al.*, 2013; De Pablo *et al.*, 2014; Almeida *et al.*, 2014; Goyanes *et al.*, 2014), thermal conditions in the active layer and its interaction with meteorological factors are not well known. In particular, the influence of snow on active-layer thickness (ALT) and the thermal regime is relatively poorly understood, despite being a major modulating factor to the atmosphere (Boike *et al.*, 2008; Vieira *et al.*, 2014). In this paper, we evaluate the effect of air temperature and snow cover on active-layer temperature in the northern part of James Ross Island (JRI) from March 2011 to April 2013, one of the largest permafrost regions in the northeastern AP.

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REGIONAL SETTINGS

The study site (63°48′S 57°52′W) is located in the Ulu Peninsula, northern JRI (Figure 1), approximately 100 m south of the Johann Gregor Mendel Station at 10 m asl. Glaciers started to retreat from the Ulu Peninsula before 12.9 ka (Nývlt *et al.*, 2014), leaving low-lying areas ice-free at the beginning of the Holocene. At present, small glaciers persist only on high-altitude volcanic plateaus and in valley heads (Engel *et al.*, 2012). Permafrost in the northern part of JRI can approach 95 m in thickness and the ALT is highly variable, ranging from 22 to 150 cm (Borzotta and Trombotto, 2004; Engel *et al.*, 2010; Bockheim *et al.*, 2013). The study site is located on a Holocene marine terrace (Figure 2) formed by beach deposits composed of gravelly sand (Stachoň *et al.*, 2014).

The climate of JRI is dominated by the advection of air masses, which are strongly influenced by the position of the AP relative to the circumpolar trough of low pressure

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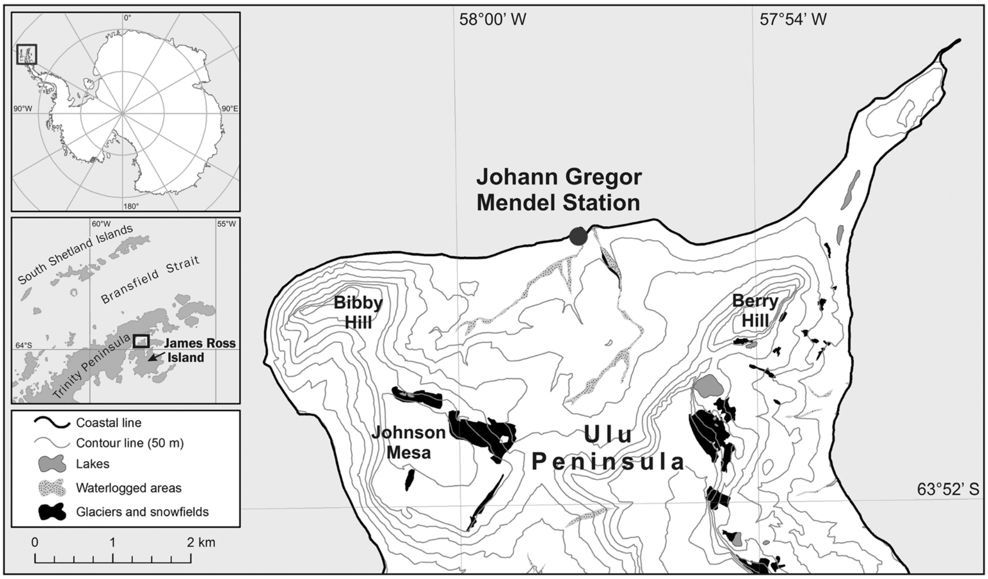

Figure 1 Location of the study site in the northern part of James Ross Island, close to the eastern coast of the Antarctic Peninsula.

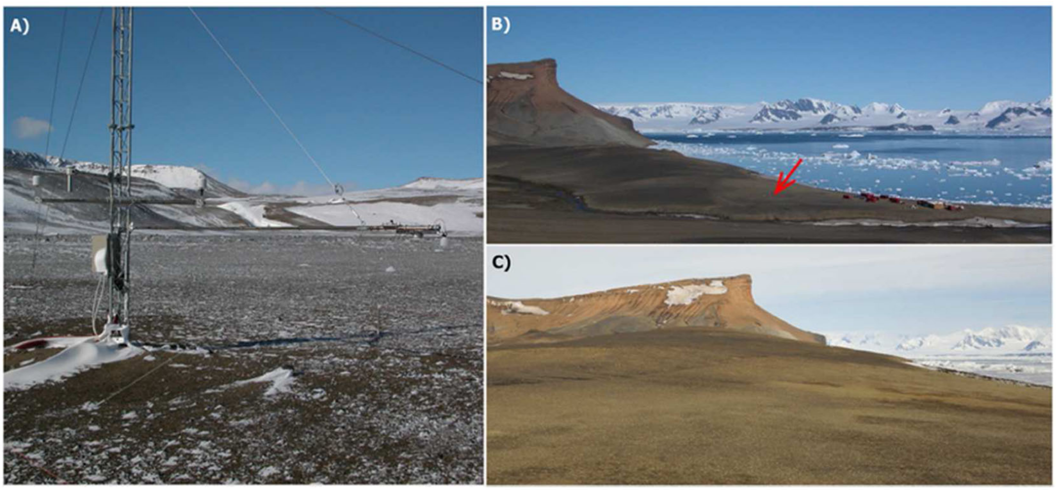

Figure 2 (A) Detailed view of the study site and (B, C) its geomorphological position on the northern coast of the Ulu Peninsula. The red arrow marks the study site near Mendel Station. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

(Domack *et al.*, 2003). A complex orography causes frequent variation between two main advection patterns: (1) cold and dry southerly winds blowing along the eastern coast of the AP, and (2) westerly winds bringing relatively warm maritime air masses across the peninsula to northern JRI (King *et al.*, 2003; Zvěřina *et al.*, 2014). The mean annual air temperature (MAAT) at Mendel Station is –6.8°C (2006–11) and the extremes of mean daily air temperatures vary between around 8°C in January and –30°C in July/August (Láska *et al.*, 2012). Mean daily temperatures above 0°C typically occur only for 2 months each summer (December–January), with hourly maximum and minimum values of 10°C and –5°C, respectively (Láska *et al.*, 2011). According to data from Esperanza, the nearest station making long-term observations on the northern AP, the temperature was 0.2°C colder in 2011–13 than over the reference period of 1961–2000, with a MAAT of –5.2°C (Turner *et al.*, 2004). Precipitation is mostly snow and estimated to range from 300 to 500 mm water equivalent per year (Van Lipzig *et al.*, 2004).

METHODS

Temperature in the active layer was measured at depths of 5, 10, 20, 30, 50 and 75 cm using Pt100/Class A platinum resistance thermometers (EMS, Brno, Czech Republic). Air temperature was measured 2 m above ground level using an EMS33 sensor (EMS Brno) with a Pt100/Class A platinum resistance thermometer placed inside a solar radiation shield. Both ground and air temperatures were measured with an accuracy of ± 0.15°C and data were recorded at 30 min intervals with an EdgeBox V12 datalogger (EMS Brno). We then calculated mean daily air temperatures, the cumulative sum of mean daily air temperatures above 0°C (the thawing-degree days – TDD_a) and the cumulative sum of mean daily air temperatures below 0°C (the freezing-degree days – FDD_a), according to Guglielmin *et al.* (2008) and De Pablo *et al.* (2014). Incoming and reflected shortwave radiation (used to estimate albedo) were measured using EMS-11 (EMS Brno) and CM6B (Kipp & Zonen, Delft, The Netherlands) pyranometers, respectively, at 10 s time intervals and stored as 30 min average values. Snow depth was recorded every 2 h using an ultrasonic depth sensor (Judd Communication, Salt Lake City, UT, USA) with an accuracy of ± 1 cm. All meteorological parameters and ground temperature data were analysed during the period from 1 March 2011 to 30 April 2013. MAAT and mean annual ground temperature (MAGT) were also calculated for a period of 2 years from March 2011 to February 2013, referred to in the text as the 2011–12 and 2012–13 periods.

The ground thermal regime for the period of 2011–13 was evaluated in accordance with recent studies investigating Maritime Antarctic (Guglielmin *et al.*, 2008; Michel *et al.*, 2012; De Pablo *et al.*, 2014), using the following parameters: (1) mean annual and monthly ground temperatures; (2) the cumulative sum of mean daily ground temperatures above 0°C (the thawing-degree days – TDD_g); (3) the cumulative sum of mean daily ground temperatures below 0°C (the freezing-degree days – FDD_g); and (4) the ALT, interpolated as the 0°C isotherm depth and derived from contours of the daily mean ground temperature interpolated using kriging algorithms in the Surfer® software program (Golden Software, Golden, CO, USA).

Freezing and thawing *n*-factors (Karunaratne and Burn, 2003) were calculated in order to evaluate the buffering effects of the snow layer on heat transmission between air and the ground surface (De Pablo *et al.*, 2014), with the effect of air temperature on the ground analysed at 5 cm depth (e.g. Zhang *et al.*, 1997).

Snow cover duration was estimated using a combination of ultrasonic depth sensors and the radiometric albedo. The criteria for snow occurrence were a depth > 2 cm (from the ultrasonic sensors) and albedo > 0.4 (which corresponds to old snow; Warner, 2004). Snow depth records were available for the period from 1 March 2011 to 11 June 2012, while radiometric albedo data were available for the periods from 20 February to 16 May 2011 and 5 March 2012 to 30 April 2013. Despite the presence of gaps in the records due to sensor malfunctions, we were able to analyse an insulation effect of snow cover on the ground temperature regime at 5 cm depth using (1) correlation analysis between mean daily air and ground temperatures during the surface snow-free and snow cover periods, and (2) comparison of the snow cover records with ground temperature daily amplitudes (Zhang *et al.*, 1997).

RESULTS

Air and Ground Temperatures

The MAAT over the whole 2 year study period was –8.0°C; although the individual MAAT values for the 2 years were equal, the temperature range differed from 44.0°C (2011–12) to 42.3°C (2012–13). The larger temperature extreme in 2011–12 was documented by a lower mean temperature of the coldest month (July 2011, –18.5°C) and a higher mean temperature of the warmest month (December 2011, 2.0°C) compared to those for 2012–13 (–15.0°C and 0.2°C, respectively). The maximum air temperature recorded during the entire study period was 11.6°C on 23 February 2013; the minimum recorded was –34.1°C on 26 July 2011.

The MAGT at 5 cm depth was –6.4°C in 2011–12 and –6.7°C in 2012–13. The mean monthly ground temperature at 5 cm depth varied between –16.3°C (July 2011) and 6.1°C (December 2011). Minimum (–26.3°C) and maximum (16.0°C) 5 cm ground temperatures over the study period were recorded on 1 August 2011 and 18 December 2012, respectively. The MAGT at 50 cm depth, which represents active-layer conditions close to the permafrost table, ranged between –6.1°C in 2011–12 and –6.0°C in 2012–13. Minimum (–16.3°C) and maximum (1.3°C) ground temperatures at 50 cm were recorded on 5 August 2011 and 26 January 2012, respectively. The MAGT at 75 cm depth, which represents the uppermost part of the permafrost zone, reached –5.8°C, while maximum and minimum temperatures for the greatest depth were –1.0°C and –14.4°C, respectively.

Thawing and Freezing Seasons

The duration of the thawing season as defined by the thermal regime at 5 cm depth differed significantly between the two periods (Table 1). In 2011–12, the thawing season started on 9 October 2011 and terminated on 27 March 2012, lasting for 170 days. In 2012–13, the thawing season both started and ended later (13 December 2012 and 20 April 2013, respectively) and its duration was considerably shorter (128 days). The mean ground temperature at 5 cm depth was lower during the longer thawing season of 2011–2012 (2.3°C) than during the shorter thawing season of 2012–13 (4.3°C). TDD_g calculated for the thawing season, however, was much higher in 2011–12 (496.1°C day) than in 2012–13 (358.3°C day). The active layer thawed slowly in 2011–12, reaching its maximum on 26 January 2012 (58 cm). In contrast, active-layer thaw was more rapid in 2012–13, reaching its maximum on 13 February 2013 (52 cm).

The freezing season at 5 cm depth lasted for 203 days in 2011 and 259 days in 2012. The mean ground temperature at 5 cm varied from –13.4°C in the freezing season of 2011 to –10.6°C in that of 2012. Despite the lower mean temperature recorded in 2011, a small difference in total FDD_g was observed between the two freezing seasons, at

Table 1 Quantitative characteristics of freezing and thawing seasons at Mendel Station during the period 2011–13.

	Freezing season		Thawing season	
	2011	2012	2011–12	2012–13
Period	19/3/2011 8/10/2011	28/3/2012 12/12/2012	9/10/2011 27/3/2012	13/12/2012 20/4/2013
Duration (days)	203	259	170	128
Mean air temperature (°C)	−13.7	−11.0	−1.0	−0.5
Mean $GT_{5\ cm}$ (°C)	−13.4	−10.6	2.3	4.3
Min air temperature (°C)	−34.1	−30.7	−17.2	−14.6
Max air temperature (°C)	5.7	7.1	9.9	11.6
Min $GT_{5\ cm}$ (°C)	−26.0	−23.5	−12.3	−11.4
Max $GT_{5\ cm}$ (°C)	−0.4	−0.3	15.3	16.0
Min $GT_{75\ cm}$ (°C)	−14.4	−12.0	−9.0	−3.3
Max $GT_{75\ cm}$ (°C)	−1.2	−1.0	−1.0	−1.1
FDD_a (°C day)	−2814.1	−2878.9	−330.4	−195.8
FDD_g (°C day)	−2735.5	−2748.5	−100.6	−77.6
n-factor	0.97	0.95	3.03	2.27
TDD_a (°C day)	22.0	28.9	163.8	157.7
TDD_g (°C day)	0.0	0.0	496.1	358.3

$GT_{5\ cm}$ = Ground temperature at 5 cm depth. See text for other abbreviations.

–2735.5°C day in 2011 and –2748.5°C day in 2012. Although positive air temperatures were recorded on several days during both the freezing seasons (Table 1), there were no signs of ground thaw at 5 cm depth.

Effect of Snow Cover on Ground Temperature

The temporal distribution and duration of snow cover on JRI varied significantly over the study period (Figure 3). In 2011–12, snow covered the study site for 167 days, with the period of continuous snow cover lasting from 22 March to 20 September (67 days). The period of maximum snow depth (21 to 34 cm) persisted from 29 June to 23 July. In 2012–13, continuous snow cover occurred between 8 May and 12 December. The maximum snow depth of 15 cm was observed on 8 May, with relatively thick snow cover (up to 10 cm) lasting until at least 6 June. The continuous period of fresh snow cover was registered between 21 June and 10 December, based on an albedo > 0.80 (Warner, 2004).

Figure 4 shows the relationship between air temperature and ground temperature at 5 cm depth for all days (Figure 4A, D), snow-free days (Figure 4B, E) and snow cover days (Figure 4C, F) during 2011–12 (Figure 4A–C) and 2012–13 (Figure 4D–F). The correlation patterns reveal a significant relationship between the air and ground temperatures (coefficient of determination $R^2 = 0.80$) in 2011–12. Moreover, a closer correlation between these temperatures was found for snow-free days ($R^2 = 0.82$) than for snow cover days ($R^2 = 0.53$). In contrast, a less significant relationship ($R^2 = 0.67$) between air and ground temperatures at 5 cm depth, as well as a very small difference between snow-free days ($R^2 = 0.56$) and snow cover days ($R^2 = 0.52$), was observed in 2012–13.

The effect of snow cover on the active-layer thermal regime was also indicated by a reduction in the daily amplitude of ground temperature. Although the influence of snow cover on amplitude values was detected to a depth of 20 cm, the most significant temperature changes were recorded at 5 cm depth (Figure 5). Mean daily ground temperature amplitudes during snow-free days in thawing seasons ranged between 5.8°C at 5 cm and 1.5°C at 20 cm. The maximum daily ground temperature amplitude was recorded between 6 and 9 March 2012, when values ranged from 15°C at 5 cm to 5°C at 20 cm. The effects of snow cover on daily ground temperature amplitudes were more significant during freezing seasons, with the longer duration of snow cover in 2012 resulting in lower amplitude values (1.9°C at 5 cm and 0.9°C at 20 cm) than those recorded in 2011 (3.7°C and 1.2°C). Diurnal amplitudes of ground temperature rarely decreased to 0.1°C during freezing seasons. The longest period of very low diurnal amplitudes at depths from 5 to 20 cm (0.1 to 0.4°C) was observed between 1 and 11 November 2012.

The overall influence of snow on the ground thermal regime at 5 cm depth during the freezing seasons can be seen in the obtained values of the freezing *n*-factors (Table 1; Figure 6). Total freezing *n*-factors varied between 0.97 (2011) and 0.95 (2012), with values ranging from 0.85 to 0.95 on snow cover days. Differences in freezing *n*-factor development were observed between the respective freezing seasons of 2011 and 2012. The slower increase in the *n*-factor during the period from the end of March 2011 to the end of May 2011 indicates a more significant effect of snow cover during this early winter than in 2012. The observed freezing *n*-factor regime indicates periods with thicker snow cover, which caused a slight decrease from values > 0.95 to approx. 0.90 in both study years.

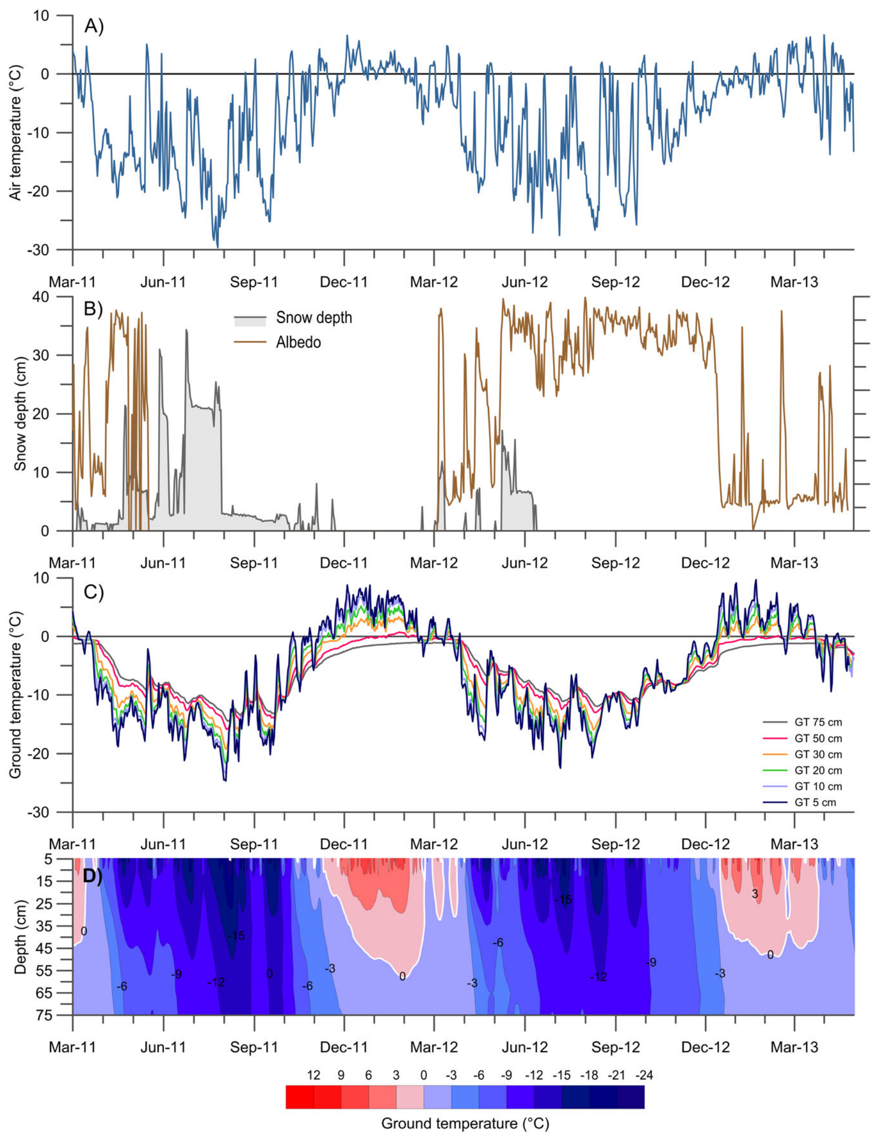

Figure 3 (A) Daily mean air temperature, (B) albedo and snow depth, (C) ground temperature (GT) at 5, 10, 20, 30, 50 and 75 cm depths and (D) GT isopleths at the study site for the period between 1 March 2011 and 30 April 2013. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

DISCUSSION

Active-Layer Conditions

The annual variability of air and ground temperatures at Mendel Station, compared to similar data from the South Shetland Islands and South Orkney Islands, suggests that considerably colder climatic conditions occur on JRI (see Table 2). This is also indicated by the significantly lower FDD_g values (-2735.5 to –2748.5°C day) calculated for Mendel Station compared to those of –500 and –900 to –1200°C day reported from the South Shetland Islands and South Orkney Islands, respectively (Michel *et al.*, 2012; Guglielmin *et al.*, 2012; Almeida *et al.*, 2014; De Pablo *et al.*, 2014).

Although winters are generally much colder on JRI than in the northern AP, we detected that subsurface conditions can potentially be warmer during thawing seasons on JRI than on South Shetland or South Orkney. TDD_g values calculated for JRI (496.1°C day in 2011–12 and 358.3°C day in 2012–13) are significantly higher than those for Livingston Island (98 to 257°C day; De Pablo *et al.*, 2014) and Signy Island (2 cm TDD_g ranged between 260.5 and 378.0°C day for the period 2006–09; Guglielmin *et al.*, 2012). An even higher TDD_g value of 618°C day has been recorded at Rothera Point, Adelaide Island (Guglielmin *et al.*, 2014).

The active layer is generally thinner and less variable on JRI (22 to 150 cm according to Borzotta and Trombotto, 2004; Engel *et al.*, 2010) than on the South Orkney Islands

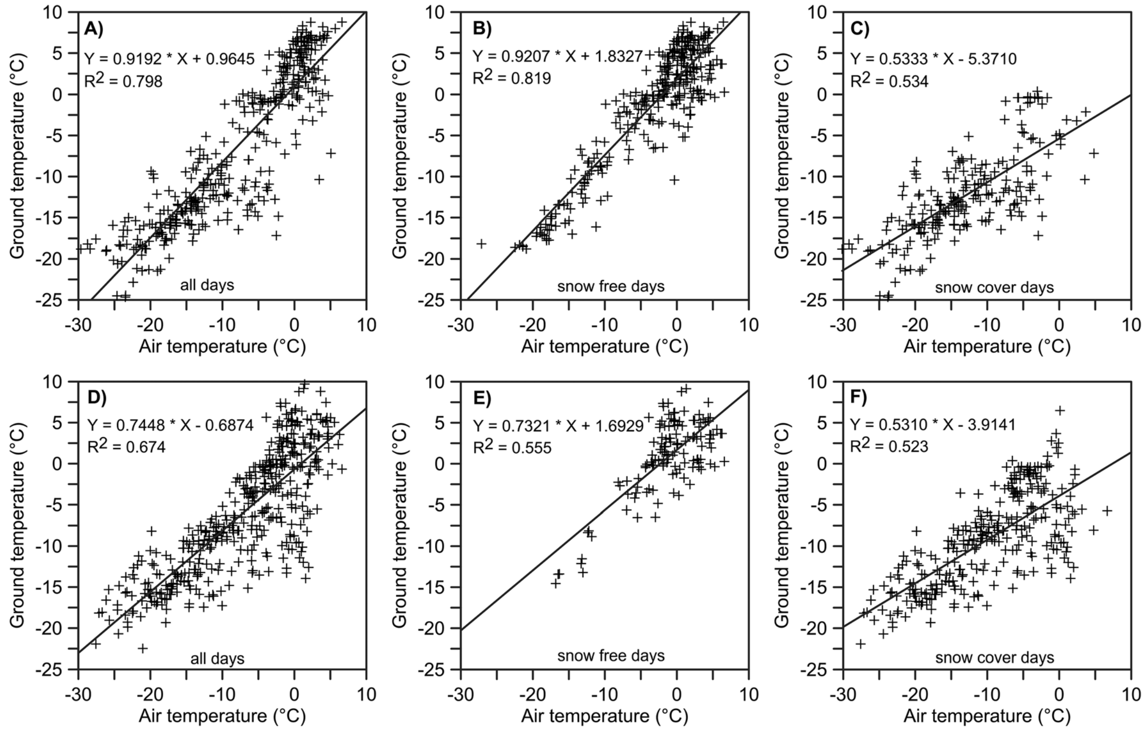

Figure 4 Relationship between air and ground temperatures at 5 cm depth for the periods (A–C) 2011–12 and (D–F) 2012–13 for (A, D) all days, (B, E) under snow-free conditions and (C, F) under snow cover. Coefficients of determination R^2 for a simple linear regression model are given in the plots.

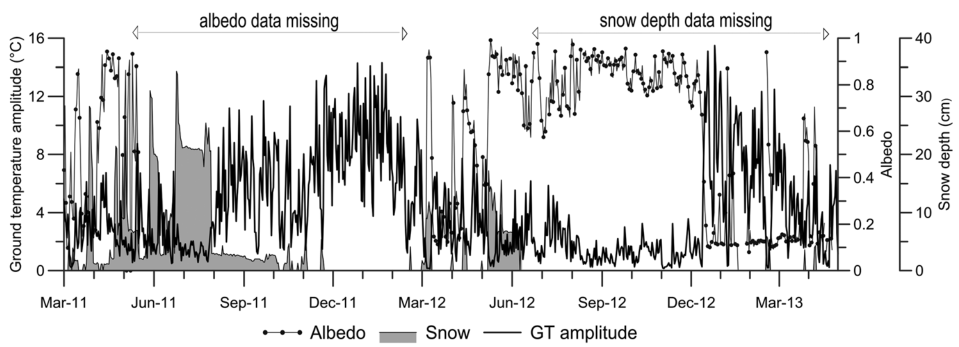

Figure 5 Variation in ground temperature (GT) daily amplitude, snow depth and albedo for the period from 1 March 2011 to 30 April 2013.

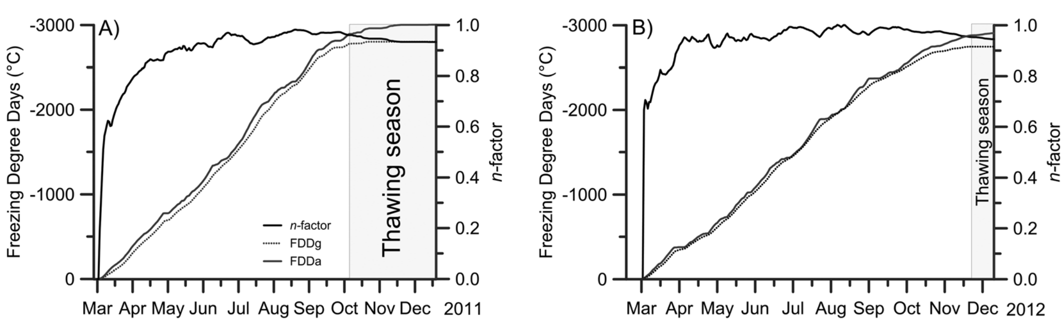

Figure 6 Cumulative sums of *n*-factors and freezing-degree days for air temperature (FDD_a) and ground temperature at 5 cm depth (FDD_g) during the freezing seasons of (A) 2011 and (B) 2012.

Table 2 Climatic conditions and active-layer depths at reported sites in the northern Antarctic Peninsula.

Region	Study area	Elevation (m asl)	Period	MAAT (°C)	MAGT (°C)	Ground temperature measurement depth (cm)	ALT (cm)	Reference
South Orkney Islands	Signy Island	80	1/06–12/09	−3.7	−2.4 −2.0[a]	2 2	112–158 101	Guglielmin *et al.* (2012)
South Shetland Islands	King George Island	65–70	2/08–1/09	NA	−0.8	8.5	89–92	Michel *et al.* (2012)
		86	4/09–1/11	−3.0	−1.4	10	120–147	Almeida *et al.* (2014)
	Livingston Island	105	2/09–2/13	−2.5	−0.8	2.5	99–105	De Pablo *et al.* (2014)
	Deception Island	130	1/10–12/10	−2.3	−1.5	2	46–67	Goyanes *et al.* (2014)
Trinity Peninsula	James Ross Island	10	3/11–2/13	−8.0	−6.6	5	52–58	This study

[a]Data for site covered by vegetation. NA = Data not available. See text for other abbreviations.

(80 to 220 cm according to Guglielmin *et al*., 2008, 2012; Bockheim *et al*., 2013) and South Shetland Islands (30 to > 500 cm; Vieira *et al*., 2010; Michel *et al*., 2012; Bockheim *et al*., 2013; De Pablo *et al*., 2014; Almeida *et al*., 2014; Goyanes *et al*., 2014). The ALT of 52 to 58 cm recorded at Mendel Station during the period 2011–13 is significantly lower than that observed in other low-elevation parts of JRI and the AP region over the last decade (Borzotta and Trombotto, 2004; Engel *et al*., 2010; Bockheim *et al*., 2013).

Effects of Air Temperature and Snow Cover on the Ground Thermal Regime

The data obtained in northern JRI between March 2011 and April 2013 reveal the impacts of air temperature and snow cover on the ground thermal regime. The correlation between air and ground temperatures indicates a close relationship between these two variables during snow-free days, with diurnal ground temperature changes on these days directly reflecting air temperature variation (Figure 3A, C). Such changes in air temperature also control the duration of the freezing and thawing seasons, as indicated by the seasonal differences observed between 2011–12 and 2012–13. Mean monthly air temperatures from October to December 2011 (–5.3 to 2.0°C) were significantly higher than those in 2012 (–8.8 to –2.7°C), resulting in an extended thawing period in 2011–12. The colder climatic conditions at the end of the 2012 freezing season also prolonged the presence of snow cover (see below), which in turn prevented the ground from thawing on days with high solar radiation.

A number of studies have suggested that the effect of air temperature on ground temperature is highly variable in the AP region (Cannone *et al*., 2006; Guglielmin *et al*., 2014). Whereas a relatively weak correlation ($r = 0.58$ to 0.82) between air and ground temperatures was reported from King George Island and Signy Island (Cannone *et al*., 2006) in areas covered by different types of vegetation, a stronger relationship ($r > 0.90$) was described in areas of bare ground at Rothera Point (Guglielmin *et al*., 2014). This difference in effect may be attributed to the variable ground surface conditions at the various study sites. The ground surface at the site on JRI investigated in the present study is free of vegetation, which is, by contrast, well developed on Signy Island, where a significant influence of vegetation cover on ground temperatures was found (Cannone *et al*., 2006). We also observed greater variability in ground temperature at 5 cm depth during winters with thinner snow cover, in contrast to the South Shetland Islands where a snow depth greater than 40 cm had a significant effect on the active-layer thermal regime (De Pablo *et al*., 2014). The minor effect of a thin snow cover on the ground thermal regime during the freezing season at the study site is also indicated by the high freezing *n*-factor values (0.95 to 0.97). Lower *n*-factor values (0.2 to 0.7) have been reported from Maritime Antarctica (De Pablo *et al*., 2014; Almeida *et al*., 2014), reflecting the deeper winter snow cover at sites on Livingston Island (De Pablo *et al*., 2014) and King George Island (Almeida *et al*., 2014).

Our conclusions regarding the effect of snow cover on active-layer conditions, however, should be treated with caution, as snow cover depth and distribution are highly variable and our field data cover only a brief time period. The irregular pattern of snow cover results from a combination of local climatic conditions, wind structure and orographic effects on precipitation (e.g. Turner *et al*., 2002). Moreover, Van Lipzig *et al*. (2004) confirmed an orographic effect of the AP on the spatial distribution and irregular accumulation of snow along the AP coast. On the Ulu Peninsula, the relationship between snow drift and prevailing wind direction was reported by

Zvěřina *et al*. (2014), suggesting a redistribution of snow deposits in areas of low elevation in the Abernethy Flats (6 km south of Mendel Station). Clearly, more work is needed regarding the snow cover distribution across JRI, using both ground-based and remote sensing observations.

CONCLUSIONS

Based on 2 years of meteorological observations and active-layer ground temperature monitoring at Mendel Station on JRI, we draw the following conclusions:

1. ALTs were observed between the end of January and the middle of February. Thicknesses of 58 and 52 cm measured in 2012 and 2013, respectively, are significantly lower than the ALT reported from low-elevation sites on the South Shetland Islands and South Orkney Islands.
2. Correlation analysis indicates a significant effect of air temperature on the ground thermal regime. This effect is especially apparent under snow-free conditions and during the advection of relatively warm air masses that cause large day-to-day changes in air temperature during winter.
3. The effect of snow cover depth on the ground thermal regime is indicated not only by the reduction in the daily ground temperature amplitude, but also by the total freezing *n*-factor values that were higher than 0.9. The overall influence of snow depth on ground temperature seems therefore to be negligible regarding the high values of the *n*-factor, associated with a thin and irregularly distributed snow cover.

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