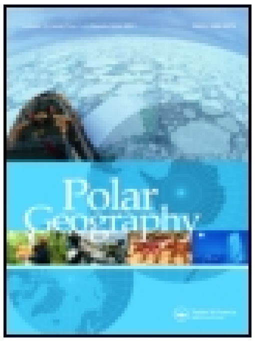

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Polar Geography

ISSN: 1088-937X (Print) 1939-0513 (Online) Journal homepage: http://www.tandfonline.com/loi/tpog20

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POLAR GEOGRAPHY, 2018
https://doi.org/10.1080/1088937X.2017.1420105

Active layer monitoring in Antarctica: an overview of results from 2006 to 2015

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ABSTRACT

Monitoring of active layer thawing depth and active layer thickness (ALT), using mechanical pronging and continuous temperature data logging, has been undertaken under the Circumpolar Active Layer Monitoring – South (CALM-S) program at a range of sites across Antarctica. The objective of this study was to summarize key data from sites in different Antarctic regions from 2006 to 2015 to review the state of the active layer in Antarctica and the effectiveness of the CALM-S program. The data from 16 sites involving 8 CALM-S and another 8 boreholes across the Antarctic have been used in the study. Probing for thaw depth, while giving information on local spatial variability, often underestimates the maximum ALT of Antarctic soils compared to that determined using continuous temperature monitoring. The differences are likely to be caused by stones limiting probe penetration and the timing of probing not coinciding with the timing of maximum thaw, which varies between seasons. The information on the active layer depth is still sparse in many regions and the monitoring needs to be extended and continued to provide a better understanding of both spatial and temporal variability in Antarctic soil thermal properties.

ARTICLE HISTORY
Received 22 May 2017
Accepted 18 December 2017

KEYWORDS
CALM-S; active layer thickness; ground temperature; Antarctica; active layer monitoring; climate

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Introduction

Antarctica is the coldest continent on Earth and contains about 90% of the World's ice. Apparently, less than 25% (ca. 3.5 mil km^2) of Antarctica has sub-glacial permafrost (Bockheim, 1995), and only about 30,900 km^2 of Antarctica comprises ice-free land (Burton-Johnson, Black, Fretwell, & Kaluza-Gilbert, 2016), which is mostly distributed around the continent margins and in nunataks. The largest ice-free areas are located in Victoria Land and the Transantarctic Mountains (about 19,750 km^2). East Antarctica has about 6930 km^2 of ice-free land, including the Vestfold Hills (about 2750 km^2), Queen Maud Land (about 2430 km^2), Enderby Land (about 1140 km^2) and Wilkes Land (about 400 km^2). Western Antarctica includes three ice-free regions, the Antarctic Peninsula (about 3800 km^2), the Ellsworth Mountains (about 380 km^2) and Marie Byrd Land (about 210 km^2). Ice-free areas are the unique environments in Antarctica where the active layer can be monitored. Active layer research in Antarctic ice-free areas includes a range of environments with varying topography, geology and climate. Thus, the study of active layer properties in different regions is important to understand the main driving factors affecting local thermal regimes and active layer thickness (ALT).

Significant advances in active layer monitoring have been made since the International Polar Year (IPY, 2007–2009), during which the number of temperature monitoring boreholes in Antarctica increased from 24 to 73 (Vieira et al., 2010). Now there are almost 100 Antarctic ground temperature monitoring sites included in the Global Terrestrial Network for Permafrost (GTN-P) database. The highest densities of boreholes are in the Antarctic Peninsula region and in the Dry Valleys in Victoria Land.

The number of studies on active layer dynamics in the Antarctic increased since 2010 and most of them have focused on characterization of the active layer thermal regime in boreholes located in soils or sediments (e.g. Bockheim, 2015; de Pablo, Ramos, & Molina, 2014; Kotzé & Meiklejohn, 2017; Schaefer et al., 2017) as well as on their climate control (Guglielmin & Cannone, 2012; Lacelle et al., 2016). Important progress has been made in understanding the effect of snow on active layer dynamics, mainly in the Antarctic Peninsula region (e.g. Guglielmin, Worland, Baio, & Convey, 2014; Hrbáček, Láska, & Engel, 2016; de Pablo, Ramos, & Molina, 2017; Oliva, Hrbacek, et al., 2017; Ferreira, Vieira, Ramos, & Nieuwendam, 2017). Other recent studies have focused on the effects of vegetation (Guglielmin, Dalle Fratte, & Cannone, 2014; Michel et al., 2012), lithological or ground thermal properties (Goyanes, Vieira, Caselli, Mora, et al., 2014; Hrbáček, Kňažková, et al., 2017; Hrbáček, Nývlt, & Láska, 2017), the active layer thermal regime and thickness, and the thermal regime in the deep boreholes in bedrock (Correia, Vieira, & Ramos, 2012; Guglielmin, Balks, Adlam, & Baio, 2011; Guglielmin, Worland, et al., 2014). The procedures for monitoring active layer dynamics, included in the Circumpolar Active Layer Monitoring (CALM) protocol, were standardized for Arctic regions by Brown, Hinkel, and Nelson (2000). Guglielmin (2006) implemented the CALM protocol in Antarctica and defined its southern form (CALM-S), which he adapted for Antarctic conditions. The CALM-S approach has been applied in various regions across Antarctica (e.g. Guglielmin, Worland, & Cannone, 2012; de Pablo et al., 2013; Guglielmin & Cannone, 2012; Ramos et al., 2017; Hrbáček, Kňažková, et al., 2017). Currently, around 15 CALM-S sites are estimated to be active in Antarctica according to the GTN-P database.

Despite the increase in CALM-S sites, recent studies focused primarily on only one or two sites and a regional perspective on the variability of active layer properties across Antarctica is still lacking. Regional synthesis is mainly limited to the Antarctic Peninsula region (e.g. Bockheim et al., 2013) and the McMurdo Dry Valleys (e.g. Adlam, Balks, Seybold, & Campbell, 2010), while the only overview for Antarctica has been conducted after the International Polar Year in 2007–2009 (Vieira et al., 2010). This work showed the gradient of ground temperature and ALT from the warmest areas in Antarctic Peninsula (ALT of 0.3–4 m) to the coldest areas in mountainous regions of Eastern Antarctica and Victoria Land (ALT of 0.1–0.5 m).

The main objective of this paper is to present an updated overview of the current state, the active layer at selected CALM-S sites and selected active layer boreholes for three sectors of Antarctica. The assessment focuses on mean annual air and ground temperatures (MAAT and MAGT), thaw depth and ALT as key variables of the active layer thermal state. The selected sites explore the potential importance of the growing dataset to understanding permafrost and climate effects in the ice-free regions of Antarctica. The strengths and weaknesses of the current data collection efforts are assessed and areas for future development are considered.

Methodology

CALM-S sites

In this study, MAAT and MAGT probed active layer thaw depth (referred to here as 'thaw depth'), thermally defined ALT and ground temperatures were studied at eight CALM-S sites in Antarctica and additionally in eight boreholes. The CALM-S sites reported in this study are located in the Antarctica Peninsula region (five), and on the coastal fringe of Eastern Antarctica (three) (Table 1 and Figure 1). The boreholes used in this study are representative of ice-free regions in Antarctica where CALM-S sites could not be established due to lithological terrain properties containing a large volume of coarse fraction impeding active layer probing. Areas with continuous temperature monitoring, rather than probing for thaw depth, include the McMurdo dry valleys (four) Eastern Antarctica (three) and the Antarctic Peninsula (one) (Table 1 and Figure 1).

The original CALM protocol, which focused on understanding local thaw depth variability (Brown et al., 2000), was modified to better suit Antarctic conditions for Circumpolar Active Layer Monitoring – South (CALM-S). The main difference was enabling probing in smaller, or irregular, grids instead of the standard 100×100 m grid as coarse and rocky terrain is difficult to effectively probe for depth to ice cement (Guglielmin, 2006) and some Dry Valley sites do not have sufficient moisture to form ice cement. Prevailing ground properties of coarse and rocky texture in Antarctica often prevent active layer probing and make this method possible to apply in some areas only. Other limitations of CALM-S probing measurements in Antarctica are also related to climate and logistic constraints, which may prevent grid measurement at, or close to, the date of maximum ALT during the thawing seasons (Guglielmin, 2006). Therefore, the active layer thaw depth measured, by probing, annually at around the same date, was used as a representative approach.

Table 1. Summary of CALM-S sites and boreholes in Antarctica selected for this study.

Region	Locality	Site	Period	CALM-S	Cont.	Lat.	Long.	Altitude (m asl.)	Borehole (m)
Antarctic Peninsula	Deception Island	Collado Irizar	2009–2015	Yes	Yes	−62.98	−60.67	130	1.6
	Deception Island	Crater Lake	2006–2015	Yes	Yes	−62.98	−60.72	85	4.5
	Livingston Island	Limnopolar Lake	2009–2015	Yes	No	−62.65	−60.11	80	1.3
	King George Island	Bellingshausen	2006–2015[a]	Yes	No	−62.19	−58.98	18	9.5[b]
	James Ross Island	J. G. Mendel	2012–2015	Yes	Yes	−63.8	−57.88	10	2.0
	James Ross Island	Rink Point	2006–2014	No	Yes	−63.90	−58.22	400	1.0
East Antarctica	Enderby Land	Molodyozhnaya	2008–2015	Yes	No	−67.66	−45.86	26	1.0[b]
	Queen Maud Land	Novolazarevskaya	2010–2015[a]	Yes	No	−70.46	11.47	94	3.0[b]
	Queen Maud Land	Vesleskarvet	2009–2014	No	No	−71.69	−2.84	805	0.6
	Queen Maud Land	Flårjuven	2008–2015	No	No	−72.01	−3.39	1220	0.6
	Quenn Maud Land	Trol	2007–2015	No	No	−72.01	2.53	1320	2.0
	Vestfold Hills	Progress	2008–2015	Yes	No	−69.24	76.2	90	3.2
Victoria Land	McMurdo	Scott Base	2006–2015	No	No	−77.85	166.76	38	1.2
	McMurdo Dry Valleys	Wright Valley	2006–2015	No	Yes	−77.52	161.87	150	1.2
	McMurdo Dry Valleys	Mount Fleming	2006–2015	No	No	−77.55	160.29	1700	1.0
	Wood Bay	Baker Rocks	2006–2015	No	Yes	−74.21	164.83	11	1.6

Note: Cont., continuous temperature data series in period 2006–2015; NA, not available.
[a]Data of MAAT was completed from READER database.
[b]Outside CALM-S grid, drilled in bedrock

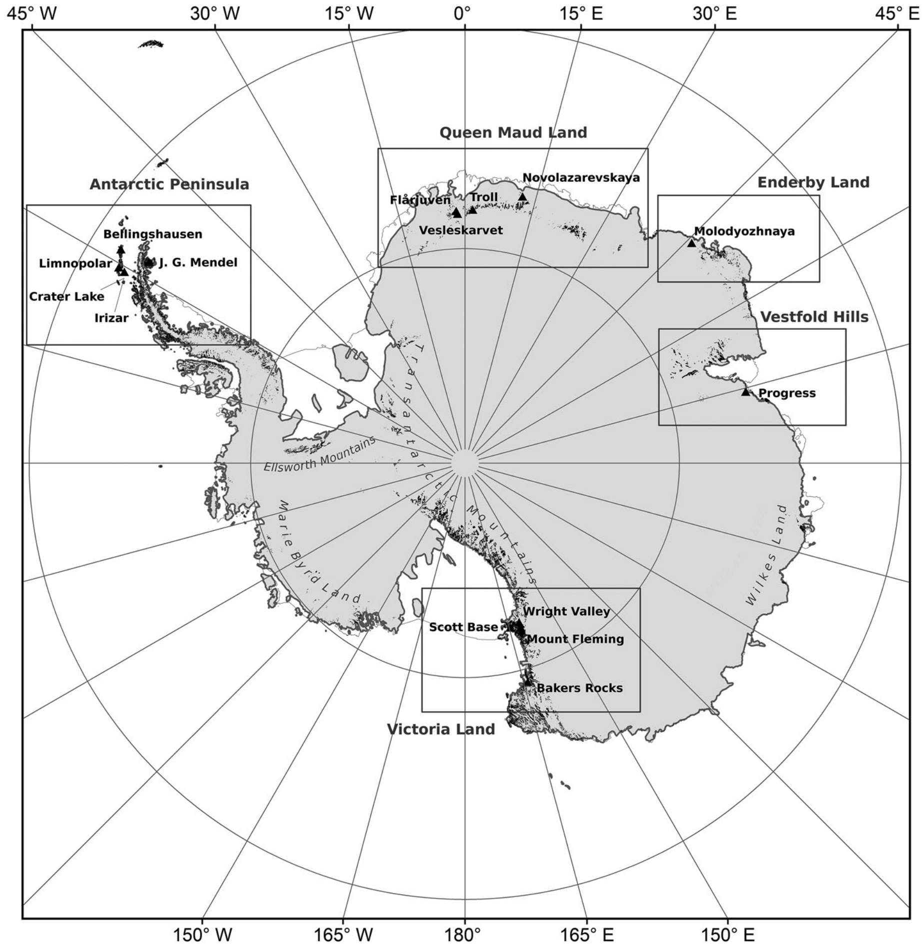

Figure 1. Localization of study sites across Antarctica continent. The ice-free regions are marked with black, the glaciers by gray color.

MAAT and MAGT data cover the period from 2006 to 2015; however, at several sites, the period is shorter or not continuous (Table 1).

Active layer thermal and thickness monitoring

Monitoring of ground temperatures in Antarctica has been undertaken both in shallow (e.g. Guglielmin & Cannone, 2012; Guglielmin, 2006; Guglielmin, Dalle Fratte, et al., 2014; Goyanes, Vieira, Caselli, Cardoso, et al., 2014; Goyanes, Vieira, Caselli, Mora, et al., 2014; de Pablo et al., 2014) and deep boreholes (e.g. Bockheim et al., 2013; Correia et al., 2012; Guglielmin et al., 2011, 2014; Ramos, Hassler, Vieira, Hauck, & Gruber, 2009) or using sensors directly placed in the soil profile (e.g. Adlam et al., 2010; Raffi & Stenni, 2011; Michel et al., 2012; Hrbáček, Láska, et al., 2016; Kotzé & Meiklejohn, 2017). Near-surface ground temperature data are available from the majority of the study sites (Table 2). One of the main inconsistencies is in the position of the near-surface thermistor. Despite the effort carried out by the 'Antarctic Permafrost, Soils and

Table 2. Characteristics of MAAT and MAGT (2–5 cm depth) and mean probed thaw depth (MPTD) and mean active layer thickness (MALT) in the different study sites during the period 2006–2015.

Region	Locality	Site	Period	MAAT	MAGT	MPTD	MALT
Antarctic Peninsula	Deception Island	Collado Irizar	2009–2015	−3.1	−2.2	54	85
	Deception Island	Crater Lake	2006–2015	−2.8	−1.6	29	45
	Livingston Island	Limnopolar Lake	2009–2015	−2.5	−0.7	30	>130
	King George Island	Bellingshausen	2006–2015	−2.3	−0.6	60	300[a]
	James Ross Island	Johann Gregor Mendel	2012–2015	−7.0	−5.7	74	60[b]–85[c]
	James Ross Island	Rink Point	2006–2014	−8.2	−7.0	NA	60
East Antarctica	Enderby Land	Molodyozhnaya	2008–2015	−11.0	NA	65	>100[a]
	Queen Maud Land	Novolazarevskaya	2010–2015	−10.3	−10.1	73	100[a]
	Queen Maud Land	Vesleskarvet	2009–2014	−15.9	−16.1	NA	16
	Queen Maud Land	Flårjuven	2008–2015	−17.9	−17.5	NA	23
	Quenn Maud Land	Troll	2007–2015	−17.8	−17.4	NA	17
	Vestfold Hills	Progress	2008–2015	−10.0	−9.4	80	80
Victoria Land	McMurdo	Scott Base	2006–2015	−17.8	−16.1	NA	37
	McMurdo	Wright Valley	2006–2015	−19.1	−18.7	NA	51
	McMurdo	Mount Fleming	2006–2015	−24.0	−23.3	NA	7
	Wood Bay	Baker Rocks	2006–2015	−15.7	−15.6	NA	40

Note: NA, not available.
[a]Borehole outside CALM-S in bedrock.
[b]Johann Gregor Mendel – profile 1.
[c]Johann Gregor Mendel – profile 2.

Periglacial Environments' (ANTPAS) group, which was approved as a core project of International Permafrost Association for Antarctic research, the proposed protocols for ground thermal monitoring have not been fully implemented yet. Currently, there are differences between sites with regard to the sensor depths in the ground as well as the height of air temperature measurement, accuracy of thermistors and measurement intervals. The near-surface thermistor is recommended to be placed at 2 cm (Guglielmin, 2006); however, it has been placed at depths of between 1 and 5 cm. Also, given the uneven nature of many Antarctic surface pavements, accurate determination of shallow depths is difficult. Similarly, the position of thermistors in the lower parts of profiles, or boreholes depth used, tends to be specific for each site depending on variables such as the ALT, soil texture or drill depth.

Data

In this study, we examine MAAT and MAGT recorded during the period 2005–2016. To obtain the most consistent datasets, MAAT from several localities included in the Reference Antarctic Data for Environmental Research database (READER, 2017) were used to cover the whole period 2006–2015 (Table 1).

Active layer thaw depth measurements were obtained from eight sites, including the CALM-S grid. Thawing depth represents the mean value from all probed measurements within each CALM-S site. On every site, probing was undertaken during the first half of February each year. No CALM-S sites were not analyzed in higher elevated areas of Eastern Antarctica and area of Victoria Land.

For all study sites, the ALT was numerically determined as the maximum annual depth of the 0°C isotherm using interpolation of maximum seasonal ground temperatures from the two deepest temperature measurements following Guglielmin (2006), the annual variability was analyzed in sites without the CALM-S grid.

Results

Northern Antarctic Peninsula

The north-western part of the Antarctic Peninsula region is the warmest part of Antarctica. The MAAT in this region varied between −2.0°C and −3.0°C for the period 2006–2015. In the colder north-eastern Antarctic Peninsula, represented by two sites on James Ross Island, the MAAT ranged around −7°C to −8 °C (Figure 2). Considerably

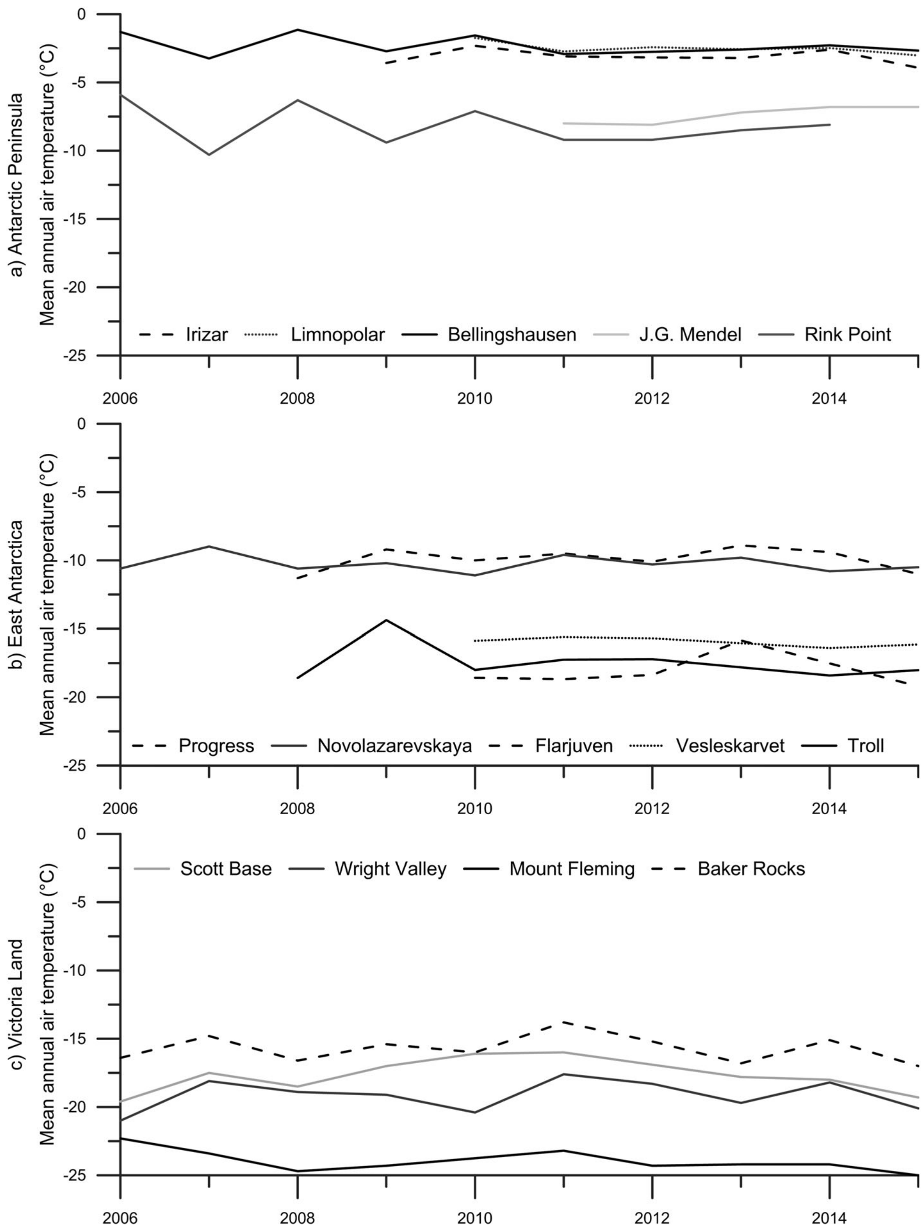

Figure 2. MAAT in particular regions of Antarctica.

higher MAAT in the western part of Antarctic Peninsula resulted in near-surface MAGT close to 0°C in King George (−0.6°C) and Livingston islands −0.7°C), and lower in Deception Island (−1.6°C to −2.2°C).

The mean thaw depth at CALM-S sites in the western Antarctic Peninsula varied from 29 cm on Deception Island – Crater Lake (2006–2016) to 60 cm on King George Island – Bellingshausen (2008–2016) (Table 2). The annual maximum mean active layer depth ranged from 36 cm on Deception Island – Crater Lake (2006) to 86 cm on King George Island (2009). In 2009, the greatest thaw depths were observed, on Deception Island, at Irízar (67 cm) and at Livingston Island (47 cm). At all sites in the western Antarctic Peninsula, a progressive decrease in ALT started in 2009 and persisted until 2015 (Figure 3). The only CALM-S site in the eastern Antarctica Peninsula is located on James Ross Island, where measurements started in 2014. Mean thaw depth for the period 2014–2016 reported 74 cm, varying between 66 cm (2014) and 78 cm (2015) (Figure 3).

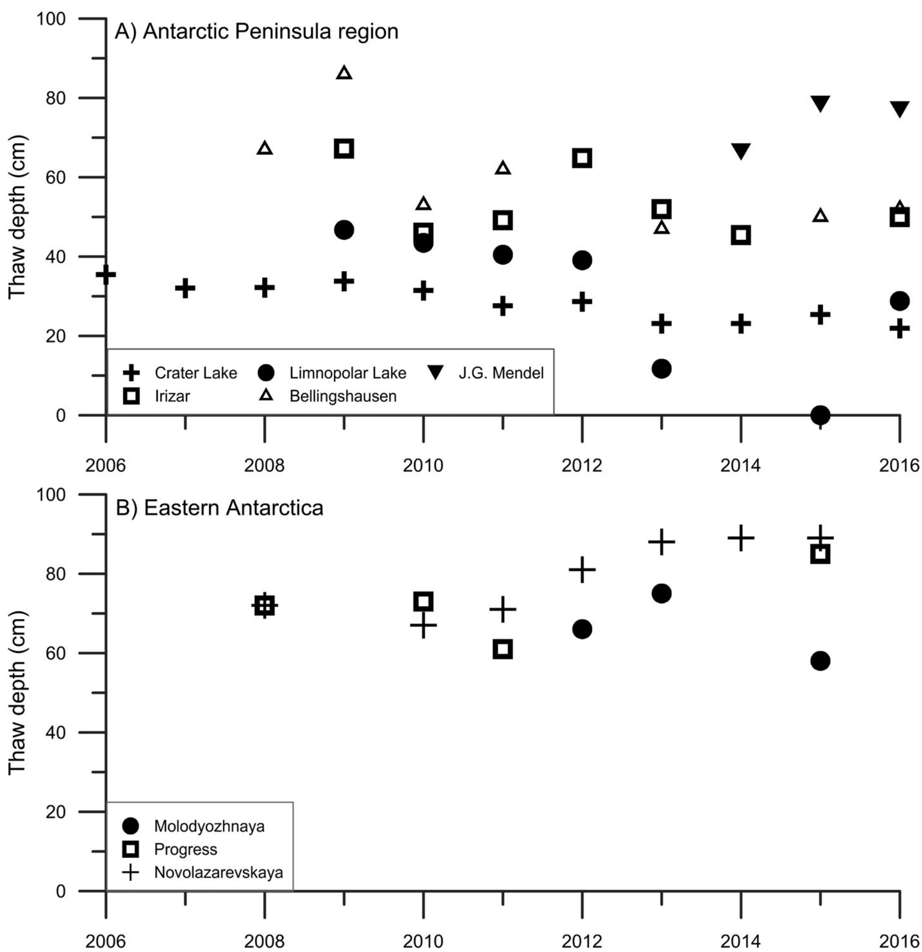

Figure 3. Active layer thaw depth measured on CALM-S sites in Antarctic Peninsula and Eastern Antarctica regions.

In the South Shetlands, the ALT regularly exceeded 130 cm at the Limnopolar site (Livingston Island) during the period 2009–2016 (Table 2). The deepest ALT observed in the vicinity of Bellingshausen was 300 cm; however, the borehole is located in bedrock. Deception Island's lower ALTs are attributed to porous pumice lapilli cover in Crater Lake (40–50 cm) and to mixed volcanic ash and pyroclastic deposits, without the lapilli cover at Irizar (70 cm). Despite cooler MAAT on the eastern side of the Antarctic Peninsula, the ALT on James Ross Island was similar to values of Deception Island ranging from 60 to 85 cm in two ground temperature measurement profiles located at the CALM-S J.G. Mendel site. An ALT between 40 and 75 cm was observed at the higher altitude Rink Point site (400 m, Table 2).

Eastern Antarctica

Eastern Antarctica represents the largest part of the continent and therefore a large variability can be expected in this region in terms of air and ground temperatures. Two main ice-free environments are found within this region: (a) the low-altitude coastal areas and (b) the interior with high mountains and plateaus. The MAAT in maritime environments in Eastern Antarctica varied between −11°C and −9°C for the period 2006–2015, while at higher altitudes it ranged from −18°C to −16°C (Figure 2). The MAGT showed similar values as MAAT in coastal zones (ci. −10°C), while it decreased to −17.5°C to −16°C in higher areas.

Thaw depth measurements from the three CALM-S sites located in the coastal zone in Enderby Land, Vestfold Hills and Queen Maud Land (Table 1 and Figure 1) show discontinuous data for the period 2008–2015 (Figure 2). Mean thaw depth varied between 58 and 75 cm in Molodyozhnaya (2012–2015), while slightly thicker mean thaw depths were recorded during four seasons between 2008 and 2015 in Progress (61–85 cm, Figure 3). The only continuous measurement of thaw depth is from Novolazarevskaya, where mean thaw depth reached 81 cm, ranging from 67 to 89 cm (2010–2015). At this site, thaw depth gradually increased from 2010 (67 cm) to 2013 (89 cm) (Figure 3).

Shallow borehole temperatures from the low-altitude coastal regions showed that the ALT regularly exceeded 100 cm at the Molodyozhnaya and Progress stations, with a maximum depth exceeding 120–130 cm. A thinner ALT of around 70–90 cm was observed in Novolazarevskaya. A much thinner active layer was observed at the high altitude sites of Queen Maud Land, where the mean ALT varied from 10 to 17 cm at Veleskarvet to 13–26 cm at Flårjuven (Figure 4 and Table 2).

Victoria Land

The Dry Valleys in Victoria Land are the largest continuous ice-free area in Antarctica. Although the region includes both coastal and mountain environments, the climate is dry polar-continental. In the Dry Valleys region, air temperature was measured along a transect from near sea level at Scott Base to 1700 m altitude at Mount Fleming. MAAT for the period 2006–2015 decreased with altitude from −17.8°C at Scott Base to −24.0°C at Mount Fleming (Table 2). A higher MAAT of −15.7°C was observed at about 3.3° latitude further north, near the coast of Wood Bay, at Baker Rocks (11 m altitude, Figure 2). The MAGT was 1.6°C higher than MAAT on Scott Base, while in other sites varied between 0.1°C (Bakers Rocks) and 0.7°C (Mount Fleming).

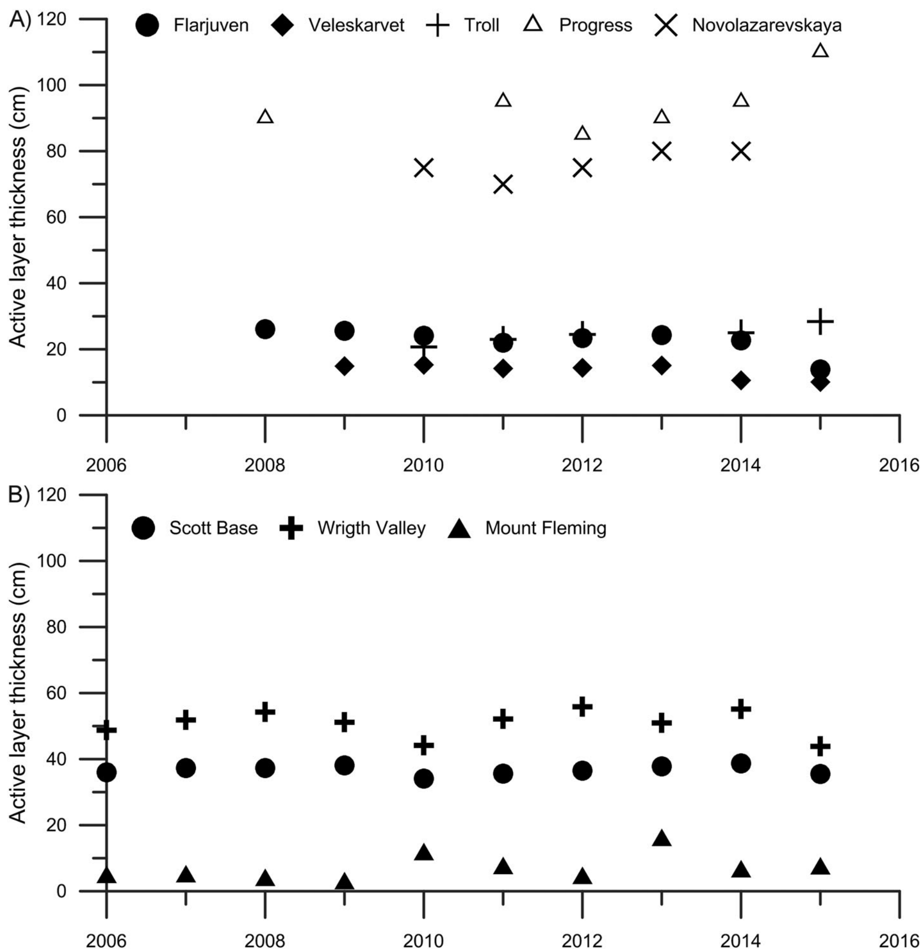

Figure 4. ALT in sites in Eastern Antarctica (A) and Victoria Land (B).

Mean ALT in the Dry Valleys varied between 7 cm (Mount Fleming) and 51 cm (Wright Valley). ALT did not follow the same pattern as MAAT and it did not correlate strictly with elevation. In general, ALT varied between 34 and 39 cm at low-altitude Scott Base, 44 and 56 cm at Wright Valley and 3–16 cm at the highest altitude Mount Fleming (Figure 4). The ALT at Baker Rocks in Victoria Land was between 40 and 50 cm (Table 2).

Discussion

Climate

Air temperatures showed significant regional differences within the study areas. In the western Antarctic Peninsula region, Vestfold Hills and northern Victoria Land, a slight air temperature cooling was detected, while at other sites in Victoria Land and East Antarctica the air temperature was more irregular, showing no strong overall trend of warming or cooling during the study period (Figure 2). The Antarctic Peninsula region has been reported as the most rapidly warming part of Antarctica (e.g. Turner et al., 2005, 2014), but cooling has been reported since 2000 (Turner et al., 2016). Relatively stable air temperature conditions during the past 20 years were reported in Victoria Land (Guglielmin & Cannone, 2012). MAGTs from 2006 to 2015 showed a spatial pattern similar to the ones identified by Vieira et al. (2010), with temperatures close to 0°C (approximately −0.5°C to −2.5°C) in north-western Antarctic Peninsula to values below −17°C in high altitude environments in Eastern Antarctica and Victoria Land.

Variability of thaw depth probing on CALM-S sites

Monitored thaw depths on CALM-S sites showed large differences between the studied localities. Some of the thinnest thaw depths (<50 cm) were observed in the western Antarctic Peninsula region (Table 2), although it is the warmest area in Antarctica (Turner et al., 2014). Significantly, thicker thaw depths were observed in the colder regions of the eastern Antarctic Peninsula and the coastal zone of East Antarctica. The general pattern suggests that factors other than regional climate should be considered when examining the ground thermal regime (e.g. Hrbáček, 2016). Between 2009 and 2014, substantial active layer thinning was observed at all sites in the western Antarctic Peninsula. The thinning was attributed to climate cooling in the region (Oliva, Navarro, et al., 2017; Turner et al., 2016) and changes in snow cover accumulation, as well as snow persistence during the summer, reducing active layer thaw (de Pablo et al., 2017). In contrast, pronounced active layer thickening between 2010 and 2013 was recorded at Novolazarevskaya in coastal East Antarctica (Figure 3).

The ALT data (Table 2) show that the mean thaw depths measured in CALM-S sites were smaller than the ALT at the same sites. There are two possible explanations for these differences. One of the most important factors causing lower reported thawing depth, compared to ALT, has been the date of probing, which is generally not coincident with the maximum thaw depth. For instance, measurements in the South Shetland Islands have generally been undertaken during the first week of February (e.g. de Pablo et al., 2013; Ramos et al., 2017) while the maximum ALT usually occurs in late February or March in this area (e.g. de Pablo et al., 2014; Goyanes, Vieira, Caselli, Cardoso, et al., 2014; Oliva, Hrbacek, et al., 2017). The most pronounced differences between thaw depth and ALT have been observed at Livingston Island (CALM-S Limnopolar), where the mean thaw depth calculated from all thaw depth measurements was less than 50 cm, while the ALT exceeded 130 cm in every year (de Pablo et al., 2013, 2014).

Other factors influencing mean thaw depths are specific for individual sites and frequently related to the fact that the reported depth is an average from the measurements within the CALM.grid. Snow, vegetation cover and soil thermal properties are the most important factors causing local decreasing of the ALT. Irregular snow deposition and seasonal duration reduces thaw depth in parts of the grid with snow cover during summer (e.g. de Pablo et al., 2013; Guglielmin, 2006). Moreover, snow cover duration was prolonged in the South Shetland Islands during the summers 2013–2016 and correlated with pronounced thinning of thaw depth (de Pablo et al., 2017; Ramos et al., 2017) and has even prevented probing the whole CALM grid and even delayed the measures. Studies on vegetation covering the CALM-S sites are limited to northern Victoria Land, where vegetation, when present, shows an insulating effect (Guglielmin, Worland, et al., 2014). On bare ground and snow-free areas, thaw depth differences within a study site are mainly related to lithological variability of the ground (Hrbáček, Nývlt, & Láska, 2017).

Thaw depth measurements showed that probing is a useful and simple tool to study spatial variability of thaw depth (e.g. Vieira et al., 2010; de Pablo et al., 2013; Ramos et al., 2017). Moreover, as Hrbáček, Kňažková, et al. (2017) showed, multiple measurements during summer and potential calculation of the maximum thaw depth according to thawing propagation of the 0°C isotherm, as recommended by Brown et al. (2000), could provide a means to minimize the differences between mean values of probed thaw depth and maximum ALT. Multiple measurements could be important due to the considerable interannual variability of the date of maximum ALT in Antarctica, which can vary by several weeks (e.g. Adlam et al., 2010; de Pablo et al., 2014; Hrbáček, Nývlt, et al., 2017).

ALT variability

Unlike thaw depth, the ALT, measured using temperature data, was greatest in the western Antarctic Peninsula region. Our results are consistent with other observations from the South Shetland Islands, with the ALT usually exceeding 100 cm in loamy soils (e.g. de Pablo et al., 2013; Michel et al., 2012; Oliva, Navarro, et al., 2017). However at Deception Island, where the ALT is impacted by the porous nature of the pyroclastic volcanic material and high soil moisture, which increases the amount of heat necessary for water phase change, the ALT reached only 30–50 cm at Crater Lake under pumice lapilli (Ramos et al., 2017) and 50–70 cm at the Irizar site under finer tephras (Goyanes, Vieira, Caselli, Cardoso, et al., 2014). The deepest ALT (>300 cm) was observed in bedrock in the vicinity of Bellingshausen site, which corresponds to other observations in bedrock in other sites across western Antarctic Peninsula region where the ALT usually exceeded 150 cm (Ramos and Vieira, 2009; Correia et al., 2012; Guglielmin, Worland, et al., 2014). In the eastern Antarctic Peninsula and coastal Eastern Antarctica, where MAAT ranged between −7°C and −10°C at sea level, the active layer has been generally thinner, with 50–100 cm (Bockheim et al., 2013; Hrbáček, Láska, et al., 2016; Hrbáček, Kňažková, et al., 2017). Maximum ALT in both the eastern Antarctic Peninsula and East Antarctica usually reached between 100 and 120 cm (e.g. Bockheim, 2015; Hrbáček, Kňažková, et al., 2017; Mergelov, 2014).

Generally, the thinnest ALT in Antarctica was observed in the high altitude areas of Eastern Antarctica in Queen Maud Land where ALT reached about 15–25 cm (e.g. Kotzé & Meiklejohn, 2017) and in Victoria Land with mean ALT of around 30 cm, rarely exceeding 50 cm. Of all the study sites reported here, the minimum ALT was observed at the highest altitude monitoring site, Mount Fleming, in the Dry Valleys region, where the ALT varied between 2 and 15 cm during the period 1999–2006 (Adlam et al., 2010) and between 3 and 16 cm between 2006 and 2015. Due to the low air temperatures during summer and lack of vegetation or snow cover, an important factor affecting ALT in the cold environment of Victoria Land is varying solar radiation, which was found to be an important influence on active layer summer thawing (Adlam et al., 2010; Guglielmin, Worland, et al., 2014).

Conclusions

In this work, we examine MAAT and MAGT, ALT and thawing depth in multiple sites across Maritime and Continental Antarctica between 2006 and 2015. This synthesis provides the first characterization of the state of the active layer state in Antarctica since the International Polar Year 2007–2009. The most detailed and consistent information on active layer thermal regime, thickness and thaw depth is from the Antarctic Peninsula and Victoria Land, two climatically contrasting regions of Antarctica. Data from coastal and mountainous parts of Eastern Antarctica are still limited to a few sites and time series are frequently discontinuous.

The monitored sites cover a range of environments from maritime, low-altitude sites on the Antarctic Peninsula, to higher altitude continental sites in the McMurdo Dry Valleys in Victoria Land. MAAT ranged from −2.5°C to −24.0°C and active layer depths in soil from 7 cm to more than 130 cm. There was a marked interannual variability, with further monitoring still needed to identify trends.

The CALM-S protocol for grid probing to determine depth of thaw and active layer measurements using temperature data logging has generated an important dataset that allowed to better characterize the ground thermal regime and thaw depth variability in Antarctica. CALM-S grids provide spatially distributed thaw depth measures and thus provide a solid approach reflecting soil heterogeneity, water content changes and topography. In some areas, there were large differences between the probed thaw depth and thermally defined ALT inferred from ground temperature measurements in boreholes. Probing generally underestimated the maximum ALT, likely due to stones impeding probing, or to the timing of probing not coinciding with the time of maximum thaw.

For a better understanding of active layer spatial variability in Antarctica, more detailed studies from individual CALM-S sites are needed. To date, research on thaw depth spatial distribution has been published from only four sites in the Antarctic Peninsula and the South Orkneys and from one site in Victoria Land. This number is clearly insufficient considering that the total number of CALM-S sites was reported as 28 in Vieira et al. (2010), although the total number of currently active sites is likely to be around 15. As such, one of the main efforts of ANTPAS should be coordinating observations and urge results to be published, especially those from outside the Antarctic Peninsula and Victoria Land. Improving and standardization of measurement methods are also needed at some sites. Repeated probing, in combination with multiple temperature-depth monitoring, inside CALM-S grids will significantly improve the results from CALM-S sites and their potential to serve the wider science community and stakeholders.

Acknowledgements

Antarctica NZ provides logistic support for the McMurdo Dry Valley sites with collaborative support from Landcare Research and the United States Department of Agriculture. Logistical support was provided by the Directorate Antarctica and Islands, Department of Environmental Affairs (South Africa). The research work of J. Strelin, T. Sone and K. Fukui in Rink Point, James Ross Island was carried out under the Instituto Antártico Argentino-UNC-CICTERRA Agreements and the Joint Research Program of the Institute of Low Temperature Science, Hokkaido University. Special words of thanks go to Mr S. Sega for his active participation in the field investigations, and Dr R. Bono for field maintenance of the thermometric station.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The research was supported by the Masaryk University project MUNI/A/1315/2015: Integrated research of environmental changes in the landscape sphere. The work was also supported by the Ministry of Education Youth and Sports (MEYS) large infrastructure project LM2015078 'Czech Polar Research Infrastructure'. G. Vieira contribution has been supported by the Portuguese Polar Program and the Fundação para a Ciência e a Tecnologia. Marc Oliva is supported by the Ramón y Cajal Program of the Spanish Ministry of Economy and Competitiveness (RYC-2015-17597). Monitoring stations at Livingston and Deception islands have been supported in the last decade by different projects funded by the Government of Spain, including projects PERMASNOW (CTM2014-52021-R), ANTARPERMA (CTM2011-15565-E), PERMAPLANET (CTM2009-10165) and PERMAMODEL (POL-2006/01918), with the collaboration of Portuguese, Russian, Swiss and Czech researchers. Research and data processing at Bellingshausen, Novolazarevskaya, Molodyozhnaya and Progress stations were supported by the Russian Science Foundation, Project No. 14-27-00133; Russian Antarctic expedition (logistical support) and UAF (data loggers for ground temperature). The work of I. Meiklejohn is based on the research supported by the National Research Foundation (South Africa). The research of R. Raffi was funded by the Italian Antarctic National Research Program (PNRA). This research waspromoted within the SCAR/IPA ANTPAS Expert Group.

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