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A permafrost warming in a cooling Antarctica?

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Abstract The magnitude and even direction of recent Antarctic climate change is still debated because the paucity of long and complete instrumental data records. While along Antarctic Peninsula a strong warming coupled with large retreat of glaciers occurred, in continental Antarctica a cooling was recently detected. Here, the first existing permafrost data set longer than 10 years recorded in continental Antarctica is presented. Since 1997 summer ground surface temperature showed a strong warming trend (0.31°C per year) although the air temperature was almost stable. The summer ground surface temperature increase seemed to be influenced mainly by the increase of the total summer radiation as confirmed also by the increase of the summer thawing degree days. In the same period the active layer exhibited a thickening trend (1 cm per year) comparable with the thickening rates observed in several Arctic locations where air warming occurred. At all the investigated depths permafrost exhibited an increase of mean annual temperature of approximately 0.1°C per year. The dichotomy between active layer thickness and air temperature trends can produce large unexepected and unmodelled impacts on ecosystems and CO_2 balance.

1 Introduction

Antarctica is considered a key area for the global climate and the part of the world least disturbed by anthropogenic impacts. Compared with other parts of the world, the record of climatic change here is well known for the period between 1950 AD to 820.000 BP because high-resolution paleoclimatic reconstructions were facilitated by the acquisition of deep ice-core records (Jouzel et al. 2007).

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In contrast, a lack of instrumental records makes Antarctica one of the least-known areas of the world with respect to recent climate change, because stations with records longer than 30 years are very scarce. For this reason, recent climate change in Antarctica is a contentious subject. Some papers argue for enhanced warming, which is particularly high along Antarctic Peninsula, coupled with substantial retreat of glaciers (Turner et al. 2007). Turner et al. (2007) pointed out that air temperatures on the western side of the Antarctic Peninsula have risen more than anywhere else in the entire Southern Hemisphere. At Faraday, an annual warming rate of +0.56°C per decade has been recorded, while the winter trend was +1.09°C per decade. On the eastern side of the Antarctic Peninsula, the largest increases in temperature occurred during summer, inducing the disintegration of ice shelves such as the Larsen B (Rott et al. 1996). Turner et al. (2007) also note, however, that the Antarctic continent shows little change. On the other hand, Doran et al. (2002), analysing the data of the station located at Lake Hoare in the Dry Valleys, for the period between 1986 and 1999 revealed a decrease of summer temperature (−1.2°C per decade) and, even more pronounced, for autumn temperature (−2.0°C per decade).

Traditionally, climatic series are considered significant only if enough long (30 years), but several authors (e.g. Hunt and Elliott 2006). assert the importance of shorter series underlying the dominance of decadal variability.

Permafrost temperature can be a very useful tool for understanding recent climate change and its impact on the cryosphere. For these reasons, the IPY project “Thermal State of Permafrost” was created to achieve a snapshot of the thermal conditions of the permafrost on the planet. The latest IPCC assessment (Fischlin et al. 2007) stresses the large feedbacks between climate and its impacts on the ecosystems in which permafrost degradation and active layer thickening occur. Among them, are large hydrological changes at the surface (e.g. Yoshikawa and Hinzman 2003; Smith et al. 2005), increased release of methane to the atmosphere (e.g. Walter et al. 2006; Zimov et al. 2006; Mastepanov et al. 2008), changes in vegetation composition (e.g. Cannone et al. 2007; Cannone and Guglielmin 2009), increases in dissolved material in rivers and oceans (e.g. Frey and McClelland 2009; Benner 2004) and increases in slope instability and rock falls (e.g. Watson and Haeberli 2004).

Following the increased awareness about these topics, several published papers describe recent general trends of permafrost warming. In such different parts of the northern hemisphere as northern Alaska (e.g. Osterkamp and Jorgenson 2005), Siberia (e.g. Malkova 2008), and northern Europe (e.g. Isaksen et al. 2007) recent permafrost warming was detected. Nevertheless, in some Arctic sites both in Alaska (e.g. Osterkamp 2008) and northern Canada (e.g. Smith et al. 2005) periods without warming or even with cooling occurred since 1994. Close to the Siberian city of Yaktusk, ground temperature at 3.2 m depth has cooled (e.g. Fedorov and Konstantinov 2008). Permafrost warming was mainly attributed to the air warming, although in several cases the role of snow-cover changes was emphasized (e.g..Osterkamp 2007; Romanovsky et al. 2007; Fedorov and Konstantinov 2008).

Active layer thickness does not always follow the trend of the underlying permafrost and, in general, appears much more closely related to the trend of summer air temperature (e.g. Osterkamp 2008; Streletskiy et al. 2008)

Due to logistical constraints, there are no permafrost monitoring records longer than 10 years in Antarctica, except for the data presented in this paper and recorded since 1996. Recently, Adlam et al. (2010) reported the absence of a significant trend across the up-to-eigth years of active layer thickness data investigated on different sites in McMurdo area. Here the data relating to air and ground temperature within permafrost at different depth recorded in the period December 1996–December 2009 are presented. The main aims of this paper are: 1) analyse the recent trends of permafrost temperature and active layer thickness in Continental Antarctica; and 2) understand the climatic meaning of the potential identified trends in order to assess the recent climate change impacts on permafrost and active layer.

2 Site description

The study site, named unofficially Boulder Clay, is located close to the Italian Antarctic Research Station "Mario Zucchelli"(MZS), in Northern Victoria Land. Boulder Clay (74°44′45″S,164°01′17″E, 205 ma.s.l.) is an ice-free area located about 6 km south of the Italian station on a very gentle slope (5°) with southeastern exposure. Lithologically a Late Glacial ablation till overlies a body of dead glacier (Guglielmin et al. 1997). Surface features include perennially ice-covered ponds with icing blisters and frost mounds, frost-fissure polygons and debris islands (Guglielmin et al. 1997; French and Guglielmin 1999, 2000).

The till matrix is generally silty-sand with small patches of clayey silt. The surface colour is dominated by light pink granitic pebbles and gravel. Vegetation is very scarce (less than 5% of the surface is covered by vegetation) that is composed mainly by patches of mosses and epilithic lichens (Cannone et al. 2008). The site of the borehole is devoided by vegetation. Climate of the area surrounding MZS is characterised by a mean annual air temperature of −13.9°C (Frezzotti et al. 2001) and a total precipitation of around 200 mm/year (Monaghan et al. 2006).

The Boulder Clay site represents the longest near-continuous data series of permafrost and active layer temperature in Antarctica (Guglielmin 2004, 2006). Since 1999 a 100× 100 m Circumpolar Active Layer Monitoring (CALM) grid (Nelson et al. 2008) was established at this site. Details on the active layer and GST spatial variability were illustrated in a previous paper (Guglielmin 2006).

3 Methods

3.1 Field measurements

Approximately 200 m outside the CALM grid in 1996 was drilled a shallow borehole (3.6 m deep) instrumented by 6 thermistors placed at depths of 2, 30, 60, 160, 260 and 360 cm. The core is characterised by an upper layer (0–15 cm) of loose gravely-sand loose layer overlying a ice-cemented gravelly-sand layer down to 35 cm and followed by massive buried ice down to te bottom. Permafrost table at the moment of the drilling was 30 cm deep. The upper two thermistors were installed directly in the ground, parallel to the surface, while the deeper ones were installed in boreholes cased with plastic tubing and insulated from each other with clay packs. Air temperature was also measured by a thermistor placed in a ventilated radiation shield at 1.5 m above the ground. In addition, also global radiation (in the range between 0.35–3 μm) was measured by a thermopyle pyranometer (accuracy ±1%).

The thermistors had an accuracy of 0.1°C and a resolution of 0.01°C. Temperatures were measured every 10 min but only hourly minimum, maximum, instantaneous and average values were recorded by a datalogger WST1400 (MTX Italia). Also the global radiation were recorded simultaneously.

Owing to a gap of two years in the record of the air temperature measured at Boulder Clay (BCA) the closest available air temperature data recorded at the PNRA-AWS named "ENEIDE" (74°41′S;164°05′E; 92 m a.s.l) were used.

The only snow cover available data are referred to a shorter period (1999–2008) in the CALM grid installed at around 50 m far from the borehole site. In this grid snow thickness was manually recorded through a probe (accuracy of 1 cm) every year in the middle of the austral summer on the 121 nodes of the grid. Therefore these data are representative of the snow cover remaining in the summer in the area surrounding the borehole but are not specifically referred to it.

3.2 Data analyses

The trends with time of the analyzed variables were obtained by linear regression. Statistical analyses were computed using the software Statistica (®).

Active layer depth (defined as 'the depth of the maximum seasonal penetration of the 0°C isotherm' according to Goodrich (1982) was computed through linear interpolation between the maximum temperature at 2 and 30 cm depth (see also Guglielmin 2006) and, according to Gold and Lachenbruch (1973), through the following Eq. 1

$$\mathrm{alt} = (\mathrm{kP}/\pi \ln|\mathrm{A0}/\mathrm{T0}|)1/2 \tag{1}$$

where k is the thermal diffusivity of the ground, P is the period of the thermal cycle, A0 is the surface temperature amplitude and T0 is the mean annual ground surface temperature (MAGST). Thermal diffusivities were obtained according to according to Carlsaw and Jaeger (1959), applying both the amplitude attenuation with depth (Eq. 2) and the phase lag with depth (Eq. 3):

$$\mathrm{ka} = \pi/\mathrm{P}[(\mathrm{z2\_z1})/\ln(\mathrm{A1}/\mathrm{A2})]2 \tag{2}$$

$$\mathrm{kp} = \mathrm{P}/4\pi\left[(\mathrm{z2}-\mathrm{z1})^2(\mathrm{t2}-\mathrm{t1})^{-2}\right] \tag{3}$$

where k is the ground thermal diffusivity, P is the time period of the thermal wave considered (days), z1 and z2 are the measuring depths, A1 and A2 are the amplitudes of the temperature variations at z1 and z2 and (t2−t1) is the phase lag during the period P.

4 Results

4.1 Ground surface temperature and climate

In the period 1996–2009 the mean monthly ground surface temperature (recorded at 2 cm) (GST) ranged between 3.8°C and −31°C, with annual fluctuations between 21.9 and 34.8°C (Fig. 1).

In the same period the mean monthly air temperature ranged between −28.2 and 0°C, with annual fluctuations between 18.9 and 28.2°C and it was always warmer than GST in winter (Fig. 1). Episodes of increase of temperature during the winter known as "coreless winter" (Guglielmin and Dramis 1999; Van Loon 1967) were pronounced, even at the monthly scale, with an increase up to 7.2°C from one month to another, and occurred generally between May and June although sometimes later.

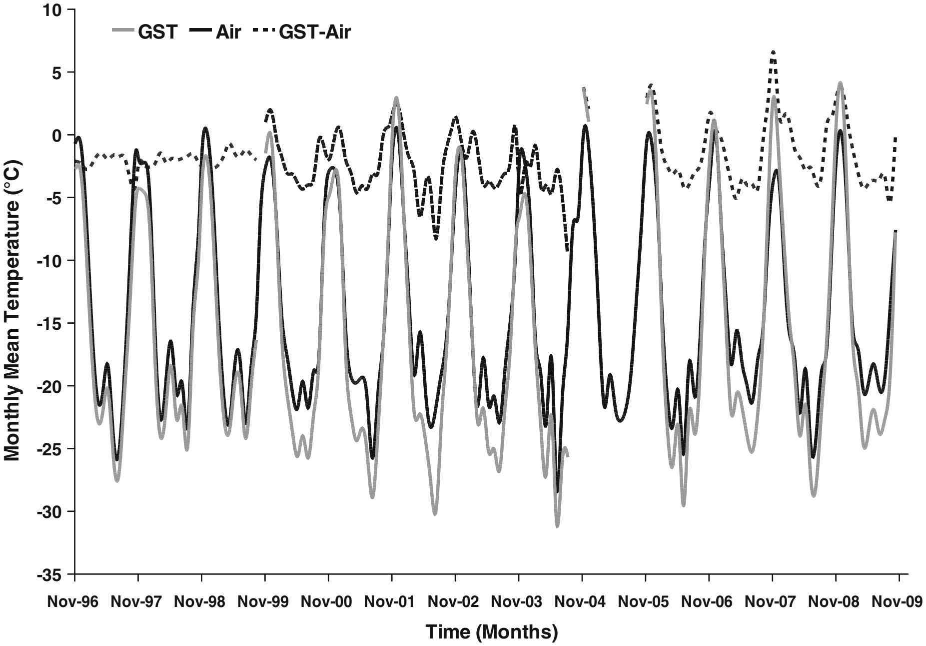


Fig. 1 Monthly mean temperatures of the air (grey solid line; recorded by PNRA AWS of Eneide) and of the GST (black solid line) and the difference between GST and Air

The difference between the monthly mean of GST and of air temperature ranged between −9.5 (September 2004) to 6.5°C (December 2007), with a generally increasing trend over the observation period. Positive differences occurred in summer, when GST was warmer than the air, while much stronger negative differences occurred in winter, when the air was warmer than the ground surface (Fig. 1). Despite their large differences air temperature shows a statistically significant relation with GST (GST=0.99air −2.28; p=0.0028; r^2=0.74) as tested by linear regression.

During the analysed period, mean annual air temperature ranged between −14.3°C (2003) and −12.7 (2007) with an average of −13.8°C while GST ranged between −16.9°C (2003) and −15.8°C (2008) with an average of −16.1°C (Table 1).

Among the available climatic factors, only the annual and winter wind speed (0.25 ms^{-1} per year and p=0.0064; 0.38 ms^{-1} per year and p=0.023 respectively) showed a significant increasing trend (Table 2).

To better evaluate the seasonal partitioning of air and GST trends, the seasonal averages were considered. Seasonally, air temperature does not show any statistically significant trend although spring (SON, Fig. 2a) shows a slight decrease and fall (MAM, Fig. 2a) exhibits the opposite trend. On the other hand, GST shows a statistically significant increase (+0.31°C per year; p=0.0496; Fig. 2b) during the summer (DJF), while it exhibits the opposite pattern during the winter GST (JJA) although not statistically significant (−0.12°C per year, Fig. 2b). Among the summer months, the warmest month, January shows the statistically most significant GST increase (+0.4°C per year; p=0.0443; Fig. 3) while the air temperature also in this month didn't show any trend. The increase trend of summer GST was enhanced by the statistically significant increase trend of the summer thawing degree days (TDD at 2 cm; +13.08 per year; p=0.0052 Fig. 3).

Table 1 Synthesis of the main annual criospheryc parameters: MAGST, MAPT, Thermal Offset and ALT (1 computed through linear interpolation; 2 calculated with the Eq. 1) and for comparison the mean annual air temperature (MAAT) recorded in the examined period. Note that the mean for the period 1997–2009 is calculated only with the complete years and that $^{*}n=303$ days $^{**}n=330$ days

	MAAT (°C)	MAGST (°C)	MAPT (°C)	Thermal Offset (°C)	ALT (cm)	
1997	−13.6	−16.1	−17.1	−1.0	20	21
1998	−13.8	−16.1	−16.8	−0.7	11	10
1999	−13.3	−15.9	−16.4	−0.5	25	18
2000	−14.2	−16.4	−16.6	−0.2	20	12
2001	−14.2	−16.4	−16.9	−0.5	N.D.	6
2002	−14.1	−16.3	−16.8	−0.5	28	35
2003	−14.3	−16.9	−17.1	−0.2	24	35
2004	−13.8	−18.4*	−18.2*	+0.2	N.D.	N.D.
2005	−13.9	N.D.	N.D.	N.D.	29	N.D.
2006	−14.6	−16.4	−16.2	+0.2	29	25
2007	−12.7	−14.6	−15.3	−0.7	25	21
2008	−13.9	−15.8	−15.8	0	28	30
2009**	−15.3	−16.7	−16.3	+0.4	30	60
Mean	−13.8	−16.1	−16.5	−0.3	24.5	24.8

Among the climate factors that could influence the summer GST and the TDD at 2 cm only the incoming radiation seems to have a statistically significant increasing trend (Fig. 4; Table 2) while both wind speed and snow cover do not show significant trends although the first shows a slight increase (+0.22 m s^{-1} per year; $p=0.19$) and the latter a slight decrease (−0.3 cm per year; $p=0.5$) (Fig. 4; Table 2).

4.2 Active layer and permafrost temperature

The depth of 0.3 m is approximately coincident with the maximum depth of the permafrost table during the observation period. The monthly mean ground temperature at this depth ranged between −28°C (July 2004) and −0.5°C (January 2009; Fig. 5). The mean annual ground temperature at 0.3 m ranging between −17.1 (1997; 2003) and −15.3 (2007; Table 1) was considered representative of the mean annual temperature at permafrost table (MAPT).

The thermal offset (defined as the difference between the MAPT and the MAGST, according to Goodrich (1982)) recorded during the observation period was small, ranging between +0.4 to −1°C (Table 1).

Monthly permafrost temperatures at deeper depth (from 0.6 to 3.6 m; Fig. 5) follow heat conduction with a progressive smoothing and delay from the upper depth to the deepest.

At annual scale all the ground temperatures between 30 cm and 360 cm were significantly increasing (Table 2; Fig. 6a–e) of approximately 0.1°C per year. Seasonally, fall ground temperatures (MAM) shown an increase at all the depths between 30 and 360 cm which was statistically significant at all the depths except for 360 cm ($p=0.059$) (Table 2; Fig. 6a–e). Also the winter (JJA) and the spring (SON) ground temperature at 260 and 360 cm showed statistically significant increases (Table 2;Fig. 6a–e).

Active layer thickness showed pronounced annual variability, ranging between 5 cm and 30 cm (17% and 100% of the maximum depth reached in the examined period; Table 1).

Table 2 Summary of the statistical analyses of the annual and seasonal trends for the period 1997–2009 on the ground temperature and on the main climatic parameters. In the semicolumns are reported the angular coefficient (B) of the linear regression and its statistical significance (p). Values statistical significant (*p*=<0.05) are in bold

	YEAR		DJF		MAM		JJA		SON	
	B	p	B	p	B	p	B	p	B	p
3.6	+0.1087	**0.0286**	+0.0933	0.3177	+0.1364	0.0590	+0.1267	**0.0280**	+0.1311	**0.0054**
2.6	+0.1226	**0.0127**	+0.089	0.4033	+0.1768	**0.0185**	+0.144	**0.0291**	+0.1199	**0.0163**
1.6	+0.1244	**0.0065**	+0.09	0.4527	+0.196	**0.0120**	+0.1334	0.1140	+0.0791	0.1811
0.6	+0.1189	**0.0092**	+0.0843	0.4917	+0.1972	**0.0162**	+0.1235	0.1764	+0.0554	0.4210
0.3	+0.119	**0.0101**	+0.0796	0.5240	+0.2069	**0.0196**	+0.1214	0.2182	+0.0361	0.6400
0.02	+0.0593	0.2940	+0.3108	**0.0496**	+0.0594	0.4714	−0.1187	0.4494	−0.0315	0.7415
air	+0.0008	0.9861	−0.0355	0.5039	+0.1351	0.1365	+0.034	0.7188	−0.0905	0.5053
total incoming radiation	+24223.1	0.1078	+12621.5	**0.0310**	+1539.6	0.2208	n.d.	n.d.	+2880.9	0.7756
wind speed	+0.253	**0.0064**	+0.191	0.1981	+0.1495	0.2091	+0.3847	**0.0230**	+0.3747	0.0948
TDD (0.02)	+11.1	**0.0009**	+13.08	**0.0052**	n.d.	n.d.	n.d.	n.d.	+0.4052	0.1790

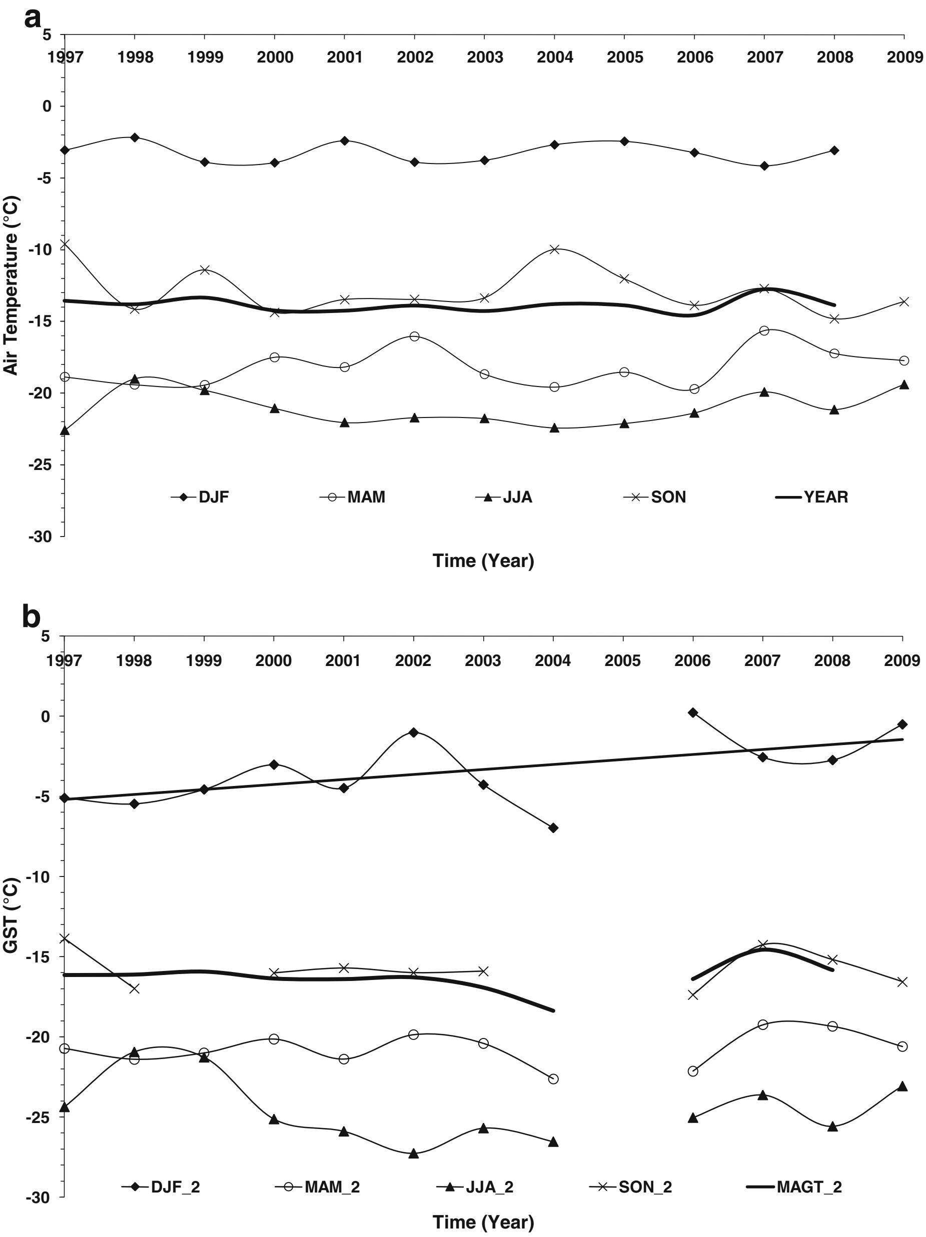


Fig. 2 Seasonals and yearly mean of air temperature (**a**) and GST (**b**) and their trends. Legend: Summer (DJF—December–February); Fall (March–May); Winter (June–August); Spring (September–November). Only the DJF GST presents a statistically significant ($p<0.05$) trend (black solid line)

The thickening of the active layer was strong and statistically significant (+1.0 cm per year, $p=0.0099$; Table 2, Fig. 7) considering the modest range of the thickness.

The active layer shows statistically significant relations with the summer GST (ALT= 2.25*SummerGST+30.6; $p=0.0241$), as well as with the summer ground temperature at

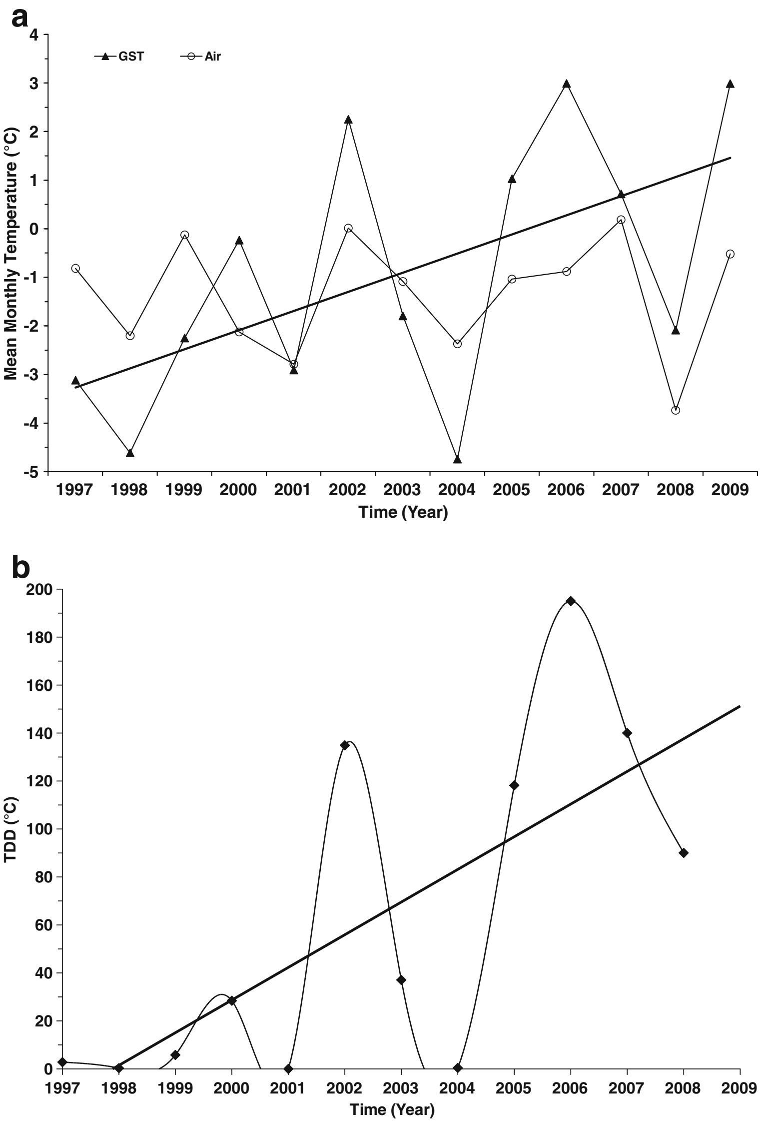


Fig. 3 (**a**) Mean of the warmest month (January) for air temperature and GST and their trends and (**b**) summer Thawing Degree Day (TDD) at the ground surface and its trend

30 cm (Summer ground Temperature 30 cm=0.542 * SummerGST - 2.93; $P=0.011$), the TDD 2 cm (ALT=0.07 * TDD2 cm+19.7; $p=0.01$), and the summer TDD 2 cm (ALT=0.06 * TDD DJF 2 cm+19.6; $p=0.005$), as tested by linear regression (Fig. 7).

5 Discussion

In northern Victoria Land since 1996 air temperature was almost stable, confirming the trend illustrated by Chapman and Walsh (2007) for this part of Continental Antarctica for

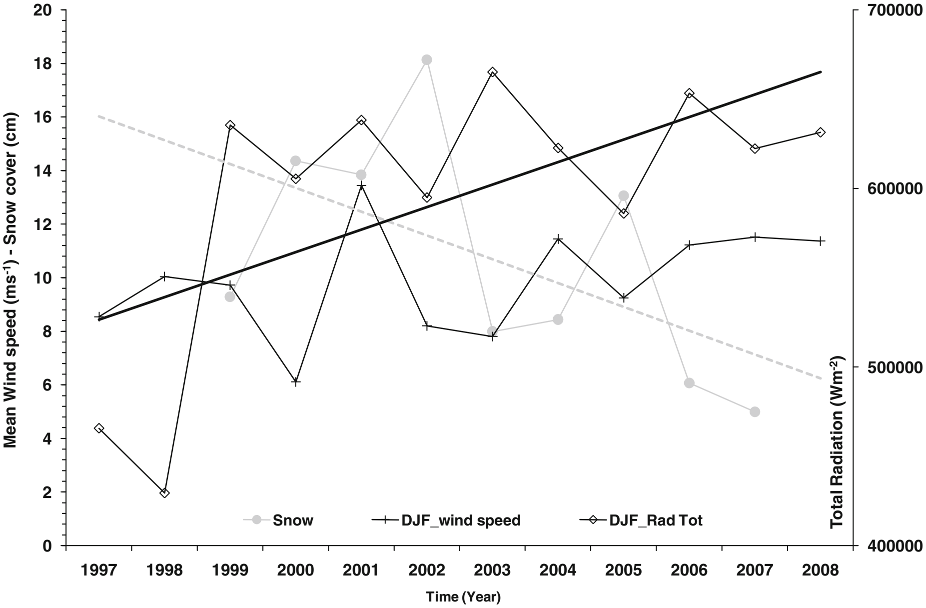


Fig. 4 Summer total incoming radiation, wind speed and snow cover and their statistically significant ($p<0.05$). Only the trend of incoming radiation (black solid line) is significant (b=+12621.5; p=0.031)

the period 1958–2002, but in contrast with the cooling trend described for McMurdo-Dry Valleys by Doran et al (2002) in the period 1986–1999. Differently from the air, permafrost temperatures (at depth >30 cm) experienced significantly increasing trends (almost +0.1°C per year) as well as the active layer thickness is increasing of 1 cm per year.

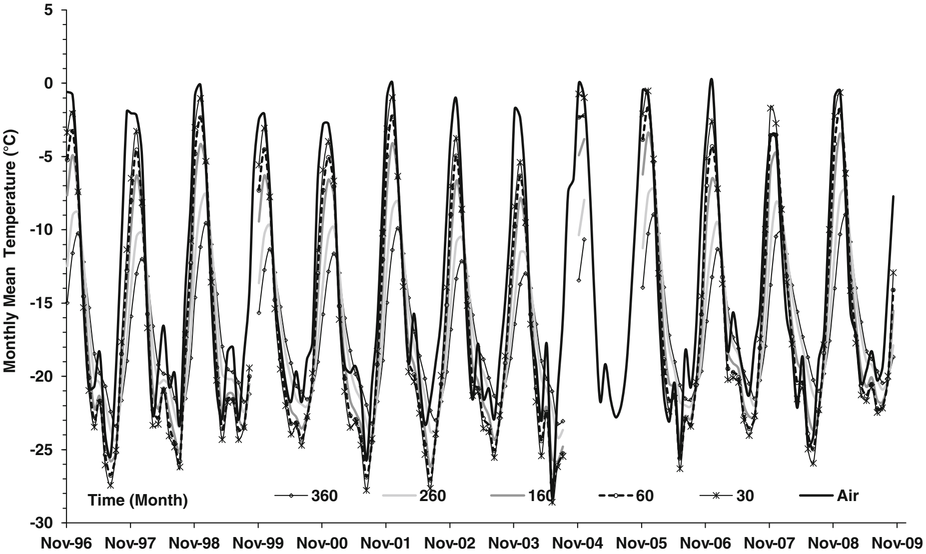


Fig. 5 Permafrost monthly mean temperatures between 30 and 360 cm of depth and, for comparison the mean monthly air temperature

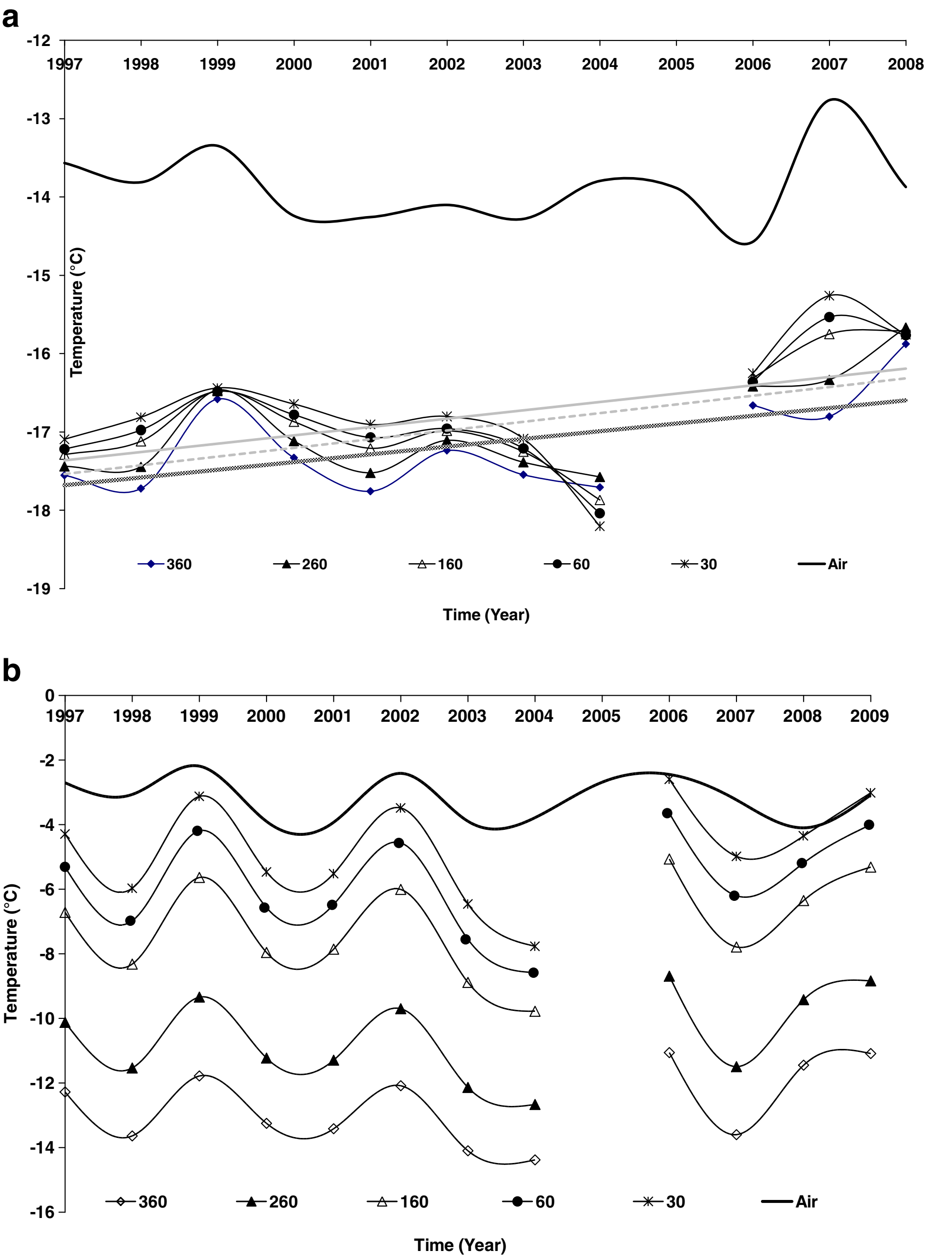


Fig. 6 Annual and seasonal Mean Ground and Air Temperature and their statistical significant trends. **a** Mean Annual Temperature; **b** Summer (DJF—December-February) Temperature; **c** Fall (MAM—March–May) Temperature; **d** Winter (JJA—June–August) Temperature; **e** Spring (SON—September–November) Temperature. All the trends line have the same legend: 30 cm=black solid line; 60 cm=black dashed line; 160 cm=grey solid line; 260 cm=grey dashed line; 360 cm=thick grey line

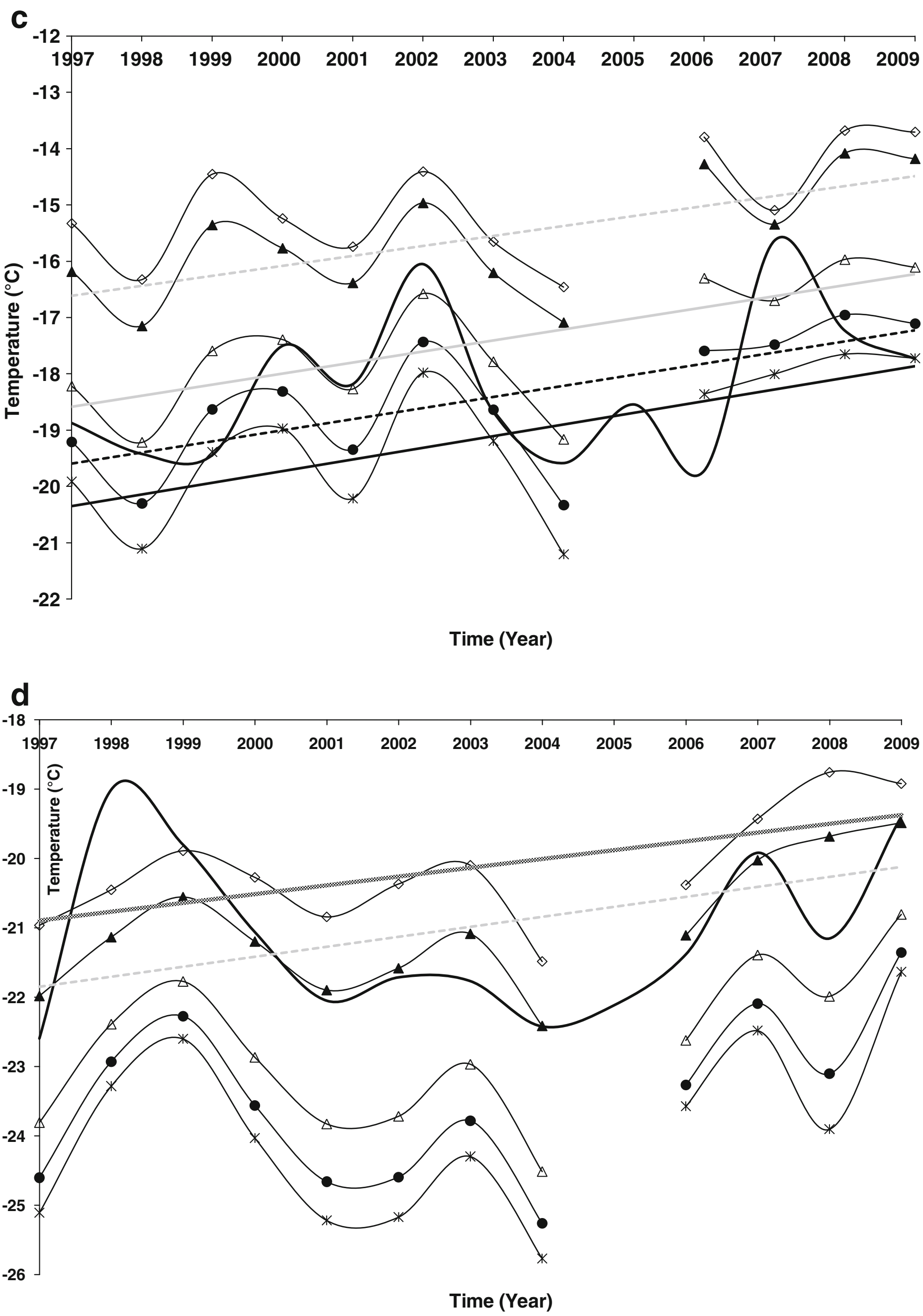
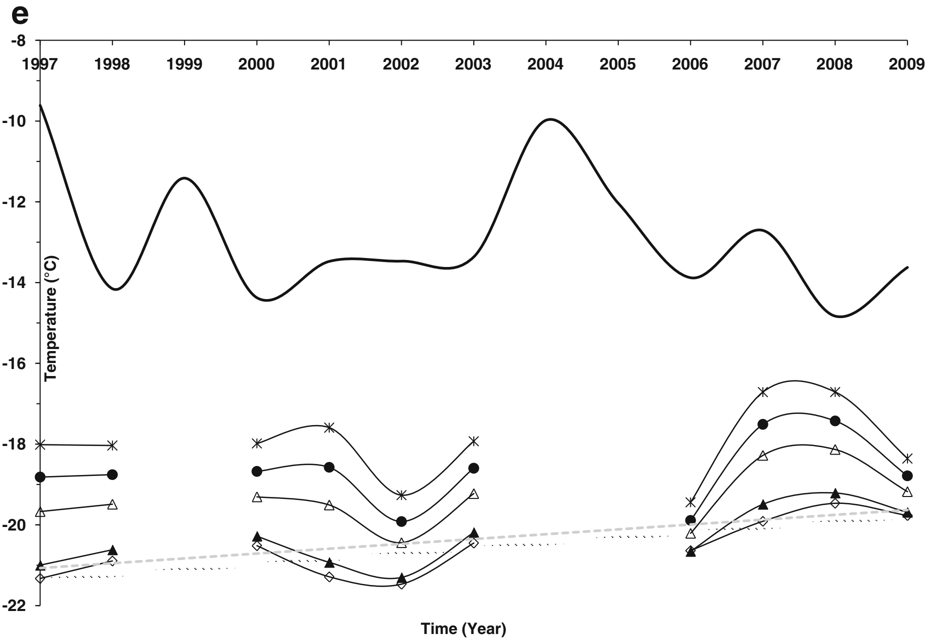


Fig. 6 (continued)



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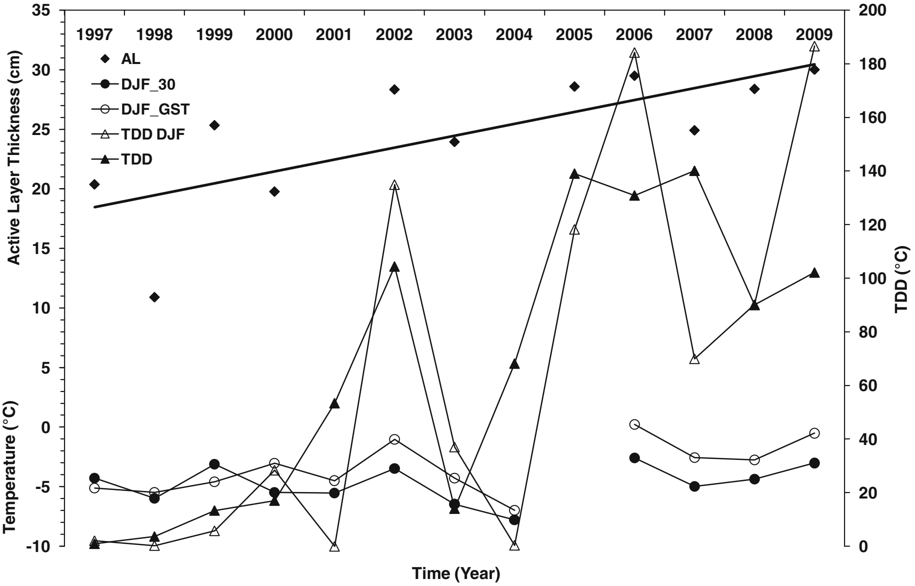

Fig. 7 Relationships among Active Layer thickness (AL) and : Mean Summer GST (DJF_GST); Mean Summer Temperature at 30 cm of depth (DJF_30); Summer Thawing Degree Days at 2 cm of depth (TDD DJF); Total Thawing Degree Days at 2 cm of Depth (TDD). Please note that the Left Y axes is referred to ground temperature (°C) in the bottom part and to the active layer thickness (cm) in the upper part

5.1 Relationships between GST and climate during the last 13 years

The strong increasing trend of summer GST and, even more pronounced, of the ground surface temperature of the warmest month (January) and of the summer TDD seem to be related only to the increasing trend of the total incoming radiation. The increasing pattern of the total incoming radiation is even stronger than that reported at Lake Hoare in the previous decade by *Doran et al*. (2002) and may be responsable of the increasing warming of the GST. The summer GST in our study site is not related to summer air temperature, differently from what reported for most cases (e.g Romanovsky et al. 2007; Åkerman and Johansson 2008; Osterkamp 2008; Streletskiy et al. 2008).

The shorter data set available for snow cover in this site, does not allow to assess its role on the GST. Indeed, the summer snow cover shows a slight decreasing trend (although not statistically significant) fitting well with the slight increase of the wind speed, and the strong increase of the total summer radiation. The increase of wind speed may have induced an increased snow sublimation and the increase of summer total radiation may have lead to a larger snow melting. Also at regional scale, it is difficult to assess the role of the snowfall: measurements of solid precipitation are still completely lacking in the coastal Antarctica, although Monaghan et al. (2006) indicate an insignificant variation of snow accumulation in the inland areas. Moreover, the absence of zero curtain periods (Fig. 8a), [zero curtain is defined as a period of “persistence of a nearly constant temperature at very close to the freezing point” due to the effect of latent heat in freezing or thawing processes, according to Outcalt et al. (1990)] at the surface indicate that snow melting does not occur, at least at the borehole site. Our data suggest that at least in our site, snow cover is not relevant as a key factor able to influence summer GST, differently from what reported for the Arctic by several authors (e.g. Osterkamp 2007; Romanovsky et al. 2007; Fedorov and Konstantinov 2008).

5.2 Active layer and permafrost responses to GST changes

Despite its limited thickness (6–30 cm) the annual variability of the active layer was pronounced and its thickening was very high (1 cm per year).

It is quite difficult to compare our data of active layer thickness with those from other parts of the world because, in some cases, the referred time period is different or that generally the reported data relate to the maximum thaw depth and not the depth of isotherm. With this proviso, our thickening rates are similar to those reported by Åkerman and Johansson (2008) for northernmost Sweden (between 0.7 and 1.3 cm per year in the period 1978–2006). Similar values (0.7–1 cm per year) were reported by Burn and Zhang (2009) for Herschel Island in Yukon, but in the period 1985–2008, while Smith et al. (2005) indicated a general thickening trend for Canada, although they detected some opposite trends at local scale. In Antarctica, Adlam et al. (2010) analysing data of Southern Victoria Land did not recognize any clear trend in the observed period (1999–2007), because, as also stated by the authors, the considered period was too short.

Our data showed that there is a statistically significant strong relation between the active layer thickness and the summer GST, the summer ground temperature at 30 cm, the TDD 2 cm, and the summer TDD 2 cm.

Among the climatic factors, our data suggest that the summer radiation is the key factor explaining why active layer is thickening, although summer air temperature is stable. A further confirm is the fact that the summer GST is increasing despite of the stability of the summer air temperature.

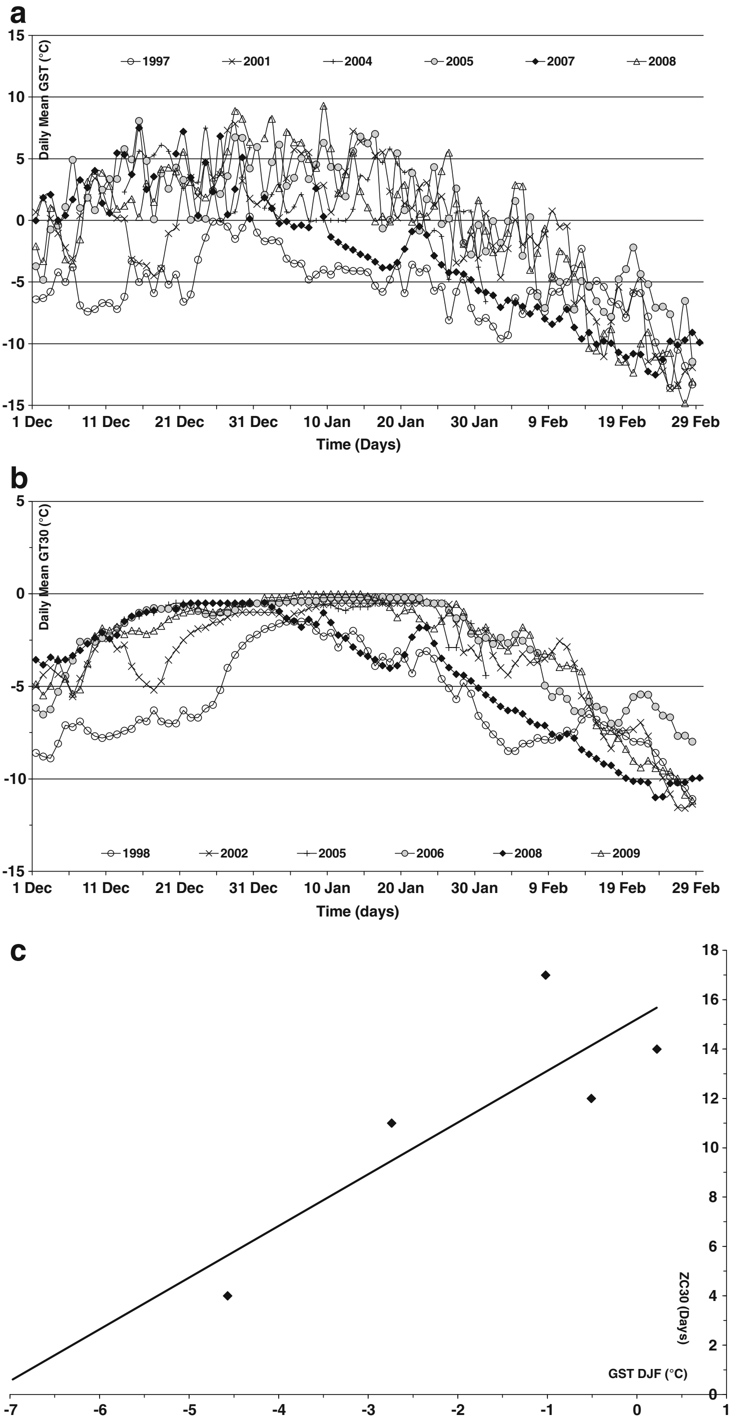

Fig. 8 Zero Curtain period in some selected years: a) at the depth of 2 cm; b) at the depth of 30 cm (close to the permafrost table) and c) the relationships between the Summer GST and the zero curtain at 30 cm (ZC30)

Table 3 Changes in thermal properties within the active layer: Thermal diffusivities (Ka $\times 10^{-7}$ m^2s^{-1}) calculated according to the Eq. 2; number of days of zero curtain at 30 cm of depth (ZC30) and their temperature (°C); mean summer (DJF) GST

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Ka	1.89	1.18	1.69	6.66	5.62	1.38	5.09	9.89	N.D.	1.00	4.54	2.48	14.0
ZC30 (T°C)	0	0	4 (−0.5)	0	0	16 (−0.5)	0	0	23 (−0.5)	18 (−0.3)	6 (−1.3)	12 (−0.6)	11 (0)
DJF GST	−5.1	−5.5	−4.6	−3	−4.5	−1	−4.3	−7	2.4	0.2	−2.6	−2.7	−0.5

Beyond the thickening of the active layer, also the increasing trend of permafrost temperatures (at depths deeper than 30 cm) confirms that air temperature, at least in our site, is not the main driving factor both on annual and seasonal bases.

The values of the thermal offset provide useful information on the GST and on the variations of the thermal characteristics of the active layer (Goodrich 1982). In our site, the thermal offset shows a statistically significant increasing trend (+0.07°C per year; $p=0.01$). This trend is due to the stronger increasing trend of MAPT (mean annual ground temperature 30 cm, Table 2) than MAGST (mean annual ground temperature at 2 cm, Table 2), allowing to hypothesize that the thermal characteristics of the active layer are able to change during the time.

Also the duration of the zero curtain periods recorded at 30 cm of depth (ZC30, Fig. 8b) shows an increasing trend (Fig. 7c) and appears to be strongly related to summer GST ($ZC30=2.8353DJF\_GST+15.2545$; $p=0.00001$).

The contemporaneous absence of the zero curtain period at the surface and its occurrence at the permafrost table suggest that the ice occurring close to the permafrost table is melting. The thermal diffusivities (Table 3) calculated for the summer within the active layer (between 2 and 30 cm) range between 1 and 14×10^{-7} m^2s^{-1}, and are remarkably higher than those measured by Ikard et al. (2009) in the McMurdo Dry Valley (Antarctica) (ranging between 0.29 and $11.6\times10^{-8}m^2s^{-1}$) and also generally higher than the values found in the Arctic (e.g. by Hinkel et al. (2001) in Alaska on thawed active layer: $2.3\times10^{-7}m^2s^{-1}$) reflecting a quite high water content.

The very poor correlation between the thermal diffusivities and both the active layer thickness and the ZC30 may indicate non-conductive heat transfer processes, as the sublimation processes close to the surfaces, as already enhanced by several authors (i.e. Kane et al. 2001; Ikard et al. 2009; Northcott et al. 2009).

These results amplify the complexity of the cryosphere because even with an almost stable atmosphere it is possible to have a warming of the GST and a thickening of the active layer. This is particularly important because the main feedbacks, such as changes of surface water (e.g. Yoshikawa and Hinzman 2003; Smith et al. 2005) increased release of methane to the atmosphere (e.g. Walter et al. 2006; Zimov et al. 2006; Mastepanov et al. 2008), changes in vegetation composition (e.g. Cannone et al. 2007; Cannone and Guglielmin 2009), increases in dissolved material in rivers and oceans (e.g. Benner 2004; Frey and McClelland 2009), are primarily related to the thermal regime of the surface and of the active layer during the thawing season.

6 Conclusions

The first 13 years of permafrost and active layer monitoring performed close to MZS in northern Victoria Land show that an important increase of summer GST (3.1°C per year) occurred despite an almost stable air temperature. Summer GST warming and the increase of summer TDD at the surface are mainly related to the increase of the total summer incoming radiation, although more data are needed to assess the role of snow cover because the available data set was too short to be statistically significant. The active layer showed a thickening trend (1 cm per year) with rates similar to what found in different parts of the Arctic (where air warming occur), although in our case the air temperature trend that remains almost stable. The dichotomy between air temperature, GST and active layer thickness may produce large unexpected impacts and unpredictable feedbacks on ecosystems and climate change.

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