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Sensitivity and responses to climate change in the Subantarctic periglacial environment

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ABSTRACT: The Subantarctic islands constitute a distinct periglacial environment of low mean annual and diurnal temperature range. Ground thermal monitoring on Marion Island demonstrates how the low radiation inputs and high moisture conditions result in near-isothermal soil temperature conditions. This paper describes and analyses this distinctive soil temperature regime and demonstrates a high sensitivity of the Subantarctic frost environment to climate change. The latter is expressed by a rapid transition from high-frequency shallow diurnal frost activity to deep seasonal freezing and permafrost. The results from this analysis are applied to the palaeoenvironmental interpretation of relict, early Holocene periglacial landforms representing colder climates, as well as to current landscape responses due to climate warming on Marion Island.

1 INTRODUCTION

The maritime Subantarctic consists of a small number of islands in the vast South Atlantic and South Indian Ocean, totaling about 11 300 km^2 of terrestrial environment (Figure 1). Due to their maritime setting, the frost climate of the islands has been characterized by its low annual temperature range (Tricart 1973, French 1996). French (1996) describes mean annual temperatures to be below +2°C, but mean annual temperatures on most islands are well above this value (Boelhouwers et al, in press). The low annual temperature ranges, high precipitation and cloudiness result in high frequencies of short duration freeze/thaw cycles with shallow frost penetration. Boelhouwers et al. (in press) argue that the hyper-maritime setting of the Subantarctic islands results in ground frost conditions highly sensitive to climate change. This paper further analyzes the soil thermal conditions in this environment and its implications for soil frost in this context.

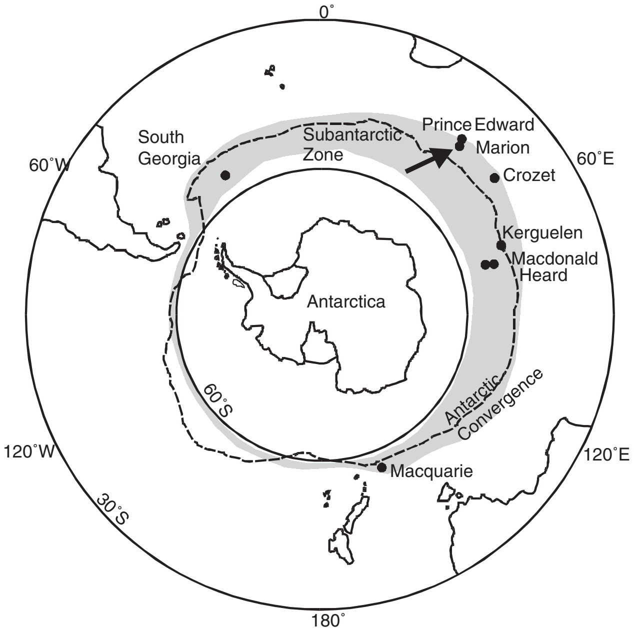

Figure 1. The Subantarctic region (shaded), its islands and their relative position to the Antarctic front.

2 STUDY AREA

The present analysis is based on a five-year study of soil frost processes on Marion Island. Marion Island (46°54′S, 37°45′E) has an area of approximately 290 km^2 and rises to 1230 m asl. The island consists of the peak of a shield volcano (Verwoerd 1971). An older sequence of pre-glacial grey basalts is overlain by post-glacial black lavas and scoria material, the most recent having formed in 1980 (Verwoerd et al. 1981). The hyper-maritime setting of the Subantarctic islands is well illustrated by the Marion climate. Mean summer maximum and minimum air temperatures at sea level are 10.5°C and 5.0°C, and the winter means are 6.0°C and 1.0°C, respectively. On average, precipitation occurs on 25 days per month, with a mean annual total of 2576 mm. The wind blows most frequently from the northwest with an average velocity of 32 km h^{-1} (Schulze 1971).

3 SOIL TEMPERATURE

Soil temperature data for this study were obtained from the eastern half of the island at Long Ridge North (200 m asl) and Delta Extension (1000 m asl). At both sites the temperatures were measured in a matrix supported diamict of glacial origin, derived from the grey lavas. *Azorella selago* covers <10% of the surface at the 200 m site while vegetation is absent at 1000 m asl. Soil surface temperatures are summarized in Table 1 with a more detailed plot in Figure 2 for the 1000 m site. The data highlight both the small average seasonal and diurnal temperature range at the soil surface and the dominance of short-term frost cycles. The low mean annual temperature at 1000 m asl concurs with observed permafrost conditions on southerly and easterly aspect slopes and at sites favourable to snow accumulation, at the summit of the island. The high frequency of diurnal frost cycles at 1000 m altitude is a result of (i) the low mean annual temperature (+1.4°C), (ii) the low seasonal and diurnal temperature range, (iii) the limited snow cover at this windswept site. These temperature characteristics are readily explained by the hyper-maritime setting of the island with very limited direct radiation inputs due to high cloud cover, high soil moisture levels and the atmospheric thermal inertia created by the surrounding ocean mass.

Table 1. Summary data for ground surface temperatures on Marion Island at 200 m asl (10/4/99–9/4/00) and 1000 m asl (17/4/99–16/4/00).

	200 m	1000 m
Absolute max temp	24.2	19.1
Absolute min temp	−3.5	−8.6
Mean annual temp	6.2	1.4
Seasonal range (mean Jan-mean Jul)	5.1	4.9
Daily range January	11.7	7.9
Daily range July	4.5	4.4
Mean daily range	7.9	6.1
Freeze/thaw days (n)	63	212
Freeze days (n)	4	43
Max soil frost penetration	5 cm	20 cm

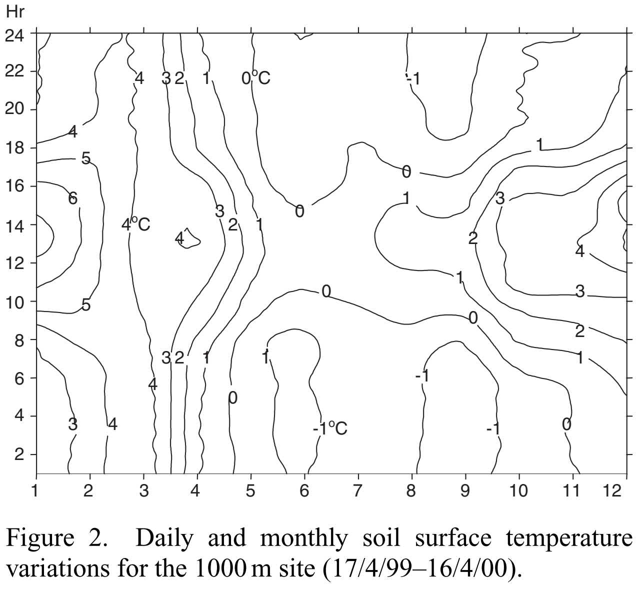

Figure 2. Daily and monthly soil surface temperature variations for the 1000 m site (17/4/99–16/4/00).

Subsurface temperature conditions at high altitude are illustrated in Figure 3. The figure illustrates the near-isothermal conditions down to 80 cm during most of the year. The summer temperature conditions, when temperatures are well above zero, show the low temperature gradients not to be solely the result of a zero-curtain effect. Here, the explanation is most likely found in the downward percolation of both meltwater and precipitation. This does not only result in a mass heat transfer, but also increases the heat conductivity of the soil. During the winter months temperatures hover around zero for almost four months. This is clearly the result of an effective zero curtain effect, as shown in Figure 4. This figure shows the hourly temperature record for August 1999, including soil moisture at 5 cm depth recorded by means of a nylon electric resistivity block (Bouyoucos 1949). The record shows high moisture levels except where unavailable in frozen condition. It is interesting to note that soil moisture availability drops to zero when soil temperatures at that level reach −2°C.This indicates a relatively large freezing point depression and therefore high solute concentrations, possibly due to high chemical weathering rates on surrounding recent volcanic materials. Chambers (1966) reported a similar freezing point depression at Signy Island.

In Figure 4, the zero-curtain is seen to be absent at 1 cm and 5 cm depth and to be discontinuous at 10 cm depth. However, from 20 cm to at least 80 cm depth the zero-curtain is continuous over the entire month. The effective latent heat release in this soil layer is made possible by the marginal frost with slow cooling rates in winter and high soil moisture conditions throughout the year. Soil moisture is known to be no limiting factor for segregation ice development on the island (Holness 2001).

Chambers (1966) reported on a similar importance of the zero-curtain effect at a permafrost site (MAAT −3.3°C) at Signy Island. Here, temperatures remained between +0.5°C and −0.5°C for seven months at the base of the active layer at 1.2 m depth and was frozen for the remainder of the year. Duration

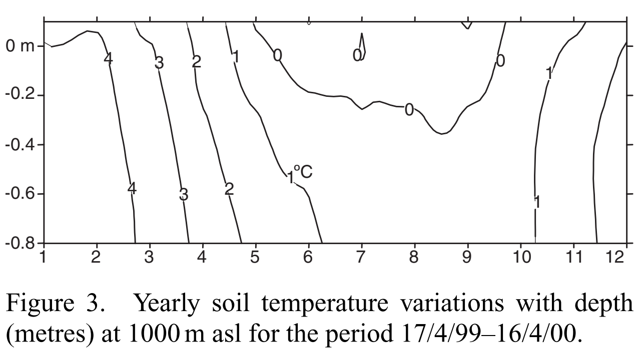

Figure 3. Yearly soil temperature variations with depth (metres) at 1000 m asl for the period 17/4/99–16/4/00.

of the zero-curtain decreased towards the surface and was absent in the upper 10 cm of the soil. Isothermal temperature profiles existed during the period when the zero-curtain was intact, but show typical inclines in summer and winter due to radiational warming and cooling, respectively. Despite marginal freezing rates at the surface, freeze-up of the active layer occurred within four weeks once the zero-curtain had been overcome. Interestingly, at this permafrost site the soil surface remained frozen for seven months, limiting the annual number of frost cycles to 42.

4 IMPLICATIONS FOR CLIMATE CHANGE

The windswept site at 1000 m asl has very limited snowcover at any time of year. Under such conditions the hypothetical impact of cooling and warming may be speculated upon assuming no changes in snowcover conditions. Under a climate warming scenario a rapid reduction of diurnal frost cycles can be illustrated (Table 2). With every one degree Celsius warming it is estimated that there will be an about 25% reduction in days with frost in the summit region of the island. The frost penetration depth of diurnal frost cycles will decrease from 20 cm to 10 cm. Changes deeper in the soil are more difficult to estimate as it is unclear to what extent the heat fluxes towards the surface in winter will be sufficient to maintain a zero-curtain effect. It can be expected however, that this will not penetrate as deeply or may even become absent altogether. Conditions are too warm at present to allow for a zero-curtain to develop at the 200 m site.

Diurnal frost cycles are responsible for the extremely high soil surface transport rates on the island at present (Boelhouwers et al. in press). Assuming that sediment transport is solely the result of frost induced creep (Holness 2001a) warming will have a similar percentage reduction in surface sediment transport rates (Table 2). With every one degree Celsius warming it is estimated that there will be an about 25% reduction in surface sediment movement rates in the summit region of the island. Testing this approach to estimate freeze/thaw cycles at the 200 m site (an almost 5°C warmer site) results in an underestimation by 26 days or 39%. An important distinction between the two sites, however, is the higher frequency of clear sky conditions and thus radiational heat exchange at the low altitude site. This has been shown by Chambers (1966) to favour diurnal freeze/thaw

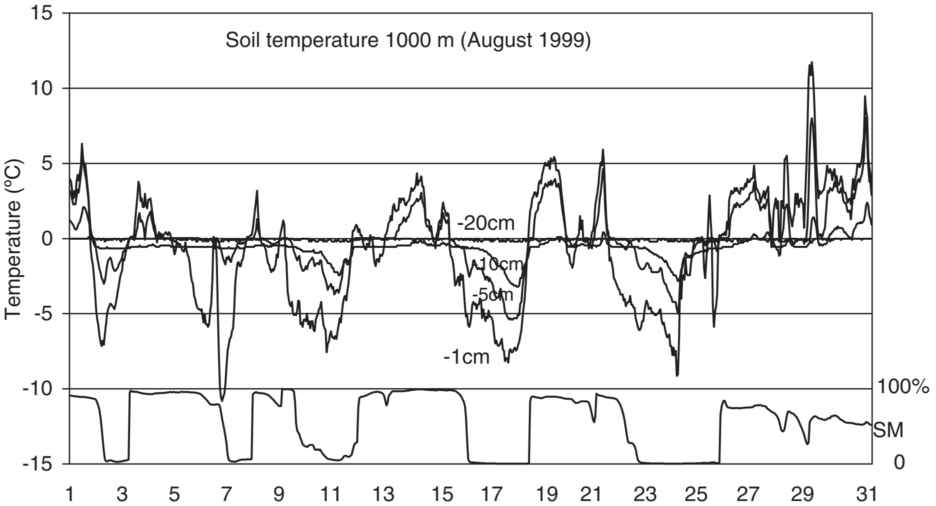

Figure 4. Soil temperature and relative moisture record at 1000 m asl for August 1999. Soil moisture (SM) is measured at 5 cm depth and is indicated as relative percentage saturation based on electric resistivity.

Table 2. Number of days with minimum temperatures below 0°C and average surface sediment transport rates under present conditions and a +1°C and 2°C warming scenario.

	Number of days with minimum temperature below 0°C						Average surface sediment movement (mm/a)*			
	−1 cm	−5 cm	−10 cm	−20 cm	−40 cm	−80 cm	All	Fine	Stony	Blocky
Present	259	162	194	137	0	0	110	257	116	40
+1°C	191	77	35	0	0	0	81	189	41	30
+2°C	142	47	13	0	0	0	60	140	30	22

* Values based on Holness (2001a).

cycling at the soil surface. Clear sky conditions are perceived to have increased at Marion Island under current climate warming. If correct, the presented impacts are likely to be over-estimates. Further work is ongoing to analyze the role of radiational heat exchange with diurnal freeze/thaw cycling in relation to long-term trends in cloudiness and global radiation inputs at Marion.

Under a cooling trend the diurnal frost environment at the 1000 m site is seen to rapidly evolve into a seasonal and permafrost environment with relatively shallow active layer. A simple shift in the temperature profiles (Figure 3) suggests a very rapid transition to deep seasonal frost to over 80 cm for a period of over four months under a one-degree temperature lowering. Any further cooling would result in mean annual temperatures below zero over the entire measured soil profile with frozen ground from the surface to 80 cm over a period of more than six months. Much of the actual ground temperature response will depend on moisture availability and actual cooling rates as these will determine the extent of the zero-curtain effect under colder conditions. However, comparison with the results from Chambers (1966) for a permafrost site in a similar oceanic environment can be made. Based on this analogy, a zero-curtain is likely to be maintained beyond the depth of diurnal frost cycling for the period when the soil is not frozen.

Based on the considerations presented it appears that the high-altitude frost environment of Marion island is highly responsive to climate change. Warming will result in rapid reductions in surficial frost cycles and sediment movement rates possibly somewhat offset by a reduction in cloudiness. On the other hand, cooling can potentially result in a rapid transition from diurnal to deep seasonal frost and permafrost. This rapid transition appears to be a function of the combined effects of low radiation inputs, high cloud cover and high precipitation typical for the maritime conditions affecting this region. Based on these theoretical considerations field evidence for both past and current climate change can be considered.

5 EVIDENCE FOR PAST CLIMATE CHANGE

Marion Island has a rich record of both active and relict periglacial landforms indicative of both past and present frost environments. Present day diurnal frost conditions result in relatively superficial patterned ground forms (Holness 2001b, Boelhouwers et al. in press). Relict Holocene periglacial landforms occur as stone-banked solifluction lobes and terraces, blockstreams and blockfields. Holness and Boelhouwers (1998) describe an altitudinal gradient in riser heights along a basalt ridge from sea level to 500 m asl. On similar slope gradients, relict solifluction terraces at sea level have risers of 0.3–0.4 m, while riser heights at 500 m asl are up to 2 m. Excavations in the back part of the tread indicate a depth of vertical sorting of 30 cm at low altitude and up to 50 cm at 700 m asl. Relict blockfields (mountain top detritus and frost heaved blocky till) and large stone-banked lobes only occur above 450 m asl, with lobes obtaining riser heights up to 4 m.

Holness (2001a) described riser heights of relict stone-banked lobes at a further 17 sites. A general increase in size (length and riser height) with both altitude and slope angle is evident from this data set. The general increase in size with altitude can be explained by an increase in frost intensity. The drop in size at 1000 m is related to an apparent reduction in frost intensity and/or duration of process activity. Holness (2001a) relates this to the presence of an ice cap at high altitudes up to 6–7 ka BP after which climate ameliorated to conditions to present (up to 1960) conditions. A second consideration is the disappearance of the local permanent snowline since the mid 1970s due to the warming trend over the past few decades. It is unlikely that the features present have been able to develop over the past few decades only, but the picture of Holocene climate change for this region is still vague.

6 INDICATORS FOR CURRENT CLIMATE WARMING

The meteorological record of the coastal weather station on Marion indicates a clear warming trend for the island over the period 1960–1996 (Figure 5). Over the same time period precipitation has substantially decreased. Impacts of this current phase of climate warming are considered in the form of snow cover, permafrost responses and soil disturbance by frost processes.

Early photographs and observations from the 1960s and early 1970s report consistently of a permanent

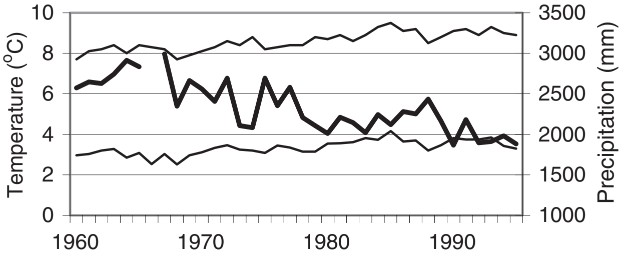

Figure 5. Mean annual maximum (upper line) and minimum (lower line) air temperature and annual precipitation totals (bold line) from the Marion weather station for the period 1960–1996. Source: SAWB (unpubl. data).

snowline around 800–900 m asl on Marion Island (Hall, Smith and Botha, pers. comm.). Snowfree areas are likely to have existed due to the high windiness at the summits. However, since the start of direct observations in 1996 no permanent snowline could be discerned on the island. Observations on snowfall by Holness (2001a) report on 148 days of snow free (13) or sparse snowcover (135) conditions at the 800–900 m zone for 1999. This implies that large parts of the summit region could have become subaerially exposed only in the last few decades.

Recent observations provide the first field evidence for the existence of permafrost conditions above 1000 m asl on Marion Island. Late summer field visits found frozen slopes of southern and eastern aspects above 1000 m asl. The permanence of their frozen condition is evident in scoria cones, which obtain slope angles of 46°, well beyond their angle of repose (38°). Surface runoff and rilling is only evident on such slopes as unfrozen scoria slopes have extremely high permeability. At present debris flow and landslide activity is present on these slopes in spring in materials overlying the permafrost table.

Observations from three basins of cirque origin provide further evidence for permafrost and its current degradation. Here clear-ice bodies develop from winter snowfall in the valley bottom and lee-side basin walls, to be overlain by windblown, slope wash and debris flow deposited material blanketing and preserving the ice in spring. Over the period 1996–2002 extensive degradation and thermal erosion has been observed in these areas. This takes the form of various thermokarst related forms, such as melt depressions, surface runoff and meltwater channels and a general hummocky terrain.

Over the 1960–1990 period there has been a 0.6°C temperature increase. Based on the 200 m and 1000 m altitude temperature records this could have resulted in a 30% and 13% decrease in days with temperatures below zero, respectively. In turn this would imply a possible decrease in slope sediment movement rates by surficial frost creep. However, no indications of increased slope stability have been noted in that no pioneering of vegetation to higher altitudes has been documented.

7 SUMMARY AND CONCLUSIONS

The ground temperature record presented here is the first to describe soil thermal conditions in the Subantarctic and provides a valuable extension of Chamber's (1966) record from the maritime Antarctic site of Signy. Despite the low mean annual temperature of 1.4°C freeze/thaw activity is restricted to the upper 20 cm of the soil. The zero-curtain effect is well developed for a period of four months down to at least 80 cm, due to the low cooling rates and high moisture availability. Near-isothermal conditions ensue in winter, but are maintained in the frost-free period by the low seasonal and diurnal temperature fluctuations. Such soil temperature profiles allow for a rapid transition to deep seasonal and permafrost conditions when mean annual temperatures are around zero. Such sensitivity appears reflected in the relict periglacial record of Marion Island and the current rapid degradation of the marginal permafrost areas at the summit of the island.

It would appear logical that the soil thermal pattern, and thus the sensitivity to climate change reported here, may be characteristic for maritime periglacial environments in the Subantarctic and elsewhere. A small diurnal and seasonal temperature range results in a rapid change in freeze/thaw cycle frequency/intensity in the surface layer under influence of such temperature cycling. This in turn will impact on process rates by frost action especially in diurnal frost environments. Such sensitivity may be absent in continental diurnal frost environments such as low-latitude mountains due to their high diurnal radiation inputs and high soil surface temperature ranges. Reduced cloudiness may be important in offsetting a reduction in frost action under current climate warming in the Subantarctic and is under further investigation.

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