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Short Note
First observations on needle ice formation in the sub-Antarctic

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The temperature regime on Marion Island in the sub-Antarctic is highly conducive to the occurrence of diurnal soil frost and needle ice growth (Holness 2003). Needle ice is the usual term applied to the accumulation of slender, bristle-like ice crystals (needles) practically at, or immediately beneath, the surface of the ground (Washburn 1979). High annual frequencies of needle ice growth on Marion, and possibly other sub-Antarctic islands, have been shown to result in high rates of soil heave and surficial soil creep (Boelhouwers *et al*. 2003). Furthermore, needle ice growth impacts on the keystone fellfield *Azorella selago* Hook f. species by means of increased seedling mortality (McGeoch *et al*. 2008), lee-side turf-exfoliation of *A. selago* cushions (Boelhouwers *et al*. 2003) and small-scale spatial variability in sediment erosion and accumulation and associated landform development (Haussmann *et al*. 2009).

Conditions for needle ice initiation are reached when heat loss from the soil to the air results in cooling to the freezing point of the near-surface soil water. This is principally by surface radiative cooling which preferentially occurs during clear and windless nights but, in maritime locations (like that of sub-Antarctic islands), cooling of the soil surface may theoretically also be affected by latent heat and convective heat loss under high wind speeds and favourable soil-air temperature gradients. Traditionally, during needle ice growth, ice nucleation is considered to initiate only from -2°C (Outcalt 1970, 1971), while in a laboratory experiment, Branson *et al*. (1996) indicated that ice nucleation occurs only when -1.5°C is reached. However, substantial frost heave was recently documented on Marion Island that was attributed to needle ice growth, but soil temperature data shows that minimum soil temperatures seldom reached -2°C during the measurement period (Haussmann *et al*. 2009). Given that the near-surface soil temperatures on Marion Island move within a very narrow diurnal and seasonal range (Boelhouwers *et al*. 2003), and that needle ice is such an important geomorphic agent, detailed knowledge of the ice nucleation temperature is essential for the accurate modelling of effective soil frost cycles and needle ice creep in this environment. Here, we present the first direct observations of soil temperatures during needle ice formation in the sub-Antarctic. Observations are from a location in volcanic scoria at the upper fellfield boundary on Marion Island at Katedraalkrans (46°53'50"S, 37°46'28.5"E, 750 m a.s.l.).

Results and discussion

Soil temperatures were measured using a Mike Cotton Systems© 10 channel logger at 1 cm, 5 cm and 10 cm depth as well as air temperature at 40 cm above the ground every 5 minutes at a resolution of 0.02°C. Wind speed was recorded with a cup anemometer at 10 cm above the soil surface. Needle ice events were visually observed in the morning at the logging station during the recording period and the temperature record of two such events are presented in Fig. 1. The thermal characteristics of the air and soil were plotted through triangulation and linear interpolation.

The first event presented here occurred on 3 December 2008 (Fig. 1a). All times given here are GMT+3. A weak vertical air temperature gradient existed from 23h00 to approximately 00h30. For the remainder of the night a stratified temperature profile prevailed with radiative heat loss from the soil surface. The soil surface froze at approximately 02h30 and remained frozen until 08h30. Needle ice growth occurred in the upper 2 cm of the soil and maintained a near uniform temperature between 0 and -0.21°C. During this period, release of latent heat of fusion by ice nucleation balances the radiative heat loss. Needle ice was observed in the morning with needle lengths ranging between 1 and 1.2 cm. Ablation occurred between 08h30 and 09h30 when direct warming of the soil surface rapidly increased the air temperature and created a sharp temperature gradient in the upper 10 cm of the soil. During ablation incoming radiation is used for melt rather than soil warming, maintaining a uniform soil surface temperature at melting temperature. In the evening of 9 December 2008 (Fig. 1b) the temperature records indicate that the soil surface froze at approximately 22h45. Soil temperatures ranged between 0 and -1°C in the upper 4 cm of the soil. Observations on the morning of 10 December 2008 indicate that needle ice formed during the night with lengths between 2.5 cm and 4 cm with ablation completed by approximately 09h00.

Both events show that needle ice formed when the night-time temperature gradient between soil and air was weak. Air temperature perturbations did not affect soil

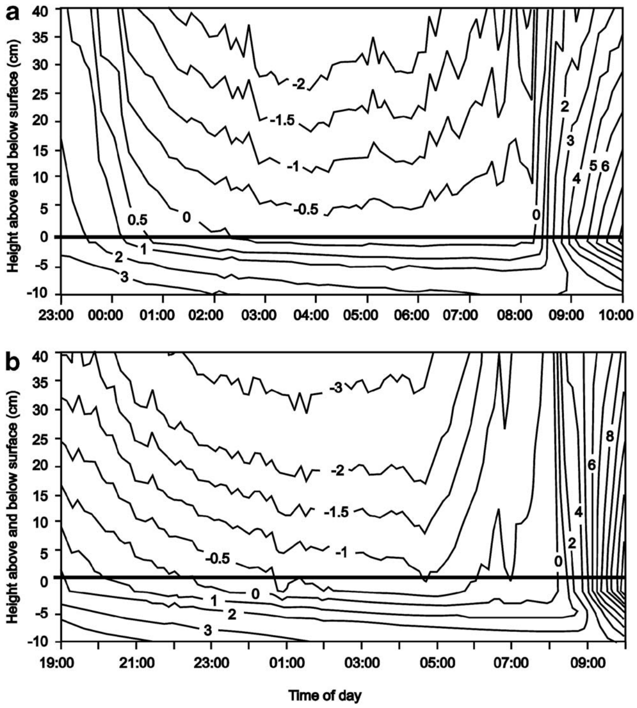

Fig. 1. Soil temperature profile of **a.** 3 December 2008, and **b.** 10 December 2008.

near-surface temperatures and the soil is found to be largely thermally inert. This is undoubtedly due to both the high heat capacity of soil water and latent heat release during needle ice growth and subsequent heat absorption during morning needle ice ablation. Furthermore, on 3 December the minimum temperature recorded was only -0.21°C at 1 cm depth, while on 10 December the temperature at 1 cm depth just reached -1°C. Wind speeds at the near-surface (not shown here) were strong during both events with the wind speed at the site during the evening/morning of 3 and 10 December ranging from 1.8 m s^{-1} gusting to 4.3 m s^{-1} and 3 m s^{-1} to gusting over 6 m s^{-1}, respectively.

Outcalt (1971) carefully defines the various components required for needle ice initiation and suggested that ice nucleation occurs at -2°C under calm, windless nights. Certainly from the observations described here, these two fundamental criteria have not been met. Ice nucleation started at temperatures at or above -0.21 and -1°C and considerable wind speeds occurred during both events. These observations therefore indicate the following. Firstly, it appears that the maritime sub-Antarctic environment do not follow the traditional estimations on ice nucleation temperatures, and other energy balance factors (i.e. latent heat release and convective heat loss) should be investigated for their role in ice nucleation. Secondly, in agreement with Haussmann *et al*. (2009), it could be that -0.2°C is a more appropriate temperature threshold for effective needle ice growth in this environment and that, given the shallow depth of frost penetration, frost pull is the main mechanism in frost heave. Thirdly, the sub-Antarctic periglacial environment as represented by Marion Island has been suggested as fundamentally different from seasonal frost and permafrost environments with regards to landform morphology and the characteristics of the landscape's environmental regimes (Boelhouwers *et al*. 2003, Nel *et al*. 2009a, 2009b, Nel 2012). It seems that this uniqueness also applies to the basic conditions for needle ice growth in the diurnal soil frost environment of the sub-Antarctic.

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