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# An assessment of needle ice, snowfall and the zero-curtain effect and its relationship with soil frost dynamics on sub-Antarctic Marion Island.

**By**

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**A dissertation submitted in partial fulfilment of the requirements of the Master of Science degree in Geography in the Department of Geography and Environmental Sciences at the University of Fort Hare**

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**2013**

# DECLARATION

I declare that this is my original work, except in cases stated. This thesis has not been submitted for a degree or part of a degree to any other department, academic institution or university.

Name: …Mphumzi Brooklyn Zilindile………………………………..
Signature: … …………………………...
Date: ……12 February 2013………………………………
Place of submission: University of Fort Hare, East London Campus.

# DEDICATION

This Masters degree is dedicated to all my peers I grew up with that did not have a chance to advance their education because of unforeseen hardships.

# ACKNOWLEDGEMENTS

There are many people that I am indebted to who contributed to the success of this project. There are few people that are mentioned here but the honest truth is that there are many people that went unmentioned and they put a hand in making this project a success and my sincere gratitude goes to all of them.

To my main supervisor Prof Werner Nel, I would like to thank him for the stimulating discussions, the relentless support both academically and personally. He not only became a supervisor to me but also played a father figure guiding me every step of the way. Without him I would never be where I am in life as he instilled confidence and self-believe that I could conquer the world.

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I would like to gratefully acknowledge The South African National Antarctic Program under the auspices of the Department of Environmental Affairs and Tourism for their logistical and financial support throughout my over-wintering research period.

Finally, this Masters degree not only represents a scientific body of work but it represents a happy part of my life where I got to travel the world, make friends, meet new people and be exposed to new things in life.

# ABSTRACT

This study aims to uncover the synoptic weather circulation pattern which is associated with the occurrence of needle ice, snowfall and the zero-curtain effect. The method of study was done through an intensive ground climate measurement campaign from April 2008 to May 2009 with a temperature logger installed throughout the recording period. Results from data analyses indicate that the complex changes in climate parameters may lead to an equally complex response in terms of spatial soil frost dynamics and its direct and indirect effects on soil sediment displacement and ecosystem dynamics. Field evidence in the study suggests that on Marion Island needle ice developed in temperatures as high as -0.2 ºC in strong winds. This confirms that the wet environment of Marion Island, which is dominated by diurnal soil frost is fundamentally different from seasonal frost and permafrost environments. The scoria material is susceptible to needle ice growth and the compacted soil alters the micro-climatology of the affected area making it more susceptible to the formation of needle ice. Soil moisture for needle ice formation and growth is provided by the misty conditions associated with the advent of the cold front (pre-cyclonic). Furthermore, observations of needle ice on Marion show that needles are mostly clear with no sediment inclusion. This is indicative of needle ice formation that has not been interrupted by a shortage of moisture. The zero-curtain effect on Marion Island can occur either as a response to the thawing of the soil after the seasonal freeze. The synoptic assessment of snowfall on Marion Island indicates that; snowfall is associated with the passage of a cold front linked to a strong meridional system of low pressure just south of the island.

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# CHAPTER 1

# INTRODUCTION

The Prince Edwards islands, constituting Prince Edward and Marion Island, are truly oceanic in more than one sense: geographically because of the remoteness from the continents, ecologically due to the predominant biologic and climatic influence of the surrounding waters and geologically, because they have arisen from the sea floor by volcanic processes (Holness, 2001a). Recent geomorphological research on this maritime sub-Antarctic island has placed emphasis on the role of synoptic weather conditions in soil temperature dynamics (Nel et al., 2009a; 2009b, Nel, 2012). The influence of anticyclones, the passage of frontal systems and mid-latitude depressions are all characteristic of the synoptic climate of Marion Island (Vowinckel, 1954; le Roux, 2008; Nel et al., 2009a). On the island, synoptic-scale weather systems influence shallow sub-surface soil temperatures through depressing or enhancing radiative fluxes (Nel et al., 2009b). At the soil surface, diurnal temperature variation results in significant impact on the frost frequencies as there seems to be absence of seasonal temperature trends (Boelhouwers et al., 2008).

Marion Island is a periglacial environment that is characterised by high moisture conditions and diurnal frost cycles (Boelhouwers et al., 2003). Snow cover is present for much of the winter period above 750m a.s.l. on the island but it is also discontinuous due to rapid wind action. This results in spatially heterogeneous ground frost conditions (Boelhouwers et al., 2003, Sumner et al., 2004). Also, diurnal snowfall influences the diurnal ground frost conditions especially in the summer (Nel, 2012). In the ground frost thermal regime, snow acts as an insulator that limits ground frost cycles beneath its cover (e.g. Chambers, 1967; Thorn, 1978, 1980, 1992; Matsouka, 1996; Boelhouwers et al., 2008). This is also believed to be the case for the ground frost dynamics on Marion Island (Nel, 2012).

Studies that investigate the modification of frozen ground characteristics are primarily focused on the northern hemisphere permafrost regions due to the interactions with the global carbon cycle (Zimov et al., 2006) and the potential positive feedbacks to current global warming and impacts on terrestrial ecosystems (ACIA, 2005). In contrast, diurnal ground frost dominates the sub-polar region of the Antarctic, and the time-scale at which climate drivers affect the ground frost conditions is in the order of hours to days (Nel et al., 2009a), rather than seasonal or annual. At the diurnal time scale, synoptic weather conditions control the temporal variability in ground temperature (Nel et al., 2009a, 2009b) which is superimposed on the seasonal shift in ground energy budget (Boelhouwers et al., 2008).

Monitoring of soil heave, downslope movement, moisture and temperature demonstrate that the repetition of frost heave cycles, fed by the temperature cycling across 0°C and periodic moisture supply, promotes soil creep (needle ice creep and diurnal frost creep) (Hall, 1979; Holness, 2003). Frost creep is the down slope movement of soil particles originating from frost heaving normal to the slope followed by nearly vertical thaw consolidation (Washburn, 1979, 1989). Frost heave refers to the raising of the ground surface as a result of ice accumulation (Matsouka, 1996) and heave tends to be greatest in silty soils and is absent in exclusively coarse grained materials (French, 1996; Holness, 2001b). Soil creep is intensified in cold regions where frost heave activity governs the movement (Matsouka, 1996).

The amount of diurnal frost heave does not necessarily reflect the intensity of freezing which is represented by the frost depth. According to Matsouka (1996), a more important control of the heave amount seems to be the moisture regimes. Typical surface rates of movement are a few centimeters per year (e.g. Washburn, 1979, 1989; French, 1996). Previous studies show that diurnal frost heave and creep are significant and dominant in many mid-latitude to tropical high mountains (e.g. Mackay and Mathews, 1974; Pérez, 1992; Matsuoka, 1996), also in part of the Antarctic mountains (Matsuoka and Moriwaki, 1992), and in the sub-Antarctic (Boelhouwers et al., 2003; Holness, 2003, 2004). The difference in frost duration affects the depth of new lenses developing during frost heaving and thus controls the depth of movement.

Presently, diurnal soil frost is a key geomorphic process occurring on Marion Island (Holness, 2003), while frost creep (initiated by needle ice) is considered the dominant sediment transport mechanism (Holness, 2001, 2003). Furthermore, *Azorella selago* a keystone species on sub-Antarctic islands, (le Roux et al., 2005) interacts with the geomorphology of the dominant fellfield vegetation by affecting sediment distribution and ultimately terrace formation (Hausmann et al., 2009). Soil frost and resulting ice segregation and soil displacement has a well documented negative impact on *A. selago* through limiting seedling establishment and survival and stimulating early plant senescence (le Roux, 2004). Understanding soil frost in sub-Antarctic diurnal frost environments is therefore essential to understanding both geomorphological dynamics and its associated effects on the ecosystem.

On the island, the major environmental significance of soil frost is dependent on the growth of needle ice through the resultant soil disturbance and sediment displacement (Nel et al., 2009b). Needle ice growth is normally associated with long-wave radiation loss from the soil surface that results in below-zero temperatures. Needle ice is a form of segregation ice which can be found in any climate susceptible to freezing temperatures (Lawler, 1988, 1993; Boelhouwers et al., 2003, 2008). The detailed account of the growth of needle ice was given with particular reference to the conditions of water supply and air temperature to be found in field conditions (Outcalt, 1969, 1971). Needle ice events are believed to indicate that cloud cover and air dew point (thermal radiation and latent heat flux levels) maintained an overriding control over the needle ice event frequency at wet soil sites (Outcalt, 1969; Lawler, 1988, 1993). An ideal soil-cooling frost night would be one with a strong negative thermal radiation balance, a low sky radiant temperature and a steep vapour gradient from a wet soil surface to the dry air (Outcalt, 1969). During clear and calm conditions, needle ice normally develops within one or two hours after sunset when air and ground temperatures drop rapidly to below 0ºC (Lawler, 1988). Needle ice develops most frequently when the near-surface ground temperature approaches -1.0ºC but has been observed to develop when the ground temperature is as high as -0.4ºC (Lawler, 1988; Holness, 2003). The basic condition would seem to be a clear night sky favouring maximum radiation from, and therefore cooling of the surface (Outcalt, 1969; Boelhouwers et al., 2003). However, previous field observations on Marion Island indicate that needle ice occurrence does not necessarily satisfy the above-mentioned conditions observed in the other cold regions of the world.

On Marion Island, needle ice is a dominant agent in the erosion of unvegetated surfaces (Boelhouwers et al., 2003, 2008; Holness, 2001a, 2003, 2004) and also plays part in inhibiting the growth of vegetation on bare surfaces (Van Zinderen Bakker, 1973; Hall, 1979; Boelhouwers et al., 2008). In field conditions, needle ice occurs on unvegetated surfaces when air temperatures fall below the freezing point, provided that an adequate moisture supply is available (Outcalt, 1969; Lawler, 1988, 1993; Boelhouwers et al., 2008). The environmental implications are numerous, for example, the erosive and preparation effects on hillslopes and in soils have been long documented (Ireland et al., 1939; Outcalt, 1970; Meentemeyer and Zippin, 1980, 1981; Boelhouwers et al., 2003; Holness, 2003, 2004). The ability of ice needles to move considerable quantities of both fine and coarse material in a selective and preferential way has led to distinctive landforms and landscape patterns (Boelhouwers et al., 2003; Holness, 2003, 2004).

The amount of soil disturbed by ice needles is affected by several characteristics. When the surface is very wet, needles tend to grow on top of it, and do not carry any soil cap (Outcalt, 1971); if the ground surface becomes desiccated, the freezing front can form deeper in the soil and needles can then lift the layer above the freezing plane (Meentemeyer and Zippin, 1981; Holness, 2001b). In very porous soils with a high proportion of fines, needles commonly form some distance below the ground surface, while in soil with a high proportion of fines, needles develop closer to or on top of the soil surface thus lifting little soil material per unit area (Pérez, 1985). Soil compaction also affects needle ice development; in heavily compacted soils, needles form near the surface and as a result, less material per unit area is lifted (Brink et al., 1967; Meentemeyer and Zippin, 1980, 1981; Lawler, 1988, 1993). Further, freeze-thaw cycles increase the breaking up of the surface, producing the characteristic puffy appearance commonly seen in the field after a period of needle ice development.

Commonly reported needle lengths vary between 1 and 5 cm, which is consistent with a single night of freezing (Meentemeyer and Zippin, 1980, 1981). Five studies, however, cite lengths in excess of 12 cm (e.g. Beskow, 1935; Soons and Greenland, 1970; Lawler, 1986, 1987, 1988). Needle ice length is influenced by moisture availability and cooling rate (Outcalt, 1971; Branson et al., 1996). The finding that the length of the needle explains less than half the variances in sediment yield suggest that the mechanism by which material becomes incorporated into growing ice needles operates intermittently (Miller, 1973). Outcalt (1969) suggested that needle ice growth is interrupted by ‘normal’ in-situ freezing of soil water if the rate of heat loss becomes too great and/or the supply of soil moisture to the freezing front becomes inhibited (Lawler, 1988, 1993). The frozen material above is then incorporated within the reinitiated growth as a band of soil (McDougall et al., 2001). There is no doubt that on Marion Island differential heaving by needle ice plays a critical role in frost activity (Holness, 2001b). However, it has not been established whether needle ice is directly responsible for the initiation, spacing and regularity of sorted stripes on Marion Island, or whether needle ice activity is reflecting pre-established patterns (Holness, 2001b).

Marion Island used to be covered with a permanent snowline which was documented by researchers that came into contact with this sub-Antarctic island (Verwoerd., 1971; Van Zinderen Bakker, 1973). There was still the existence of permanent snow and ice above 950m a.s.l. in the late 1970’s as noted by Hall (1979). However, since the start of direct observations in 1996 no permanent snowline could be discerned on the island (Boelhouwers, 2003). To ascertain the disappearance of the former snowline, Hedding (2006) notes that the first observations of permanent snow on Marion Island was noted at 800 feet (approximately 270m a.s.l.) in 1873. The disappearance of the former permanent snowline is considered to be associated with the recorded climatic change on the sub-Antarctic Marion Island (Sumner et al., 2004).

Snow is a key variable in the rates of soil warming and permafrost thawing. Because snow effectively insulates the upper soil layers during winter, increases in snow depth generally result in higher soil temperatures during the cold season, while an absence of snow results in more rapid and greater cooling of the soil (Hinkel and Outcalt, 1993). It has been suggested that on Marion the snow cover that remains on the ground keeps the shallow soil temperatures at the freezing point of soil water and buffers the soil from temperature fluctuations (Nel et al., 2009b). If snowfall changes substantially as climate changes, warming and thawing or cooling and freezing may significantly affect the upper soil layers (Hinkel and Outcalt, 1994). A period with very small daily temperature ranges is indicative of significant snow covering the ground (Hall, 1997). Therefore, presence of snow could lead to deeper soil freezing coupled with ground heat flow to the contact surface with the snow (Nel et al., 2009b).

In soil frost dynamics the zero-curtain effect is the persistence of a nearly constant temperature, very close to the soil water freezing point, during annual freezing (and sometimes thawing) of the active layer (Outcalt et al., 1990). Outcalt et al. (1990) demonstrated that the effect also occurs outside permafrost regions. The term zero-curtain refers to the effect of latent heat in maintaining temperatures below freezing point over extended periods in freezing or thawing soils (Hall, 1998). The zero-curtain effect appears to be produced and maintained by vapour transport induced by freeze-thaw events at the soil surface (Hall, 1998). It can persist for several hours or several weeks depending largely on the total water content of the ground, snowcover and air temperatures (Outcalt et al., 1990). Research shows that it can appear in radically different soils and over a wide range of spatial and temporal scales, conditions conducive to formation of a zero-curtain occur when and where a freeze-thaw cycle at the surface produces an upper and lower freezing isotherm in the underlying soil (Hall, 1997). Owning to the importance of vapour transport in the process, the zero-curtain effect is probably absent in dryer, coarse soils and in clays with low hydraulic conductivity (Hall, 1999). The zero-curtain is not only evident in freezing and thawing of undisturbed natural terrain but is also an important factor with respect to frost action, refreezing of the ground (backfill or slurry) around foundations, and can have a major effect on the thermal regime of the active layer and of the permafrost (Outcalt et al., 1990). The importance of the zero-curtain effect on Marion Island could be that it influences the freeze-thaw effect and the number of soil frost cycles. The zero-curtain closes when thermal disturbances at the surface fail to produce temperatures higher than the ice point. Under such conditions a strong soil water tension gradient develops between the surface and warmer regions at depth, triggering strong advective flow that desiccates the region experiencing the zero-curtain effect (Outcalt et al., 1990). On Marion it has always been a challenge when analysing automated temperature data from logger recordings, to distinguish between the ground thermal effect from the occurrence of snow fall and the zero-curtain effect.

## Aim and objectives of the research

On Marion Island, diurnal frost is one of the most important geomorphic processes and needle ice is the dominant sediment transport mechanism on the island. Also, snowfall has a major influence on frost dynamics and the zero-curtain effect has largely been unstudied in a maritime sub-Antarctic environment, this study aims to address the following:

First, the formation and climatic drivers of needle ice and its resultant form are investigated. This includes a synoptic scale assessment of the weather associated with the formation of needle ice as well as the resultant soil temperature (micro-climatic) dynamics during formation. Second, the synoptic weather circulation pattern associated with the occurrence of snowfall and its effect on the soil temperature and soil frost are analysed. Lastly, the formation and occurrence of the zero-curtain effect will be specifically addressed.

Key objectives include:

- Assessing the synoptic weather conditions associated with needle ice occurrence.
- Assessing the characteristics of needle ice and the micro-climate dynamics associated with needle ice development.
- Identifying the synoptic weather conditions associated with snowfall occurrence and its effect on soil temperature dynamics.
- Investigating if the zero-curtain effect occurs on Marion Island and assessing the possible reasons for the formation of the zero-curtain effect and its implications for soil frost dynamics.

The structure of the dissertation is as follows: Chapter one contains an introduction to the study with a literature review, aim and objectives and thesis outline. Chapter two includes a detailed analysis of the study area, which includes an outline of its general environment and setting. Chapter three describes the study site and research methodology. Data presentation is dealt with in Chapter four while Chapter five covers a discussion on findings. Chapter six: conclusions and recommendations for future research.

# CHAPTER 2

# MARION ISLAND AS STUDY AREA

Marion Island (46º 54` S, 37º 45` E) is located in the south Indian Ocean (Fig. 1) and has a maritime climate that is dominated by strong westerly winds and relatively low temperatures (Sumner et al., 2002; Nel et al., 2003, 2009a). It has an area of 290km² and rises to a height of 1230m a.s.l. (Sumner et al., 2004). The island is a peak of a shield volcano and has a dome-like profile with slope angles that do not exceed 10˚ (McDougall et al., 2001). Recent eruptions (Verwoed et al., 1981; Meiklejohn and Hedding, 2005; Boelhouwers et al., 2008) are clear indications that volcanic activity still continues.

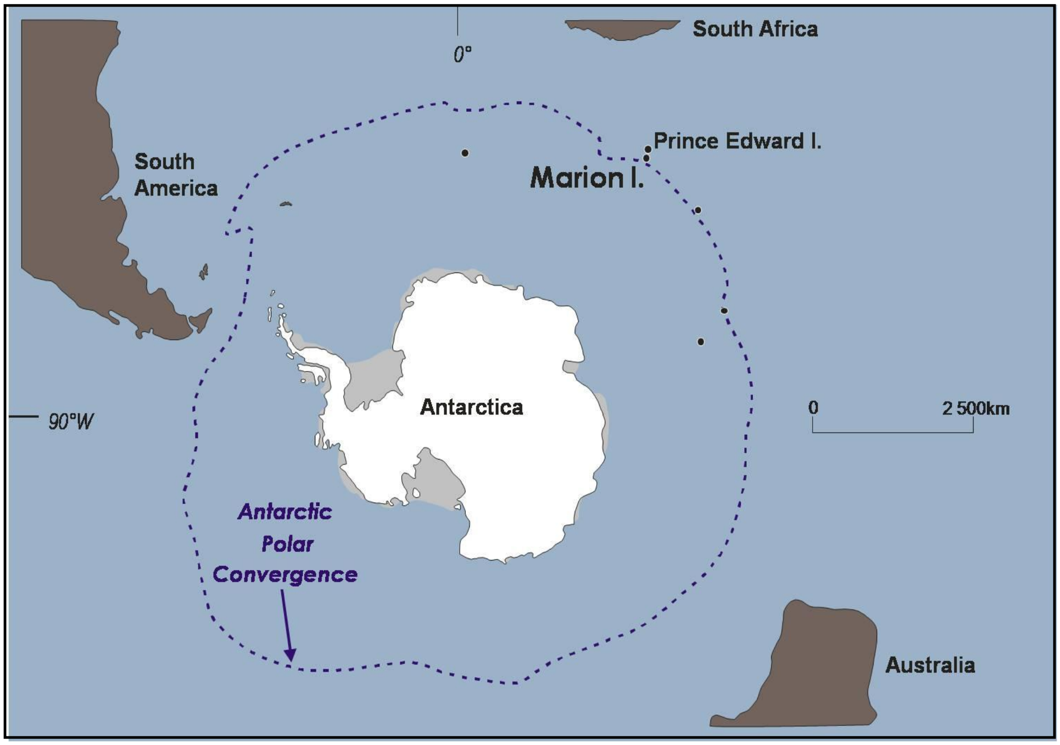

Figure 1: Location of Marion Island (Hedding, 2006).

Mean summer maximum and minimum temperatures at sea level are 10.5 and 5.0°C, and the winter means are 6.0 and 1.0°C, respectively. On average, precipitation occurs for 25.6 days per month, with a mean annual total of 2332 mm (Holness, 2004). The island exhibits high relative humidity (averaging 80%) although short periods of low humidity occur due to Föhn winds (Schulze, 1971; Smith and Steenkamp, 1990; le Roux, 2008). The hyper-oceanic sub-Antarctic climate of low temperatures, high annual precipitation and low radiation inputs give rise to an almost continuous cloud cover (Schulze, 1971; Holness, 2001a, b). Marion Island is situated in the ‘‘Roaring Forties’’ and is subject to a succession of mid-latitude depressions, frontal systems and migratory anticyclones (Vowinckel, 1954). These mid-latitude depressions (cyclones) are initiated somewhere in the Atlantic Ocean between latitude 30° and 40°S and travel in an south-eastward direction, with their centres usually passing over or to the west of Marion Island (Vowinckel, 1954). Cyclones are associated with upward movement of air and an increase in cloudliness (Tyson and Preton-Whyte, 2000) and on Marion Island an approaching cold front is associated with a strengthening of the north-westerly winds, an influx of warm Subtropical air and an increase in cloudliness. Once passed an advection of cooler dry Antarctic air with associated weak south-westerly and clear skies occurs. Marion Island is also under the influence of the South Indian Ocean anticyclone with its centre to the north-east of the island (Rouault et al., 2005). This brings warm air from the north and moderate north-westerly to north-easterly winds. The island is also affected by a ridging anticyclonic cell that ridges in to the northwest of the island and winds are dry south-westerly.

Because of its location the island has a very windy climate (le Roux, 2008). The wind blows most frequently from the northwest with an average velocity of 32 km/h (Holness, 2001; Boelhouwers et al., 2003). Precipitation, pressure, temperature and wind speed and direction show a relatively small annual range in values as expected for a maritime mid-latitude location impacted throughout the year by the eastward moving low pressure systems (Vowinckel, 1954; Rouault, et al., 2005).

The climate of Marion Island changed significantly over the last thirty years, with recorded increases in sunshine hours, pressure and temperature, together with a reduction in rainfall (Smith, 2002; Rouault et al., 2005). Smith (2002) reports an increase in air temperature of 1.2°C recorded between 1969 and 1999. This trend in air temperatures correspond to a 1.4°C increase in sea-surface temperature measured over the same period (Mélise et al., 2003). The warming that has been recorded takes place at more than twice the mean global rate (le Roux, 2008). It has been shown that under a changing climate, Marion Island experiences less cloud cover and more direct sunlight (Smith, 2002). Rouault et al., (2005) proposes that the pressure increase in summer measured on Marion Island corresponds to a decrease in rainfall, an increase in the number of days without precipitation and a northward shift in the wind direction. This change in cyclonic activity affects the island with the reduction in the westerly wind component. This implies relatively more anticyclonic conditions over the island or a reduction in low pressure affecting the island in summer (Rouault et al., 2005). Smith and Steenkamp (1990) propose that the radiation and air temperature increases can be explained by the positions of cyclone tracks relative to the island. Approximately 100 cyclones pass the island in a year and in warmer years the cyclonic centres pass, on average, further to the south of the island (Smith and Steenkamp, 1990).

It has been documented that this high rate of warming is consistent among the sub-Antarctic islands (Frenot et al., 1997; Tweedie and Bergstrom, 2000; Weimerskirch et al., 2003; Thost and Allison, 2005). These changing climatic trends (decreased precipitation and cloud cover, coupled with warmer temperatures) can be seen in the loss of the permanent snowline which was present in the 1960s (Huntley, 1970; Sumner et al., 2004). The changes in climate on the island have also had considerable impacts on the physical (Chown and Smith, 1993, Sumner et al., 2004) and biotic (Chown and Smith, 1993; Pakhomov et al., 2004; le Roux and McGeoch, 2008) features of the Prince Edwards Islands. Continuation of these climate trends will result in further ecological changes (Smith and Steenkamp, 1990; Chown and Smith, 1993).

The climate and geographic isolation of the sub-Antarctic islands, coupled with their biotic influences makes them unique (French and Smith, 1985; Smith and French, 1988; le Roux, 2008). Marion Island is one of these sub-Antarctic islands and has one of the most oceanic climates (le Roux, 2008), termed hyper oceanic by Smith and Steenkamp (1990). The island has low daily and seasonal thermal variability (Smith and Steenkamp, 1990; le Roux, 2008). A consequence of the island's low thermal variability is that sub-zero temperatures can be experienced during any month of the year (see Boelhouwers et al., 2003; le Roux, 2008). The island exhibits characteristics similar to other sub-Antarctic islands in that it is distinguished by high precipitation and humidity, strong winds and near complete cloud cover (French and Smith, 1985; Bergstrom and Chown, 1999). As a consequence of all the climatic variations discussed above, Marion Island is oceanic and, on average cold, cloudy and windy (le Roux, 2008).

Marion Island is a distinct periglacial environment (Boelhouwers et al., 2003) and can be divided into four frost zones, (1) a coastal diurnal frost zone dominated by needle ice, (2) an upper diurnal frost zone with needle ice and ice lens formation, (3) a high altitude zone of seasonal freezing, (4) and summit pockets of permafrost (Boelhouwers *et al.*, 2001). The diurnal frost zone is between sea level and 300m a.s.l. and soil frost is the dominant geomorphic agent. The upper diurnal frost zone is situated between 300m and 750m a.s.l. and the general absence of vegetation allows for extremely high transport rates. The seasonal frost zone is found at and above 750m a.s.l. and sporadic permafrost bodies above 1000m a.s.l. (Sumner et al., 2004).

Previous studies have assessed periglacial landforms and their environmental implications (Hall, 1981, 1983a, Holness and Boelhouwers, 1998; Boelhouwers *et al.*, 2001). In these studies, which mainly relate to patterned ground, it was observed that some of the landforms were relict and a product of cooler than present post-glacial conditions (Hall, 1983a). Observations on stone-banked lobes also support this theory (Hall, 1981). Present day periglacial morphology on the island is dominated by patterned ground on grey lava and scoria areas from close to sea level through to the highest altitude.

The island surface is characterised by extensive areas of black and grey lava, and scoria cones (Fig. 2), grey lava moraines and tills from earlier glaciations, and scarps caused by radial faulting on deglaciation (Hall, 1978; Holness, 2004). Geologically, the island is composed of two basaltic sites: older, glaciated grey and recent unglaciated black lava (Verwoed, 1971; Boelhouwers et al., 2008). The island has 130 scoria cones which are geomorphologically active landforms due to their relatively steep slopes and unconsolidated substrate (Holness, 2004). Substrate mobility on scoria cones is due to frost-heaving as a result of regular diurnal freeze–thaw cycles and small debris flows (Boelhouwers et al., 2000; Holness, 2004). Active and relict periglacial landforms are found throughout the island and show distinct trends of increasing size with altitude, a function of deeper frost penetration (Hall, 1978; Boelhouwers et al., 2008). Marion

Island’s landscape is highly dynamic as is reflected by active coastal erosion cliffs and weathering of slope processes on scoria cones (Boelhouwers et al., 2008).

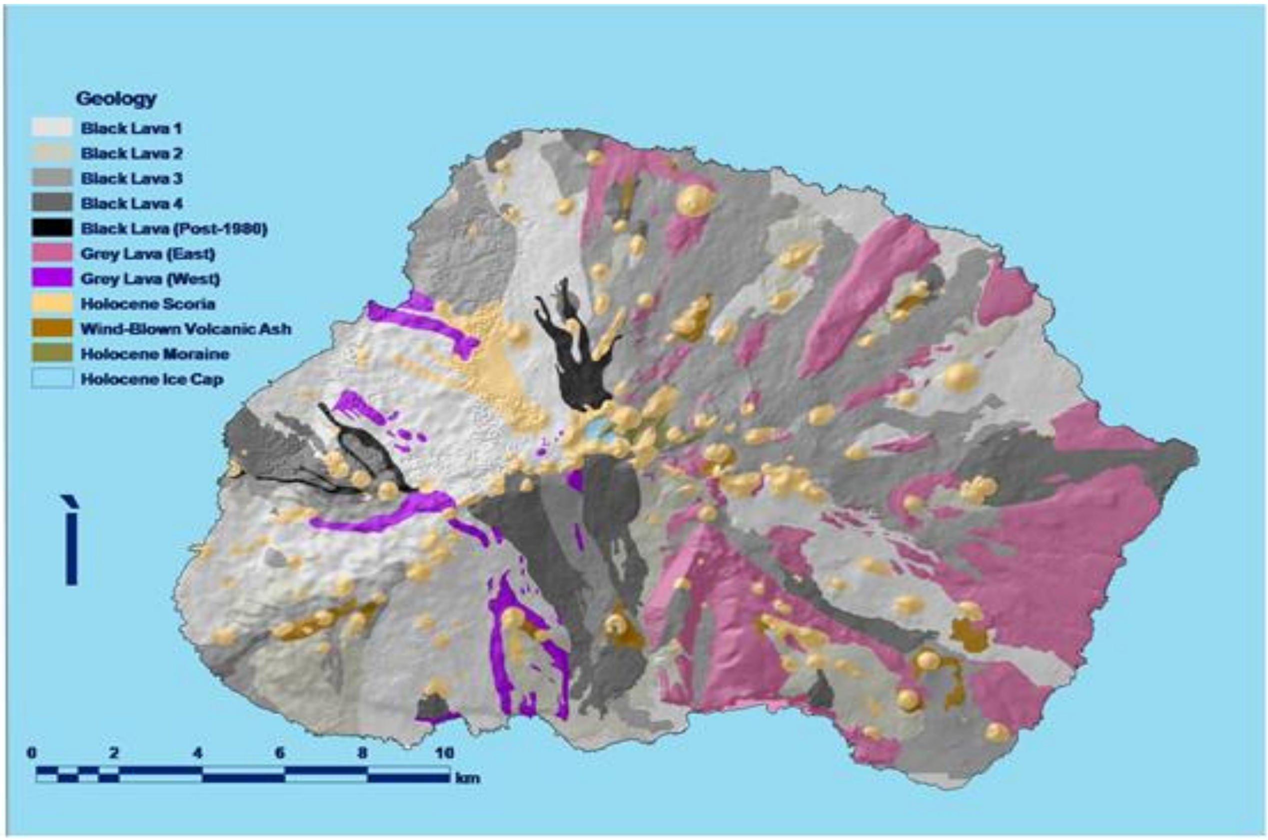

Figure 2: The geological map of Marion Island (Hedding, 2006).

Maritime periglacial environments have traditionally been assumed to be the most suited to freeze-thaw processes (French, 1996; Boelhouwers et al., 2001) and this assumption is supported by the extremely high number of freeze-thaw days recorded on Marion Island (Holness, 2003). The only other periglacial environment where similar high frequencies of freeze-thaw cycles occur are alpine regions, but even these regions typically experience less than half the number of freeze-thaw events recorded in the high altitudes of Marion Island (French, 1996; Matsouka, 1996; Boelhouwers, 1998). Hence, the number of freeze-thaw days on Marion Island, with its associated high number of freeze-thaw cycles, is higher than almost any other periglacial environment with the possible exception of other sub-Antarctic islands such as Kerguelen Island and high tropical mountains such as the Venezuelan Andes (Boelhouwers et al., 2001).

The frost environment is characterized by an extremely high frequency of diurnal frost cycles which occur on an average of 119 days per year at low altitudes (Holness, 2001b, 2004). In addition to diurnal cycles, longer-duration frost cycles occur at altitudes above 750m a.s.l., with the ground remaining frozen for approximately two months of the year (Holness, 2003).

Observations show that needle ice is the dominant form of segregation ice, although ice lens formation also occurs above 300m a.s.l. (Hall, 1979, 1981; Holness and Boelhouwers, 1998; Boelhouwers et al., 2000; Holness, 2004). In summary, the present day soil frost regime of the island is characterised by short-duration, high-frequency and low-intensity frost cycles. Some higher altitude areas experience mild seasonal frost, with isolated pockets of permafrost occurring in association with permanent ice masses (Holness, 2003). Thus, the processes such as frost heave by needle ice that are associated with a diurnal periglacial environment are likely to play a significant role in the movement of slope material.

# CHAPTER 3

## STUDY SITE AND METHODOLOGY

This study was conducted in the interior of Marion Island at Katedraalkrans (750m a.s.l.) (Fig. 3), which is within the upper diurnal frost zone that is situated between 300 and 750m a.s.l. (Holness, 2001a; Nel, 2001). This zone is characterised by very frequent diurnal frost cycles and some longer freezing events. Needle ice induced frost creep dominates at this altitude, but longer frost cycles are associated with deeper ice lens formation and solifluction (Boelhouwers et al., 2001).

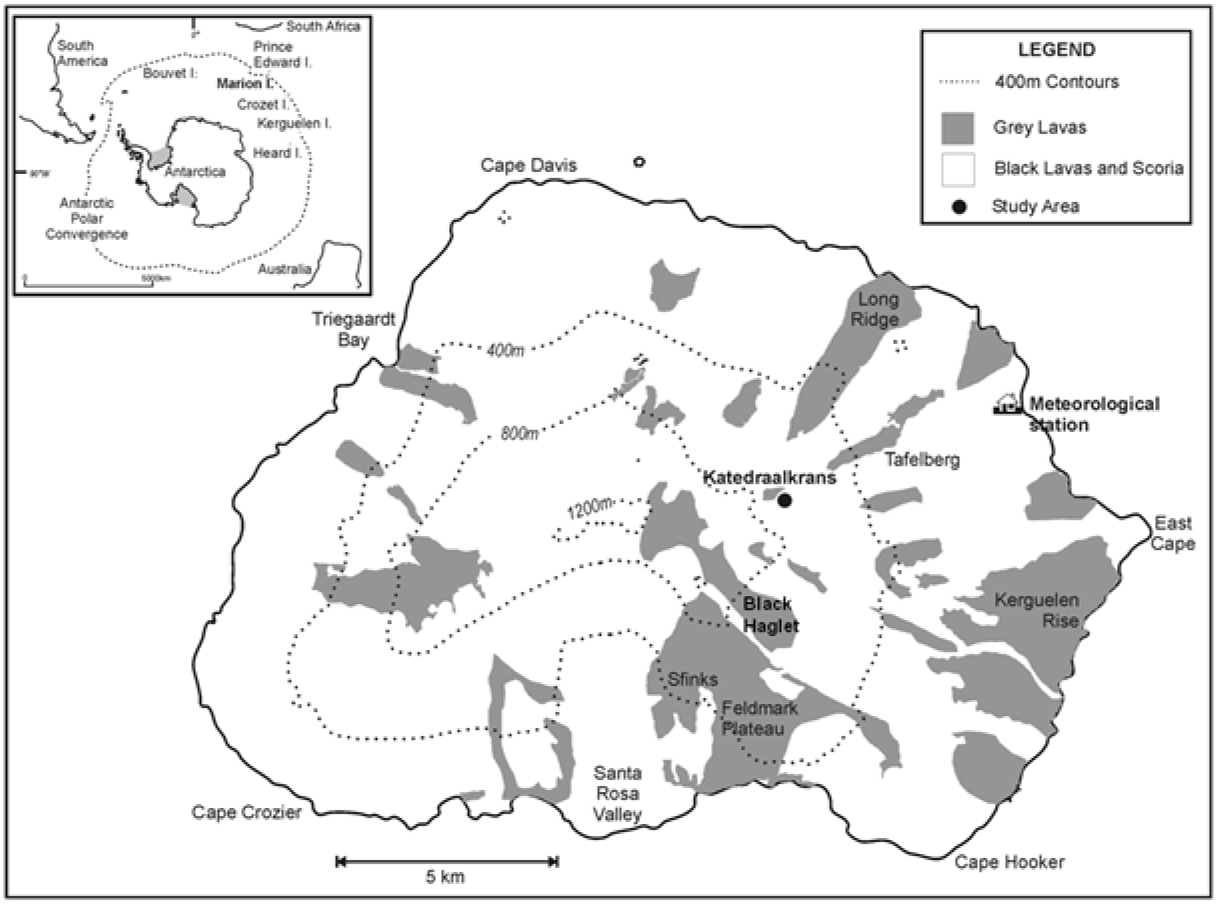

Figure 3: Location of Marion Island and the study site at Katedraalkrans (After Nel et al., 2009a).

Katedraalkrans experiences a large number of freeze-thaw days, with 178.5 days being recorded per year in the air. However, fewer soil surface freeze-thaw days are experienced, with 125 days/annum measured (Holness, 2001a). The study area consists of scoria and black lava deposits and is almost completely unvegetated, with vegetation being restricted to some moss and lichen growth on the leeward side of boulders. Since the area is largely devoid of vegetation it allows for a more direct linkage between atmospheric conditions and ground temperatures.

## Methodology

To investigate the formation and climatic drivers of needle ice and its resultant forms as well as the synoptic weather patterns associated with the occurrence of snowfall and the zero-curtain effect and its effect on the soil temperature, an intensive ground climate measurement campaign was implemented from April 2008 to May 2009. A Mike Cotton Systems© (MCS) 10 channel logger was installed at at exactly 765m a.s.l. (S 46° 53' 56.9''; E 37° 46' 30.2''), soil temperatures were recorded through thermocouple wire sensors inserted into the fine scoria at 1 cm, 5 cm and 10 cm depth every 5 minutes at a resolution of 0.01 °C. Also, attached to the logger was a temperature sensor housed in a radiation screen measuring air temperature (same interval and resolution as for soil) at 40cm above the surface. A second MCS logger recorded wind speed (in m/s every 10 minutes) through a cup anemometer. The synoptic weather systems dominant during the recording period were assessed through the synoptic shipping charts issued 6 hourly by the South African Weather Services (SAWS). These methodology and logging arrangements has been successfully used on Marion island in other experiments (see Nel et al., 2009a; Nel, 2012)

Needle ice observations and monitoring of events presented challenges and this required the monitoring methodology to be refined. The occurrence of needle ice events was first monitored when conditions seemed ‘favourable’ (see Outcalt, 1969, 1971). The so-called favourable conditions are when there is clear skies, no prevalent cloud cover, no wind and the preceding day had sunlight (Lawler, 1988). Previous research documented that if all these conditions were satisfied, the probability for the formation and growth of needle ice was high. Therefore, diurnal synoptic weather conditions were monitored at Katedraalkrans and the “probable” days identified. During the night, the hourly observations were undertaken (from 20:00 to 23:00) for a period 30 minutes every hour around the logger to investigate and document observations of needle ice formation. After some regular observations, it was noted that on Marion Island, the occurrence of needle ice is not necessarily in line with the attributes necessary in other cold regions of the world (Outcalt, 1969, 1971; Lawler, 1988). This led to a change in the observation strategy as the above-mentioned ‘favourable’ conditions did not amount to any needle ice observations in Marion Island’s interior.

The implementation of the new method of analysis included observations conducted every early morning and night on the days the author was at the study site. No observations were done in rainy conditions. Early morning observations started at 06:00 GMT and night observation from 20:00 – 23:00 GMT. The areas close to the logger were ‘patrolled’ and any signs of needle ice (such as ‘puffed’ ground) would be noted and photos taken. Even though the observations of needle ice were limited during the recording period, it is the first real-time observations of the growth of needle ice in the field supported by high- resolution soil and air temperature data in the sub-Antarctic region.

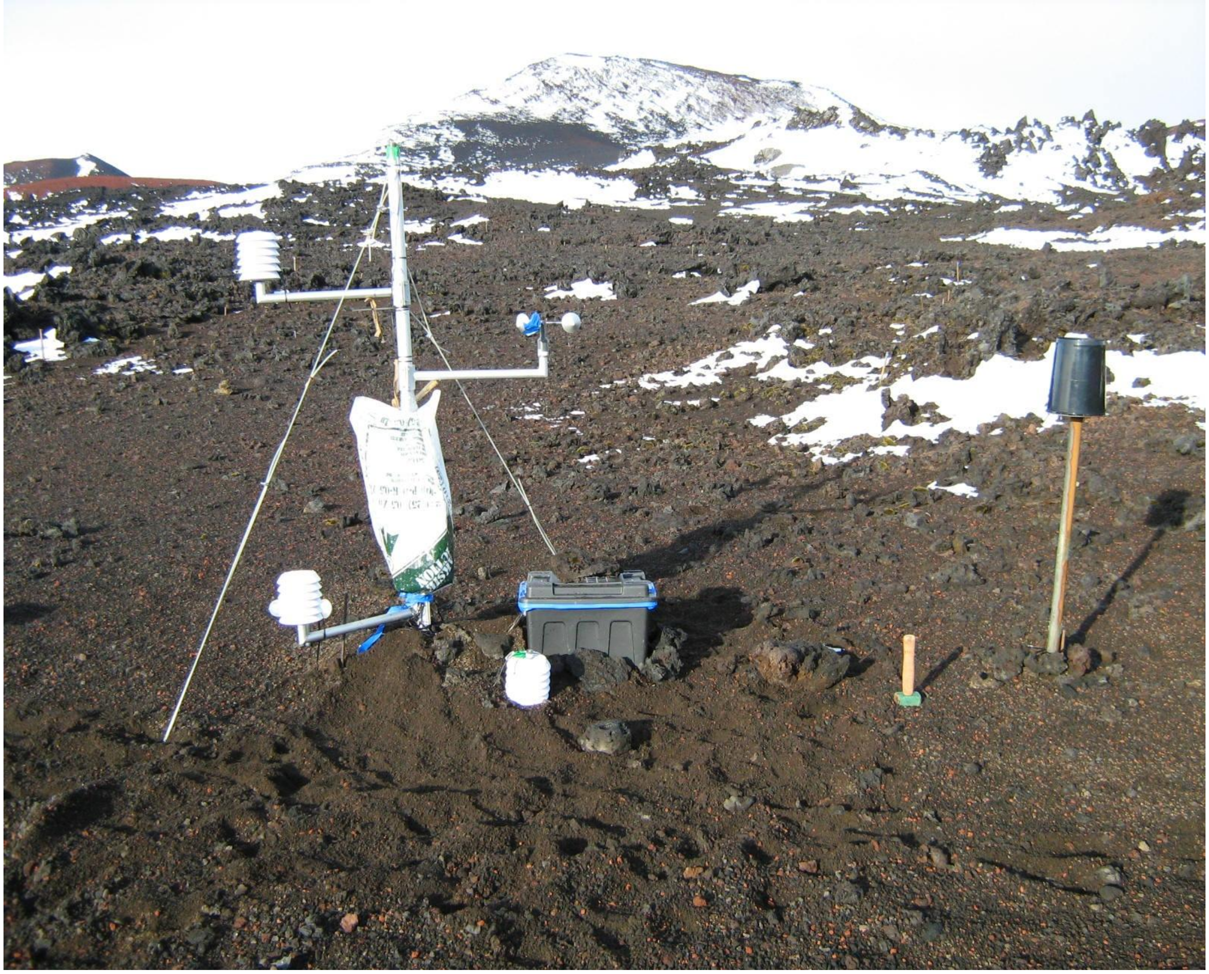

Figure 4: Mike Cotton Systems© (Automatic Weather Station) located in Katedraalkrans at 750m a.s.l.

Accordingly, the AWS assists with the assessment of what atmospheric conditions lead to soil frost; the relationship between frost cycles and its relationship with soil frost dynamics on sub-Antarctic Marion Island. The temperature data from the AWS is helpful in answering questions relating to daily temperature fluctuations, freeze-thaw cycles and the zero-curtain effect. In addition, daily synoptic weather charts were collected from the SAWS (South African Weather Services) office for the duration of the study to aid in analysis. These charts and averages are useful in assessing the relationship between the soil frost dynamics and needle ice, snowfall and the zero-curtain effect occurrence on Marion Island.

Personal field observations throughout the study period (from April 2008 to May 2009) provided insight of other environmental parameters that were not recorded by instrumentation. For instance, it was possible to monitor the occurrences of snowfall and depth of snow at the study site through direct observation. Observations of snow cover presence is important when determining the presence and the duration of the zero-curtain and what period of time was characterised by longer duration of snow cover in the ground. The importance of cloud cover observations is to determine what atmospheric conditions lead to frost on a diurnal range. Previous studies have already shown that cloud cover or absence of it plays a role in diurnal temperature ranges (Holness, 2003).

During the recording period a number of technical problems with the MCS loggers were encountered. Unfortunately due to cold temperatures and memory capacity problems the loggers did not operate for the full duration of the study period (Table 1). During most of the winter of 2008 the logger was snow covered (Fig. 5). This made it impossible to download data from the logger and resulted in some of the recording channels being dysfunctional. For example, the wind sensors were frozen and could not rotate, which resulted in erroneous data.

Data downloading of the logger was very sensitive as it exposes the downloading equipment and the logger to wet and unfavourable conditions. As a result, the downloading period of the weather station is not consistent as it was necessary to wait for a snowfall-free or dry day in order to protect the downloading and logger equipment from damage. This sometime resulted in the logger memory being full and subsequent logging time lost.

The technical problems mostly related to the programming and the ability of the weather station to withstand challenging weather conditions. Because of the problems discussed above there were was missing data and some data was not able to be used for this study as it was corrupted because of inconsistencies in the weather station recording (see Table 1 for logger recordings).

Table 1: Katedraalkrans logger recording periods (April 2008 to May 2009).

| **Katedraalkrans logger recording period** |
|---|
| 10-27 April 08 |
| 6-23 May 08 |
| 2-5 August 08 |
| 1-18 Sept 08 |
| 1-13 October 08 |
| 1-14 November 08 |
| 2-19 December 08 |
| 29 Dec 08 – 15 January 09 |
| 30 Jan – 16 February 09 |
| 3-18 March 09 |
| 30 March – 16 April 09 |

Figure 5: The weather station at Katedraalkrans covered with snow during the winter season.

Needle ice observations at night and in the early morning were conducted in Katedraalkrans whenever feasible. Needle ice observations were first done when the conditions seemed ‘favourable’ (see Outcalt, 1969, 1971). Subsequently, night observations were stopped as there was no needle ice growth during night-time and only morning observations were conducted. Needle ice occurrence is opportunistic hence observations at any given day (when the author was in the location of the study site) were done. Also, the author was not always present in Katedraalkrans due to the work schedule and weather conditions. Therefore, the few needle ice recordings in this study only account for the days that the author was able to observe and other events might have possible occurred in Katedraalkrans. There are other days that needle ice was observed in other locations on the island and a brief discussion about these events is undertaken in the next chapter.

# CHAPTER 4

# RESULTS AND OBSERVATIONS

## Needle ice formation and its climatic drivers

Chapter four gives an account of direct observations and measurements of needs ice from Katedraalkrans and also discusses results of recordings from data loggers of the South African Weather Services. The assessment of needle ice formation and growth and the climatic drivers associated with needle ice formation are given in this section. The observations of the needle ice length and type is from direct measurements. The ensemble of automated temperature and wind data are supplemented by synoptic shipping charts from the SAWS to show Marion Island's synoptic weather patterns during the time of needle ice occurrence. Notwithstanding the limited observations this is the first in-depth assessment of needle ice in the sub-Antarctic.

### *Needle ice evidence at Katedraalkrans*

#### *3 December 2008*

The first day of needle ice observations at the temperature logger at Katedraalkrans was on 3 December 2008. Observations were made the previous night as discussed in the methodology chapter; when it was very windy, misty and wet. On the morning of 3 December 2008, direct field observations were undertaken in the morning and it was partly cloudy, windy and cold. The needle ice had melted by 09:30 and photographic evidence and field notes were taken before the melting of the needles (Fig. 6 and Fig. 7). Figure 6 shows the type of needles that developed on the morning of 3 December. Needle ice length ranged between 1 and 1.2 cm in all the areas of measurement.

Figure 6: Needle ice evidence taken at 09:00 on the 3rd December 2008 (9cm knife is used as length of reference).

Figure 7: Melting ice needles, photo taken just before 9:30 in the same location as the photo in Figure 6 (9cm knife is used as length of reference).

Figure 8 presents the ensemble of measurements from the logger during the formation and ablation of the needle ice on the 3rd of December 2008. The sub-surface soil temperature measurements indicate that the soil only froze at 1 cm depth. Minimum soil temperatures at 5 cm and 10 cm depth were 0.77 ºC and 1.94 ºC respectively. At 1 cm depth the soil minimum temperature during needle ice development was –0.21 ºC (Fig. 8). Air temperature however, were substantially lower than the sub-surface soil temperatures with a minimum temperature recorded of -3.02 ºC. The air frost also started earlier with the air temperature dipping below zero at approximately 00:30, while soil frost only occurred at 04:00 hours. Wind speed measurements during the start of soil frost (Fig. 8) indicate that it was not wind still. Wind speed of approximately 1.5 m/s were recorded when soil frost occurred (04:00).

Needle ice ablation occurred at 09:30. It can clearly been seen that this is also the time when the air temperature and the shallow sub-surface soil temperature increased rapidly (Fig. 8). This rapid increase of shallow sub-surface soil temperature follows the increase of air temperature but the rate of change is much higher (Air temperature Δ 2.67 ºC/hour; Soil temperature at 1cm depth Δ 4.80 ºC/hour). Wind speed also increased steadily during the period from needle ice development to ablation (Fig. 8)

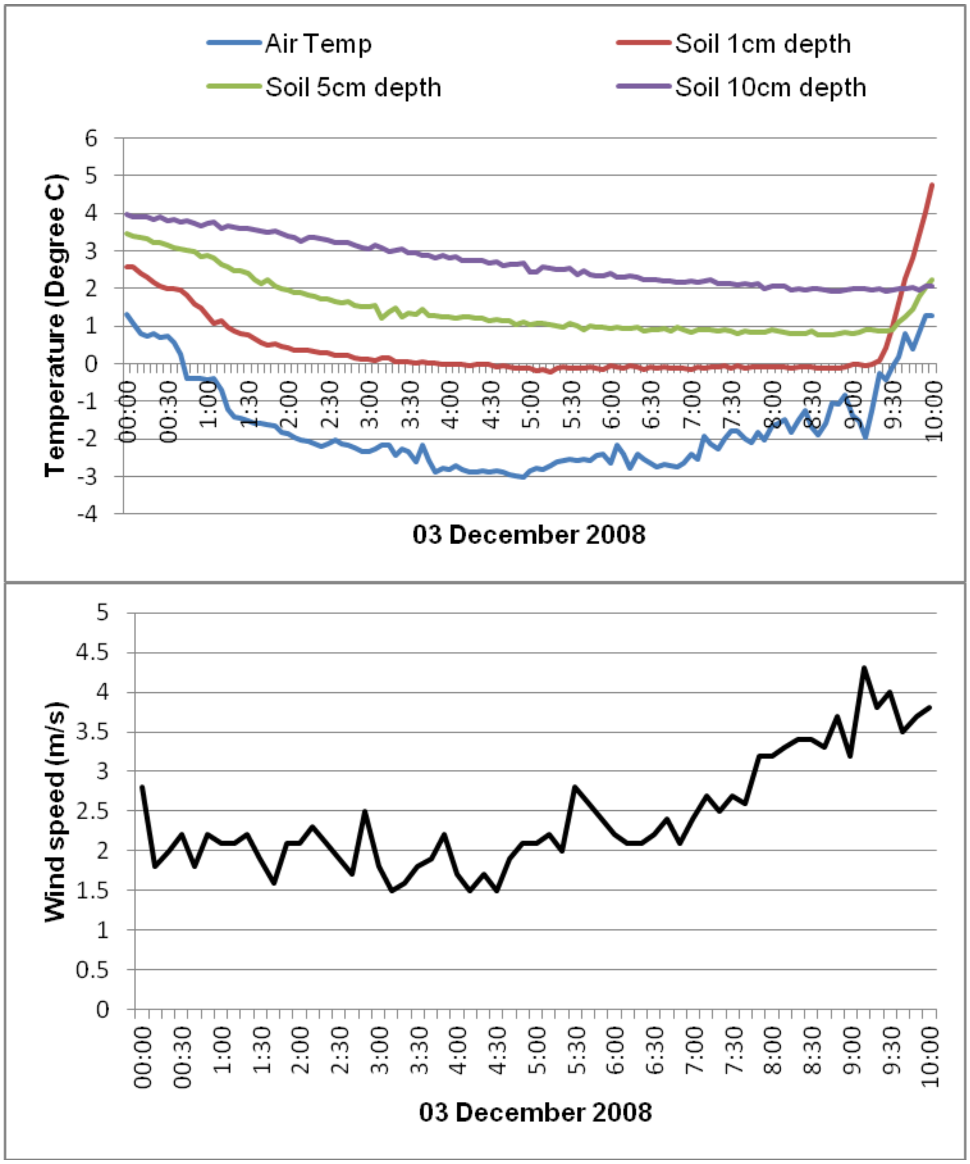

Figure 8: Air temperature, soil temperature and wind speed measurements during the formation and ablation of the needle ice on the 3rd of December 2008 (Time is GMT+3).

The synoptic chart from the South African Weather Services describes the synoptic conditions at the time of needle ice occurrence (Fig. 9). The chart displays the surface pressure lines on 3 December 2008 at 00:00 GMT (03:00 Marion Time). The characteristics of the major atmospheric circulation drivers associated with the needle ice observation are given. It seems that the needle ice occurrence at Katedraalkrans on the morning of the 3rd of December was initiated by the passage of a cold front connected to a mid-latitudinal cyclone with subsequent post-cyclonic (South-westerly) airflow. The position (latitude) of the cyclone centre was at approximately 58º S when the cold front passed over the island and the pressure at the centre were given as 968 hPa (Fig. 9)

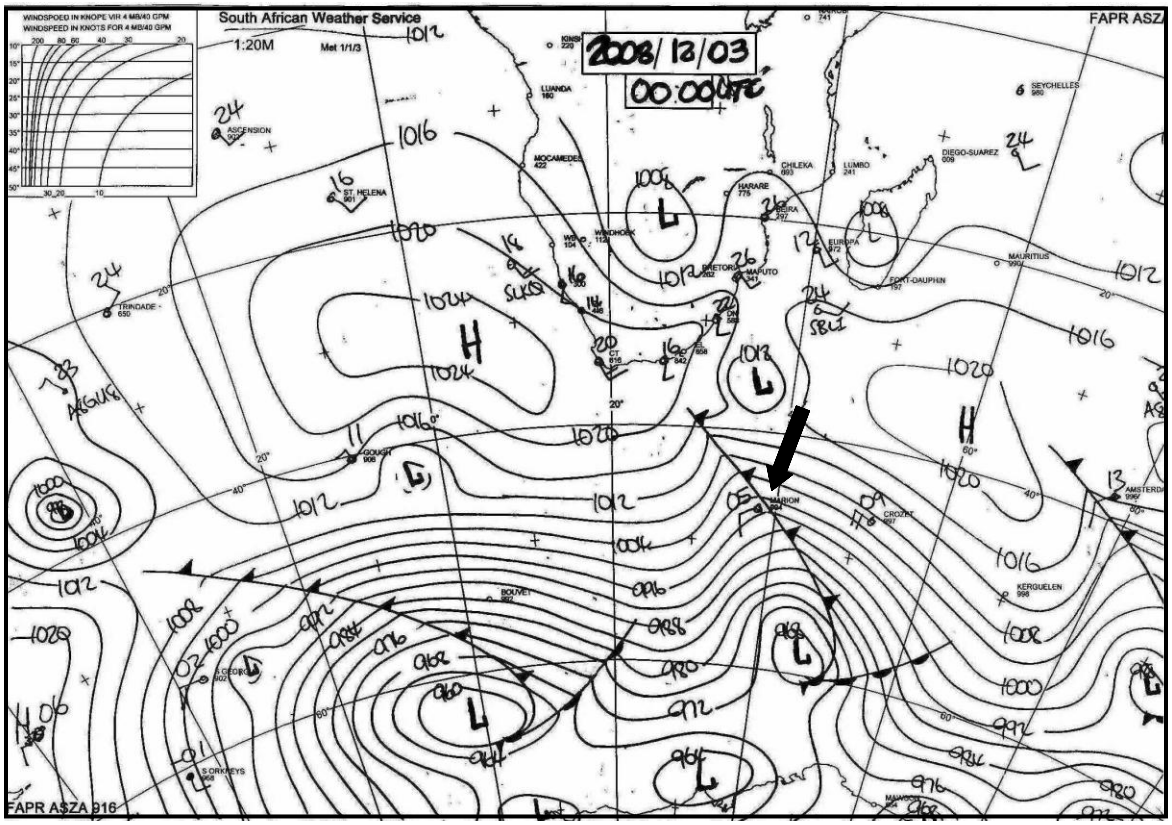

Figure 9: Synoptic weather chart (surface pressure lines) of the Southern Ocean on 3 December 2008 at 00:00GMT (03:00 Marion Time). Black arrow shows the position of Marion Island.

*4 December 2008*

The second needle ice observation at the temperature logger at Katedraalkrans was on the 4th of December 2008. During the nightly observations on 3 December 2008, there was no wind and it was partly cloudy and warm. On the morning of 4 December 2008 (observations started at 06:50), it was still partly cloudy and the wind was moderate to strong with cold air.

The needle ice that formed overnight (Fig. 10) was not ubiquitous across the study area as there was only needle ice occurring on the imprints of the footsteps created during the previous night's observations. During observations in the morning the surrounding area was scrutinized. It became clear that needle ice only occurred on the disturbed surfaces that were compacted by the boot imprint as there was no signs of any needle ice activity in the area that was not disturbed. The needle ice length of all the needles measured ranged between 2.5 – 2.6cm (Fig. 10) and these needles were synonymous with needles that are sediment included (Outcalt, 1969) (Fig. 10).

Figure 11 presents the ensemble of measurements from the logger during the formation and ablation of the needle ice on the 4th of December 2008. The sub-surface soil temperature measurements indicate that the soil at the logger did not freeze. Minimum soil temperatures at 1 cm, 5 cm and 10 cm depth were 0.06 ºC, 1.11 ºC and 1.98 ºC respectively (Fig. 11). Air temperature however, was below zero with a minimum temperature recorded at -1.98 ºC.

Figure 10: Needle ice with sediment inclusion measured within the disturbed areas around the logger on the morning of 4 December 2008 (9cm knife is used as length of reference).

Wind speed measurements during the morning of the 4th December indicate strong winds with wind speed ranging between 4 and 5 m/s. (Fig. 11). As mentioned from direct observation the needle ice formed only in the disturbed area and also just below the surface. This could indicate either that the soil probe at 1cm was too deep to measure the soil frost, or that the disturbed area provides a micro-climate that is conducive for needle ice development when the micro-climate in the undisturbed areas is not favourable.

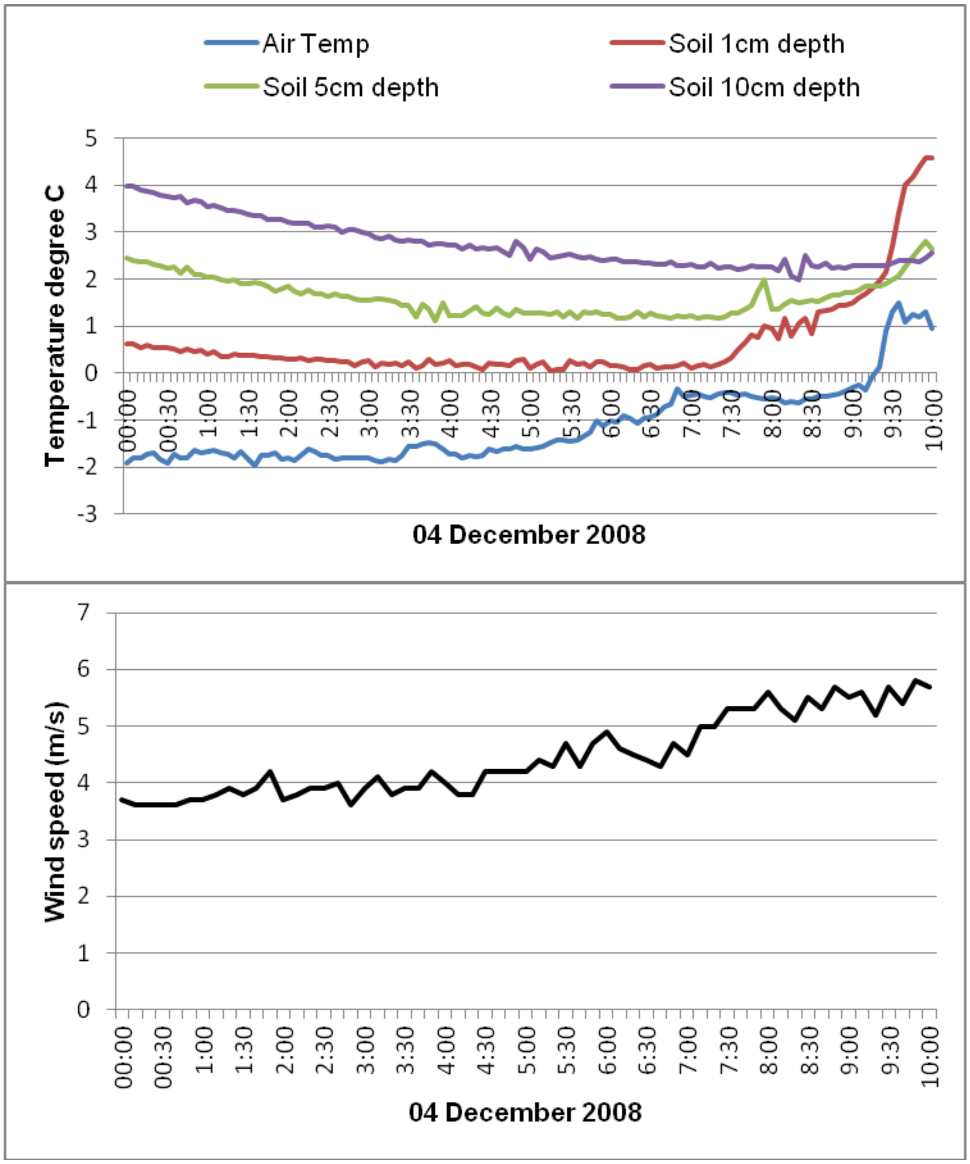

Figure 11: Air temperature, soil temperature and wind speed measurements during the formation of the needle ice in the disturbed areas around the logger on the 4th of December 2008 (Time is GMT+3).

The synoptic chart from the South African Weather Services describes the synoptic conditions at the time of needle ice occurrence on the 4th of December 2008 (Fig. 12). The chart indicate the surface pressure lines at 03:00 Marion Time (GMT +3). It seems that the synoptic condition when needle ice occurred at Katedraalkrans on the morning of the 4th of December in the disturbed area is associated with pre-cyclonic north-westerly airflow. Marion Island is positioned in the pre-frontal zone connected to a mid-latitudinal cyclone. The latitudinal position of the cyclone centre was at approximately 47º S when the needle ice occurred (Fig. 12).

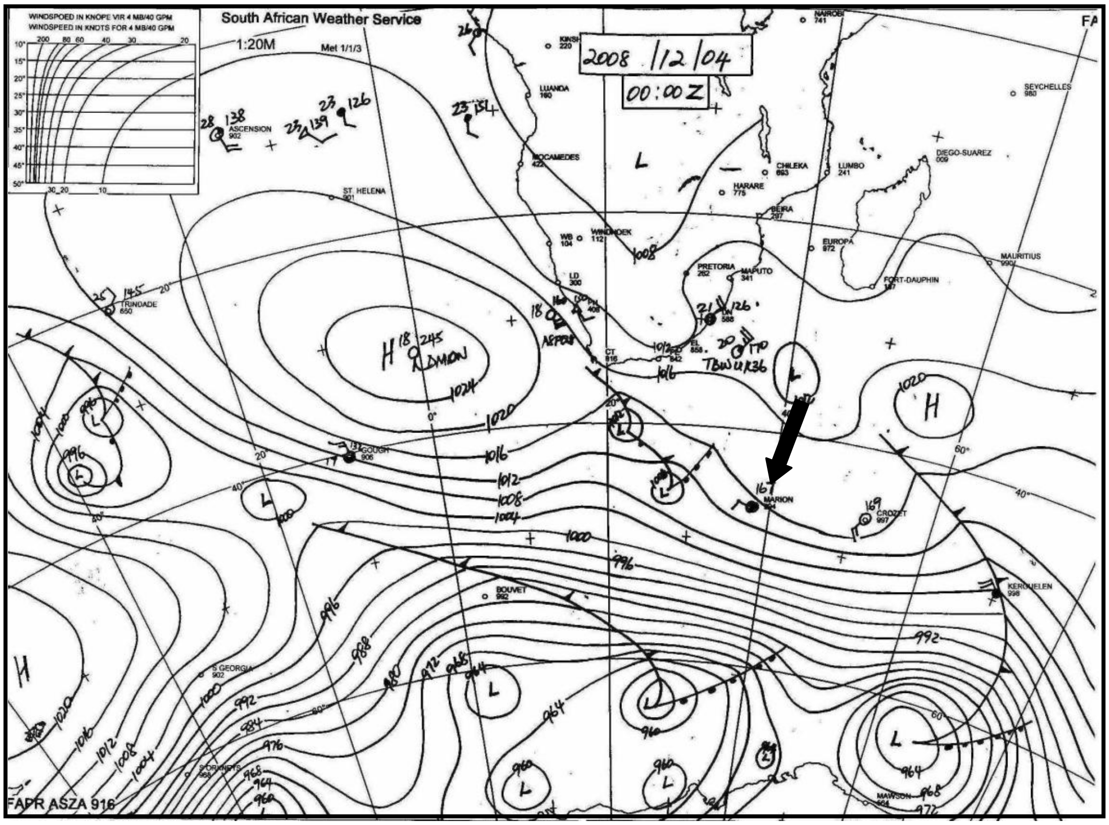

Figure 12: Synoptic weather chart (surface pressure lines) of the Southern Ocean on 4 December 2008 at 00:00GMT (03:00 Marion Time). Black arrow shows the position of Marion Island.

*10 December 2008*

On the evening of 9 December 2008, strong winds and drizzle with mist conditions dominated the evening. However, the morning of the 10th December revealed weather conditions that resemble those of the morning of the 3rd of December. Weather conditions were sunny, partly cloudy with light to moderate wind speed. The observations on 10 December 2008 started at 06:25. The minimum needle length was measured as 2.5cm and the measured maximum needle ice length was 4cm (Fig. 13). The needles were clear with no sediment inclusion. Only a small cap of sediment was visible on the top of the needle.

Figure 13: Clear needle ice with no sediment inclusion measured at the logger on the morning of 10 December 2008 (9cm knife is used as length of reference).

Figure 14 presents the ensemble of measurements from the logger during the formation and ablation of the needle ice on the 10th of December 2008. The sub-surface soil temperature measurements indicate that the soil again (same as on the 3rd) only froze at 1 cm depth. Minimum soil temperatures at 5 cm and 10 cm depth were 0.32 and 1.35 ºC respectively. At 1 cm depth the soil minimum temperature during needle ice development was –1.0 ºC (Fig. 14). Air temperature however, was again substantial lower than the sub-surface soil temperatures with a minimum temperature recorded of -4.02 ºC. Air temperatures were below zero during the whole evening of the 9th/10th with air frost already starting at 16:00 hours on the afternoon of the 9th of December.

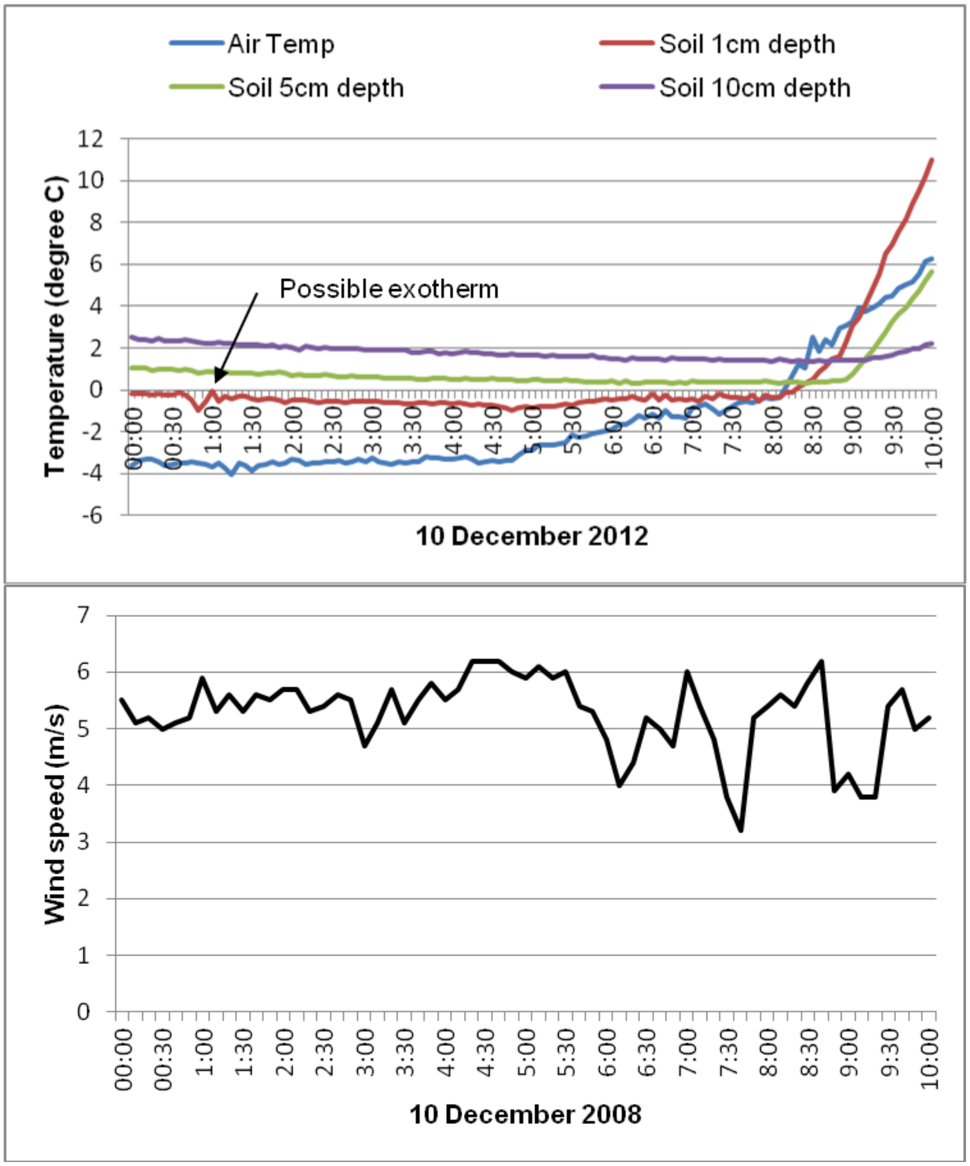

Figure 14: Air temperature, soil temperature and wind speed measurements during the formation and ablation of the needle ice on the 10th of December 2008 (Time is GMT+3).

Soil frost at 1cm depth occurred at 23:15 hours on the eve of the 9th and the soil remained frozen until 08:15 of the morning of the 10th. From the data it seems that the needle ice started to form at approximately 01:00 when a possible exotherm could be discerned (Fig. 14). At the spontaneous freezing temperature, latent heat is released as the water begins to freeze the rise in temperature resulting from the latent heat is termed the ‘exotherm’ (Matsuoka, 2001). Wind speed measurements during the possible start of the needle ice is approximately 6 m/s and the wind remained strong the whole evening (ranging from 3 to over 6 m/s) (Fig. 14).

Needle ice ablation occurred at approximately 08:30 when a clear rapid increase in air temperature and the shallow sub-surface soil temperature could be discerned (Fig. 14). This rapid increase of shallow sub-surface soil temperature again followed the increase of air temperature and the rate of change in soil temperature was (as on the 3rd of December) much higher (Air temperature Δ 3.35 ºC/hour; Soil temperature at 1cm depth Δ 5.69 ºC/hour).

The synoptic chart from the South African Weather on the 10th December 2008 at 03:00 Marion Time clearly indicates that the weather was post-cyclonic after the passage of a cold front connected to a mid-latitudinal cyclone with south-westerly airflow. The position (latitude) of the cyclone centre was at approximately 48º S when the cold front passed over the island and the pressure at the centre was given as 1000 hPa (Fig. 15)

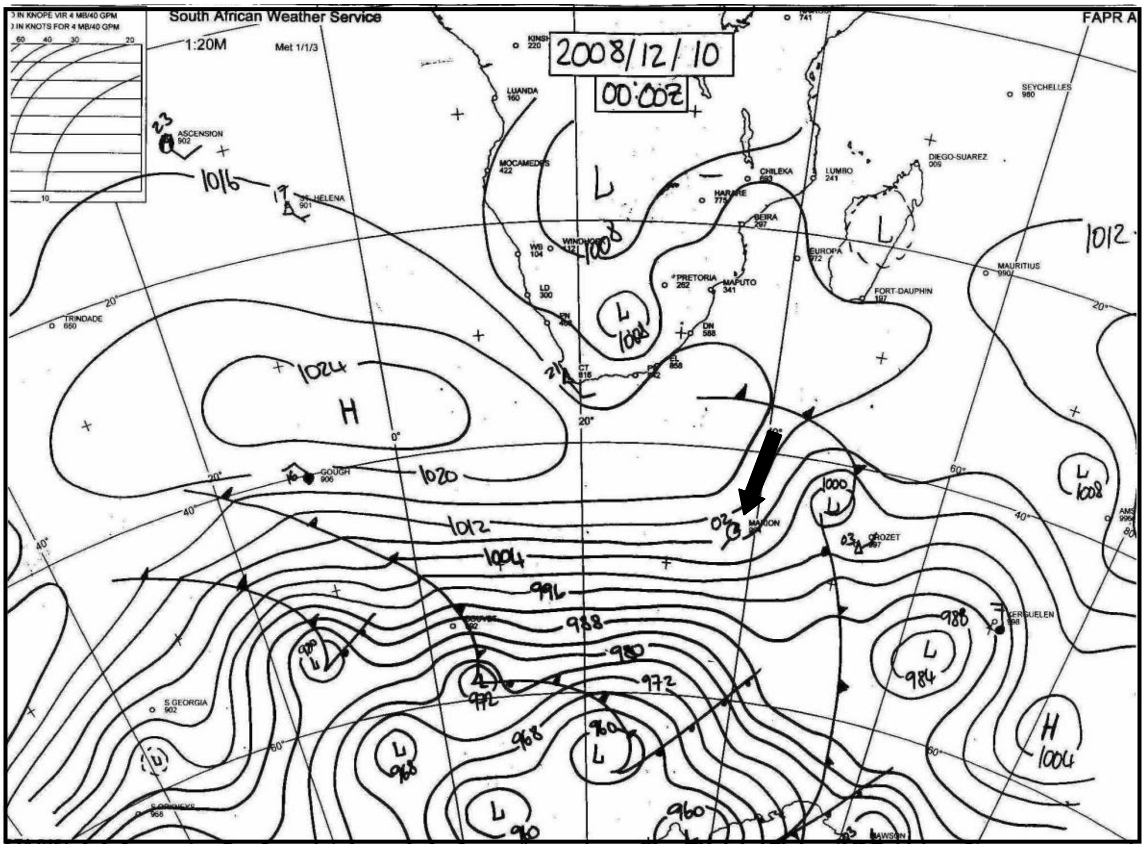

Figure 15: Synoptic weather chart (surface pressure lines) of the Southern Ocean on 10 December 2008 at 00:00GMT (03:00 Marion Time). Black arrow shows the position of Marion Island.

*Needle ice observation in other areas (6 December 2008)*

A further needle ice observation was made at Black Haglet on the 6th of December 2008. Black Haglet is a grey lava valley at a geographical location of S46 55.231', E037 45.347' (see Figure 3). Because the needle ice evidence in Black Haglet was discovered ‘accidentally’, there were no night observations as needle ice was discovered on a walk from one site to another. Unfortunately, no measurement of needle ice length or ground temperature was taken and only photographic evidence is available (Figs. 16, 17 and 18).

Figure 16: Needle ice observed at Black Haglet.

Figure 17: A toppled clear needle ice (area in the ground where needle ice was attached is still visible in the photography) (5cm battery is used as length of reference).

Figure 18: Photographic evidence showing the ability of needle ice to lift particles and transport it down slope.

The synoptic chart from the South African Weather on the 6th December 2008 at 03:00 Marion Time again clearly indicates that the weather was post-cyclonic after the passage of a cold front connected to a mid-latitudinal cyclone with south-westerly airflow. The position (latitude) of the cyclone centre was at approximately 65º S when the cold front passed over the island and the pressure at the centre was given as 948 hPa (Fig. 19).

The needle ice photographic evidence of the event in Black Haglet shows that other locations in the island are susceptible to needle ice growth although the soil frost activity might be less prominent compared to the interior around 750m a.s.l. Although no personal field observations was done in some areas, needle ice has been observed by the author in areas such as Tafelberg and Karookop (at between 300m to 500m a.s.l.).

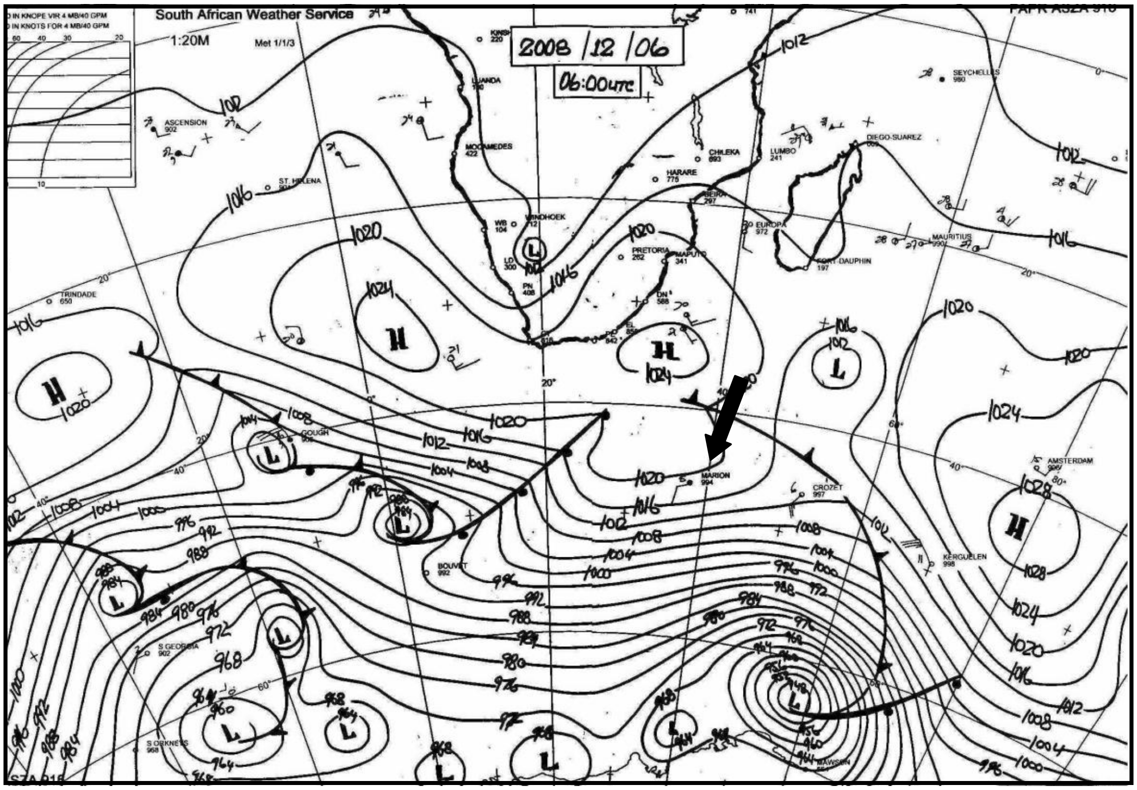

Figure 19: Synoptic weather chart (surface pressure lines) of the Southern Ocean on 6 December 2008 at 06:00GMT (09:00 Marion Time). Black arrow shows the position of Marion Island.

### An assessment of snowfall and its effect on soil frost

The assessment of snowfall and its effect on soil frost dynamics are given in this section. The observations of the timing of snowfall and depth of snow are from direct measurements and observation. The observations are supplemented by the synoptic shipping charts from the SAWS to show Marion Island's synoptic weather patterns during the time of snowfall and with automated temperature measurements that show the soil temperature dynamics.

Snowfall observations and measurements were made on Marion Island for the duration of the study period. The majority of snowfall observations and measurements were undertaken in the interior at Katedraalkrans. Table 2 shows the snow measurements in Katedraalkrans over the observation period in the area in close proximity to the automatic logger. Therefore, the data represent the days that the author was in the area and managed to make recordings and is not an indication of all the snow days during the recording period. The exact depth of the snow covering the ground was measured with a tape measure in close proximity to the logger.

Table 2: Snow measurements at Katedraalkrans around the automatic temperature logger.

| **Date of measurement** | **Snow depth measured at the Automatic Weather Station (cm)** |
|---|---|
| 27/06/08 | Snow depth between 15 and 33 cm |
| 11/09/08 | Snow depth between 65 and 72.5 cm |
| 19/09/08 | 18cm |
| 25/09/08 | 30cm |
| 26/09/08 | 18cm |
| 24/10/08 | 10cm |
| 03/01/09 | Snow depth between 5 and 30cm |
| 04/01/09 | Snow depth between 5 and 30cm |
| 30/03/09 | Snow depth between 1.2 and 10 cm |
| 01/04/09 | Snow depth between 3.4 and 13.2 cm |
| 11/04/09 | Snow depth between 10.8 and 15.1cm |
| 20/04/09 | Snow depth between 8.5 and 10.2 cm |

On 27 June 2008, snow fell at Katedraalkrans with a minimum depth of 15 cm to a maximum of 33 cm in the area around the logger. On 11 and 12 September 2008 more snow fell on the island with a maximum of 72.5 cm of snowfall measured on 12 September. The snow on the ground melted and new snow fell on the 18th and 19th of September 2008 ranging from 10 to 18 cm (Table 2). Warmer weather was prevalent after this snow fall and melted the shallow snow between the 20th and the 22nd of September. Subsequent snowfall occurred on the 23rd of September resulting in snowfall

measured to 30 cm on the 25 September 2008 which still existed on the next day. Superficial snow (maximum height 10cm) fell on the morning of 29 October 2008.

The first snowfall measurements of 2009 were taken on 3 and 4 January 2009 with snowfall depth of 5 to 30 cm measured on both days. On the 17 of January 2009 snowfall in the interior was observed and noted from the Meteorological Station at the eastern side of the island (Fig. 1) and on 19 January snow depths up to 20 cm were measured around the logger at Katedraalkrans. Shallow snowfall depths were measured on 30 March and 1st of April 2009 with depths of 1.2 to 13.2 cm respectively and on the 11th of April with 10.8 and 15.1 cm. The last measurements of snowfall made during the study period was on the 20th and 21st of April 2009 with snow depth measured between 8 and 10 cm during both days.

The synoptic air circulation patterns associated with the four heaviest snowfall events (in terms of snow depth) are given in Figure 20.  From the synoptic charts it is possible to discern a strong relationship between snowfall initiation and the passage of a cold front. The cold front in all instances is linked to a strong meridional (longitudinal) extending low pressure system moving south of Marion Island.

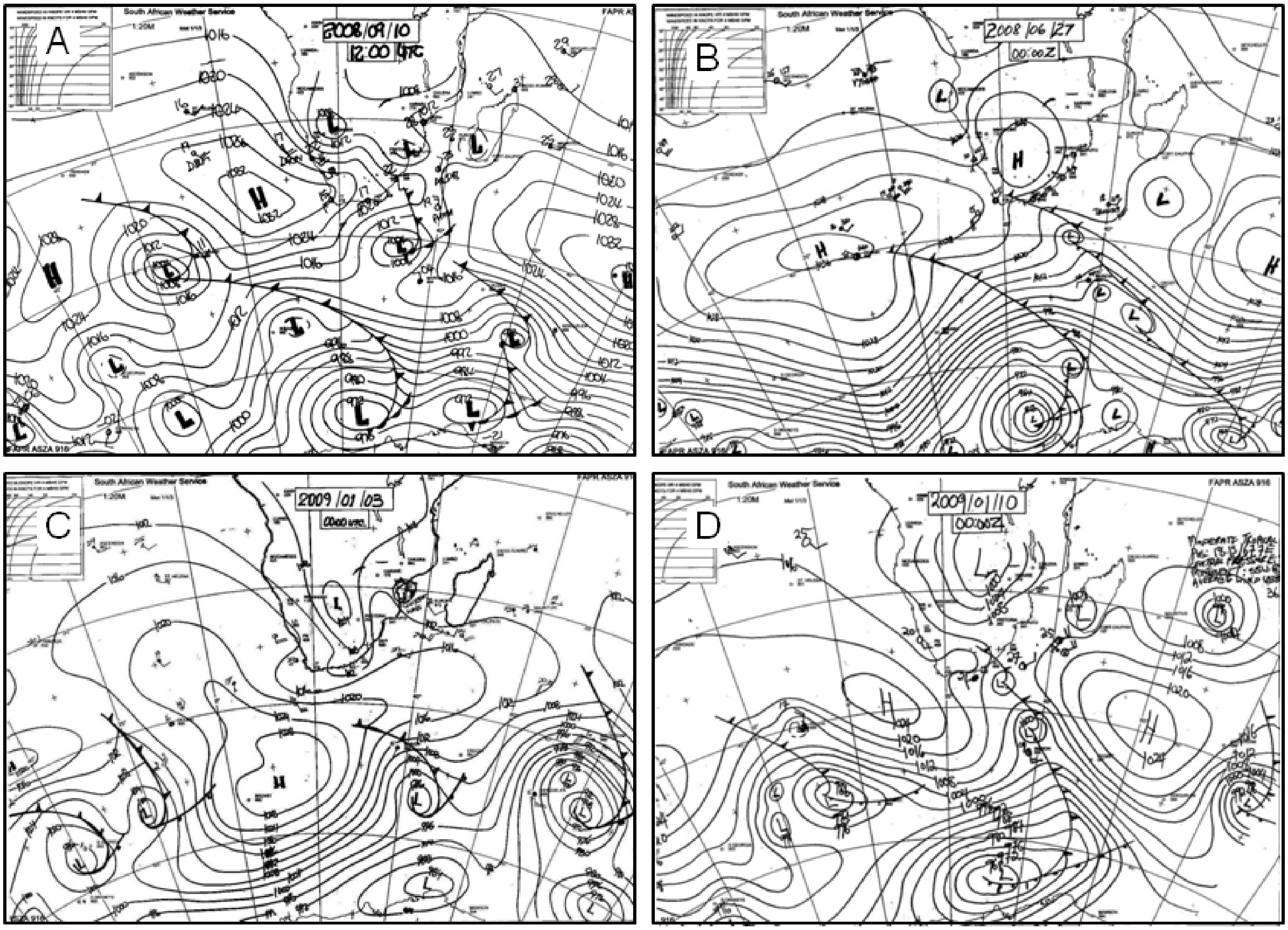

Figure 20: An ensemble of synoptic weather chart (surface pressure lines) of the Southern Ocean on a) 10 September 2008 at 12:00 GMT b) 27 July 2008 at 00:00 GMT c) 3 January 2009 and d) 10 January 2009.

The snowfall event recorded on the 3rd of January 2009 was associated with long and deep soil frost cycles at 1 and 5cm depth (Fig. 21). The duration of the soil frost lasted 37 hours at 1cm depth and 24 hours at 5cm depth. It also seems that the surface snow plays an insulating role that limits diurnal sub-surface soil fluctuations.

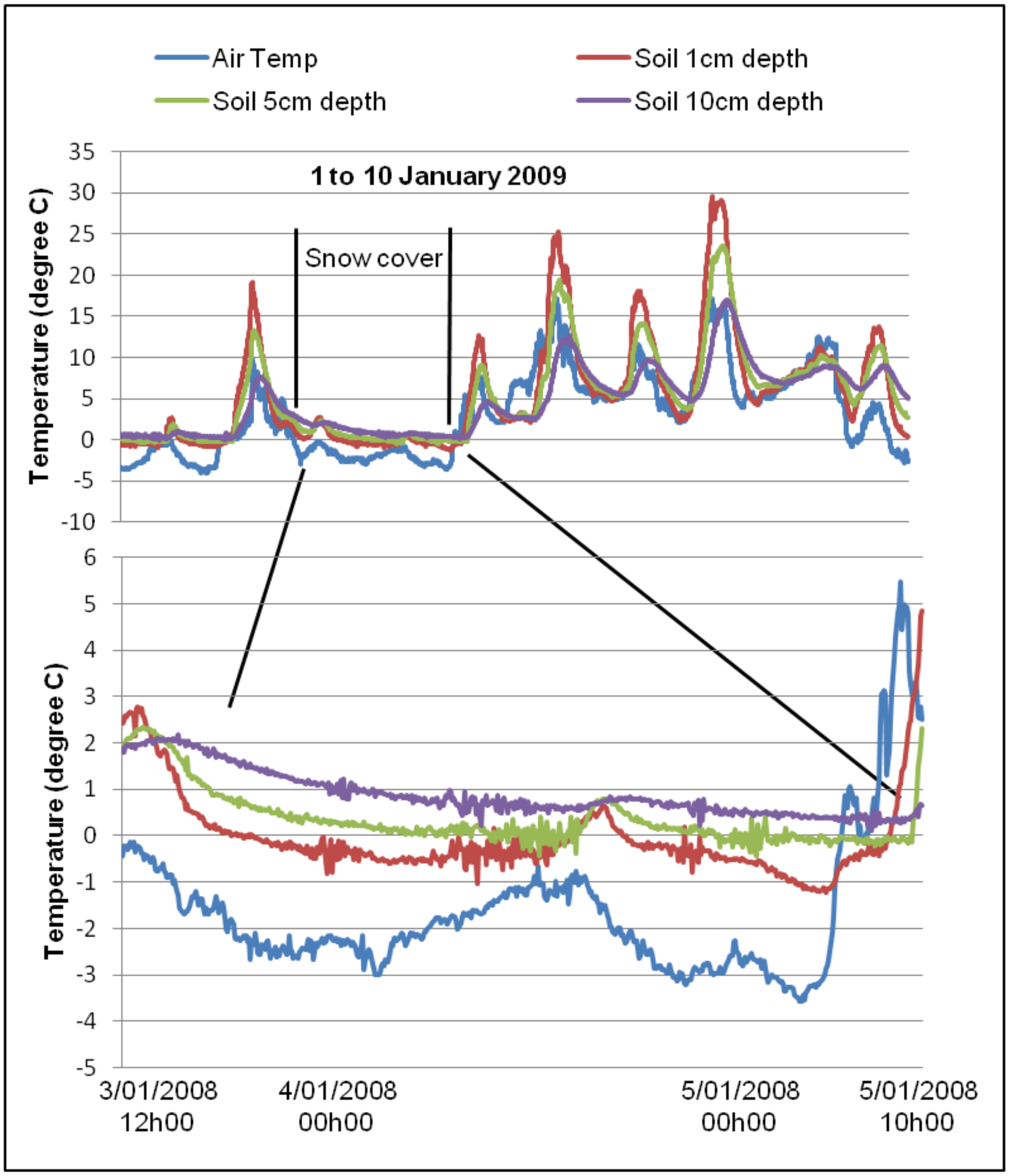

Figure 21: Air and soil temperatures measured from the 1st to the 10th of January (Top). Bottom figure is air and soil temperatures measured from 12h00 on the 3rd of January 2009 to 10h00 on the 5th of January 2009.

The synoptic air circulation patterns associated with this event are given in Fig. 22. As with the other events marked in Fig. 20, the snowfall and subsequent deep soil frost event are associated with the passage of a cold front linked to a strong meridional extending low pressure moving south of Marion Island and subsequent post-cyclonic airflow from the ridging Anticyclone whose air mass had a long southerly trajectory that could be traced further south than 60°S close to the Antarctic coast (Fig. 22).

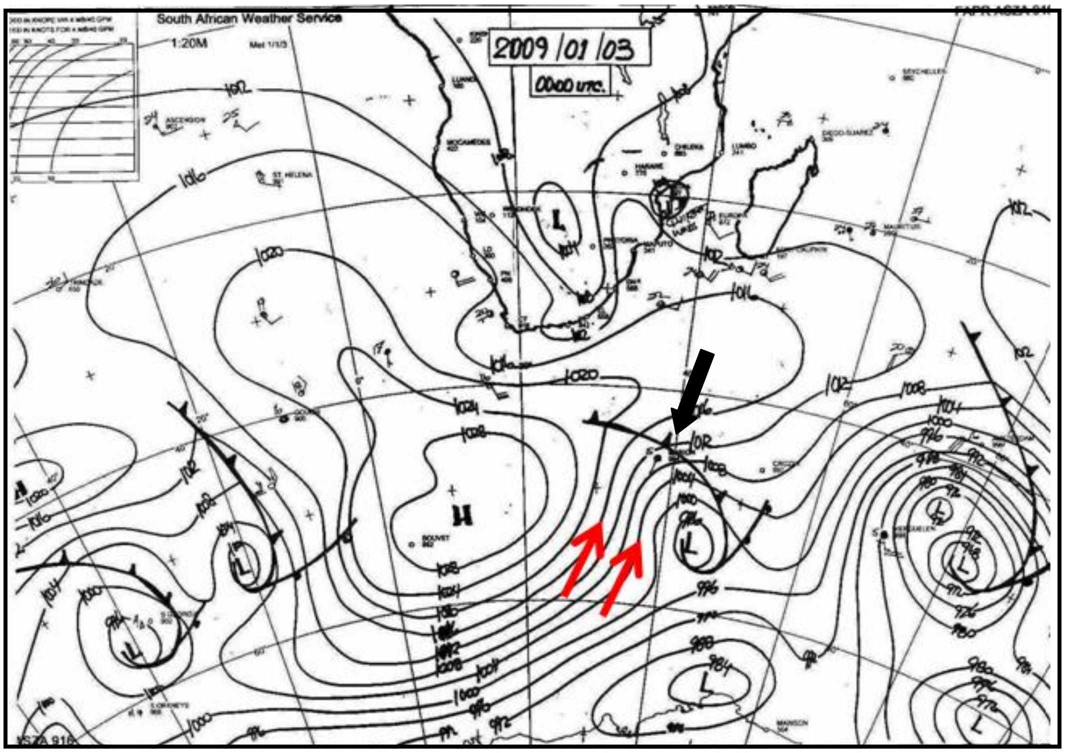

Figure 22: Synoptic weather chart (surface pressure lines) of the Southern Ocean on 3 January 2009 at 00:00GMT (03:00 Marion Time). Single arrow shows the position of Marion Island; the two arrows show the trajectory of airflow.

The snowfall events measured on the 11th of April 2009 (Table 2) actually started to fall on the 9th of April. Snow on the ground lasted until the 14th of April with a measured depth of between approximately 10 and 15cm (measured on the 11th of April; Table 2). The soil temperatures associated with that snowfall event are given in Fig. 23.

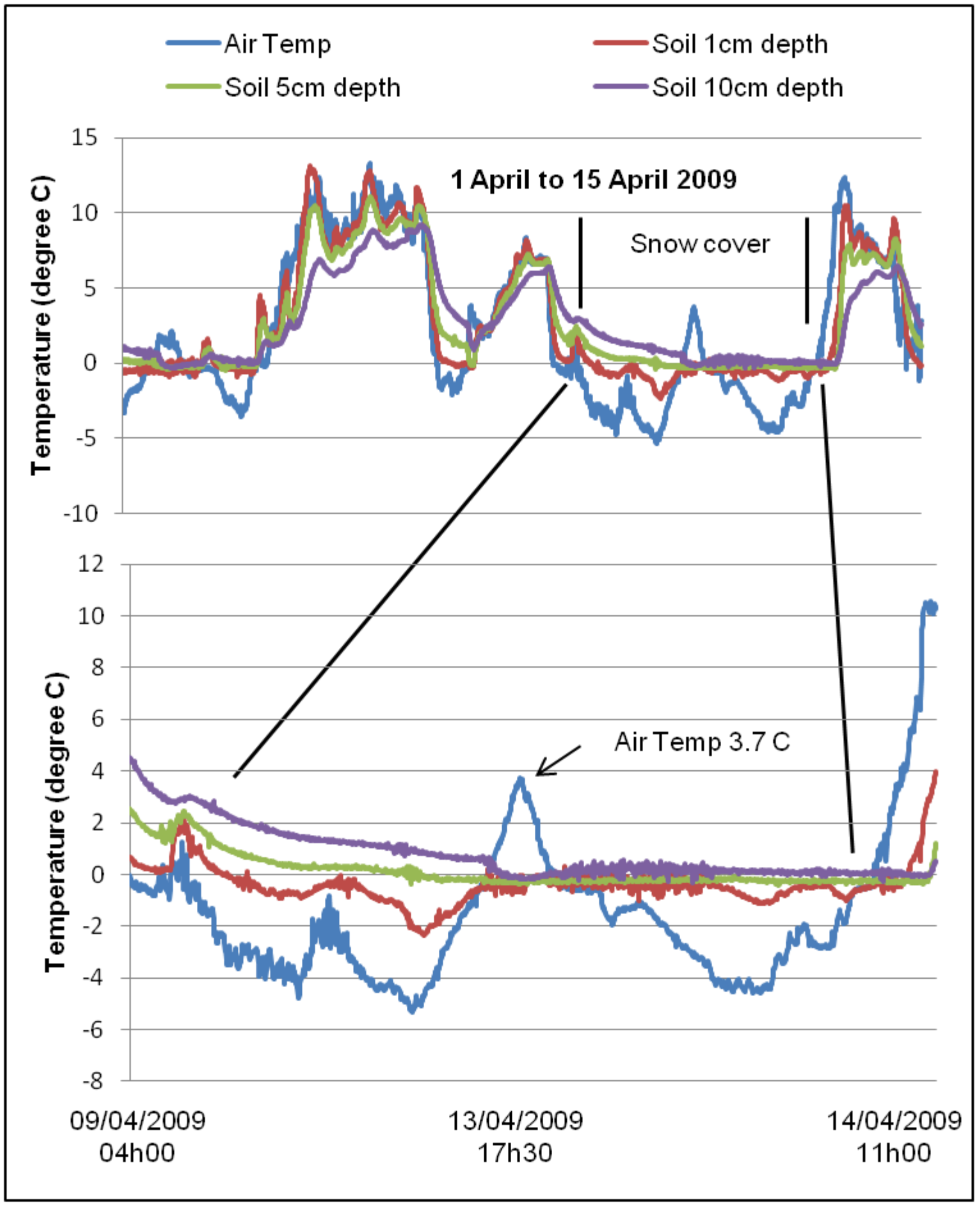

Figure 23: Air and soil temperatures measured from the 1st to the 15th of April (Top). Bottom figure is air and soil temperatures measured from 04h00 on the 9th of April 2009 to 11h00 on the 14th of April 2009.

Again the soil frost cycle associated with this event was of a long duration (108 hours at 1cm depth and 83 hours at 5cm depth) and intense (minimum temperature measured at 1cm depth were -2.35 ºC and at 5cm depth were -0.4 ºC) . The cycle were also deep with soil frost penetrating to 10cm depth (cycle duration was 5 hours with a minimum temperature recorded of -0.33 ºC). While the soil was covered in snow the air temperature reached above freezing on the 13th of April. However the snow did not melt and the soil remained below freezing and showed no upward trend. This is a clear indication that the snow thermally insulates the soil from diurnal heat fluxes.

The synoptic air circulation patterns associated with this event (9 April 2009) is given in Fig. 24. As with the other events marked in Fig. 20 the snowfall and subsequent deep soil frost event are associated with the passage of a cold front. This cold front is linked to a very intense low pressure system (956 hPa at the centre) south of Marion Island (centre at 60ºS). Subsequent post-cyclonic airflow is provided from the ridging Anticyclone. Again the trajectory of post-cyclonic air flow can be traced further south than 60°S (Fig. 24).

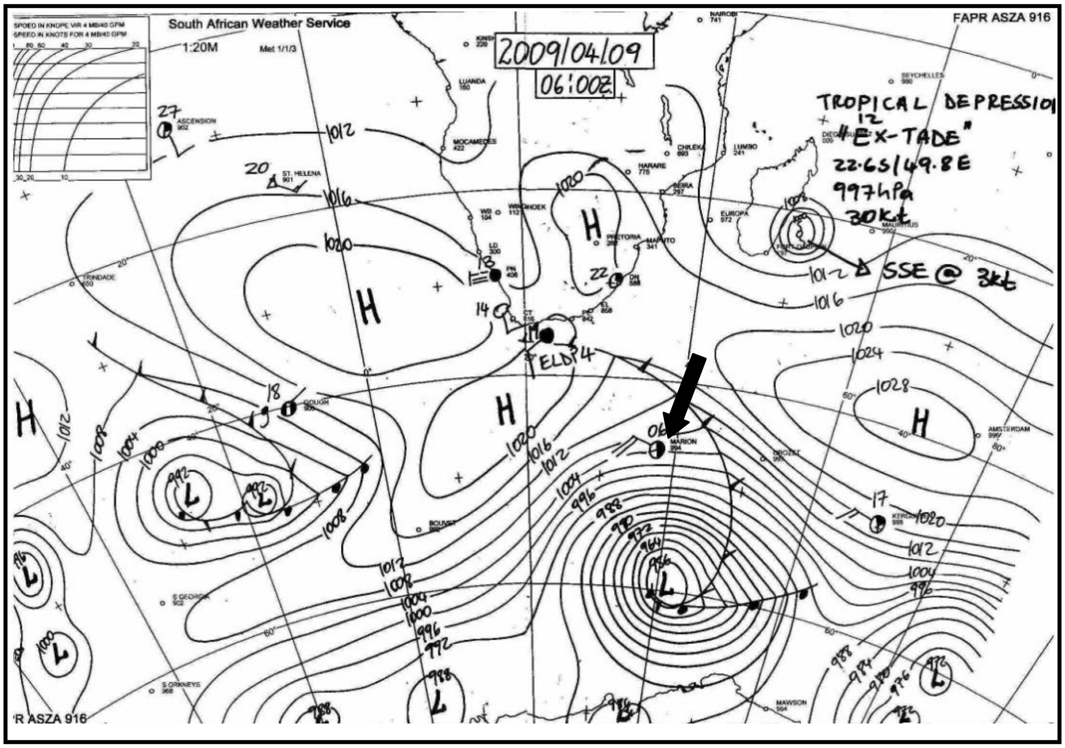

Figure 24: Synoptic weather chart (surface pressure lines) of the Southern Ocean on 9 April 2009 at 06:00GMT (09:00 Marion Time). Black arrow shows the position of Marion Island.

## The zero-curtain and its effect on soil frost

An assessment of the zero-curtain effect and the micro and synoptic scale climatic drivers associated with this soil frost phenomenon is given in this section. In soil frost dynamics the term zero-curtain refers to the effect of latent heat in maintaining temperatures near 0ºC over extended periods in freezing or thawing soils. As the zero-curtain appears to be produced and maintained by vapour transport induced by freeze-thaw events at the soil surface (Hall, 1998) it occurs in absence of snowfall. The zero-curtains were assessed through the ensemble of automated temperature data when known snowfall did not occur. The data were supplemented by the synoptic shipping charts from the SAWS to show Marion Island's synoptic weather patterns during the occurrence of the zero-curtain.

Seasonal freezing of the soil occurs above 750m a.s.l. (Hedding, 2006). Unfortunately due to adverse weather the temperature logger did not operate during the winter months (June and July 2008; Table 1.) However, a glimpse of the seasonal soil frost can be seen from the measurement taken during a short spell in August 2008 (Fig. 25). Clear diurnal oscillations in sync with the air temperature oscillations can be seen during this period. The soil remains below zero up to 10cm depth in the absence of snow even though the air temperature rose above zero on the 4th of August. From the data it can be seen that the diurnal soil temperature oscillations are superimposed on the seasonal freeze occurring at this altitude.

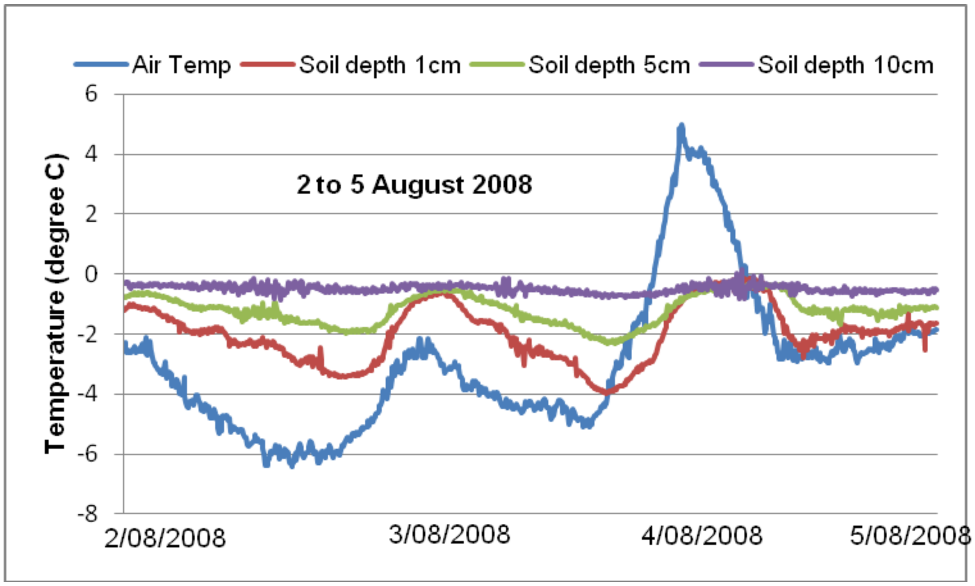

Figure 25: Air and soil temperatures measured from the 2nd to the 5th of August 2008.

Implicitly the seasonally frozen ground thawed end of August. This is associated with more air temperature cycles above 0ºC. The effect of the thawing of the soil and the resultant moisture release can be seen in the near constant temperatures of the soil at depth during the first couple of weeks in September (Fig. 26). This zero-curtain effect at 5 and 10cm depth was maintained by the constant freezing and thawing of the soil at the surface to 1cm depth. The soil at depth were kept constant at between -0.2 to -0.7 ºC at 5cm depth and -0.2 to -0.5 ºC at 10cm depth in the absence of snow.  The shallow soil (1cm depth) shows a large number of soil frost cycles during this period.

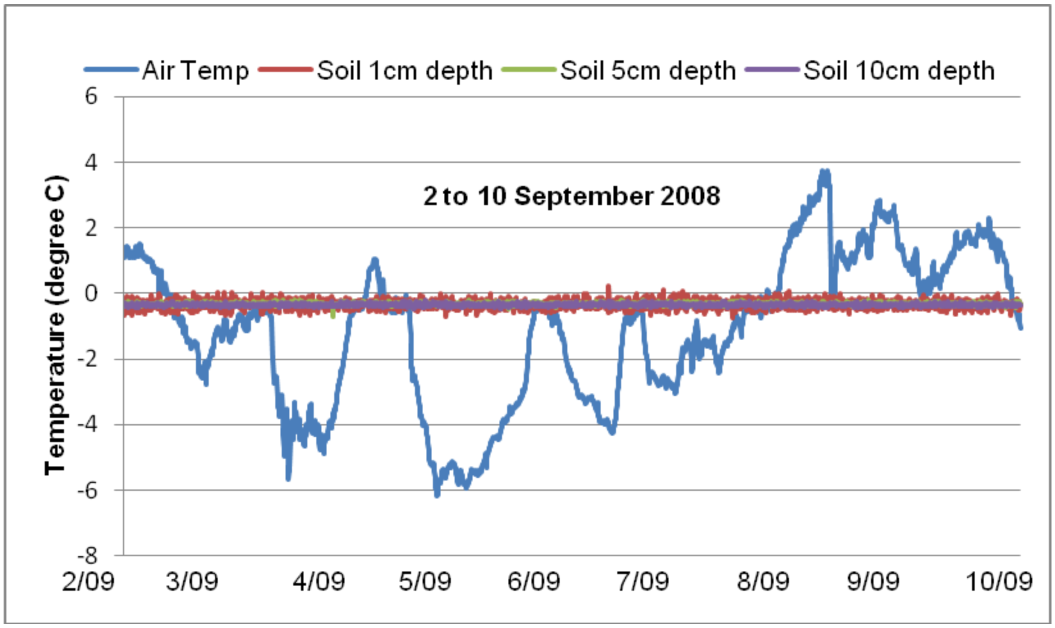

Figure 26: Air and soil temperatures measured from the 2nd to the 10th of September 2008.

As the initiation of winter occurs the soil undergoes longer duration diurnal soil frost cycles. Data from the temperature logger from the 10th to the 16th of May 2008 show clear diurnal soil temperature cycles below zero degrees at all depths. The soil frost at depth (in absence of snowfall) is associated with very cold air temperatures recorded during this period with a minimum of -6.3 ºC (not shown). After the cold spell the air temperature increased drastically by the 16th and with it the soil temperatures. As soil moisture is released on thawing the zero curtain effect occurred from the 16th to the 17th of May (Fig. 27). The thawing of the soil and the resultant moisture release influences the constant freezing and thawing of the soil at the shallow sub-surface (with a large number of soil frost cycles). A near constant temperature of the soil at depth is maintained by the constant freezing and thawing of the soil. The synoptic air circulation pattern associated with this warming event (16 May 2008) is given in Figure 28. During the 16th of May the island found itself within the warm sector (between the warm front and the cold front) of the mid-latitudinal cyclone (Fig. 28).

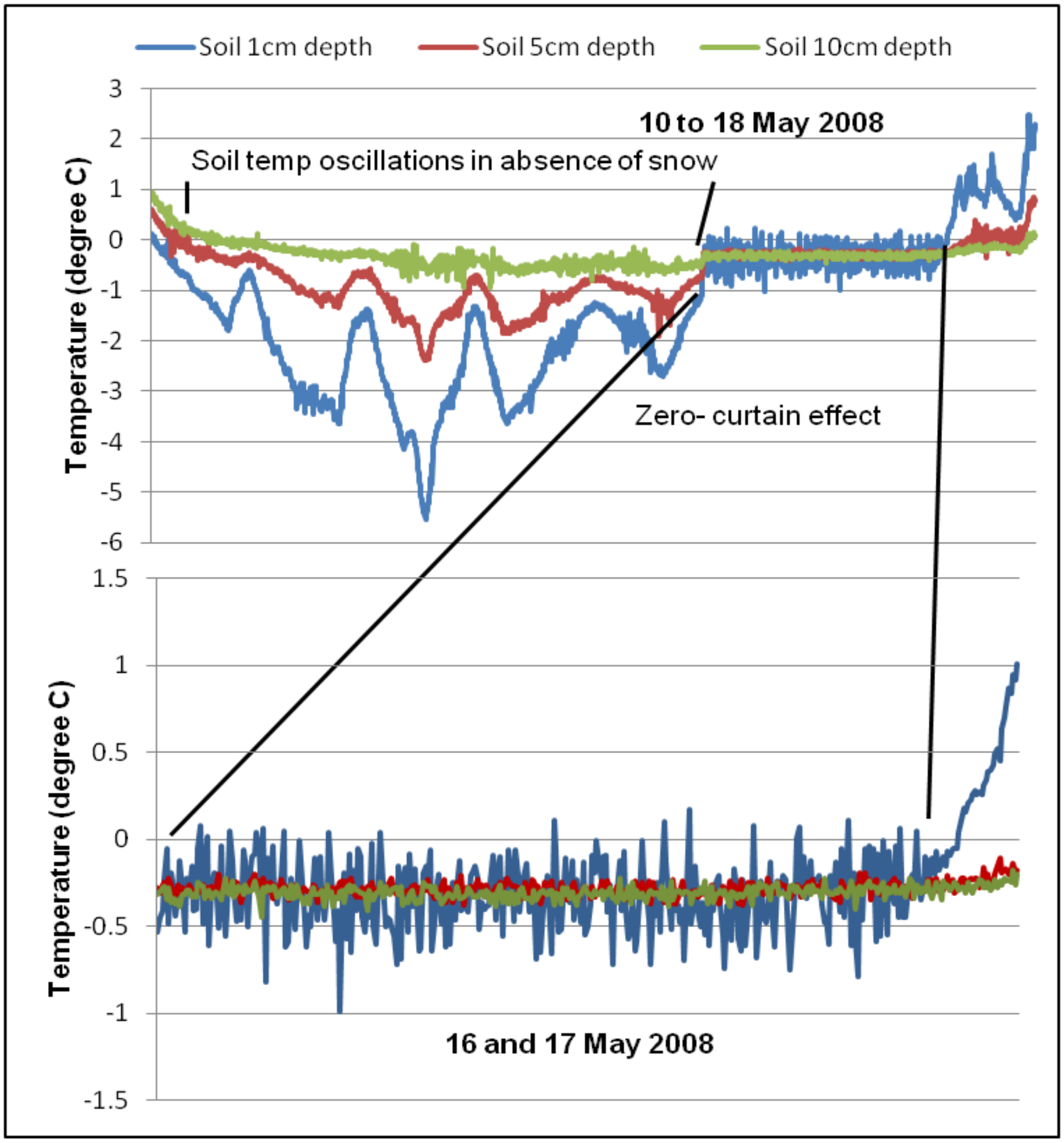

Figure 27: Air and soil temperatures measured from the 10th to the 18th of May 2008 (Top). Bottom figure is air and soil temperatures measured on the 16th and 17th of May 2009.

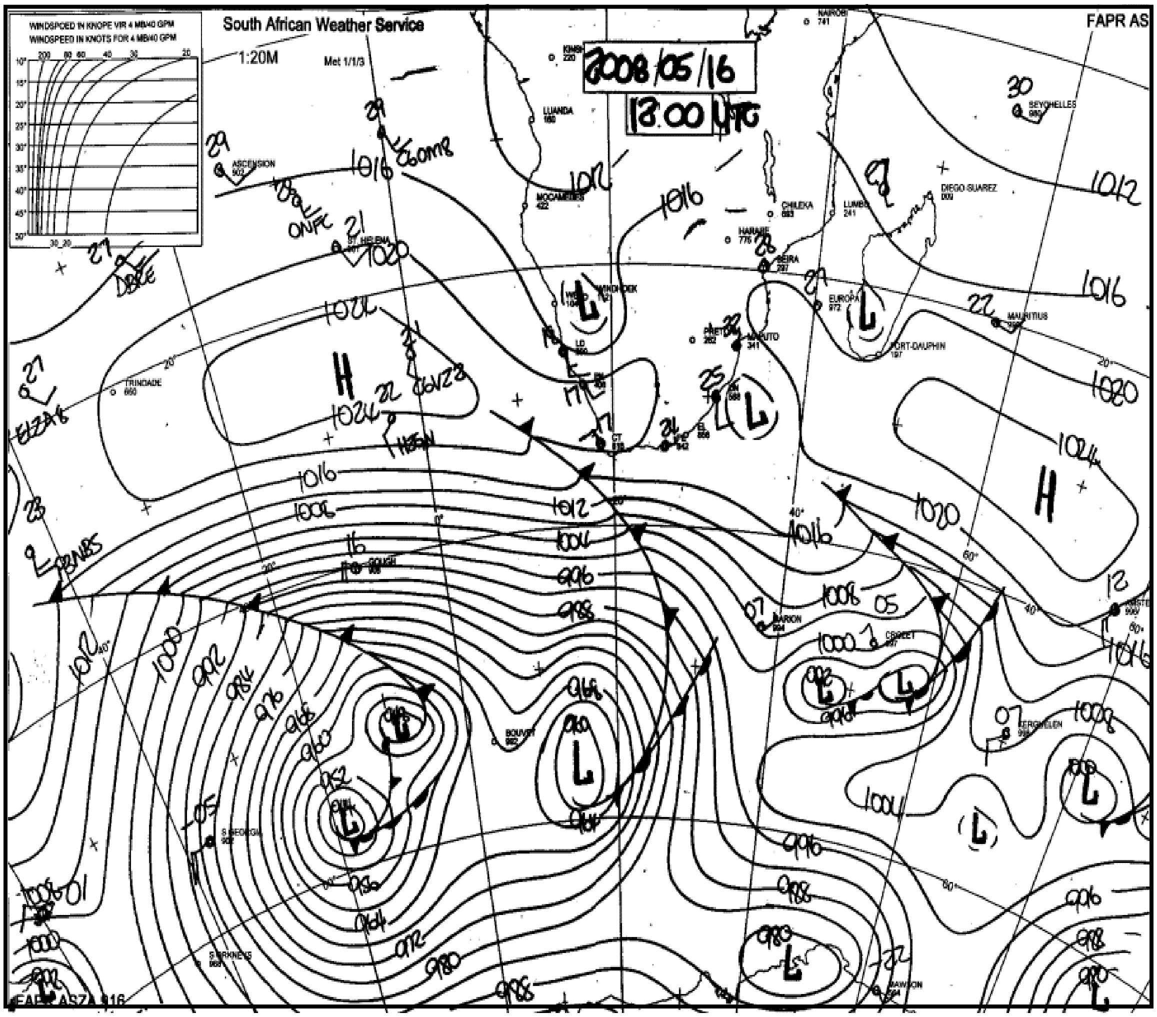

Figure 28: Synoptic weather chart (surface pressure lines) of the Southern Ocean on 16 May 2008 at 12:00GMT (15:00 Marion Time).

# CHAPTER 5

# DISCUSSION

Recently the emphasis on the role of synoptic weather conditions in soil temperature dynamics have been highlighted (Nel et al., 2009a, 2009b, 2012). It has been suggested that synoptic-scale weather systems influence shallow sub-surface soil temperatures through depressing or enhancing radiative fluxes (Nel et al., 2009b). Soil frost is significant as it drives the growth of needle ice, which in turn results in soil disturbance and sediment displacement. Globally, needle ice growth is associated with long-wave radiation loss from the soil surface that results in below-zero temperatures and needle ice events are believed to indicate that cloud cover was minimal (Outcalt, 1969). The basic condition would seem to be a clear night sky favouring maximum radiation from, and therefore cooling of the surface (Outcalt, 1969). During clear and calm conditions, needle ice normally develops within one or two hours after sunset when air and ground temperatures drop rapidly to below 0ºC (Lawler, 1988). On Marion Island, all the needle ice that was observed and recorded occurred during the early mornings in misty and overcast conditions. Furthermore, previous field measurement indicates that an equilibrium surface temperature at least as low as -2 ºC is necessary for ice nucleation (Outcalt, 1969, 1970). However, on Marion Island needle ice developed in temperatures as high as -0.2 ºC in strong winds.

From Boelhouwers et al. (2003) it is clear that the Sub-Antarctic periglacial environment as represented by Marion Island is fundamentally different from seasonal frost and permafrost environments. This applies to the characteristic ground frost, moisture and wind regimes, but is also expressed through landform morphology. While a grouping with other climates of low annual temperature range is appropriate as far as it identifies highly active diurnal frost environments, a fundamental difference exists between the sub-Antarctic and other cold climates with regards to the wind conditions and diurnal temperature ranges. This distinct sub-Antarctic environment is further enhanced by the difference in the basic conditions for needle ice growth between permafrost and seasonal freeze environments and that of a wet, diurnal soil frost environment.

There are limited studies (if any) that mainly focus on needle ice assessment and its occurrence in Marion Island, however, some studies noted its occurrence and measurements were taken in the field when it was spotted (e.g. Hedding, 2006). In this study needle ice occurrence was monitored on a daily basis when the author was in the study site. It has been suggested that in heavily compacted soils, needles form near the surface (Meentemeyer and Zippin, 1980). This was also the case on Marion where very shallow needle ice only occurred in compacted soil. It seems that with compacting the soil the soil texture is altered which favours needle ice development or the compacted soil may alter the micro-climatology of the affected area making it more susceptible to the formation of needle ice. Needles that form near the surface in compacted soils lift less material per unit area (Brink et al., 1967; Meentemeyer and Zippin, 1980, 1981; Lawler, 1988, 1993).

Commonly reported needle lengths vary between 1 and 5 cm (Meentemeyer and Zippin, 1980, 1981), which is consistent with a single night of freezing on Marion Island. Outcalt (1969) suggested that when frozen materials are incorporated within the needle it is indicative of ice growth that was interrupted by ‘normal’ in-situ freezing of soil water. This interruption could be due to the rate of heat loss becoming too great and/or the supply of soil moisture to the freezing front becomes inhibited. Observations of needle ice on Marion Island show that needles are clear with no sediment inclusion except for the observations on the 4th of December which show needle ice formation in the disturbed soil. Again this is indicative that the micro-climate and moisture supply was very marginal for the formation of needle ice (on the 4th) and the synoptic conditions associated with the formation of needle ice are not deemed representative of ideal conditions.

With the passing of each cyclone, Marion Island experiences a repeated exchange from wet, warm pre-cyclonic conditions, to cold, clear and dry post-cyclonic conditions (Smith and Steenkamp, 1990). It was suggested that in field conditions, needle ice occurs on unvegetated surfaces when air temperatures fall below the freezing point, provided that an adequate moisture supply is available (Outcalt, 1969; Lawler, 1988, 1993). From the data presented in this study on Marion Island it seems that the soil moisture is provided by the misty conditions associated with the advent of the cold front (pre-cyclonic). The needle ice is then initiated by sensible heat exchange through the drop in air temperature provided by the passing of the cold front. Clear and cold Antarctic air (post-cyclonic) maintains the needle ice growth until daylight temperatures raises the soil temperatures above 0º C and ablation occurs.

Several factors influence the amount of soil disturbed by ice needles. If the ground surface becomes desiccated, the freezing front can form deeper in the soil and needles can then lift the layer above the freezing plane (Meentemeyer and Zippin, 1981). On Marion Island needle ice formation is associated with relatively high wind speeds. This wind has a desiccating effect on the shallow sub surface soil which could in turn force the freezing front below the surface. The data presented here have shown that the freezing front is deeper than 1cm and could reach anywhere close to 5cm depth. From observation the needle ice on Marion Island tends to form in the fine material below the course material. Given that the freezing front is below the surface, needle ice has the potential to displace large amounts of coarse material.

Snow is an extremely important control of ground microclimate in high altitude areas of the island (Holness, 2003). On Marion Island the snow cover that remains on the ground keeps the shallow soil temperatures at the freezing point of soil water and buffers the soil from temperature fluctuations. The freezing cycles that were associated with snow cover had long durations and depth, as the presence of snow leads to deeper soil freezing coupled with ground heat flow to the contact surface with the snow. The synoptic assessment of snowfall on Marion Island indicates that snowfall is associated with the passage of a cold front linked to a strong meridional system of low pressure just south of the island. Furthermore, post-cyclonic airflow has a more southerly trajectory than those systems associated with the formation of needle ice.

The limited data presented here shows that the zero-curtain effect on Marion Island occurs either as a response to the thawing of the soil after the seasonal freeze or during the thaw of the soil after a long diurnal soil frost cycle due to the advection of warm air associated with the warm sector of a cyclone. During both these scenarios the zero-curtain effect of the soil at depth was probably caused by vapour transport induced by freeze-thaw events at the soil surface that produces an upper and lower freezing isotherm in the underlying soil (Hall, 1997). The importance of the zero-curtain effect on Marion Island is that it influences the freeze-thaw effect and the number of soil frost cycles. This creates constant production of an upper and lower freezing isotherm in the underlying soil and results in a large number of soil frost cycles at the surface. This in turn enhances frost heave and could influence the formation of sorted patterned ground, which is dominant in the interior of Marion Island (Hall, 1979; Holness, 2001a, 2001b, 2003).

### Possible implications for climate change

To determine the effect micro-climate has on Marion Island's landscape, a synoptic-scale assessment needed to be undertaken. There is large amount of data focusing on the sub-Antarctic's micro-climate (e.g. Smith, 2002), however, previous studies mainly focused on the island's historical setting and climate change at an island-scale. Smith (2002) highlights that the island needs to be explored more thoroughly and this served as a motivation to undertake this kind of stud. This thorough investigation is of importance considering that Barsch (1993) ascertained that climate change represents an enormous geomorphic experiment which needs to be explored further.

The results and observations indicate that the synoptic-scale assessment of micro-climate is of utmost importance when assessing its effects on landform changes. Climate change that could affect Marion Island is non-linear and a slight change in climatic variables could result in changes in the landscape. From the data it is clear that frost related processes are mainly influenced by changes in synoptic weather conditions (especially in the interior of the island), and a slight change or shift in duration and/or magnitude plays an important role in frost mechanisms. Soil temperature, air temperature and soil moisture are the dominant parameters influencing diurnal soil frost processes. Diurnal soil temperature and soil moisture changes plays an effective role in frost cycles and a slight change in these parameters are highly influential to ground frost processes.

It has been shown that under a changing climate, Marion Island experiences less cloud cover and more direct sunlight (Smith 2002). Rouault et al., (2005) also suggest that the pressure increase in summer measured on Marion Island corresponds to a decrease in rainfall, an increase in the number of days without precipitation and a northward shift in the wind direction. This suggests a change in cyclonic activity affecting the island with the reduction in the westerly wind component. This implies relatively more anticyclonic conditions over the island or a reduction in low pressure affecting the island in summer (Rouault *et al*. 2005). Smith and Steenkamp (1990) propose that the radiation and air temperature increases can be explained by the positions of cyclone tracks relative to the island. Approximately 100 cyclones pass the island in a year and in warmer years the cyclonic centres pass, on average, further to the south of the island (Smith and Steenkamp, 1990).

Climate change implications for soil frost dynamics on Marion Island therefore show various complex trends. The trend associated with a more southerly position of mid-latitudinal cyclones or a reduction in cyclone activity would reduce post-cyclonic airflow and the frequency, intensity and duration of soil frost through a reduction in cooling by sensible heat exchange. Also, recent climate amelioration has resulted in a reduction in snow cover at high altitudes (Sumner et al., 2004). The absence of snow cover facilitates a higher frequency of soil frost cycles in the interior (Holness 2001; Boelhouwers et al., 2003), but less snow will imply less deep penetrating soil frost cycles with long durations.

Another consideration is the impact of relatively more anticyclonic conditions over the island (Rouault et al., 2005). A persistent southerly positioned anticyclone has the potential to generate substantial Antarctic air mass circulation which will reduce cloud cover and increase radiational heat exchange at the soil surface. This could facilitate nocturnal cooling to an extent that it may offset the influence of a warmer overall climate. It thus appears that the complex changes in climate parameters may lead to an equally complex response in terms of spatial soil frost dynamics and its direct and indirect effects on soil sediment displacement and ecosystem dynamics.

# CHAPTER 6

# CONCLUSION

This study which was conducted in the interior of Marion Island at Katedraalkrans aimed to address the formation and climatic drivers of needle ice, the synoptic weather circulation pattern associated with the occurrence of snowfall and its effect on the soil temperature and soil frost as well as the formation and occurrence of the zero-curtain effect. This was done through an intensive ground climate measurement campaign from April 2008 to May 2009. A temperature logger was installed at the study site and air temperature and soil temperatures were recorded at 1 cm, 5 cm and 10 cm depths every 5 minutes at a resolution of 0.01 °C. Wind speed was also measured with a cup anemometer and the synoptic weather systems dominant during the recording period were assessed through the synoptic shipping charts issued 6 hourly by the South African Weather Services (SAWS).

Several key findings are presented during the assessment of needle ice, snowfall and the zero-curtain effect and its relationship with soil frost dynamics on sub-Antarctic Marion Island:

- Unlike general conditions for global needle ice development in cold regions, on Marion Island, needle ice occurred during misty and overcast conditions. Furthermore, previous field measurement indicates that an equilibrium surface temperature at least as low as -2 ºC is necessary for ice nucleation (Outcalt, 1969, 1970). However, on Marion Island needle ice developed in temperatures as high as -0.2 ºC in strong winds. This confirms that the wet environment of

Marion Island, which is dominated by diurnal soil frost, is fundamentally different from seasonal frost and permafrost environments.

- Very shallow needle ice can occur in compacted soil when the soil texture is altered favouring needle ice development. Furthermore the compacted soil may also alter the micro-climatology of the affected area making it more susceptible to the formation of needle ice. In the compacted soils needles form near the surface and as a result the potential to lift material per unit area is limited.

- Commonly reported needle lengths vary between 1 and 5 cm (Meentemeyer and Zippin, 1980, 1981), which is consistent with a single night of freezing on Marion Island. Furthermore, observations of needle ice on Marion show that needles are mostly clear with no sediment inclusion.  This is indicative of needle ice formation that has not been interrupted by a shortage of moisture.

- Soil moisture for needle ice formation and growth is provided by the misty conditions associated with the advent of the cold front (pre-cyclonic). The needle ice is then initiated by sensible heat exchange through the drop in air temperature provided by the passing of the cold front. Post-cyclonic, clear and cold Antarctic air maintains the needle ice growth until daylight temperatures when radiational input raises the soil temperatures above 0º C and ablation occurs.

- On Marion Island needle ice formation is associated with relatively high wind speeds. This wind has a desiccating effect on the shallow sub surface soil which could in turn force the freezing front below the surface. The data presented here have shown that the freezing front is deeper than 1cm. From observation the needle ice on Marion Island tends to form in the fine material below the course material and since the freezing front is below the surface, needle ice has the potential to displace large amounts of coarse material.

- Snow cover that remains on the ground keeps the shallow soil temperatures at the freezing point of soil water and buffers the soil from temperature fluctuations. The freezing cycles that were associated with snow cover had the longest duration and depth, as the presence of snow tends to led to deeper soil freezing coupled with ground heat flow to the contact surface with the snow.

- The synoptic assessment of snowfall on Marion Island indicates that snowfall is associated with the passage of a cold front linked to a strong meridional system of low pressure just south of the island. It seems that post-cyclonic airflow have a more southerly trajectory than those systems associated with the formation of needle ice.

- The zero-curtain effect on Marion Island can occur either as a response to the thawing of the soil after the seasonal freeze or during the thaw of the soil after a long diurnal soil frost cycle due to the advection of warm air associated with the warm sector of a cyclone. During both these scenarios the zero-curtain effect on Marion Island influences the freeze-thaw effect and the number of soil frost cycles. This constant production of an upper and lower freezing isotherm in the underlying soil results in a large number of soil frost cycles at the surface. This in turn influences the formation of sorted patterned ground which is dominant in the interior of Marion Island.

- It thus appears that the complex changes in climate parameters may lead to an equally complex response in terms of spatial soil frost dynamics and its direct and indirect effects on soil sediment displacement and ecosystem dynamics. The trend associated with a more southerly position of mid-latitudinal cyclones or a reduction in cyclone activity could reduce the frequency, intensity and duration of needle ice. Less snow will imply less deep penetrating soil frost cycles with long duration. A persistent southerly positioned anticyclone has the potential to generated substantial Antarctic air mass circulation which will reduced cloud cover and increased radiational heat exchange at the soil surface. This could facilitate nocturnal cooling to an extent that may offset the influence of a warmer overall climate.

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