Geomorphic and Ambient Environmental Impacts on Lichen Distribution on Two Inland Nunataks in Western Dronning Maud Land, Antarctica

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Abstract

Feedbacks between abiotic variables and community structure in Antarctica are poorly understood. Research is, therefore, required to elucidate the patterns of biodiversity that exist and the factors that influence them, particularly under changing climates. Landscape processes affect environmental heterogeneity, which in turn affect patterns of biodiversity. Two inland Antarctic nunataks, Robertskollen and the Northern Buttress of Vesleskarvet, were selected for investigation to determine the potential impact of selected environmental factors on lichen distribution and abundance, at the intra- and inter-nunatak scales. Lichens were found to prefer rock faces with dips between 1° and 45°, and northern/southern aspects. Lichen colonisation was mostly in microtopographical features that result from rock weathering. The distribution of lichens was found to be regular at the intra- and inter-nunatak scale, whereas lichen abundance was found to be mostly influenced by temperature. On the Northern Buttress, rock hardness displays a similar pattern to lichen abundance, both of which are suggested to be a function of exposure time, which is dependent on deglaciation. The two nunataks serve as excellent laboratories that can potentially be used as proxies for investigating the possible impacts of climate change.

Dedication

This thesis is dedicated to the late Lyle Irvine, and Chay Bachar. Mr Irvine and (the then) Miss Jordaan, as I knew them, were major influences in me ever going to Antarctica. Mr Irvine had a passion for Antarctica and played a big role in fostering mine in my early high school years. Miss Jordaan was the one who encouraged me to pursue my dream of going to Antarctica and is the main reason I went on to study Geography at university. It is these great teachers that I have to thank for me ever getting far enough to take on this project and realise the dream!

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“The mediocre teacher tells. The good teacher explains. The superior teacher demonstrates. The great teacher inspires” – William Arthur Ward

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1 Introduction

1.1 Background, context and motivation

Antarctica is often cited as the last pristine environment on Earth. The continent has been completely separated from all other continents for roughly 30 million years, when the Antarctic Peninsula split from South America (Bargagli, 2008). It was the last continent to be discovered and explored, and remained uninhabited until the 20th century (Baroni, 2013). The Antarctic environment is a very hostile one; it is renowned for being the highest, driest, windiest, and coldest continent. The environment is a hyper-arid one with the ice-free areas representing that of high latitude periglacial environments (Baroni, 2013).

Antarctic biodiversity is not only facing human related challenges, but also those of climate change (Terauds *et al.*, 2012). The polar regions have been identified as important areas to monitor the implications of climate change as due to their sensitivity to warming, they are expected to respond in a very quick and noticeable manner (Cannone *et al.*, 2006). Understanding the distribution of biodiversity at various spatial scales is needed in order to implement effective conservation schemes (Terauds *et al.*, 2012); high latitude ecosystems have been identified as ideal gauges for potential biological reactions to environmental change (Chapin *et al.*, 2005 *in* Convey *et al.*, 2009a). Monitoring is essential in quantifying current conservation measures, especially mosses and lichen, which make up most of Antarctic biota and are widespread throughout the continent, and can act as important biomonitors (Bargagli, 2008). The area in which this study is situated, Dronning Maud Land, only has two Antarctic Specially Protected Areas (ASPAs) covering 0.2% of the ice-free area (Terauds *et al.*, 2012); this is not due to a lack of areas that need to be protected, but rather due to a lack of data in the area.

It is widely accepted that climate change is going to affect the Antarctic environment, particularly vegetation and permafrost. This issue is being addressed in the Arctic; however, the possible responses to a changing climate are still inadequately addressed for the Antarctic (Cannone *et al*., 2006). Due to the human and economic threats that a change in climate poses on the Arctic, most of the research of this kind has been conducted there as opposed to the

Antarctic. However, findings from the Arctic cannot be applied to the Antarctic as contrary to popular belief the two are very different (Convey *et al*., 2003).

An Antarctic horizon scan by Kennicutt *et al.* (2014) identifies important questions that need to be addressed while moving forward in Antarctic science. One such question directly pertinent to the present study is “How can natural and human-induced environmental changes be distinguished, and how will this knowledge affect Antarctic governance?” (Kennicutt *et al*., 2014:10).

The presented research represents a case study of the extent to which geomorphic features and climate influence lichen distribution and abundance on two inland nunataks, Vesleskarvet and Robertskollen, in western Dronning Maud Land, Antarctica. Antarctica is an ideal place for such a study due to the relative simplicity of the system and its mostly untouched environment (Kennicutt *et al*., 2014, Shaw *et al*., 2014); investigations such as these provide baseline data which can help inform issues such as environmental changes. Data contributing to this study was captured during five Austral summers, as part of two different overarching projects interested in the geomorphology and climate of the area.

This dissertation is comprised of six chapters. The first chapter provides the context for the study, introduces the study sites, and outlines the aim and objectives. Chapter two provides a comprehensive review of current literature surrounding the topic, which places the research into a broader context. Chapter three provides a concise summary of both the field and computational methodologies employed to generate data to inform on the aim. The fourth chapter summarises the results and adds a discussion for each of the four objectives, and then finally synthesises it into one narrative. The fifth chapter summarises the project, and provides some recommendations for further work.

1.2 Study Area

The sites investigated for this research are situated in the Ahlmannryggen (Ahlmann Ridge) in western Dronning Maud Land (also known as Queen Maud Land). Dronning Maud Land is bounded by the Stancomb-Wills Glacier (20°W) and Shinnan Glacier (44°38'E), making it one of the biggest areas in East Antarctica (Stewart, 2011). It was first discovered and named in 1930 by Riiser-Larsen, who named it "Dronning Maud Land" after the queen of Norway (Stewart, 2011). Dronning Maud Land was later claimed by Norway on 14 January 1939 (Stewart, 2011). The Ahlmannryggen is a broad ridge bordered by the northeast-trending glaciers, Jutulstraumen and Schyttbreen (Marshall *et al*., 1995). The ridge, 112 kilometres long, is mostly covered by ice and snow, but does have scattered nunataks and peaks throughout (Stewart, 2011).

Data were collected from two nunataks in the Ahlmannryggen, namely, Vesleskarvet and Robertskollen (Figure 1). These two nunataks were chosen for comparison in order to aid understanding of how abiotic factors influence biological growth, as unpublished logger data show that even though they are close in proximity (roughly 25 kilometres apart) they have different local climates, and display notable differences in biological growth abundance (pers. obs.). Robertskollen and Vesleskarvet were first mapped by Norwegian cartographers during the first expedition to Antarctica that included an international team of scientists, the Norwegian-British-Swedish Antarctic Expedition (NBSAE), between 1949 and 1952 (Giaever, 1954). A total of 100 000 km^2 was mapped using a combination of ground surveys and aerial photography (Scott Polar Research Institute, 2008).

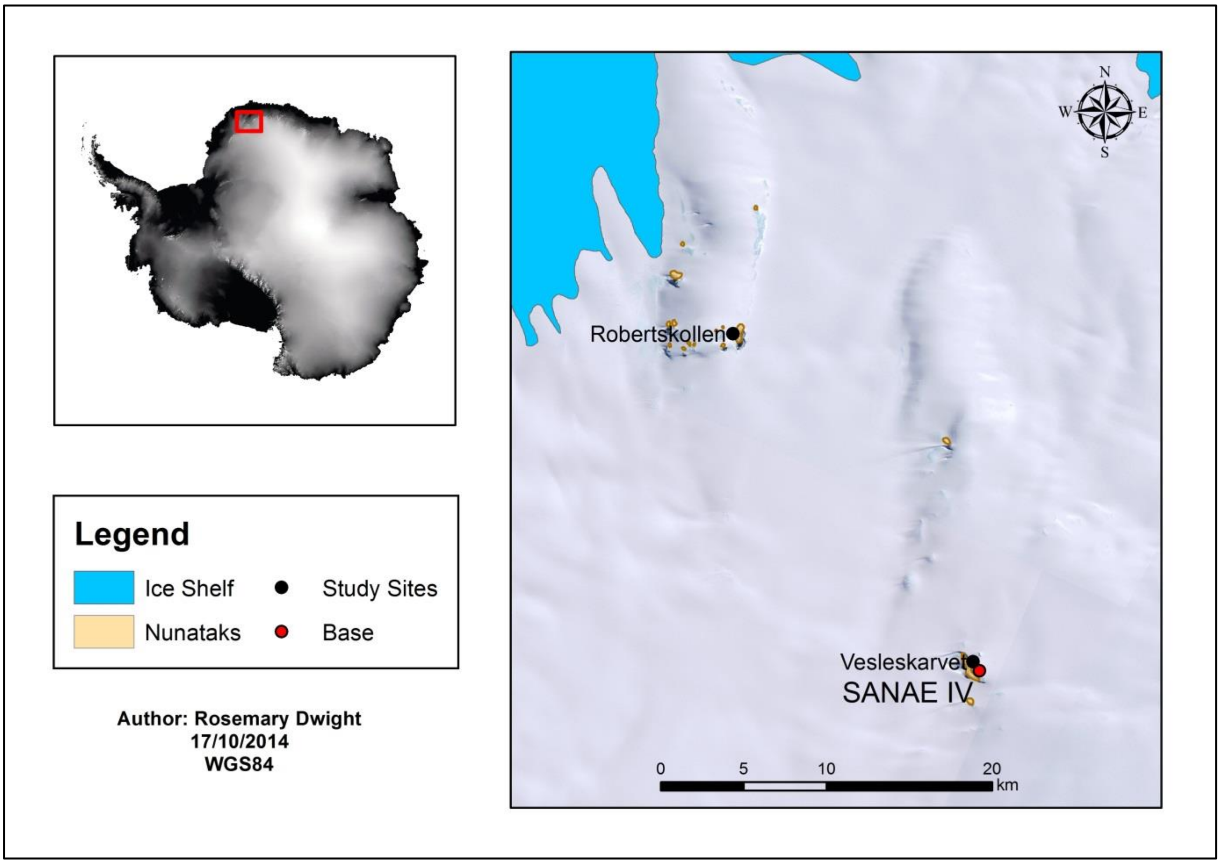

Figure 1: Study sites in western Dronning Maud Land

Vesleskarvet (71°40’S, 2°50’W) is the nunatak on which the South African base (SANAE IV) is situated, roughly 160 kilometres from the ice shelf edge (Steele *et al*., 1994). It is a flat-topped nunatak consisting of two main parts, the Northern and Southern Buttresses (see Figure 2), covering a total area of approximately 22.5 hectares (Steele *et al*., 1994). The highest point, situated on the western edge of the Northern Buttress, is 856 meters above sea level (Steele *et al*., 1994). The western and northern edges are along 200 meter cliffs above a windscoop, whereas the eastern and southern edges transition smoothly into the south-east sloping ice-sheet (Steele *et al*., 1994). The SANAE IV base is on the southern buttress, and the northern buttress is an off-limits zone which can only be visited by scientists who have permission to conduct research there. It was named Vesleskarvet by the Norwegians as it bares resemblance to its meaning, “little barren mountain” (Stewart, 2011).

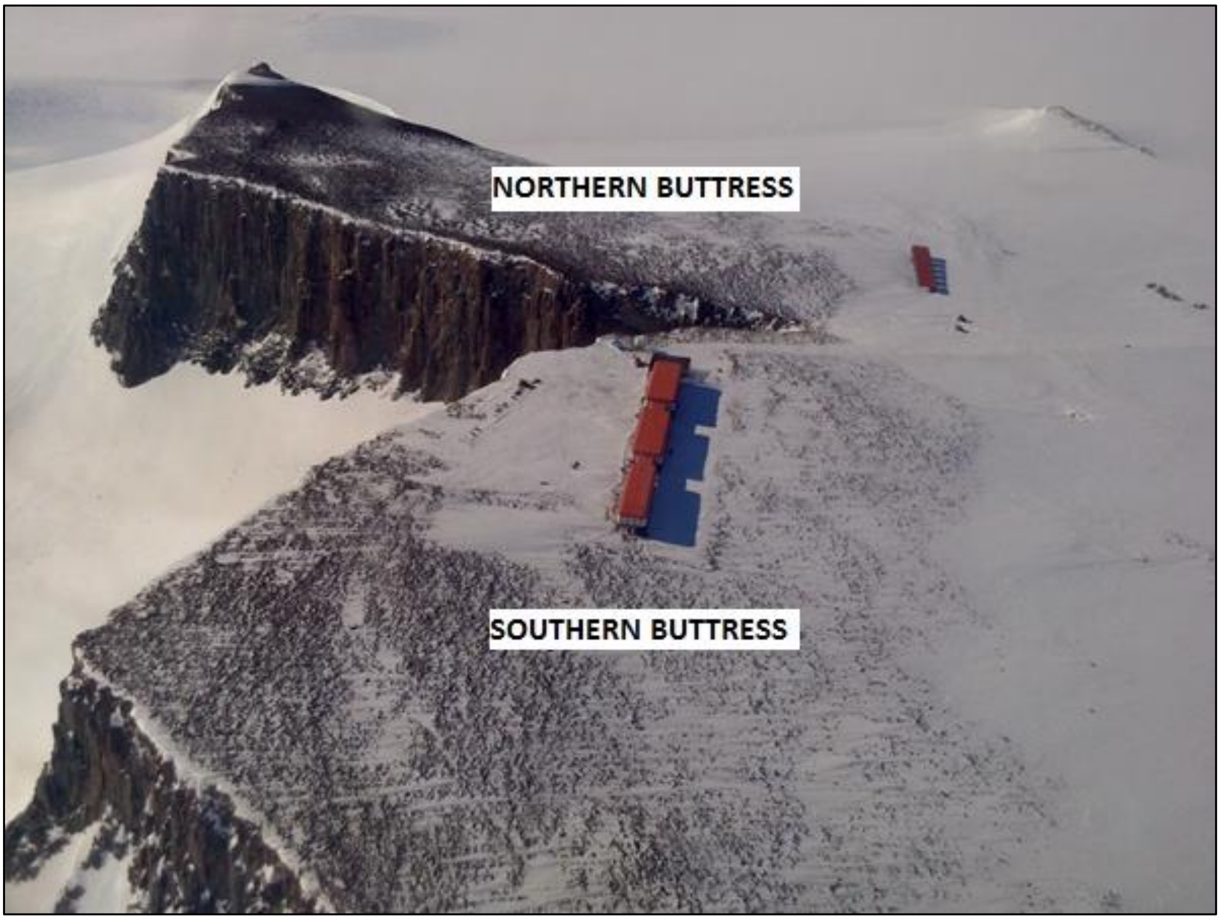

Figure 2: The Northern and Southern Buttresses of Vesleskarvet (Photo credit: Esterhuyse, 2014)

The geology of Vesleskarvet comprises of homogenous mafic igneous rocks of the Borgmassivet Intrusions (Classen and Sharp, 1993 *in* Steele *et al*., 1994; Hansen, 2013). The surface of the nunatak is made up of large angular boulders (Steele *et al*., 1994). The mean annual air temperature for Vesleskarvet is -24°C, with the highest recorded air temperature being 6°C and the lowest is -27.8°C (Hansen, 2013). The very little precipitation that does fall, is in the form of snow (Beyers and Harms, 2003), and the average relative humidity is 63% (Hansen, 2013). The prevailing wind direction is from the east, with an average speed of 11 meters per second (Hansen, 2013).

Robertskollen (71°27'S, 3°15'W) is situated in the northwest of the Alhmannryggen; the peaks are some of the northern-most in the region (Ryan *et al*., 1989). It consists of a group of five large (Glacier's Edge, Ice Axe Peak, Peaceful Hill, Petrel's Rest, and Tumble Ice), and several smaller nunataks (Tibbles and Harris, 1996). The nunataks range between 200 and 500 metres above sea level (Ryan *et al.*, 1989). The Robertskollen group of nunataks were named after Dr Brian Birley Roberts; the nunatak is also known by its translated name, Roberts Knoll (Stewart, 2011).

The underlying geology is the intrusive Robertskollen complex; it consists of a lower ultramafic made up of mostly mela-olivine gabbronorite, overlain by a mafic unit containing gabbronorite and gabbro (Von Brunn, 1964; and Krynauw, 1986 *in* Ryan *et al.*, 1989). Ice Axe Peak and Tumble Ice nunataks also have dolerite dykes, and there are lithosols found throughout the group of nunataks (Ryan *et al.*, 1989). There is no long-term weather data for Robertskollen, however on a regional scale it is assumed to be similar to that of Vesleskarvet due to their close proximity. The temperatures recorded there are, however, relatively mild due to its low altitude; temperatures of up to 25°C on rock surfaces have been recorded, and meltwater has been noted as plentiful (Ryan *et al.*, 1989). The predominant wind direction is from the northeast, with occasional winds from the east and southeast, and very infrequently the wind blows from the north and west (Ryan *et al.*, 1989). The eastern side is characterised by high cliffs, whereas the tops and western sides are mostly comprised of gently sloping boulder slopes, some of which are unstable screes (Ryan *et al.*, 1989).

1.3 Aim and Objectives

This project aims to investigate the extent to which geomorphic features (landforms) and the ambient environment provide favourable habitats for lichen establishment.

In order to achieve the aims, the following are the objectives of this research:

1. Provide a detailed site analysis of each lichen species occurring on the Northern Buttress.
2. Investigate lichen abundance and distribution at intra- and inter-nunatak scales.
3. Measure specific environmental factors which could play a role in lichen distribution and abundance.
4. Compare the patterns of lichen distribution and abundance to those of influencing environmental factors in order to gain a better understanding of their relationship with lichen establishment.

2 Background

This chapter aims to provide the reader with the necessary background information about Antarctica. The first part addresses the Antarctic environment, to place the research that follows in context. The following two parts are about climate change, and human impacts and conservation in the Antarctic, which provide motivation for this research. The final section of this chapter discusses other studies done in the Antarctic which are similar in some ways to the present one.

2.1 The Antarctic environment

Antarctica is a cold desert with very little ice-free covered surface area that can act as habitats for living organisms (Allen *et al.*, 1967). Only roughly 0.34% of Antarctica is free of ice and snow in the summer; it is on that small percentage of land where terrestrial ecosystems are situated (Convey *et al.*, 2009a). These ice-free areas are mostly situated in the western Antarctic Peninsula, the rest are scattered throughout the continent in the form of steep mountain slopes or nunataks (Bargagli, 2008). Biota are sparse, but these ecosystems are unique for studies on cold adaption and colonization processes in extreme environments (Bargagli, 2005). Antarctica is split into three markedly different zones, namely, the sub-, maritime and continental Antarctic, shown in Figure 3 (Convey *et al.*, 2009a).

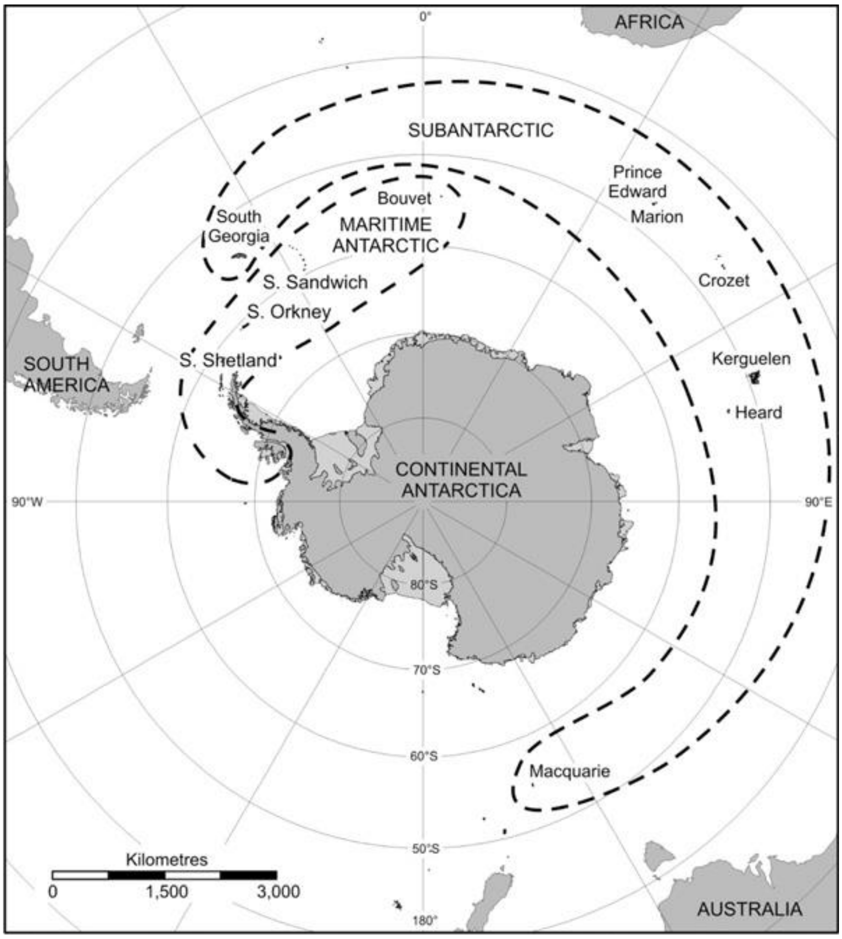

Figure 3: The terrestrial biogeographical zones of Antarctica (Source: Convey et al., 2009a)

Areas in continental Antarctica generally have a mean monthly temperature below zero degrees Celsius in even the warmest month (Bargagli, 2005). Habitats range from the very harsh ones, such as isolated nunataks, on the polar plateau, to the coastal ice-free areas which experience milder climatic conditions (Bargagli, 2005). The inland ecosystems receive very low precipitation, have low atmospheric humidity, and experience low and widely fluctuating temperatures on a seasonal and diurnal basis (Thompson *et al.*, 1971; Vincent, 1988; Brinkman *et al.*, 2007). On the contrary, coastal ice-free areas are influenced by the sea and experience more moderate temperatures, a higher amount of snow precipitation and seabirds contribute toward nutrient availability. Continental Antarctica is comprised of species poor systems and does not have any vascular plants. Thus, feedback mechanisms between plants and soil biota do not function as they do in other ecosystems (Wardle *et al.*, 2004; Adams *et al.*, 2006). Inland nunataks have lower diversity and quantity of biota compared to that of coastal ice-free areas (Convey and Smith, 1997; Convey and McInnes, 2005; Brinkman *et al.*, 2007). They are comprised of mostly bare rock and soil with occasional algae, moss or lichen (Bargagli, 2005).

Antarctica has some of the most extreme terrestrial environments on Earth, and is different to those in the Arctic (Cowen and Ah Tow, 2004; Øvstedal and Smith, 2001; Brinkman *et al.*, 2007). However, comparatively little is known about Antarctic ecosystems. In addition, continental Antarctic terrestrial ecosystems and biodiversity are not nearly as well understood as those in the maritime Antarctic (Brinkman *et al.*, 2007).

2.1.1 Antarctic climate and abiotic variables

Antarctic climate conditions have been created as a result of numerous natural factors over a long period of time on a geological scale (Baroni, 2013). The environmental conditions at the poles makes them unique compared to the rest of the world; they are energy poor environments due to a combination of factors. The low angle of incidence results in lower mean annual solar radiation received than anywhere else (Baroni, 2013). Albedo plays a major role in reflecting most of the solar energy, and long-wave radiation is encouraged due to the clarity of the atmosphere which has little dust and water vapour (Baroni, 2013). What does separate the Antarctic from the Arctic, is that Antarctica has very cold summers, which is an influence in determining survival of terrestrial biota (Øvstedal and Lewis Smith, 2001).

The combination of biotic and abiotic factors in an environment form a unique set of conditions for colonisation by certain species is known as a habitat (Molau, 2008). Microclimates are thought to be foremost in determining patterns of Antarctic vegetation; factors which are known to bare an influence on vegetation colonisation include moisture availability, temperature and ground-level wind speed (Beyer *et al.*, 2000). Kappen (2000) cites cold stress as a factor that has a larger influence on vegetation in the Antarctic compared to that in the Arctic and could, thus, elucidate the low species diversity in the former. In order to be successful, Antarctic plants need to be able to survive extreme physiological stresses, such as low temperatures, repeated freezing and thawing, desiccation, limited water supply and high levels of solar radiation (Leishman and Wild, 2001; Alberdi *et al.*, 2002).

At the continental scale, biological diversity and complexity becomes simpler with increasing latitude, yet, at a smaller scale patterns are governed by local environmental parameters such as “altitude, precipitation patterns, wind speed and direction, and extent of available ice-free ground” (Hughes and Convey, 2010:98). Armstrong (2002) discusses aspect preferences with regards to lichen colonisation. Aspect can result in differing microclimates on each slope or rock faces, this includes differences in solar radiation and temperatures. Higher solar radiation encourages lichen growth (Palmqvist and Sundberg, 2000 *in* Armstrong, 2002), but higher temperatures could have a negative drying effect on the growth of specific lichen species (Armstrong, 1975 *in* Armstrong, 2002). A study by Peck *et al*. (2006) in the maritime Antarctic found that microhabitat temperatures do not follow the ambient air temperature closely; this is mostly due to the effect of insolation in summer and snow-cover acting as protection in the winter. They conclude that microhabitats can experience short-term temperature highs of between 20°C and 40°C. Therefore, biota need to be able to survive both large annual (40-80°C) and diurnal (~30°C) temperature ranges (Peck *et al*., 2006).

The impacts of climate change in Antarctica are visible in both the abiotic and biotic components of ecosystems (Guglielmin *et al*., 2008). Permafrost, active layer thickness, vegetation and soil are all environmental components that are sensitive to climate change (Guglielmin *et al*., 2008). Temperatures are rising in parts of Antarctica as a result of global and regional climate change (e.g. Oppenheimer, 1998; Seppelt *et al*., 2010; Bockheim *et al*., 2013). Ecosystems in Antarctica depend largely on the proximity to and duration of available liquid water (Barrett *et al*., 2006; Seybold *et al*., 2010), therefore, it is imperative to have an understanding of soil moisture and water regimes in Antarctica (Seybold *et al*., 2010). An early indicator of global climate change could be manifested in terrestrial ecosystems (Sancho *et al*., 2007). It is, thus, it is important to have a comprehensive understanding of the floral communities of continental Antarctica (Petersen and Howard-Williams, 2001; Seppelt *et al*., 2010).

2.1.2 Permafrost and active layer

Permafrost is defined as the layer of earth material which remains below 0°C for two consecutive years or more (Anisimov *et al*., 2007). It is very vulnerable to warming and, thus, an important environmental indicator to monitor (Anisimov *et al*., 2007). Anisimov *et al*. (2007) highlight three roles that permafrost plays in terms of global change: it records temperature changes, acts as a proxy for other observed changes in the environment, also contributes to climate change by the release of trace gases (see Anisimov *et al*., 2007 for sources). In permafrost terrains, most biological and hydrological activities are limited to the active layer which acts as a boundary layer of heat, moisture and gas exchanges between the atmosphere and the terrestrial cryosphere (Anisimov *et al*., 2007).

Active layer processes and landforms provide a substrate for biological activity in the Antarctic. Thus, it can be argued that the abiotic processes provide the habitat in which the biotic components of the environments can survive. However, determining the exact relationship between active layer biodiversity and ecosystem functioning is hindered by the lack of essential taxonomic knowledge of soil organisms and their contribution to ecosystem functioning (Adams *et al*., 2006). Antarctic soils, which are a component of the active layer, are ideal for modelling the fundamental relationship between biota and ecosystem functioning as they are simplified due to the fewer number of species which have an influence on the processes (Barrett *et al*., 2004; Adams *et al*., 2006).

2.1.3 Biota

Biotic communities in Antarctica are fairly simple as patterns of biodiversity are assumed to be determined by climatic conditions (Kennedy, 1993; Caruso *et al*., 2010). Understanding the controls on the distribution and abundance of biota is one of the largest standing questions in ecology (Gaston, 2000). The severity of the Antarctic climate, its isolation, and limited areas for suitable habitats are all factors which shape Antarctica's terrestrial biota (Kennedy, 1995; Hughes and Convey, 2010). Continental Antarctic biota occur mainly as small, isolated communities comprising of species which can tolerate stark differences in water availability, temperature, light and UV radiation (Bargagli, 2005).

Antarctic flora is made up of mostly of algae, fungi lichen, liverworts, and mosses, with just two vascular plants occurring in the Peninsula; terrestrial fauna is limited to invertebrates such as mites, springtails, tardigrades, and rotifers (Kennedy, 1995; Hughes and Convey, 2010). Microorganisms are the most abundant, followed by soil invertebrates, and then lower order plants such as lichen and mosses (Hughes and Convey 2010). Lichens are pioneer species in arid ecosystems due to their ability to tolerate and survive harsh conditions by occupying suitable niches (Holder *et al*., 2000). It is estimated that there are approximately 260 species of lichen in Antarctica, of which only 40% are endemic (Bargagli, 2005).

The distribution of Antarctic invertebrates has been assumed to be predominantly shaped by abiotic factors that accompany geographic ranges (Caruso *et al*., 2010). This originates from the notion that environmental stress increases with increasing latitude, or altitude (Caruso *et al*., 2010). However, (Caruso *et al*., 2010) found that this is not entirely true with regards to the species distribution of Antarctic invertebrates. Some of their main findings include that species distributions vary at multiple scales, spatial-scale variability is a result of the processes acting at those scales, and latitude does not have a major influence on distribution (Caruso *et al*., 2010). These findings should also prove true for Antarctic vegetation, which this study aims to address.

Microorganisms are most often the pioneer colonisers of bare rocks and soil, thus play a vital role in soil ecosystem development and pedogenesis (Bliss and Gold, 1994; Brinkmann *et al*., 2007). Rocks and soil can act as sources of moisture during the summer months which provides an ideal location for propagules to settle and grow (Bargagli, 2005). Weathering processes in Antarctica are thought to be very slow (Bargagli, 2005). One such process of interest is that of biotic exfoliation by endolithic communities (Bargagli, 2005). Indications from studies of the interface between lichens and their rock substrates show that the growth of lichen can accelerate the weathering of minerals by means of both chemical and physical processes (Chen *et al*., 2000). In order to achieve a better understanding of soil ecosystem processes, a compilation of all the influencing species, their distribution and abundance at varied time scales is imperative (Wall, 2005; Adams *et al*., 2006). There is still not a complete understanding of the early colonisation processes involved in Antarctic terrestrial habitats (Wynn-Williams *et al*., 1990; Brinkmann *et al*., 2007).

Periglacial features play a role in shaping the composition and distribution of flora and vegetation biodiversity in Antarctica by providing a range of ecological niches (Cannone and Guglielmin, 2010). Even though the relationship between periglacial features and vegetation is acknowledged, it has not been investigated enough in Antarctica (Cannone and Guglielmin, 2010). The micro-relief of periglacial features affects the micro-topographical and micro-edaphic conditions, which in turn could influence the shelter or disturbance on plants, and the patterns of snow accumulation (Cannone and Guglielmin, 2010). Conversely, the vegetation has a buffering effect on the ground thermal regime and, thus, has possible feedbacks on active layer thickness and freeze-thaw cycles which could influence soil chemical characteristics (Cannone and Guglielmin, 2010). Soil moisture is the determining factor in a number of soil processes including microbial activity and pedogenesis (Seybold *et al.*, 2010). The amount of available water is the limiting factor with regards to the presence, abundance, and diversity of terrestrial biota (Cameron and Conrow, 1969; Bargagli, 2008; Seybold *et al.*, 2010).

It has been suggested that the majority of the flora in continental Antarctica originated after the last Pleistocene glaciation through a number of dispersal processes (Lindsay, 1977; Bargagli, 2005). The chance for the successful establishment of a propagule or an organism in Antarctic is low (Hughes and Convey, 2010). In order for dispersal to occur, the dispersal mechanism needs to be capable of moving the species great distances, and the organism or propagule has to be able to withstand the harsh elements during transport (Hughes and Convey, 2010). There is also the added problem landing on some of the scarce ice-free areas. “Lichens are the most widespread organisms on rock and boulder surfaces”; they can even be found in the form of surface mats in areas which have moisture and protection from wind (Bargagli, 2005:68). It was thought that patterns of microbial diversity are similar throughout the continent, however, it has been suggested that with increasing latitude there is a broad pattern of decreasing diversity of biota (Clarke, 2003; Peat *et al.*, 2006; Brinkmann *et al.*, 2007; Hughes and Convey, 2010).The question of patterns of diversity throughout the continent has only recently been addressed by Lawley *et al.* (2004), thus any further research on this topic would be of great value towards a greater understanding of biota on the continent (Brinkman et al., 2007).

2.1.4 Biogeography

Ecology and geomorphology are both expansive and complex subjects, but there is a large avenue of interface between the two which presents many opportunities for collaborative research (Molou, 2008). Geomorphic processes and landforms play a role in shaping the distribution of biota, however biota also alter geomorphic processes and landforms (Stallins, 2006). This is just one example illustrating the connection between these two fields of research.

Environmental Domains Analysis (EDA) was conducted by Morgan *et al.* (2007) across the Antarctic continent in order to classify the continent into areas of similar environmental and geographical characteristics. The result, (shown in Figure 4) is 21 different regions (Environmental Domains) which are similar in characteristics such as ecosystem, habitat, geographic area, terrain, geology, and climate (Morgan *et al.*, 2007; Terauds *et al.*, 2012). This was achieved by using a combination of climate, slope, land cover and geological data in a Geographic Information System (GIS) (Morgan *et al.*, 2007).

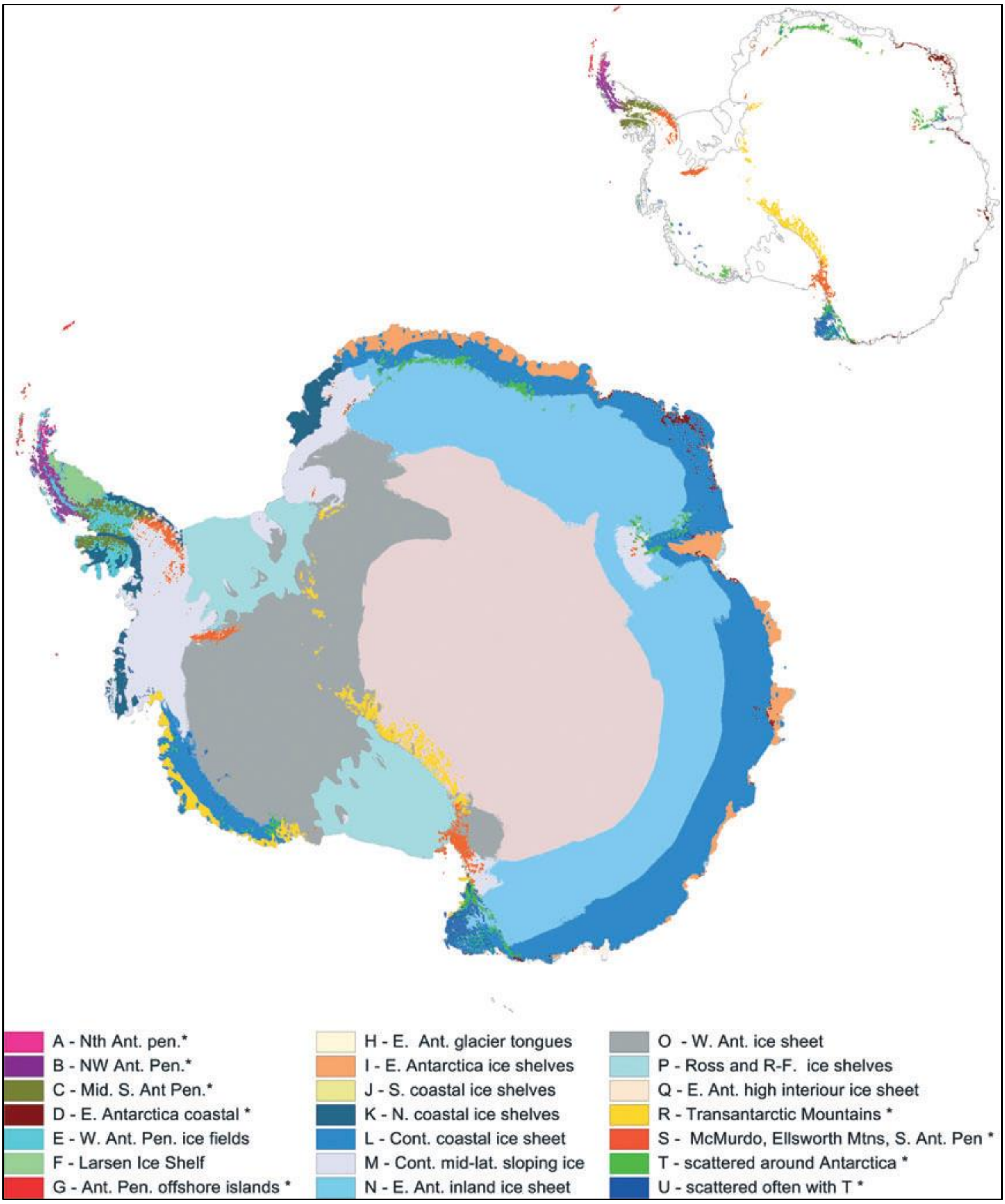

Figure 4: The 21 Environmental Domains. Domains denoted by * include ice-free areas, which are shown in the inset. (Source: Terauds et al., 2012)

Dronning Maud Land, the region in which this study took place, falls into Environment T (Figure 5), "Inland continental geologic (Dronning Maud, MacRobertson, Victoria, Oates lands, Ford Range)" (Morgan *et al.* 2007). This environment is small, covering only 24742km^2, but it does cover an extensive area around the continent, mostly between the 70°S and 75°S parallels (Morgan *et al.* 2007). This environmental domain comprises wholly ice-free areas and contains all four of the geological units (Morgan *et al.*, 2007). It is mostly comprised of intrusive (71%), with subsidiary metamorphic (14%) , sedimentary (11%), and finally a mere 1% of volcanic rock (Morgan *et al.*, 2007).

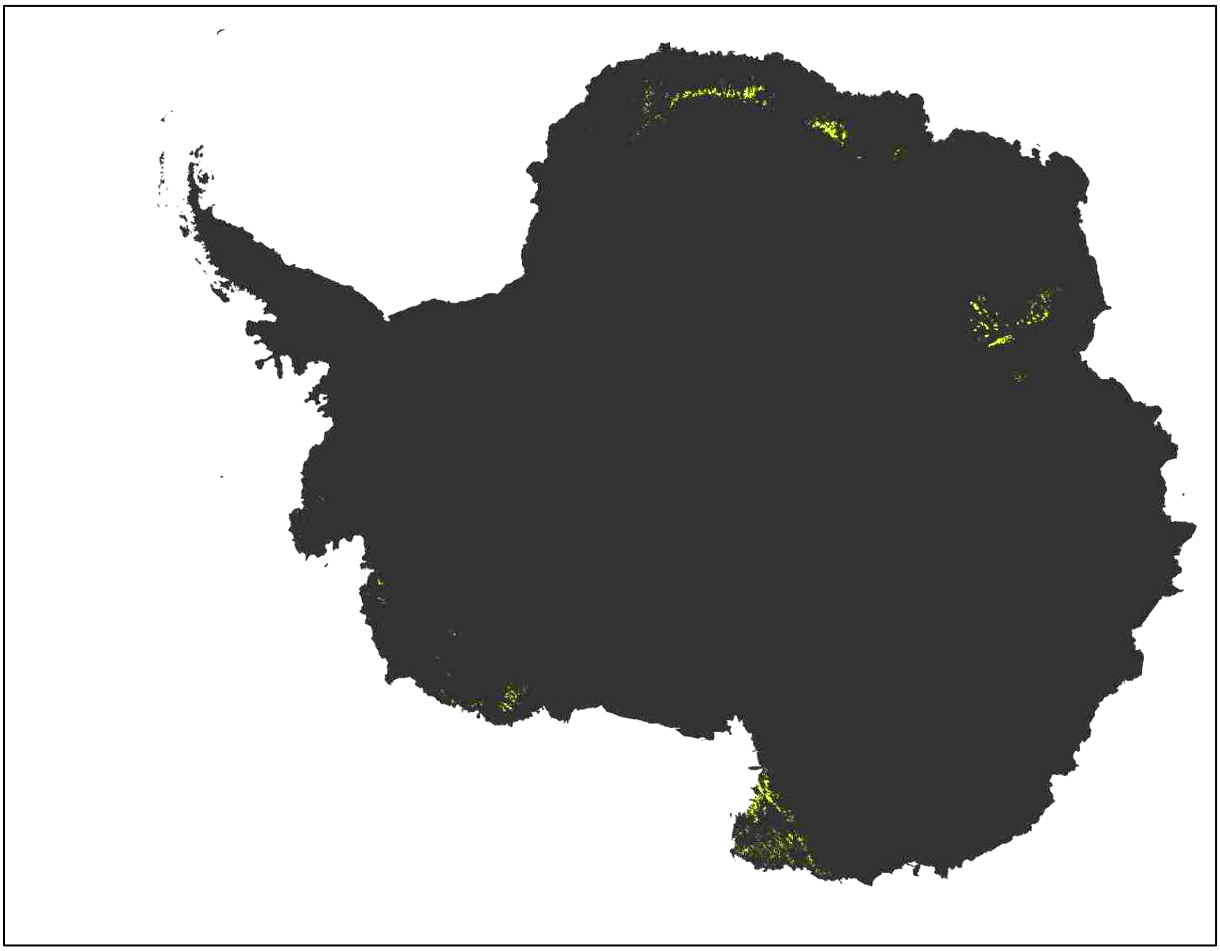

Figure 5: Environment T (Source: Morgan et al., 2007)

2.2 Climate change

Antarctic ice sheets hold roughly 70-80% of Earth's freshwater (Bargagli, 2005). Along with the Arctic, the poles are important in controlling global sea levels and ocean circulation, any changes in the poles will impact areas outside of them due to their influence on the planetary energy balance (Baroni, 2013). The Antarctic is a unique continent in that it is partly covered by ice and surrounded by ocean (Baroni, 2013). During winters the continent is surrounded by roughly 20 million km^2 of sea ice (Baroni, 2013). Owing to its unique environment and sensitivity to change, Convey *et al*. (2003) aptly cite the polar regions as a "canary in a coal mine". The Antarctic has the potential to give scientists an insight into the effects that climate change is having on biodiversity (Convey *et al*., 2003).

When considering the continent as a unit, there is strong evidence that climate change has impacted Antarctica (Anisimov *et al*., 2007). Observed changes in the Antarctic include: a reduction in permafrost extent and an overall increase in ground temperatures, a general warming trend, an increase in precipitation, and warming and reduction of salinity of surface waters in the Southern Ocean (Anisimov *et al*., 2007). Evidence of past climate change in the Antarctic has been recorded by The West Antarctic Ice Sheet (WAIS) which underwent major fluctuations during the warmer Pliocene (Naish *et al*., 2009). The WAIS is currently unstable and could lead to major sea-level rises if it were to collapse (Oppenheimer, 1998; Pollard and DeConto, 2009).

The possible ramifications of climate change on Antarctic biodiversity are still largely unknown. In order to identify vulnerable species and communities, it is imperative to set up new baseline monitoring programmes as currently there are very few of such datasets (Hughes, 2000). Factors such as elevated temperature, UV radiation, carbon dioxide, and precipitation will combine to create conditions which favour new community development (Kennedy, 1995). Thus added to the observed increasing rates of change, it can be expected that species' geographic ranges will reach higher altitudes and latitudes (Hughes, 2000). Ice retreat will increase the total area of a currently small proportion of ice-free areas, which will result in the creation of new habitats allowing for colonisation (Kennedy, 1995).

One of the major factors accounting for the low terrestrial biodiversity in the polar regions are the extreme environmental stresses that biota have to overcome (Convey *et al.*, 2003). It is expected with a changing climate that there will be rapid and visible responses by biota (Convey *et al.*, 2003). The physiology, distribution and phenology of certain species have been found to respond to climate change in a manner very similar to that of predictions (Hughes, 2000). Hughes (2000) notes that although there may be other influencing factors, a change in climate accounts for most of the changes.

Polar habitats are characterised by a low thermal energy budget, thus an increase in this could have major impacts on terrestrial biota (Convey *et al.*, 2003). Earlier thawing and later freezing events will lead to a longer period available for organisms to be active (Convey *et al.*, 2003). Although it has been confidently projected that there are going to be increases in temperatures in Antarctica, there is little confidence on the regional scale (Convey *et al.*, 2009b). As already established, liquid water is one of the most influential limiting factors for biota in Antarctic ecosystems (Kennedy, 1993). There is no conclusive evidence about the extent of precipitation increases; however, increases in temperatures, glacial retreat and loss of snow cover will all contribute to increases in available meltwater (Convey *et al.*, 2003). Changes in radiation is one phenomena which could have numerous different impacts on the Antarctic climate; on the one hand it could lead to increases in primary production, but on the other hand biota may be exposed to more damaging radiation for longer periods of time (Convey *et al.*, 2003).

Permafrost known to be very sensitive to climate change (Anisimov *et al.*, 2007; Baroni, 2013). Active layer thickness reacts to factors such as “aboveground climate, vegetation type and density, snow-cover properties, thermal properties of the substrate, and moisture content” (Anisimov *et al.*, 2007). With rises in air temperature, and assuming all the other factors remain constant, active layer thickness is expected to increase and permafrost extent decrease (Anisimov *et al.*, 2007; Baroni 2013). Such changes will result in landscape changes across extensive areas (Baroni, 2013).

2.3 Human impacts and conservation

Antarctica and the Southern Ocean are thought of by some as the last pristine environment on Earth (e.g. Terauds *et al.*, 2012, Guglielmin *et al.*, 2014); however others argue that it may no longer have this status due to an rise in anthropogenic impacts (Bargagli, 2008; Tin *et al.*, 2009). Even though the entire continent and Southern Ocean south of 60°S is already protected by the Antarctic Treaty System (ATS) (Berkman *et al.*, 2011), there are growing concerns about the conservation of the continent (Hughes and Convey, 2010; Shaw *et al.*, 2014). The earliest recorded presence of humans in Antarctica was in the early 19th century and because of this, biodiversity has been relatively unaffected by human impacts compared to the rest of the world (Bargagli, 2008; Hughes and Convey, 2010). However, with a relatively recent increase in research and public interest in Antarctica, the number of people visiting the continent has increased significantly (e.g. Bargagli, 2008; Tin *et al.*, 2009; Hughes and Convey, 2010; Terauds *et al.*, 2012; Shaw *et al.*, 2014). Through a number of human related operations, the negative effect on biodiversity has increased (Bargagli, 2008; Shaw *et al.*, 2014). Human activities can affect Antarctic biodiversity from habitats all the way through to individuals (Shaw *et al.*, 2014). Therefore, it has become necessary to formulate policies more specific than just the protection of the continent on a whole.

The ATS was compiled in 1959 and came into effect on 23 June 1961 (Holdgate, 1970). It banned military activities and nuclear testing within the area south of 60°S, limiting the purpose of the continent to peaceful scientific exploration (Holdgate, 1970). The treaty also stipulates that measures are taken in order to preserve and conserve the continent's living resources (Tin *et al.*, 2009). The ATS has subsequently been expanded beyond just the Antarctic Treaty and now includes three other legal instruments (Tin *et al.*, 2009). In the context of this research, the most important of those is the Agreed Measures for Conservation of Antarctic Fauna and Flora, which was added to the ATS in 1964 and came into effect in 1982 (Green and Paine, 1997; Tin *et al.*, 2009). The Protocol on Environmental Protection, also known as the Environmental Protocol or Madrid Protocol, came into effect in 1998. This protocol allows for areas to be deemed areas of special protection for their cultural, physical, or ecological values (Shaw *et al.*, 2014). These areas are protected as ASPAs, coupled with and Antarctic Specially Managed Areas (ASMAs); currently there are 73 ASPAs within the Antarctic (Shaw *et al.*, 2014). ASPAs and ASMAs may not, however, be sufficient to prevent invasion of non-native species and protect unique species assemblages; the consequences of this may be irreversible (Hughes and Convey, 2010). Of Antarctica’s 46,253 km^2 of ice-free area, only 688km^2, a mere 1.5%, is designated to protect terrestrial biodiversity. Hughes and Convey (2010) question whether ASPAs and ASMAs actually provide protection beyond that of the Antarctic Treaty which applies to the whole continent. This matter cannot be settled with current knowledge, which has many geographic areas without relevant survey data, thus, emphasising the need for continent wide studies (Hughes and Convey, 2010). Another shortfall of the Antarctic protected areas system is that management plans only apply to the areas specified in the management plan as opposed to the entire biogeographical region, therefore, the spread of non-native species by natural dispersal means will not be stopped (Hughes and Convey, 2010).

The number of people visiting Antarctica is constantly growing due to the increasing ease of travelling there; the effect of which, is one of concern (Terauds *et al.*, 2012). People visiting Antarctica do so in one of two capacities: as part of a national Antarctic programme in order to conduct or support science, or as a tourist (Shaw *et al.*, 2014). It is estimated that 4000 people involved in national Antarctic programmes and over 30 000 tourists visit Antarctica annually (COMNAP, 2009; IAATO, 2009; in Hughes & Convey, 2010). This allows for increasing opportunities for the transfer and dispersal of non-indigenous species (Hughes and Convey, 2010). Of the 4000 people who visit the 53 research stations within Antarctica, 1000 spend the winter on the continent (Shaw et al., 2014). It is this population which has the greatest impact on Antarctica as only 0.3% of Antarctica is ice-free and it is on these areas where research stations are mostly built (Tin *et al.*, 2009). Fuel combustion, oil spills, waste incineration and sewage are all results of human related processes which are increasing with higher visitation numbers and therefore could affect marine and terrestrial ecosystems to a greater extent than already perceived (Bargagli, 2008). Most human presence is on ice-free areas where the terrestrial ecosystems are found, and with increased travel both to and across the continent there is a major threat of homogenization (Hughes and Convey, 2010).

Although human activity is the prime cause of introduction events, combined with climate change, the barriers to establishment of alien species are lowered, and thus increasing the threat of alien encroachment (Convey *et al.*, 2009a). There is also the issue of population growth and industrial development in the Southern Hemisphere which is spreading contaminants to other continents, including Antarctica; unfortunately these global anthropogenic impacts cannot be prevented with the Protocol on Environmental Protection (Bargagli, 2008). Indicators of these impacts include the presence of metals, pesticides and other pollutants in the air, snow, mosses and lichens and marine organisms (Bargagli, 2008).

2.4 Similar studies

The following section discusses studies which are similar in some ways to the one undertaken for this project. This investigation encompasses elements from these selected literatures, but also expands on areas which were not directly addressed by them or were applied to a different question.

Two similar studies which have been conducted at the same study sites as this investigation are Ryan *et al.* (1989), and Steele *et al.* (1994). The Ryan *et al.* (1989) study was conducted at Robertskollen, whereas the Steele *et al.* (1994) study took place at Vesleskarvet. Both these studies comprised of preliminary biological surveys. The Ryan *et al.* (1989) paper is based on a survey done during the 1987/1988 Austral summer; they described the topography, flora, and fauna of all of the nunataks. They found that the roughly 600 breeding pairs of snow petrels on three of the five nunataks had a major influence on the distribution and abundance of other biota. Their preliminary findings included the identification of four species of mosses and 20 lichen taxa. This study was the first and only (based on literature searches) of its kind at Robertskollen, hence the gap to have a more intensive focus on specifically lichen distribution and abundance still exists. The Steele *et al.* (1994) conducted their surveys during the 1991/1992 and 1992/1993 Austral summers prior to the construction of the SANAE IV base on Vesleskarvet. These surveys found nine lichen species and one unidentified moss species amongst other biota. Steele *et al.* (1994) describe the site as an uncommon and little studied ecosystem, and suggested it be made a Specially Managed Area. SANAE IV was built on Vesleskarvet partly due to the sparse nature of biota (Steele *et al.*, 1994).

Johansson and Thor (2008) monitored terrestrial vegetation at 120 permanent plots along 11 transects at various distances within the vicinity of the Wasa and Svea stations in Dronning Maud Land. The aim of this study was to quantify the local impact on the environment by the nearby Swedish research stations (Johansson and Thor, 2008). The initial study was conducted during the 1991/1992 Austral summer, and the 120 sample plots were returned to ten years later during the 2001/2002 Austral summer (Johansson and Thor, 2008). It was found that there was a slight increase in lichen density and abundance, however there was an observed decline in lichen species, *Umbilicaria decussata*, which was attributed to maintenance activities at the Svea station (Johansson and Thor, 2008).

Cannone and Guglielmin (2010) were the first to investigate the relationship between vegetation patterns and periglacial landforms in continental Antarctica. Their study took place across four sites in northern Victoria Land, Antarctica. The features sampled included debris islands, gelifluction lobes, patterned ground, and terraces (Cannone and Guglielmin, 2010). It was found that the microtopography associated with these features provided unique conditions which constituted favourable habitats (Cannone and Guglielmin, 2010). The associated micro-edaphic and micro-environmental conditions such as wind-exposure, snow cover and resultant water supply are what were found to act as a control on vegetation patterns (Cannone and Guglielmin, 2010). The Cannone and Guglielmin (2010) study does not classify the type of microtopography in which the vegetation occurs, which leaves a gap for this investigation to fill.

Favero-Longo *et al*. (2012) studied the diversity and abundance of lichens and byrophytes across three different sites on Signy Island, which were deglaciated in very different times; one in the late 20th century, another following the little ice age and the final after the Last Glacial Maximum. Favero-Longo *et al*. (2012) found that early successional stages of colonisation happen soon (within a few decades) after deglaciation, however in order for the communities to become more established, favourable environmental factors such as snow cover duration, and surface stoniness and stability need to be met. These findings can be applied to the present study, but within one site (Vesleskarvet) as opposed to across sites as done in the Favero-Longo *et al*. (2012) study. The Favero-Longo *et al*. (2012) study was conducted in the maritime Antarctic, which provides an opportunity for the present study to conduct similar work, but in the continental Antarctic.

High resolution imagery suitable for investigations into local processes is not available for much of Antarctica (Lucieer *et al*., 2012). The use of Unmanned Aerial Vehicles (UAVs) for the acquisition of aerial imagery is still a relatively new technique; Lucieer *et al*. (2012) were the first to use this method in order to map moss beds and environmental characteristics at ultra-high resolution. The methodology included using overlapping UAV aerial photography in order to create a dense 3D point cloud using structure from motion (SfM), resulting in a two centimetre digital terrain model (DTM) which can be used along with other mapped characteristics to inform the state of moss bed health (Lucieer *et al.*, 2012). A similar method was used by this project; instead the mapping was done at a much coarser scale as the focus was more on the topography of the study areas as opposed to the vegetation cover which in this case would not even be visible from the air.

Results from long term monitoring on climate, permafrost, active layer and vegetation in Victoria Land, Antarctica are reported in Guglielmin *et al.* (2014). In 2002 a vegetation survey was carried out at 121 x 50 cm^2 plots, where total percentage of vegetation cover, species present and percentage cover of each species were noted (Guglielmin *et al.*, 2014). Twenty-five of these plots were revisited in 2012/2013 (Guglielmin *et al.*, 2014). A similar survey was conducted at numerous other sites with permanent plots which were established in 2001/2002 and revisited in 2011/2012/2013 to quantify any changes over time (Guglielmin *et al.*, 2014). Guglielmin *et al.* (2014) found a general decrease in vegetation cover, but the species composition within the plots remained largely the same.

3 Methods

This chapter outlines both the field methods, and computational methods used by this research in order to address the objectives and overall aim set out in chapter one. The field methods section comprises of the manner in which the surveys were conducted and the variables measured in them, as well as the method used for measuring temperature variability, and how aerial imagery was created for the study sites. Following this, is computational methods used to synthesise and analyse the data; the subsections are data preparation, statistical methods, and geostatistical methods.

3.1 Field methods

3.1.1 Surveys

Data from five surveys have been used for this project, the first one being in the Austral summer of 2009/2010. In 2009/10 Meiklejohn and Lee conducted the original lichen survey as part of a larger project titled “Geomorphology and Climate Change in Antarctica”. Hansen then conducted two surveys on the Northern Buttress during the 2010/2011 and 2011/2012 Austral summers as part of her Master’s dissertation, “The Characterisation of an Openwork Block Deposit, Northern Buttress, Vesleskarvet, Dronning Maud Land, Antarctica”, under the same overarching project (Hansen, 2013). I conducted two surveys during the 2012/2013 and 2013/2014 Austral summers to conclude the field work for this investigation, under the broader project “Landscape Processes in Antarctic Ecosystems”. Data from all five surveys have been used for the purposes of analysis in this project; the type of data used from each survey is outlined Table 1 below.

Table 1: Data collected during the five surveys, indicated by the shaded blocks.

Surveys	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014
Lichen identification	■				
Lichen occurance	■				■
Rock hardness	■	■	■		■
Dip	■				■
Aspect	■	■	■		■
Clast support		■	■		
Lichen habitat				■	

The survey conducted by Meiklejohn and Lee in the 2009/2010 formed the basis for this study. They sampled 166 x 1m^2 quadrats in transects roughly 50 meters apart; each sample point along the transects was 20 paces a part (Figure 7). Opportunistic sampling was done where possible in order to fill in some of the areas which were insufficiently sampled. Sample points were marked using a handheld global positioning system (GPS); the waypoints were noted alongside the attribute information for each sample plot. At each point a rock meeting the suitable criteria (criteria mentioned under the rock hardness section) for testing rock hardness was chosen to be sampled. Sampling included measuring rock hardness, aspect, dip and the presence or absence of lichen on each face of the rock. Photos were taken of the lichen to allow for identification and a count of each species per face was also noted. During the 2012/2013 Austral summer, as many of those rocks were re-visited as possible using a combination of GPS coordinates and photographs. The location of lichen (i.e. in weathering related landforms) occurrence was noted and added to the existing dataset.

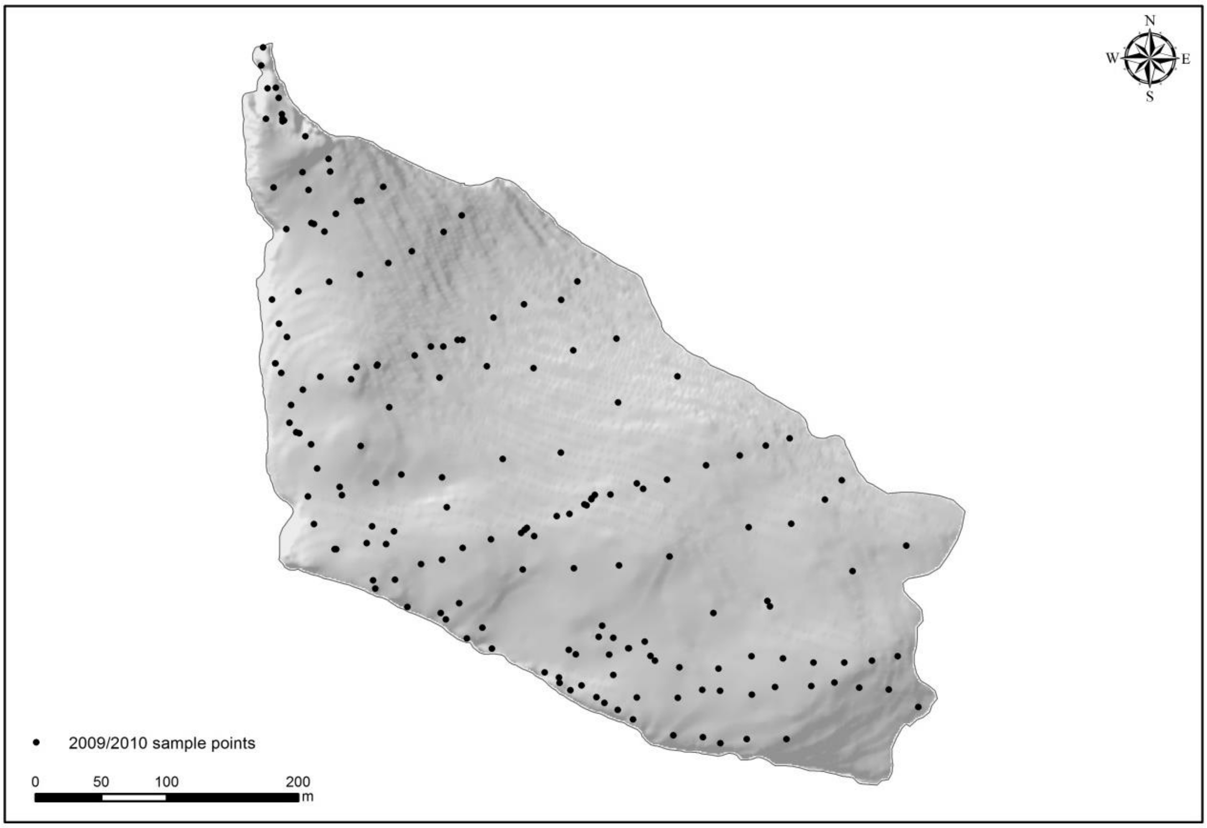

Figure 7: 2009/2010 survey sample points

The 2012/2013 survey was a pilot survey in order to test some of the field methodologies to be employed by this research. The sample points from the 2009/2010 survey were re-visited and sampled. In the 2013/2014 a new survey was undertaken using a systematic sampling method in order to get an even spread over the surface of the study area. The points were generated in ArcMap®; the points were set to a distance of 40 meters apart, which equated to 100 sample points (Figure 8). The coordinates were loaded on to a GPS and then navigated to at the study site (waypoint accuracy of ±3m). The same methodology with regards to what is sampled at each 1m^2 quadrat was employed as the 2009/2010 survey.

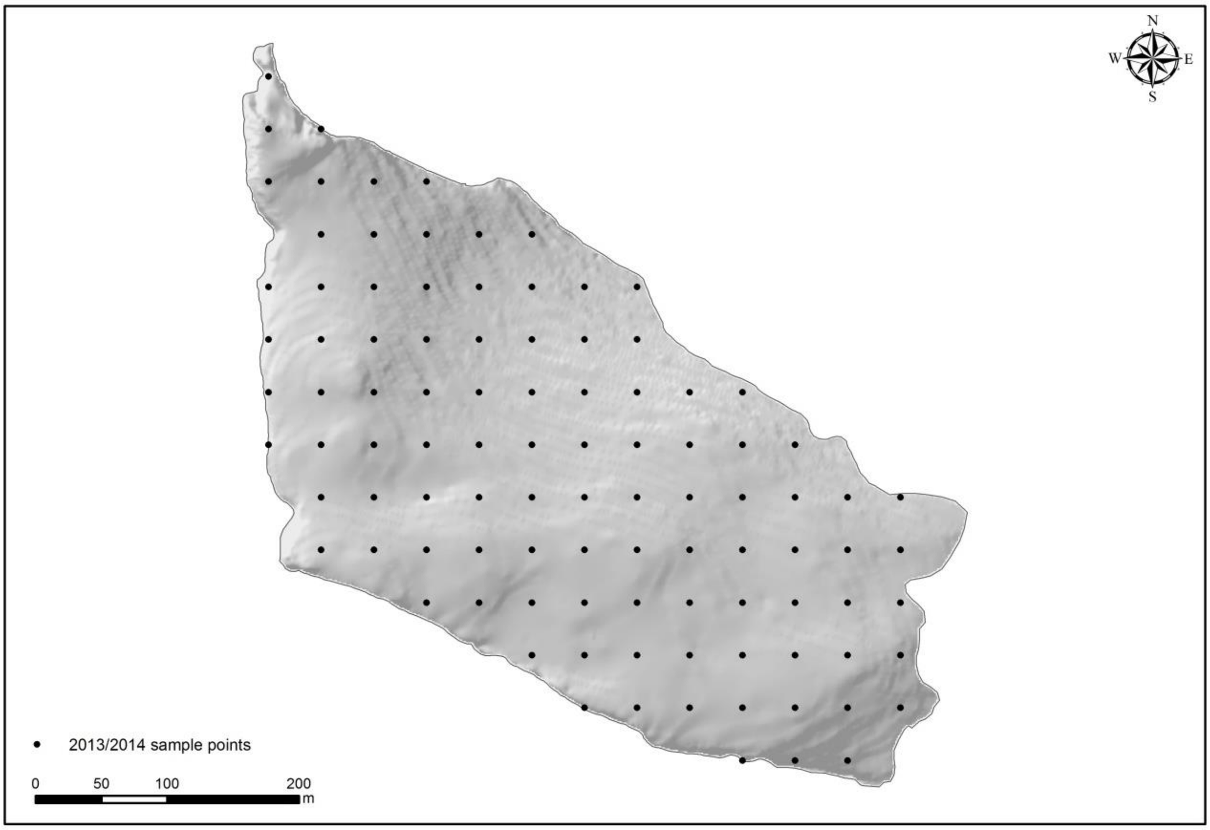

Figure 8: 2013/2014 survey sample points

The Robertskollen survey was also undertaken during the 2013/2014 Austral summer on Ice Axe Peak (Figure 6). The Ice Axe Peak group consists of four individual peaks and together the nunatak is the largest in the Robertskollen group (Ryan *et al.*, 1989). The northernmost peak is Cairn Peak where ten sample sites were located. The southernmost peak is Ice Axe Peak where the remaining five sample sites were located; Kleinfjell and Middlefjell are situated in between these two peaks. Unfortunately site access was only permitted for researchers once, so time was the biggest factor in limiting the survey to just 15 points. The two slopes which were sampled, were selected as they have high lichen abundances (Ryan *et al.*, 1989). The sampling at each sample point was conducted in the same manner as the other surveys, and a GPS was used to mark the points where sampling took place.

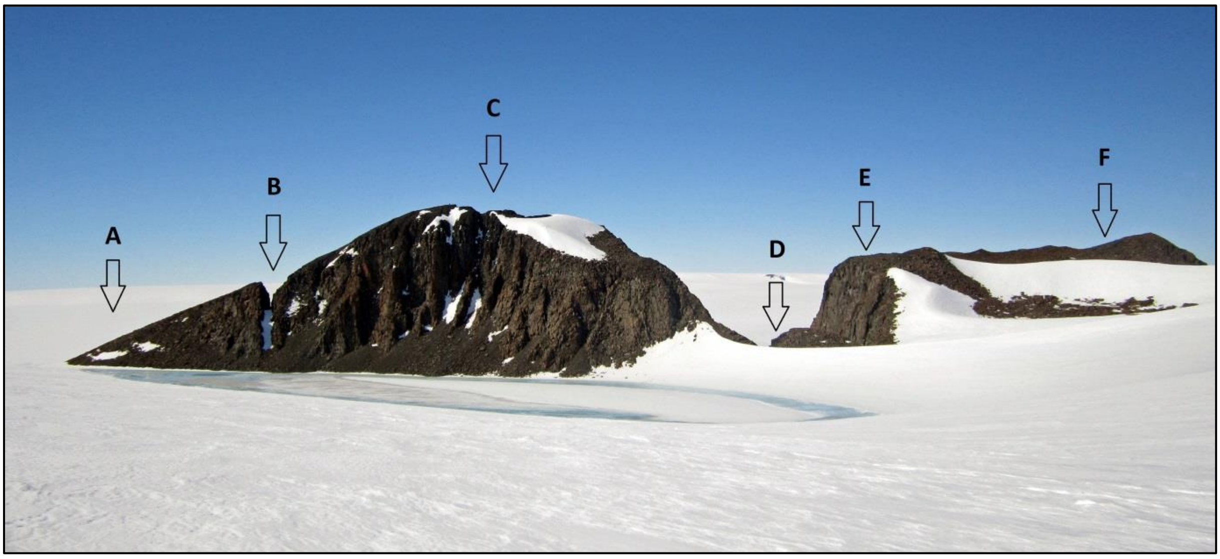

Figure 6: The Ice Axe Peak group; from left to right: a) Cairn Peak north, b) The Gap c) Cairn Peak south, d) Kleinfjell, e) Middlefjell, f) Ice Axe Peak

3.1.1.1 Lichen count and identification

During the 2009/2010 survey, lichen instances for each species were counted for each face of the sampled rock. However, during the 2013/2014 survey lichen were counted in "clusters", as it is a more repeatable method than counting individuals, which was not within the expertise of those undertaking the fieldwork. This method may have a certain amount of inaccuracy in it, but it was consistently applied throughout the survey and the number was expressed in a size class, which results in a true relative distribution.

Photographs were taken of all lichen on the sampled rocks. Identification was done after the 2009/2010 survey by Lee and Meiklejohn. Lichen species identification was not possible during the 2013/2014 survey, so all data was captured at the community level. All mapping and analysis of species distribution was conducted based on the 2009/2010 data.

3.1.1.2 Rock Hardness

Lichen are assumed to colonise on more weathered rock, with weathering related landforms; yet they can also contribute to further weathering through both chemical and mechanical means (Matthews and Owen, 2008; Zambell *et al.*, 2012). A measure used to quantify weathering is rock hardness. Rock hardness can be measured by numerous instruments, two common ones being the Schmidt Hammer and the Equotip (Viles *et al.*, 2011). In order to measure rock hardness, this study made use of an Equotip with a D-type impact device and an N-type Schmidt Hammer. Both these instruments use a rebound value as an indicator of the extent of weathering on a surface (Sumner and Nel, 2002). Weathering is thought to decrease rock strength, thus the more weathered the rock, the lower the rebound values are expected to be (Sumner and Nel, 2002).

The Schmidt Hammer, originally designed for testing the hardness of concrete, has been adopted by geomorphologists due to its widely applicable capabilities (Goudie, 2006). It works by being pressed against the surface which releases its piston into the plunger, which reflects the hardness as a measure of the amount of impact penetration resistance of the surface (Viles *et al.*, 2011). The measure of the hardness is the distance that the piston travels after it rebounds; this is called the rebound (R) value (Viles *et al.*, 2011). The Schmidt Hammer can be calibrated, however, this study made use of the default which is on a scale of 10-100, with the harder rocks having higher R values (Aydin and Basu, 2005).

The Schmidt Hammer has received a fair amount of criticism (e.g. Aoki and Matsukura, 2007) due to a number of shortfalls; therefore, the Equotip has also been used for the purposes of this study. A study conducted by Viles *et al*. (2011) found that using the Schmidt Hammer and Equotip in conjunction provided the best insight into weathering and surface crusting. The Equotip was designed for testing the strength of metals, but it has joined the Schmidt Hammer in use by geomorphological studies (Viles *et al.*, 2011). The device makes use of a tungsten carbide ball which is fired at the surface of the material being tested (Viles *et al.*, 2011). The ratio of the recorded rebound velocity to the impact velocity, multiplied by 1000, is known as the Leeb Number (*L* value) or Leeb Hardness (HL) (*Viles et al.*, 2011).

The *L* value is the Equotip's measure of hardness, with low hardness values having a low *L* values (*Viles et al*., 2011).

With regards to a representative sample of rock hardness, there is no conclusive recommended sample size published in the literature (Aydin and Basu, 2005). There have been numerous suggestions about the best method of gaining representation; rock hardness data used in this study were collected using a method similar to that of Mol and Viles (2012). The surveys for this study used the "single impact" method (Aoki and Matsukura, 2007), which involves taking different points at least one plunger width a part and using the mean of those points as the hardness value. The sample number varied by survey according to what the operators saw fit as a representative sample and accounting for time constraints in some cases. In order to avoid operator variance as described by Viles *et al*. (2011), one person was tasked with taking the measurements for the duration of the survey.

Figure 7 shows the sample points of the complete rock hardness dataset from surveys over the span of five years. All of the surveys stayed within the correct selection criterion for rocks, but each had a slightly different methodology. The 2009/2010 survey made use of only the Equotip 2, and measured rock hardness on all suitable rock faces. The 2010/2011 and 2011/2012 surveys made use of an Equotip 3 and the Schmidt Hammer, and once again measured all aspects (Hansen *et al*., 2013). Due to time constraints, the 2013/2014 survey was limited to only one sample set per sample site; the readings were however taken from more than one face. All clasts (of all surveys) were selected ensuring that they met the following criteria for measuring rock hardness: over 25kg in weight, and should be a minimum size of 54.7mm in diameter (Sumner and Nel, 2002; Aydin and Basu, 2005).

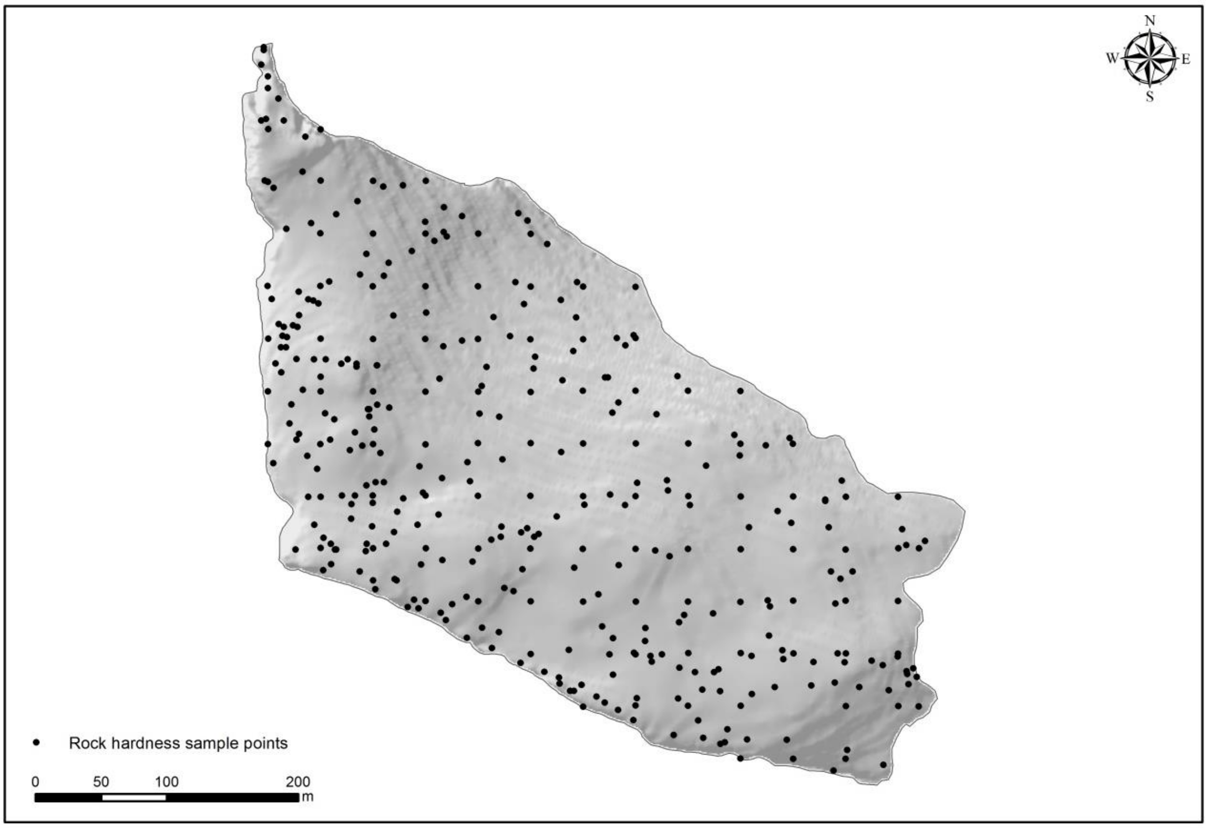

Figure 7: Sample points of the complete rock hardness dataset

3.1.1.3 Clast characteristics

In order to gain a better understanding of whether or not lichen colonise on rocks with preferential characteristics, dip, aspect and clast support were measured. During the 2009/2010 survey, dip and aspect were measured for each sampled rock face and just each rock face containing lichen in the 2013/2014 survey. Dip was measured using a SILVA Clino Master clinometer, whereas aspect was measured using a Brunton compass. Dip is represented as the slope of the rock in degrees. In order to gain a more representative measurement of dip, the clinometer was placed on a wooden stick, as done by Hansen (2013).

Clast support data were obtained by Hansen (2013) in the 2010/2011 and 2011/2012 surveys at each of the sample points in Figure 8. The clasts were classified as supported by ice, block or block and ice support (Hansen, 2013).

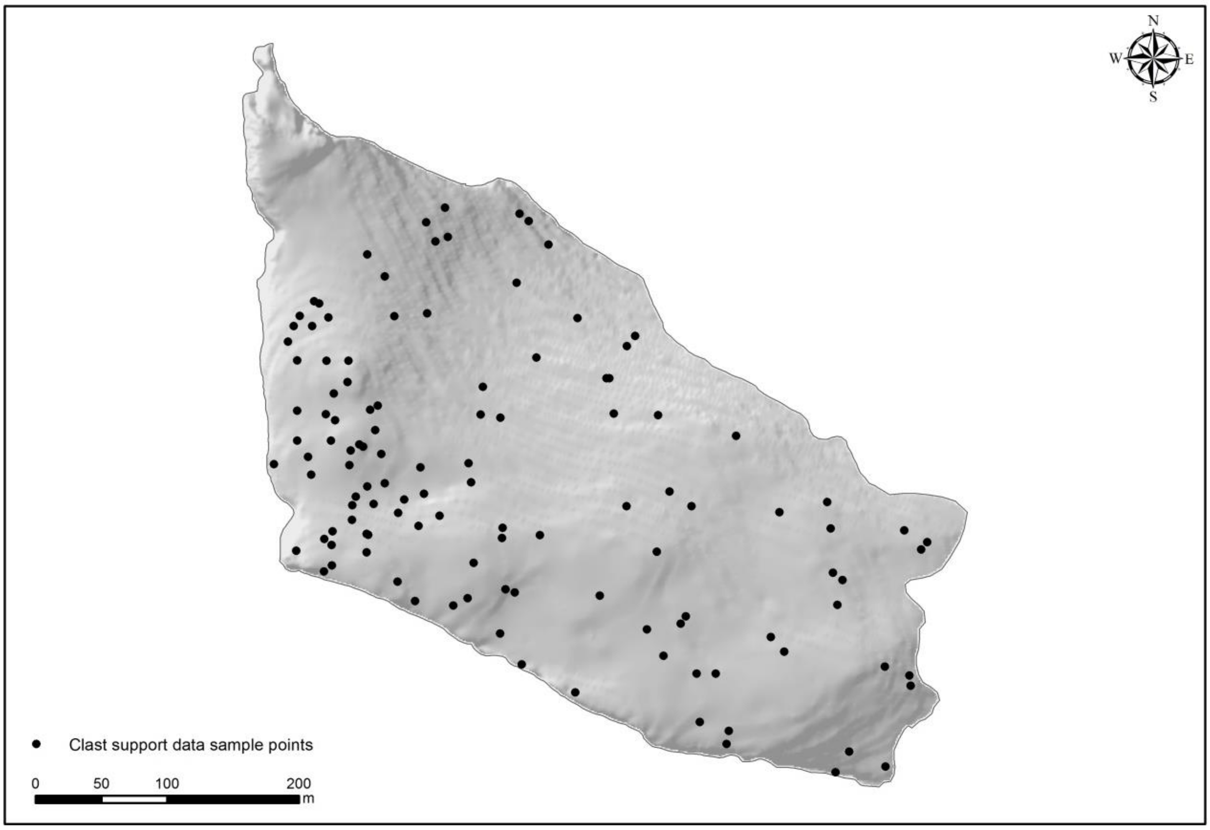

Figure 8: 2010/2011 and 2011/2012 clast support sample points

3.1.1.4 Microtopography

During the 2012/2013 survey, the observed lichen were classified to be occurring in/on one of the following microtopographical landforms: in cracks or small fissures, on rough/weathered surfaces, under the shelter of other rock, in pitting, on smaller rocks/substrate, or on the edge of rock (for examples, see Figure 9). The rough definition of microtopography, which is adopted for this study, is "topographic heterogeneity on the scale of individual plants" (Bledsoe and Shear, 2000:126).

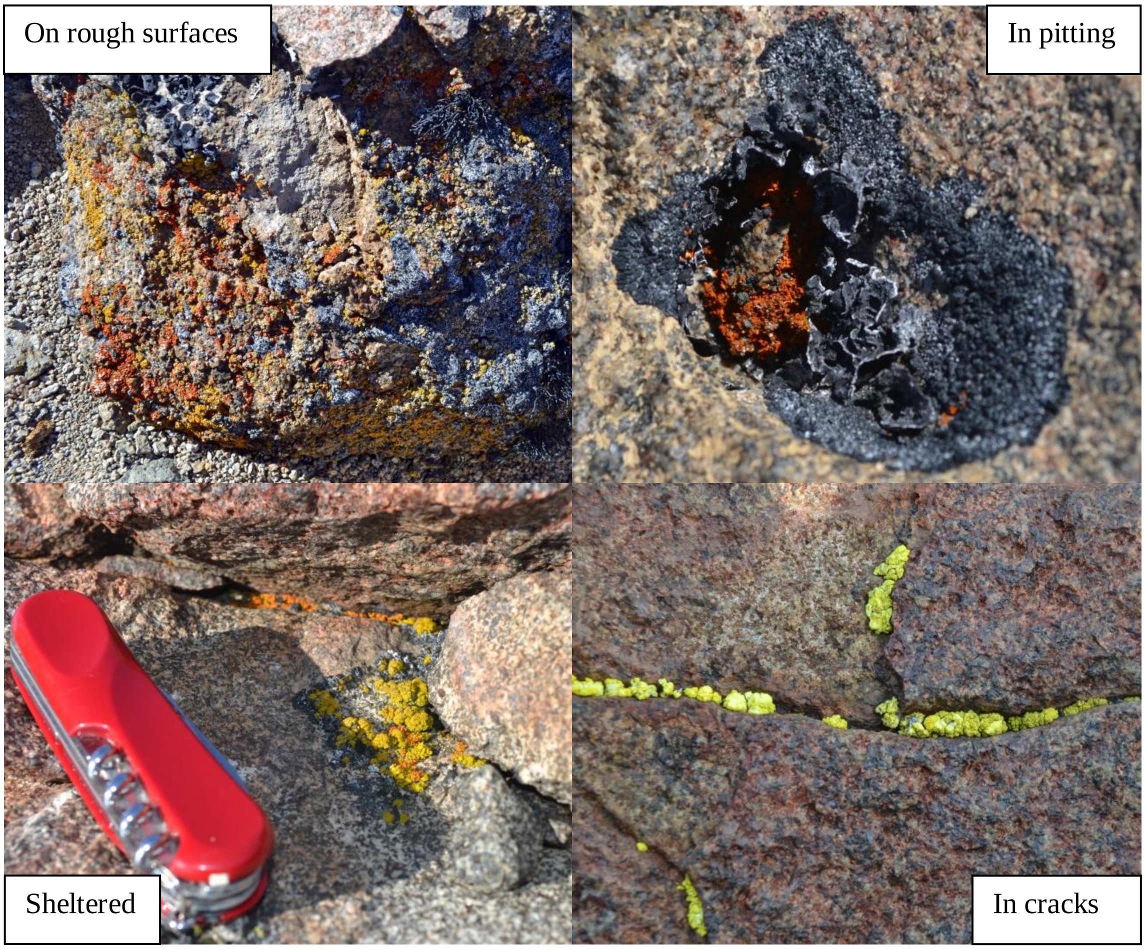

Figure 9: Types of weathering related microtopography with lichen occurrence

3.1.2 Temperature variability

Temperature is an important factor which influences lichen growth (e.g. Kappen *et al.*, 1998); a relatively inexpensive method for measuring temperature at numerous sites is by use of iButtons (Lewkowicz, 2008). In order to get short term insight into temperature variation within the nunataks and between the nunataks, 15 iButtons were placed on Vesleskarvet and 15 on Robertskollen. The distribution of the iButtons on the Northern Buttress of Vesleskarvet can be seen in Figure 10 below. On the Northern Buttress, the locations were chosen in order to get a spread across the study area. They were "paired" close to each other, one in a sheltered spot and the other in an unsheltered spot; this allowed for the quantification of how much shelter plays in governing air temperature. At Robertskollen, the iButtons were placed at the same location as the sample sites of the 2013/2014 survey.

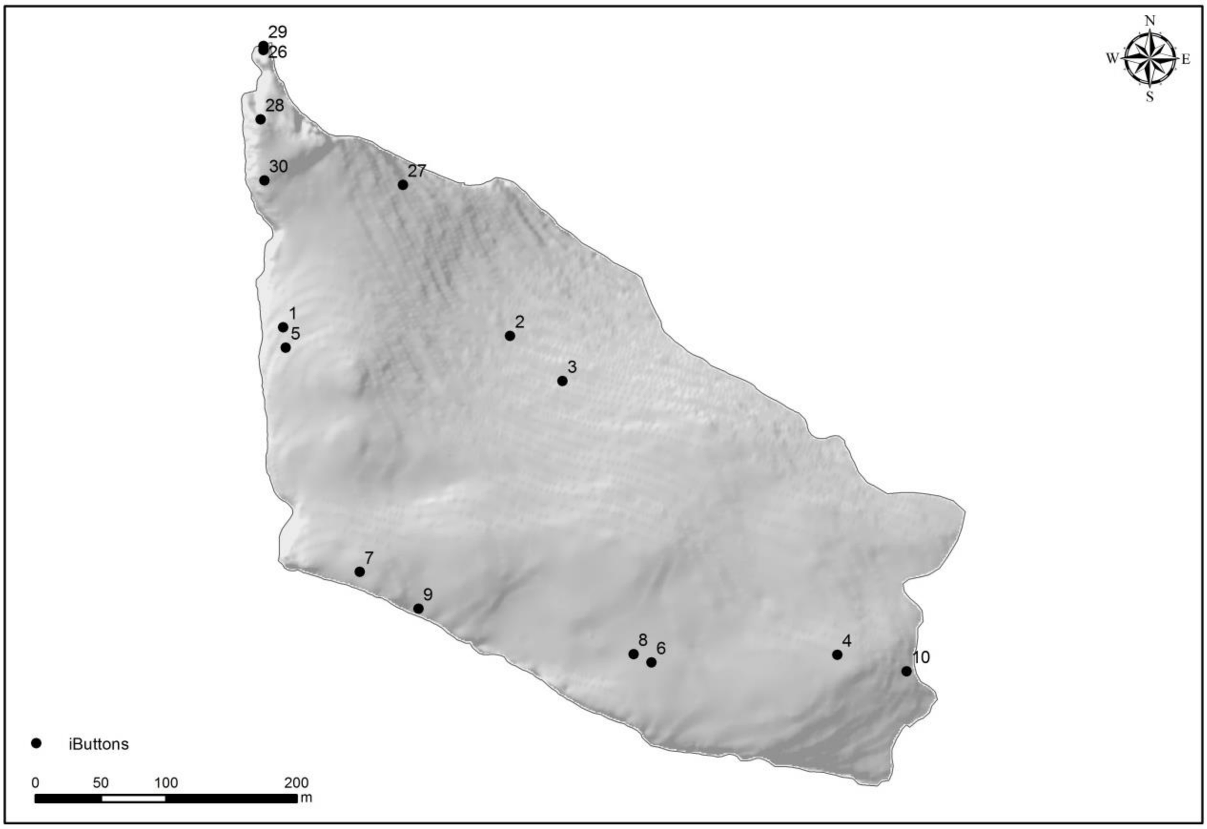

Figure 10: Locations of the 15 iButtons on the Northern Buttress

The thermochron iButtons were set to log air temperature every ten minutes for a period of 15 days on the Northern Buttress and a shorter 10 days at Robertskollen due to the logistics of retrieving them. The iButtons were set to log at a precision of 0.0625°C. They were all placed roughly 20 cm above the surface in temporary radiation shields (Figure 11) which shielded them from the sun and yielded a more accurate air temperature. These shields were coated with heat resistant spray paint and had air holes in order to prevent them from heating up and creating their own “microclimate”.

Figure 11: Radiation shield set up for the iButtons

3.1.3 Aerial imagery

To get a better understanding of local topography and surface characteristics, researchers often use aerial imagery. However, there is limited fine scale aerial imagery for Antarctica and that which does exist is not always up to date. Recent developments with Unmanned Aerial Vehicles (UAVs) has allowed this spatial and temporal gap to be filled; imagery captured from UAVs is at a very fine scale (up to cm) and can be done as often as needed (Lucieer *et al*., 2012). Aerial imagery was captured for the two study sites, the Northern Buttress of Vesleskarvet and Robertskollen in order to create a three-dimensional model of these areas.

Two different methods were used in order to obtain the imagery for mapping. At Robertskollen an UAV (Figure 12) was flown over the study area, and a GoPro camera attached to a manually operated hexacopter took photos at one second time intervals. Ground control points were placed on the surface in order to give the resultant image a spatial reference (Figure 13).

Figure 12: The hexacopter used for capturing aerial imagery

Figure 13: Crosses used as ground control points

Due to the size of the Northern Buttress, using this method would have been very timely, so a helicopter was used instead. The Bell 212 helicopter (operated by Starlite Aviation) was flown at a height of roughly 30 metres (100 foot) and at a ground speed of 111 kilometres per hour (60 knots). In order for the model to be successful, at least 60 percent and preferably 80 percent overlap in the photographs is required. To ensure complete coverage of the nunatak, transects every 50 metres were flown first in a north-south direction, and then in a west-east direction. Multiple cameras were used to guarantee that all areas were photographed; two GoPros were attached to the helicopter's underside, while two more Canon 600D digital single-lens reflex cameras (DSLR) were operated by people out of each side door. The cameras were all set to face downwards at different angles and captured a photograph every second. The Canon cameras were set to a high shutter speed of 1/1600 to reduce blur, and the focal length was fixed to 18mm. The images from only one of the Canon DSLRs were used as they had a higher resolution than the GoPros. One camera proved to be sufficient in capturing the entire area. The images were then sorted and prepared for input into the imaging software, AgiSoft®. The post-processing and final product was done by Scott (2013) as part of his research.

3.2 Computational methods

3.2.1 Data preparation

All raw data were captured and initially prepared in Microsoft ® Excel. Graphs and charts were then also created using Microsoft ® Excel. Any data inputted into ArcMap® for mapping purposes was saved as a .dbf file and read into the program in that format. Data used in the R v3.0.1 statistical environment were saved in the .csv file format. The following section outlines how the lichen and environmental data were prepared for analysis.

Rock hardness was measured during four field seasons by a number of people and by three different instruments. On rocks where more than one set of measurements were taken (i.e. one set per aspect), the mean of the measurements was used as the rock hardness for that point. In order to standardise the data to allow for comparisons between the data and to combine it into one dataset for mapping purposes, the data were converted into Z scores. Converting to Z scores is a way of standardising a normal random variable by representing the quantity of Z representing according to how far X is from the mean in terms of standard deviation (Wilcox, 2009). The data were converted using the following formula: $Z = \frac{x-\mu}{\sigma}$, with x being the raw score, μ representing the mean of the population, and σ being the standard deviation of the population. The scores were calculated independently for each population first and then combined into one data set of 502 observations. By using Z scores the data is standardised, and thus minimises variation from different instruments, present environmental conditions when measurements were taken, and inter-annual operator variance.

Lichen count from the 2013/2014 survey was put into categorised according to the estimation of the number of thalli per sample plot, as seen in Table 2. The classes used in the field were given a rank from zero to six, which was used for the lichen abundance map, whereas the midpoint of each class was used for abundance analysis purposes.

Table 2: Lichen class classification

Lichen abundance class	Midpoint	Rank
0	0	0
1-5	3	1
6-10	8	2
11-20	15.5	3
21-50	35.5	4
51-100	75.5	5
101-200	105.5	6

Aspect data were adjusted for magnetic declination in order to get true orientation. The 2009/2010 survey data were adjusted by 18.18°W based on the magnetic declination for 71°S 2°W. The 2013/2014 survey data were adjusted by a further 0.30°, making it 18.48°W, as the declination for that area is changing by 0.06°W annually (National Oceanic and Atmospheric Administration, 2014). The rose diagrams for the aspect and dip data were created using a freeware package called WRPLOT View™ (Version 7.0.0), created by Lakes Environmental™. The package was originally created to display meteorological data, however for the purpose of this study wind direction was replaced by the aspect of the rock face being measured, and wind speed was replaced by the dip in degrees of the rock face being measured.

In order to be able to include aspect as a variable in the models, it was converted into "northness" and "eastness" according to the metric of Zar (1999). Northness converts the aspect value into a number between -1 and 1, with more northerly values being closer to 1 and more southerly values being closer to -1; whereas eastness converts the aspect value into a number between -1 and 1, with more easterly values being closer to 1 and more westerly values being closer to -1 (Wallace and Gass 2008). The formula for northness is: $Northness = \cos\left(\frac{aspect \times \pi}{180}\right)$, and eastness is: $Eastness = \sin\left(\frac{aspect \times \pi}{180}\right)$ (Zar, 1999 *in* Wallace and Gass 2008).

Temperature data from all of the iButtons were combined into one dataset for each study site. The data from each iButton were then condensed to just the mean temperature for each hour of the day. The overall graphs then made use of the mean of all of the iButton's means at a particular time.

3.2.2 Statistical methods

Hypothesis testing is undertaken in order to establish whether or not there is a statistically significant difference between measured variables. One such method that can be used to test for this is the student's t-test (referred to from here forth as a t-test) (Tello and Crewson 2003). This study made use of independent t-tests which tests whether or not the means from two samples are different from each other (Tello and Crewson 2003). The independent t-test assumes normality, and does not require the sample number (n) to be the same for both populations. The t-tests were conducted at the 95% level of confidence as it imitates a realistic certainty in physical geography (Briggs, 1977). T-tests were conducted using STATISTICA 12 software; the hypotheses were structured according to the criteria below.

H_o = *The independent samples are comparable to each other*
H_a = *The independent samples are not comparable to each other*

Spatial and temporal patterns of biodiversity in Antarctica have not been adequately addressed to date (Lee *et al*., 2013). Species distribution modelling aims to detect environmental factors which are important in influencing ecological patterns, and thus provide explanations for observed patterns and allow for predictions (Miller, 2012). A series of generalised linear models (GLM) and simultaneous autoregressive models (SAR) were run to determine which factors are important in shaping lichen distribution and abundance. GLMs have been used broadly across the fields of geomorphology, and are particularly useful for geomorphic data which is often in the binary form (presence/absence) (Hjort and Luoto, 2013). Such models can cope with nonlinear relationships and different types of statistical distributions, which makes them valuable in testing the patterns of response variables and testing the significance of the predictors (Hjort and Luoto, 2013). These models are ideal for this study as the number of observations required is relatively low, they do not require expert knowledge in order to be conducted, and they have a high level of interpretability which facilitates the use of them in explanations (Hjort and Luoto, 2013).

GLMs were run in order to investigate the relationships between the measured environmental variables and lichen species presence or absence, based on the 2009/2010 survey data. The lichen abundance models were based on a combination of the data from 2009/2010 and 2013/2014 surveys. This was done in R v3.0.1, by using the “glm” function, and set to use a Binomial distribution for the lichen distribution models (presence/absence), and a Gaussian distribution for the lichen abundance models. The results were then ranked according to their Akaike information criterion (AIC) using the dredge function from the *MuMIn* library. The model with the lowest AIC was chosen as the model with the best fit, as advised by Johnson and Omland (2004). The selected model was then rerun using only the parameters which were found to be significant. The fit of the resultant model was then assessed using R^2 as a measure, which was calculated based on the following equation: $R^2 = 1 - \frac{Residual\ Deviance}{Null\ Deviance}$.

The use of standard statistical methods often fail to account for the spatial nature of ecological data, and thus can end up with poor models and unfitting predictions (Miller, 2012). Tobler’s First Law of Geography states that “everything is related to everything else, but near things are more related than distant things” (Tobler, 1970:236). Species abundances are often positively autocorrelated, resulting in points in close proximity having more similar values than can be attributed to random chance (Legendre, 1993; Lichstein *et al*., 2002). Spatial autocorrelation has recently been acknowledged in ecology, which leads to new insights into ecological relationships (or the lack-thereof) when space is taken into account (Lichstein *et al*., 2002). By not accounting for spatial autocorrelation, the likelihood of a type I error increases (Diniz-Filho *et al*., 2003). A type I error occurs when the null hypothesis is rejected, but it is in fact true (Wilcox, 2009); this could result in finding a relationship which is not actually present (Lichstein *et al*., 2002; Dormann *et al*., 2007).

Spatially structured environmental variables, such as air temperature and rock hardness in the case of this study, can influence the spatial structure of species distributions (Legendre, 1993). If this is the case, spatial autocorrelation is a problem for spatially inexplicit models as they assume independently distributed variables (Legendre, 1993). To account for the problem of spatial autocorrelation, a spatially explicit SAR model was implemented on the lichen abundance data for the Northern Buttress and Robertskollen. The SAR model script used by this study was adapted from Appendix S1 in “How to construct SAR models in R” from Kissling and Carl (2008). A SAR spatial error model was run in R v3.0.1, as suggested by Kissling and Carl (2008) for when dealing with species distribution data. The “errorsarlm” function in the *spdep* library was used, was well as the *ncf* library. The best model was selected and then rerun based on the same method used for the GLMs, as described above.

3.2.3 Geostatistical methods

GIS techniques are useful in giving a visual representation of spatial data, which aids researchers interpreting their findings. Advances in geographical information systems (GIS) have boosted geostatistics, allowing for consistent interpolation methods and effective data visualisation tools (Burrough, 2001). ESRI's ArcGIS suite of products were used for the creation, analysis, and display of selected spatial data. WGS84 was used as the geographical coordinate system, and then projected to Transverse Mercator -3, as it preserves shape without compromising on distance and area accuracy too much.

A single aerial image for the Northern Buttress and Robertskollen was created using Structure from Motion techniques. AgiSoft® was used in order to create and georeference the images; these images were created for use by another project, thus the ready-made product was simply inputted in to ArcMap®. In order to improve the appearance of the image, boundaries of the study sites were created and then used as the mask to clip the image using the "Extract by Mask" tool available in the spatial analyst tool box in ArcMap®. The aspect maps for the Northern Buttress and Vesleskarvet were created using the "Aspect" tool, also available in the spatial analyst toolbox.

To display the lichen distribution and abundance data, as well as some of the measured environmental parameters, a continuous surface representation was computed using methods of interpolation. This study made use of the Inverse Distance Weighting (IDW) tool (in the spatial analyst toolbox) to interpolate data. This technique estimates values at unsampled locations based on surrounding weighted measurements (Kravchenko and Bullock, 1999). Although it is less accurate than kriging (a different interpolation tool) as it does not account for spatial autocorrelation, IDW was chosen as it produces a much "smoother" surface (Kravchenko and Bullock, 1999). Even though accuracy may be slightly compromised, it does not pose a problem for this study as the created surfaces were used purely for visualisation purposes and not for spatial statistical analysis.

4 Results and discussion of findings

The following chapter presents a summary of the results obtained from this study, and provides a discussion based on these results. It comprises of four sections, each addressing one of the objectives set in chapter one. Objectives one to three build up to objective four. The final section of this chapter synthesises the results into one final discussion with regards to the overall aim of this study.

4.1 Objective 1

Provide a detailed site analysis of each lichen species occurring on the Northern Buttress.

During the 1991/1992 and 1992/1993 Austral summers, Steele *et al*. (1994) undertook an environmental impact assessment (EIA) at Vesleskarvet before the SANAE IV base was constructed. One component of the EIA was a biological survey which included lichen observations. They found lichen in only nine out of their 30 x 2m^2 plots (Steele *et al*., 1994). Further inspection of the nunatak was then conducted to search for any species that may have been missed in the plots (Steele *et al*., 1994). A total of nine lichen species were identified by using reference samples from the Ryan *et al*. (1989) survey at Robertskollen. The lichens which were accounted for on Vesleskarvet were: *Acarospora gwynii, Buellia spp. A*, *Buellia spp. B, Lecanora expectans, Pseudephebe minuscula, Rhizocarpon acographicum, Umbilicaria decussata, Usnia sphacelata,* and *Xanthoria elegans* (Steele *et al*., 1994).

The initial survey by Steele *et al*., (1994) does not give a description of how the lichen species are distributed across Vesleskarvet. A paper by Melick *et al.* (1994) highlights that when vegetation distribution is sparse, often no attempts of detailed site analyses are made. Vegetation on Vesleskarvet (both the Northern and Southern Buttresses) is very sparse, the majority of the vegetation occurs on the most northern part of the Northern Buttress which comprises of less than 0.5% of the nunatak (Steele *et al*., 1994). This study will show from this objective (objective one) that it is possible to create an approximated distribution of sparse vegetation, and thus give a detailed site analysis. Data to support this analysis was collected by Meiklejohn and Lee during the 2009/2010 Austral summer. The nomenclature for the following lichen descriptions is taken from Øvstedal and Lewis Smith (2001); the names used are the same as given by Steele *et al*. (1994) with the exception of *Rhizocarpon acographicum* and *Usnia sphacelata,* which will be written as *Rhizocarpon geographicum* and *Usnea sphacelata* respectively as in Øvstedal and Lewis Smith (2001).

Based on the 2009/2010 survey, of the 166 plots sampled, 119 had lichen present. The lichen species are not evenly distributed in terms of species occurrence; certain species are far more abundant than others as shown in Figure 14. *Acarospora gwynii* was found to be the most abundant, occurring at 50.6% of the all of the plots (n=166), and 70.6% of the plots containing lichen (n=119). *Lecanora expectans* is almost as abundant as *Acarospora gwynii,* with it occurring at 41% of the total plots, and 57% of the plots with lichen (n=119). On the other end of the spectrum, *Xanthoria elegans* was only found at one of the sample plots.

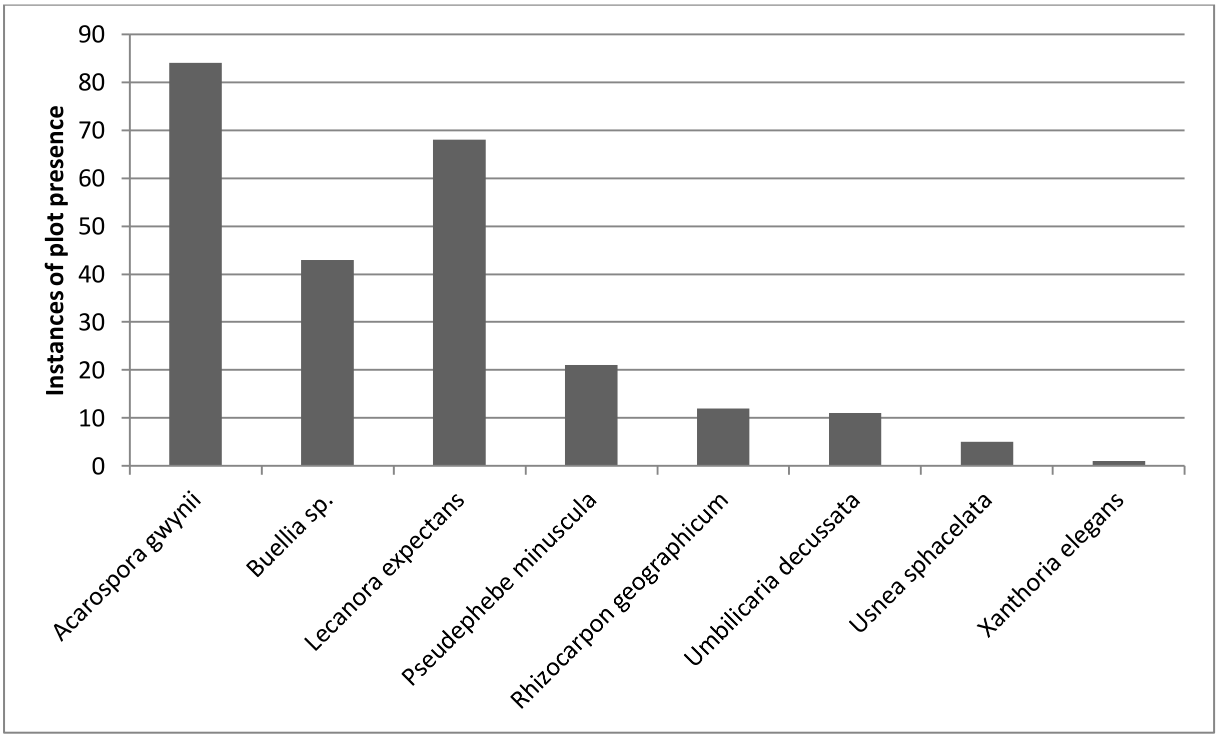

Figure 14: Number of plots including specific species

Species richness (Figure 15) is not evenly spread across the Northern Buttress. The richness is highest on the northern part of the Northern Buttress, which coincides with where Steele *et al*. (1994) found the lichen to be most abundant. The highest richness recorded was six at just one plot, whereas there were 47 plots completely devoid of lichen and thus have a richness of zero.

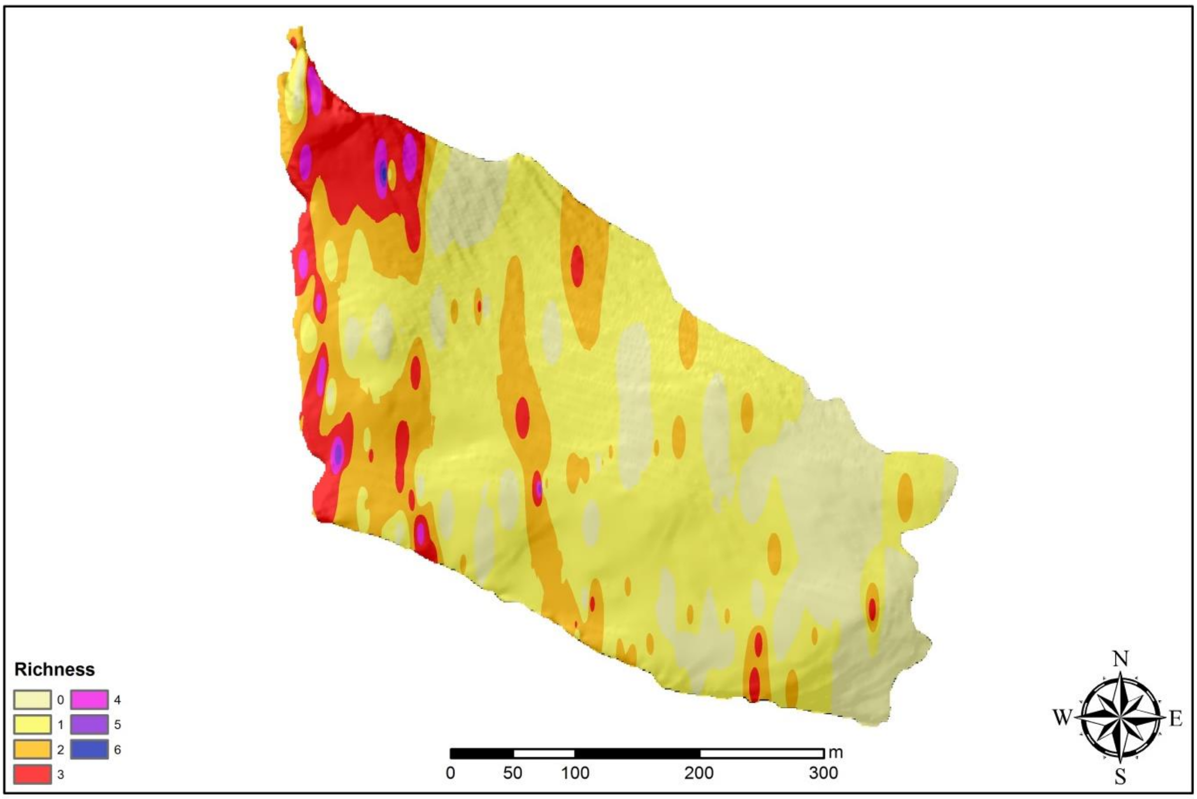

Figure 15: Interpolated species richness across the Northern Buttress

4.1.1 *Acarospora gwynii*

Acarospora gwynii (e.g. Figure 16) is a pale yellow to yellow-green Antarctic endemic lichen which is particularly widespread in continental Antarctica (Øvstedal and Lewis Smith, 2001). The thallus clumps to roughly one centimetre in diameter, and it forms in very small colonies in rock fissures in very exposed conditions (Øvstedal and Lewis Smith, 2001). As mentioned above, *A. gwynii* is the most abundant lichen on the Northern Buttress, with it being present at 84 of the 166 sampled plots. *Acarospora gwynii* also appears to be the most uniformly distributed lichen on the Northern Buttress (Figure 17).

Figure 16: ***Acarospora gwynii***

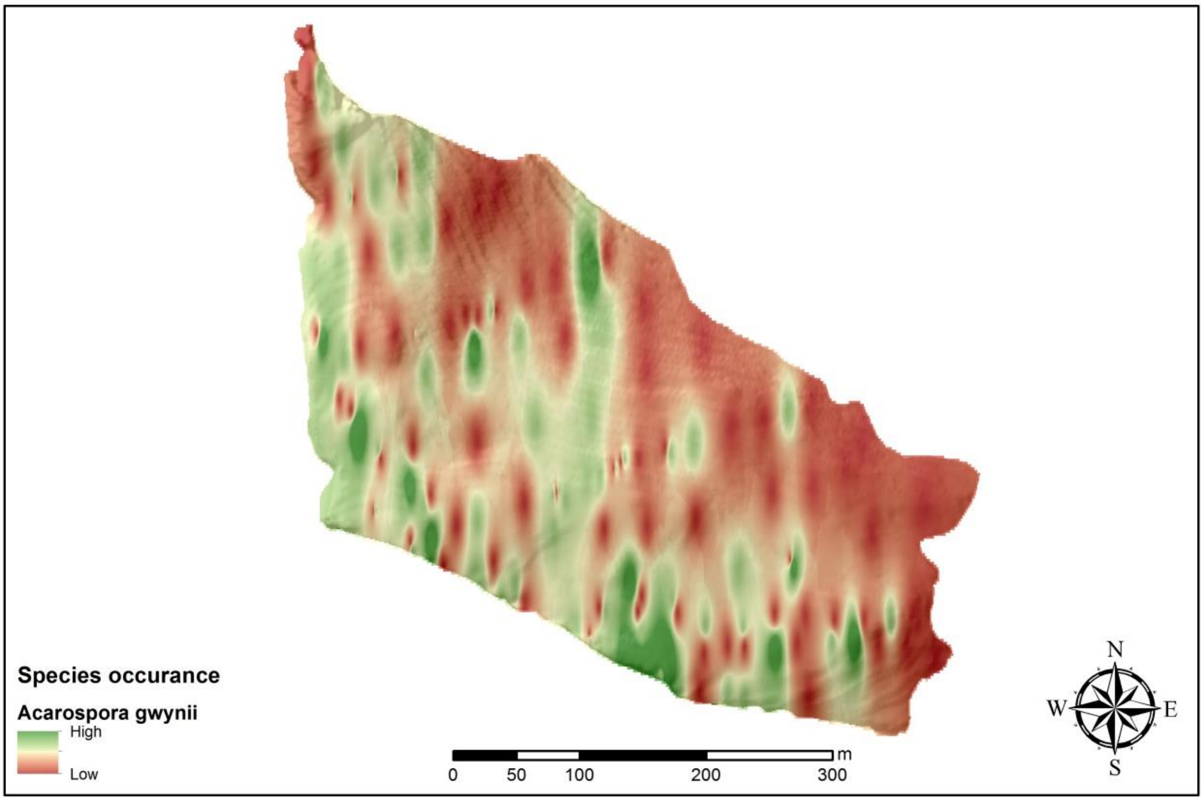

Figure 17: Interpolated distribution of *Acarospora gwynii* on the Northern Buttress

4.1.2 *Buellia* species

Buellia frigida is a grey to blackish crustose lichen which grows to approximately 15cm in diameter (Øvstedal and Lewis Smith, 2001). It is one of the most collective lichens in continental Antarctica, found on rock in particularly very exposed locations, even on some of the furthermost inland nunataks (Øvstedal and Lewis Smith, 2001; Meeßen *et al*., 2013). Inexpressible Island, Victoria Land, which is known for its high incidence of very strong winds and low temperatures has remarkably large *B. frigida* thalli on large granitic boulders (Øvstedal and Lewis Smith, 2001). A study over a 17 year period done by Green *et al*. (1999) found by means of photographs that the radial growth of the species is roughly 1mm per century (*in* Øvstedal and Lewis Smith, 2001).

Buellia latemarginata typically have thalli up to several centimetres in diameter, with a grey inner and blackish outer margin (Øvstedal and Lewis Smith, 2001). This Antarctic endemic prefers areas which are enriched by bird excrement (Øvstedal and Lewis Smith, 2001). It is often found with the *Acarospora* and *Buellia* species which are also found on the Northern Buttress, as well as others which are not present on the study site of interest (Øvstedal and Lewis Smith, 2001).

Figure 18: One of the *Buellia* species

The two *Buellia* (e.g. Figure 18) species are discussed and mapped as one, as it was not possible to distinguish between them in the field. The *Buellia* species was found at 25.9% of the plots (n=166), and does not appear to be occurring in a particularly preferential area, with it being distributed in patches across the Northern Buttress (Figure 19).

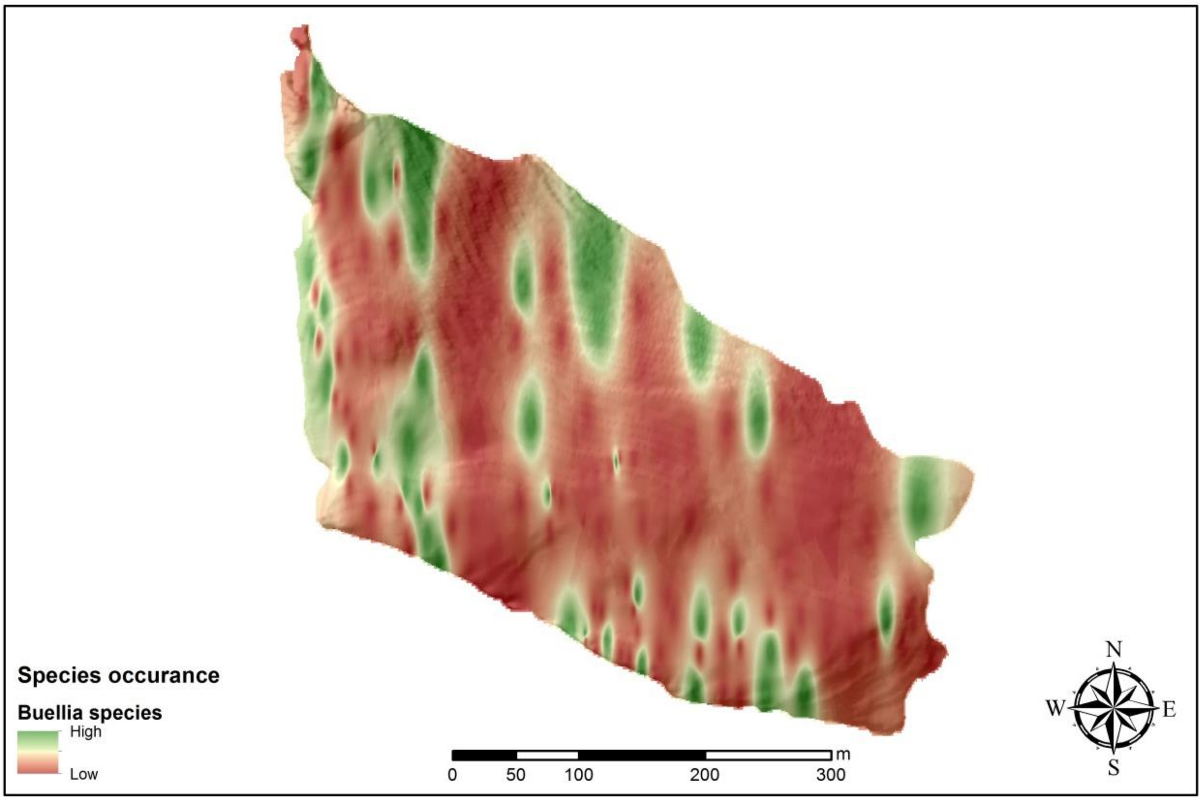

Figure 19: Interpolated distribution of the *Buellia* species on the Northern Buttress

4.1.3 *Lecanora expectans*

Lecanora expectans (e.g. Figure 20) has a white thallus with a powdery surface; the margins are also white, but are rough-textured and undulating (Øvstedal and Lewis Smith, 2001). This lichen species, which is an Antarctic endemic, is found widespread on mosses in coastal areas and in Dronning Maud Land (Øvstedal and Lewis Smith, 2001). *Lecanora expectans* is the second most abundant species on the Northern Buttress, with it occurring at 68 (41%) of the 166 plots. It occurs throughout the Northern Buttress; but it appears to be more abundant on the western part of the nunatak (Figure 21).

Figure 20: *Lecanora expectans*

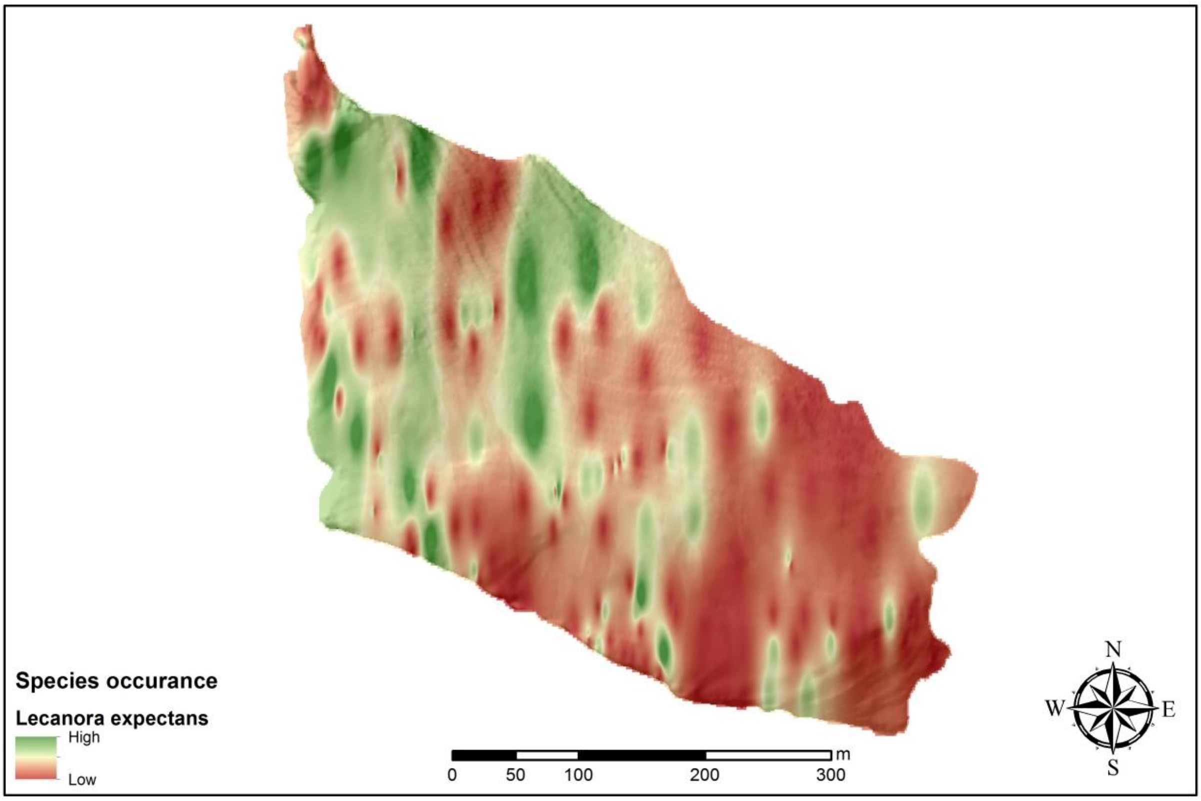

Figure 21: Interpolated distribution of *Lecanora expectans* on the Northern Buttress

4.1.4 *Pseudephebe minuscula*

Pseudephebe minuscula (e.g. Figure 21) has a fruticose thallus, which usually takes upon a circular form to roughly five centimetres in diameter, but thalli of this species are known to reach roughly 20-25 centimetres in coastal continental sites (Øvstedal and Lewis Smith, 2001). The branches are usually shiny dark brown to black and flattened (Øvstedal and Lewis Smith, 2001). This lichen is one of the most widespread lichen of continental Antarctica (Øvstedal and Lewis Smith, 2001). This lichen is bipolar and has a relatively wide distribution throughout a number of differing environments (Øvstedal and Lewis Smith, 2001). Thalli which reach over 5 centimetres in diameter often erode or die in the centre, leaving a partial or complete ring of surviving lichen (Øvstedal and Lewis Smith, 2001).

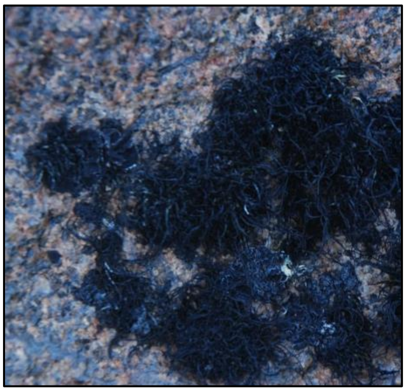

Figure 21: *Pseudephebe minuscula*

Pseudephebe minuscula is one of the less abundant lichen species on the Northern Buttress; it was present at 12.7% of the plots (n=166). It was found across the study area, and does not appear to prefer any particular area (Figure 22).

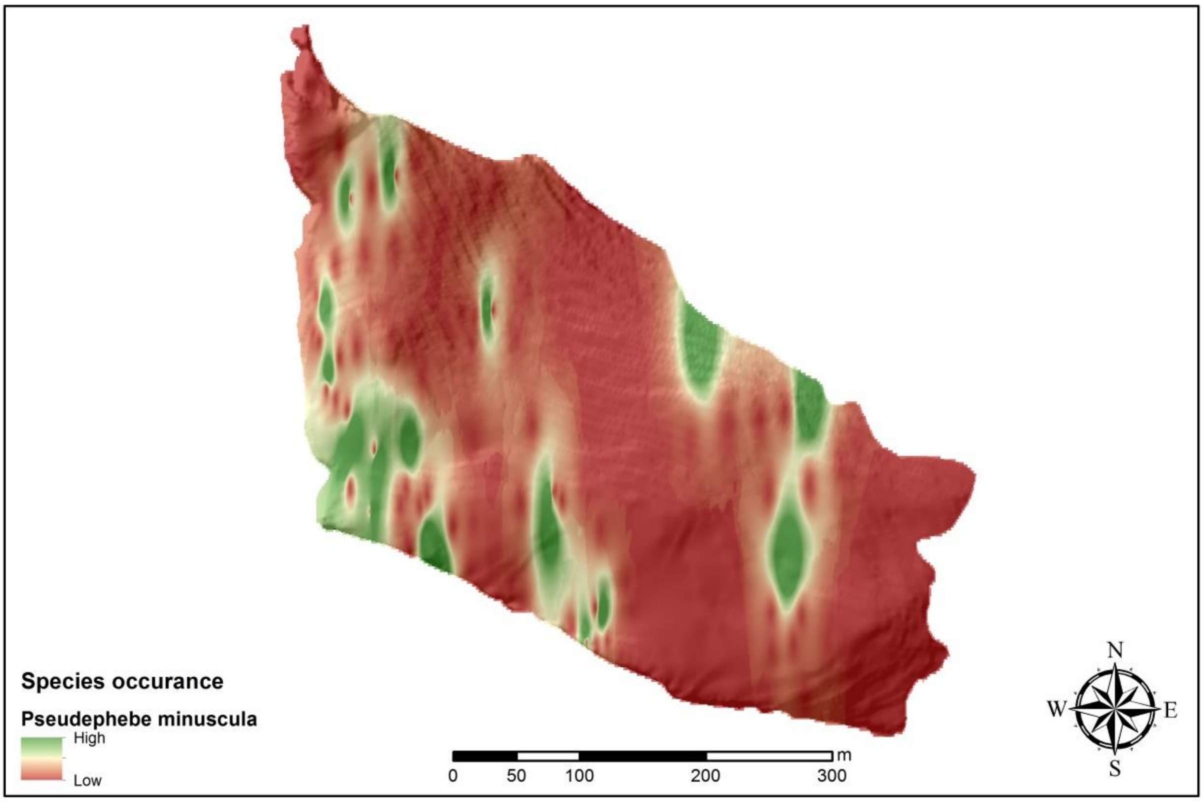

Figure 22: Interpolated distribution of *Pseudephebe minuscula* on the Northern Buttress

4.1.5 *Rhizocarpon geographicum*

Rhizocarpon geographicum (e.g. Figure 23) is a yellow-green lichen with thalli which have no distinct form and often clump together to form colonies 20 or more centimetres across (Øvstedal and Lewis Smith, 2001). This cosmopolitan species in cold regions is often found on dry exposed rock faces with other crustose lichens (Øvstedal and Lewis Smith, 2001). A study by Sancho and Valladares (1993) on a moraine on Livingston Island, Antarctica, yielded an annual growth rate of 0.34mm.

Figure 23: *Rhizocarpon geographicum* (Photo: Meiklejohn, 2010).

Contrary to the above description by Øvstedal and Lewis Smith (2001), *R. geographicum* was found to colonise flat rocks where there was meltwater present (pers. obs.). The species was present in just 12 of the sample plots (n=166), and was mostly found on the western edge of the Northern Buttress (Figure 24).

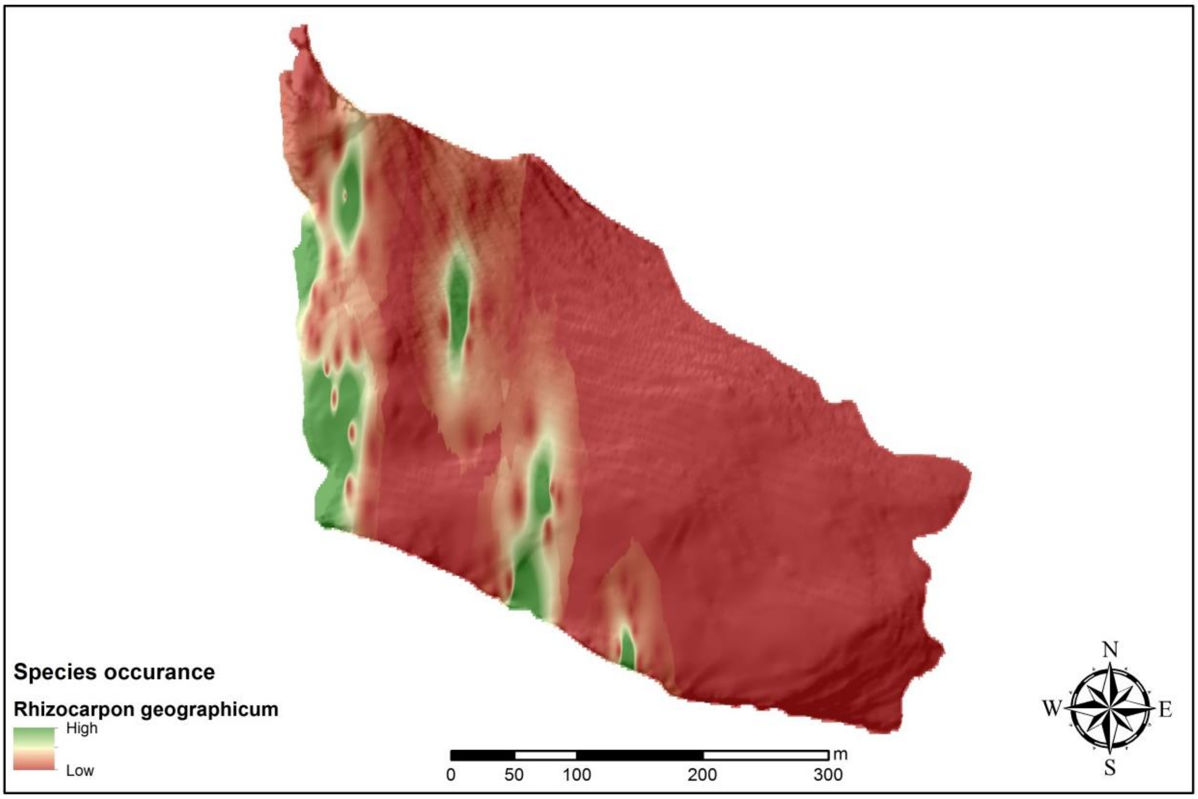

Figure 24: Interpolated distribution of *Rhizocarpon geographicum* on the Northern Buttress

4.1.6 *Umbilicaria decussata*


Figure 25: ***Umbilicaria decussata***

Umbilicaria decussata (e.g. Figure 25) is a grey to black lichen, typically with a monophyllous thalli up to three centimetres in diameter, but thalli up to 8-10 centimetres have been recorded (Øvstedal and Lewis Smith, 2001). They are known to be widespread on exposed, dry rock (Øvstedal and Lewis Smith, 2001). This statement is directly contradicted by Bargagli *et al.* (1999) and Bargagli *et al.* (2000) who suggest that the species prefers rocks which are sheltered from desiccating winds, and in niches where snowmelt provides water in summer. They are a cosmopolitan species in cold regions, stretching from the maritime Antarctic and becoming progressively more abundant with increasing latitude (Øvstedal and Lewis Smith, 2001). According to Øvstedal and Lewis Smith (2001), they are often found with *Buellia frigida*, *Pseudephebe minuscula* and *Usnea sphacelata*, all of which are also present on the Northern Buttress. Bargagli *et al.* (1999) found *Acarospora gwynii* and *Rhizocarpon geographicum* and others to be associated with *Umbilicaria decussata*, which are also present on the Northern Buttress.

Umbilicaria decussata was present in just 11 of the total 166 sample plots, and was found exclusively in the area of the northern part of the Northern Buttress (Figure 26). There is a snow-ridge very close to the tip of the Northern Buttress (as can be seen in Figure 36). Beyond this ridge, *U. decussata* is very abundant, and occurred in all six of the plots sampled in this area.

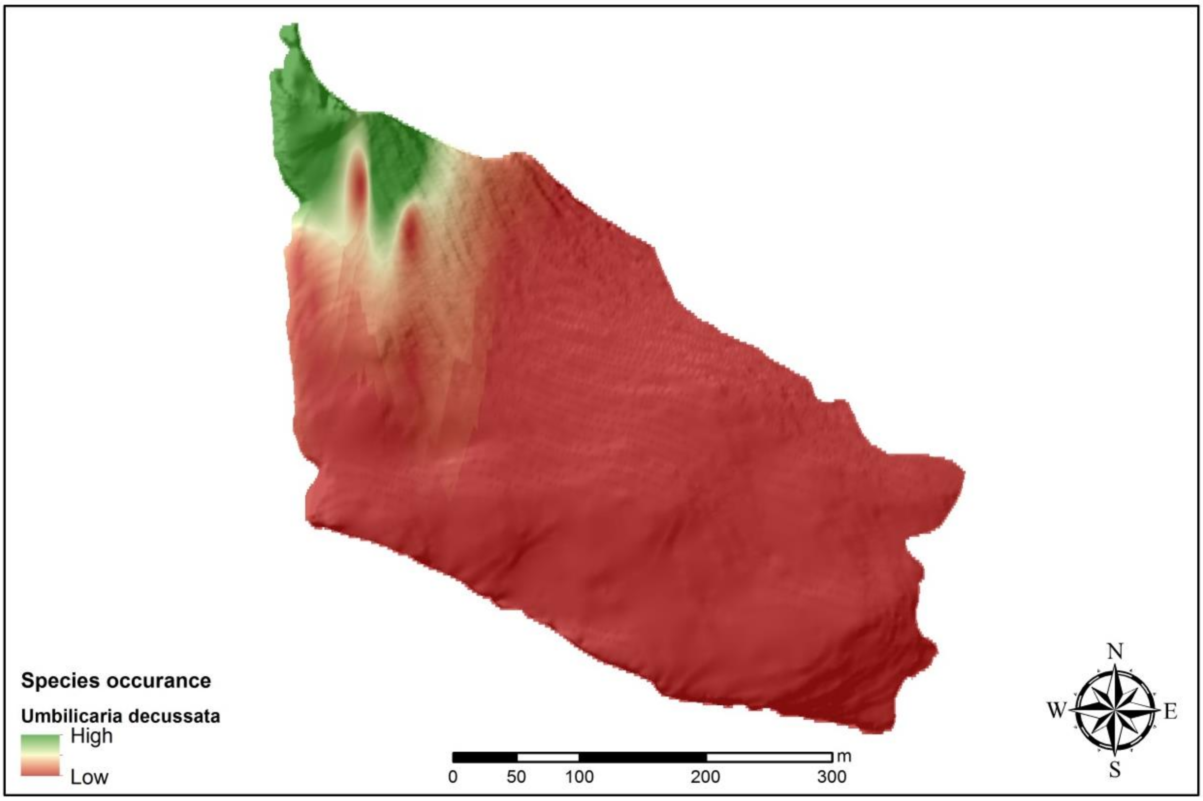

Figure 26: Interpolated distribution of *Umbilicaria decussata* on the Northern Buttress

4.1.7 *Usnea sphacelata*

Usnea sphacelata (e.g. Figure 27) is a black to yellow-black, and sometimes yellow-green in shaded areas, fruticose lichen with thalli normally reaching up to 5cm in height, but are known to reach up to 10cm on occasion (Øvstedal and Lewis Smith, 2001). The species is the only known one of the *Usnea* group which occurs at both poles (Seymour *et al*., 2007). It is the most widespread macrolichen in continental Antarctica, ranging from sea level to above 2000m.a.s.l. (Øvstedal and Lewis Smith, 2001; Seymour *et al*., 2007). They occur mostly on rocks, boulders, and stones, at sites which are dry, exposed and windswept (Øvstedal and Lewis Smith, 2001; Hancock and Seppelt, 1988). It is known to form communities with *Buellia frigida, Pseudephebe minuscula, and Umbilicaria decussata* (Øvstedal and Lewis Smith, 2001; Hancock and Seppelt, 1988).

Figure 27: *Usnea sphacelata*

Usnea sphacelata is not widely distributed across the Northern Buttress, but instead bares a very similar distribution to that of *Umbilicaria decussata*, which it is known to be associated with (Øvstedal and Lewis Smith, 2001). It was only present at five of the 166 sample plots (Figure 28), where all five of the sample plots also contained *U. decussata*. Of those five, four of them are beyond the snow ridge discussed above. However, unlike *U. decussata*, it was not present at all of the sample plots beyond the ridge.

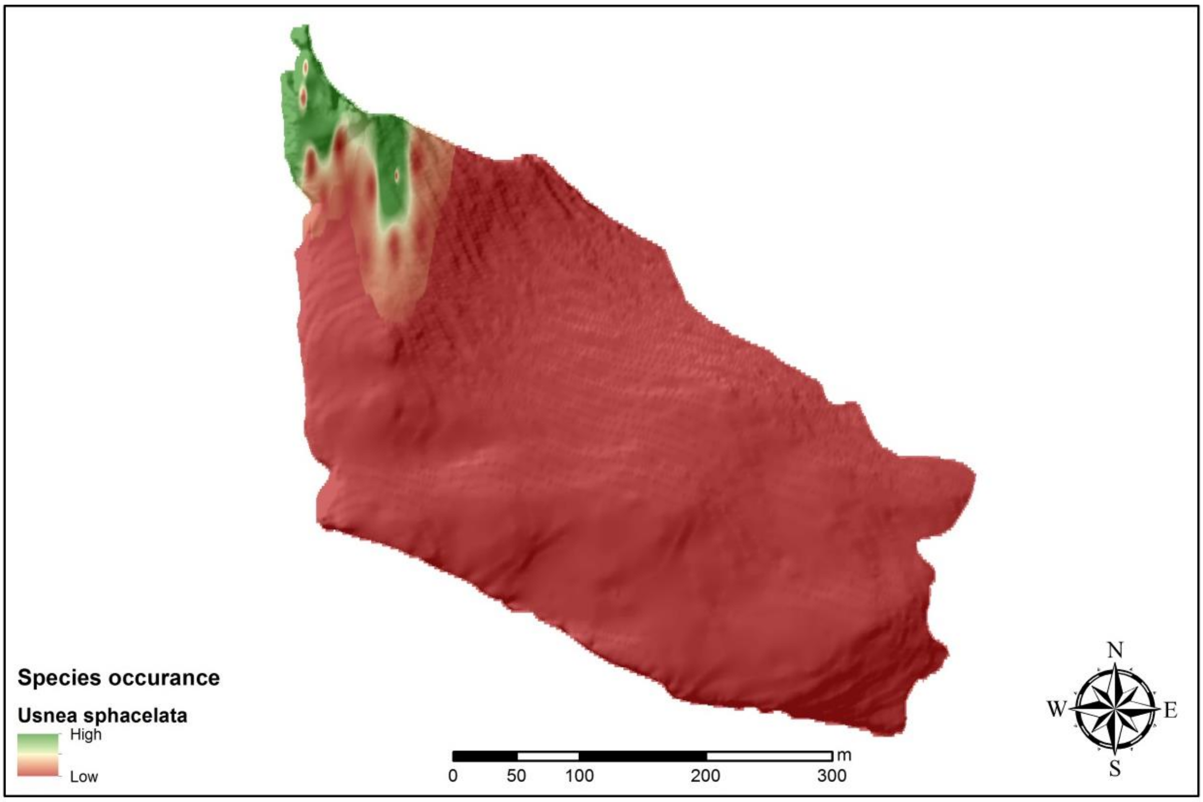

Figure 28: Interpolated distribution of Usnea sphacelata on the Northern Buttress

4.1.8 *Xanthoria elegans*

Xanthoria elegans (e.g. Figure 29) has orange foliose Thalli of five or more centimetres in diameter (Øvstedal and Lewis Smith, 2001). The cosmopolitan species is bipolar, and is known to extend from sea-level in the Antarctic Peninsula to up to 1700m in continental Antarctic sites (Øvstedal and Lewis Smith, 2001). It is most abundant on rock faces, boulders and stones; they also spread over other lichens and mosses on occasion (Øvstedal and Lewis Smith, 2001). The occurrence of *X. elegans* is a good indicator that there may be snow petrel colonies in the area or could be rocks used by skuas as perches (Øvstedal and Lewis Smith, 2001).

Figure 29: ***Xanthoria elegans***

Xanthoria elegans was by far the least abundant species on the Northern Buttress (Figure 30), it was found at just one plot out of the 166 sample plots. It thrives off of bird excrement (Øvstedal and Lewis Smith, 2001). Its relative lack in abundance could be attributed to the fact that there is not a large bird presence at Vesleskarvet compared to other sites where *X. elegans* is more abundant.

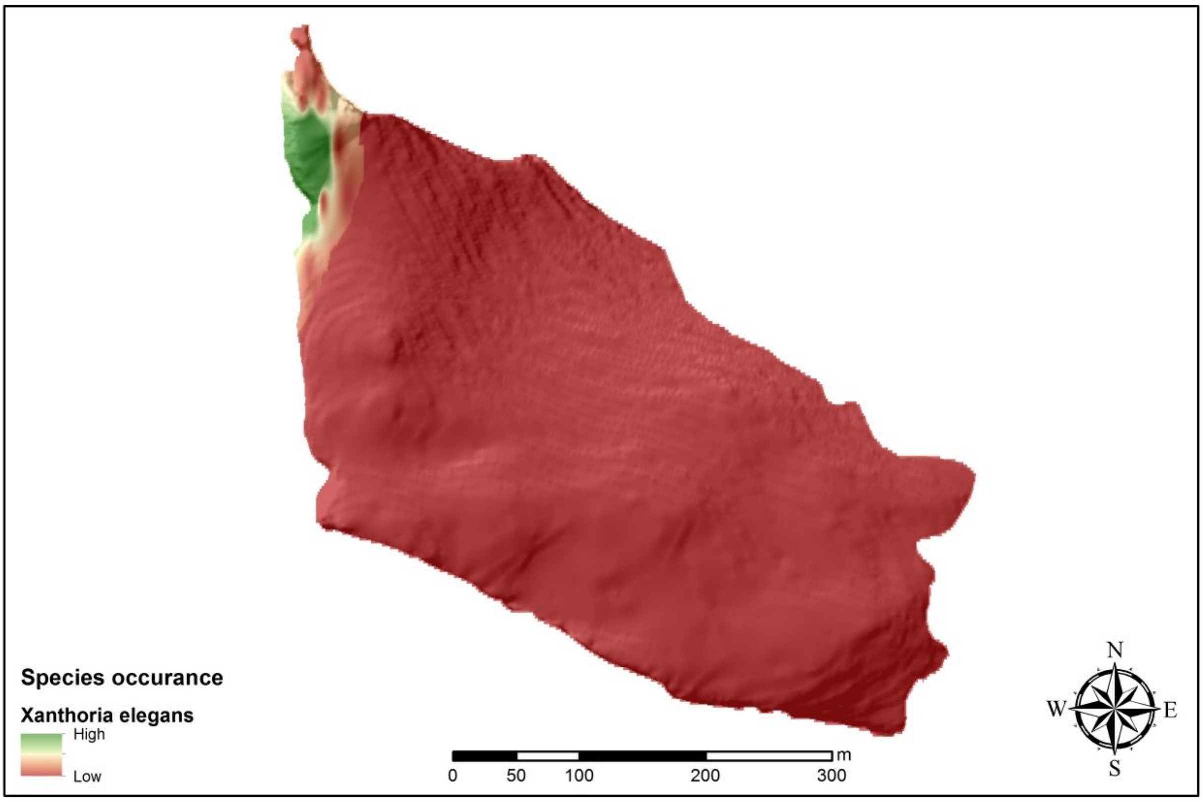

Figure 30: Interpolated distribution of *Xanthoria elegans* on the Northern Buttress

4.1.9 Summary

The relative abundance of each lichen species on the Northern Buttress varies greatly, and most species appear to have an indiscriminate distribution across the Northern Buttress. This could be due to the lichen colonising in places which have favourable microtopography (this will be discussed in objective four). The occurrence of *Umbilicaria decussata* and *U. sphacelata* is suggested to be related to local environmental conditions and, hence less erratically distributed. Species richness also bares a similar pattern to that of *U. decussata* and *U. sphacelata*. Again, this could be attributed to favourable environmental conditions, which will also be discussed under the fourth objective of this study. Using this method of interpolating the survey data to create an estimation of species distribution across the study area proved to be very successful and provides valuable insights into patterns by having a visual representation of them.

4.2 Objective 2

Investigate lichen abundance and distribution at intra- and inter-nunatak scales.

Biological distribution and abundance shows considerable spatial variability, with some being homogeneous, and others being more heterogeneous. Determining the reasons for observed biological patterns is one of the central objectives of ecology and biogeography (Brown, 1984; Gaston, 2000). The relationship between abundance and distribution is acknowledged, however more studies need to be conducted on this matter from a local to the global scale (Brown, 1984). Areas with increased environmental stresses are often represented by low biological diversity (Lawley *et al.*, 2004). This has been addressed across latitudinal gradients, however, it is also important to address how these patterns occur along latitudinal gradients (Gaston, 2000), as well as at smaller spatial scales. Lawley *et al.* (2004) reiterate that the Antarctic is an ideal place for studying how environmental gradients impact community structure.

The Northern Buttress is used by this research as an intra-nunatak study due to the availability of data, accessibility, and as it is a designated science area which limits foot traffic and simplifies the system. Robertskollen was chosen as a comparative site as it is relatively close to Vesleskarvet (the Northern Buttress), but is more abundantly vegetated (pers. obs.). A comparison in lichen distribution and abundance, coupled with environmental data should inform on the patterns of biodiversity at the intra- and inter-nunatak scales; this will be addressed in objective four.

4.2.1 Intra-nunatak

At the species level, lichen is not evenly distributed across the Northern Buttress; but at the community level lichen is scattered across almost the entire surface of the nunatak. Figure 31 shows the lichen distribution across the Northern Buttress from presence/absence data obtained from the 282 sample plots of the 2009/2010 and 2013/2014 surveys. Of the 282 sample plots, only 79 (28%) did not have any lichen present at all. These plots were mostly arbitrarily scattered across the Northern Buttress and generally did not create a “zone” of almost no lichen, except for the north eastern corner.

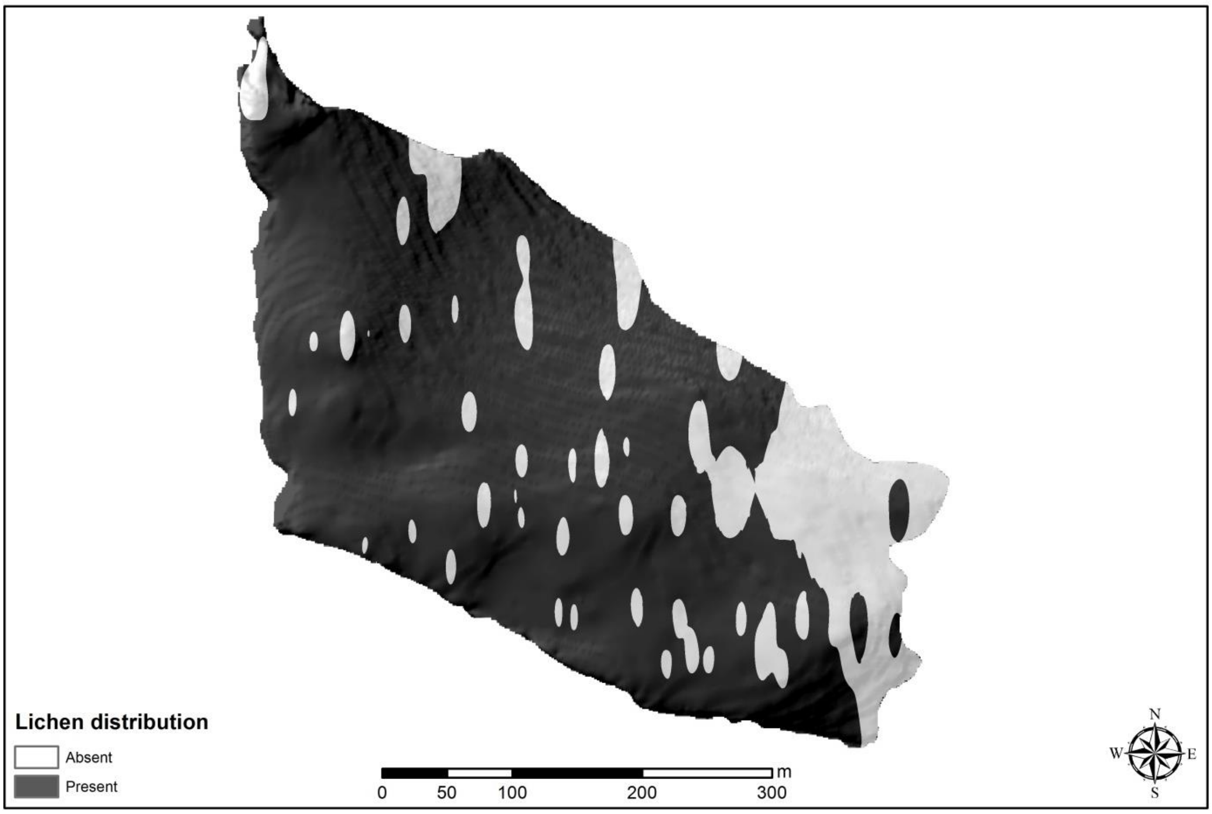

Figure 31: Interpolated lichen distribution on the Northern Buttress

Lichen abundance appears to be more heterogeneous across the Northern Buttress, as shown in Figure 32 and Figure 33 below; the resultant spatial patterns are very similar to that of species richness as shown in Figure 15. The patterns suggested by these visual representations are very similar in that lichen is most abundant on the western edge and northern tip of the nunatak. It is hypothesised by this research that these patterns are a result of a combination of a number of favourable environmental factors. This will be discussed in further detail in objective four.

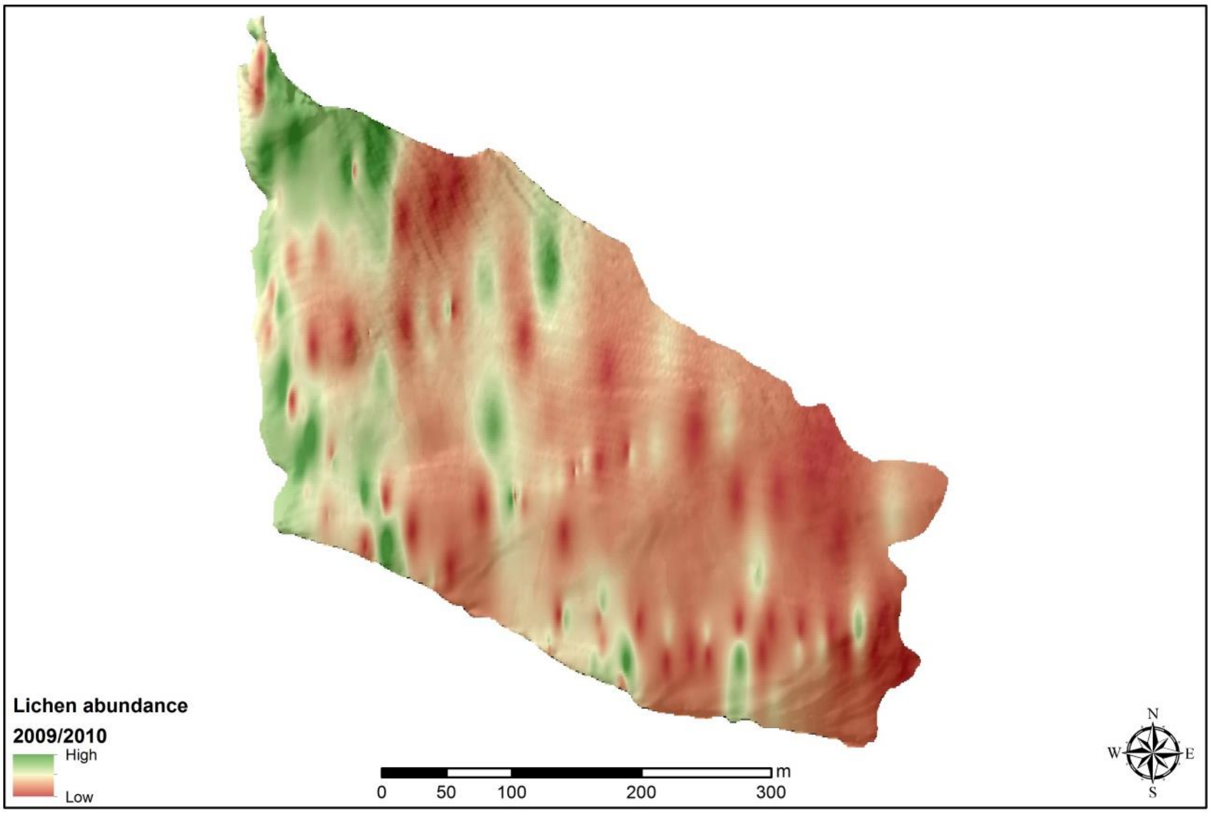

Figure 32: Interpolated lichen abundance on the Northern Buttress, based on the 2009/2010 survey

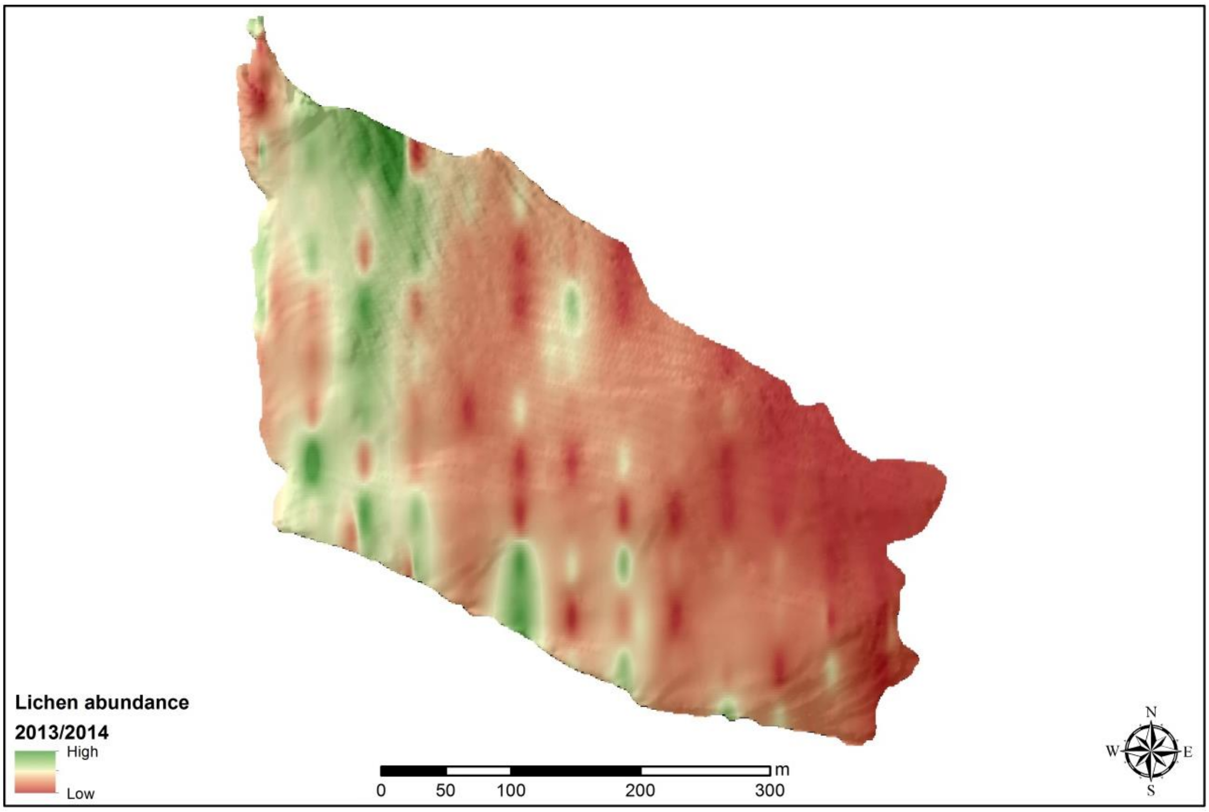

Figure 33: Interpolated lichen abundance on the Northern Buttress, based on the 2013/2014 survey

4.2.2 Inter-nunatak

Intra-nunatak studies are useful in informing on local variations in lichen distribution and abundance. In order to get a greater understanding as to the extent environmental parameters play a role in shaping lichen occurrence at a regional scale, an inter-nunatak study was conducted. A survey in the 2013/2014 Austral summer was conducted at Robertskollen to facilitate the inter-nunatak comparison.

Of the 15 sample plots at Robertskollen, only one sample square was lacking any lichen occurrence. This translates to just 6.7% of the plots being devoid of lichen, which is slightly lower than the 28% on the Northern Buttress. A t-test was undertaken in order to compare lichen distribution and abundance on the Northern Buttress and at Robertskollen. The hypothesis for lichen distribution is shown below:

H_o: There is no significant difference in lichen distribution at Robertskollen and on the Northern Buttress

H_a: There is a significant difference between lichen distribution at Robertskollen and on the Northern Buttress

The t-test yielded p-value of 0.086641, thus at the 95% confidence level the null hypothesis is not rejected and it can be concluded that there is no significant difference between lichen distribution at Robertskollen and on the Northern Buttress.

The conclusion that there is no significant difference between lichen distributions on the two nunataks does not automatically mean the same for lichen abundance. Hence, a t-test was computed in order to test the following hypothesis:

H_o: There is no significant difference in lichen abundance at Robertskollen and on the Northern Buttress

H_a: There is a significant difference between lichen abundance at Robertskollen and on the Northern Buttress

At the 95% level of significance, the null hypothesis is rejected ($p<0.00001$), and the alternate that there is a significant difference between lichen abundance at Robertskollen and on the Northern Buttress is accepted. Lichen abundance is greater on Robertskollen (group mean of 14 lichens per plot) than on the Northern Buttress (group mean of 4 lichens per plot). The reasons for this difference in abundance will be explored further by the fourth objective of this investigation.

4.3 Objective 3

Measure specific environmental factors which could play a role in biodiversity distribution.

To achieve the overall aim of determining how geomorphic features and the ambient environment affect lichen distribution and abundance, specific environmental factors were measured on the Northern Buttress, and at Robertskollen. These factors include clast characteristics (dip, aspect and support), rock hardness, temperature, and microtopographical features.

4.3.1 Clast characteristics

Aspect (orientation) is an important factor which relates to other possible environmental controls. Received solar radiation is directly associated with aspect and dip, whereas rock hardness can be influenced by solar radiation. These are environmental parameters which can influence lichen distribution and abundance.

The Northern Buttress is a relatively flat nunatak, with almost the whole area (99.96%) occurring on a slope of less than 25 degrees (Hansen, 2013), therefore, the overall aspect (shown in Figure 34) will not be as great a controlling factor as the aspect of the individual rock faces. An investigation by Hansen (2013) found that the clasts on the Northern Buttress are randomly orientated (Figure 35), which is indicative of an autochthonous deposit. The majority of the clasts are supported by other clasts and bedrock (85.83%), followed by a combination of bedrock and ice (12.5%), and finally a mere 1.6% of clasts are supported only by ice (Hansen, 2013). There is a large amount of snow and ice present on the Northern Buttress, as can be seen in the aerial image in Figure 36, which was created by the SfM imaging software.

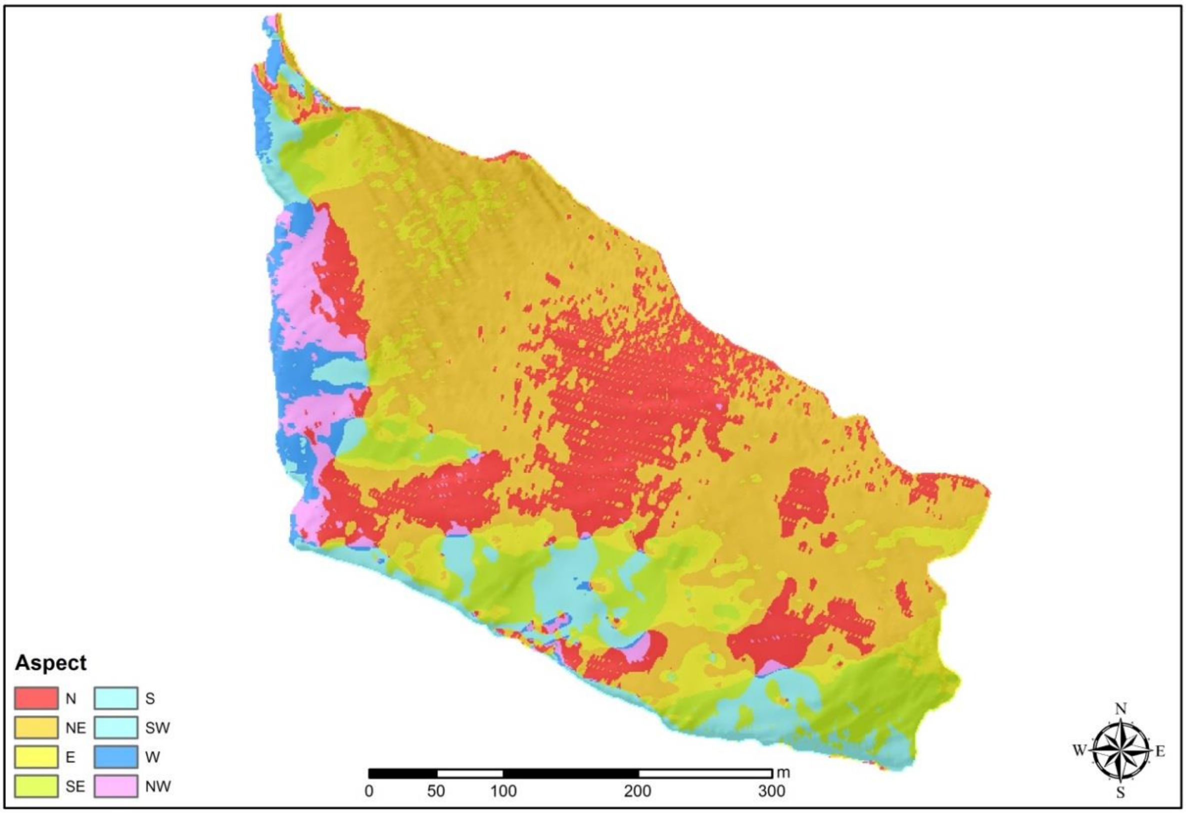

Figure 34: Interpolated aspect of the Northern Buttress

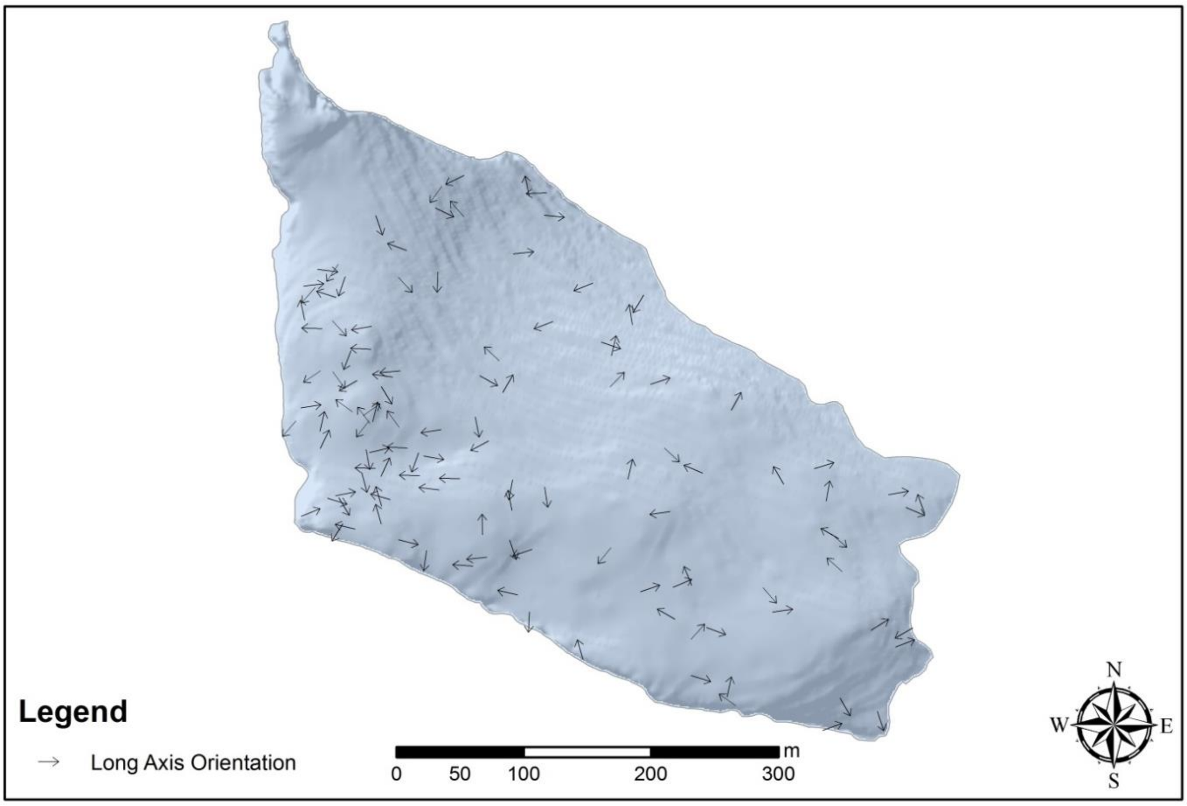

Figure 35: Long axis orientation of clasts on the Northern Buttress

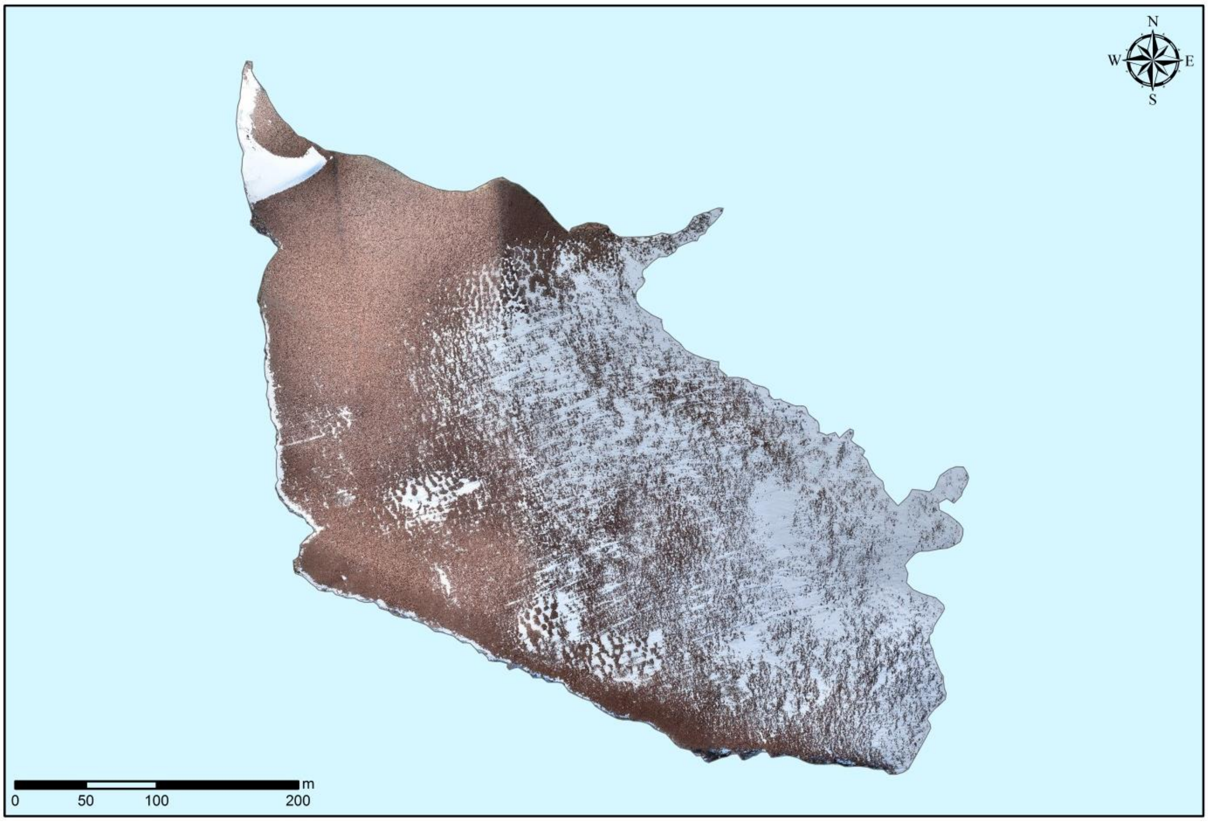

Figure 36: Aerial image of the Northern Buttress, created by the SfM survey

The dip and aspect was measured for each rock face with lichen present in the sample plots during the 2009/2010 and 2013/2014 surveys. The predominant orientation of rock faces containing lichen is the northern, followed by southern aspects (Figure 37). The remaining aspects each only represent between 7.9% and 11.2% of the population, however they account for 56.9% of the total lichen accounts. The prevalent wind direction on the Northern Buttress is from the east, thus, shelter from direct wind could be the main reason lichens are mostly found on northern and southern aspects.

Lichens on flat rocks represented only 5.6% of the population (n=552), which is not displayed on the rose diagram below as they do not have an orientation and have a dip of zero degrees. The mean dip of rock faces with lichen present is 36°, with the majority of the rock faces having a dip of between 1° to 45°, followed by 45° to 90°, and finally a very small portion occurring on rock faces more than 90° (Figure 37). As the nunatak is relatively flat, and the clasts are randomly orientated, it can be assumed that preferential orientation and dip of clasts with lichen occurrence is due to aspect related factors and not due to other factors such as elevation, and local aspect.

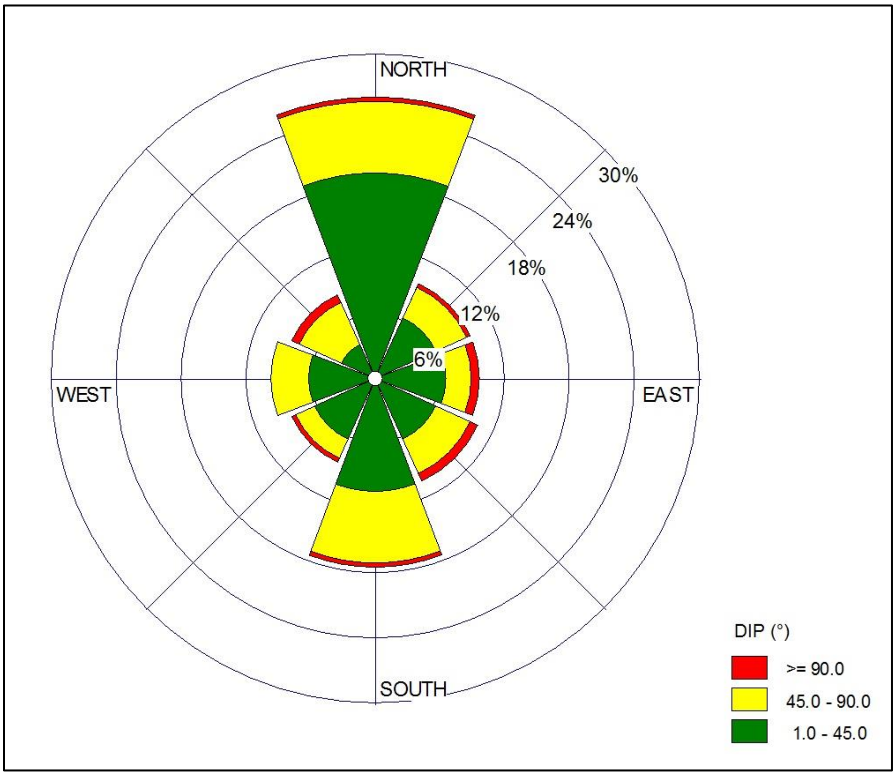

Figure 37: Rose diagram of orientation and dip of rock faces with lichen present

4.3.2 Rock hardness

Rock hardness was measured on the Northern Buttress during four of the five field seasons since the 2009/2010 survey using both the Equotip and Schmidt Hammer. Measurements from a total of 502 points across the Northern Buttress were used in rock hardness calculations and for interpolation of the map in Figure 38 below.

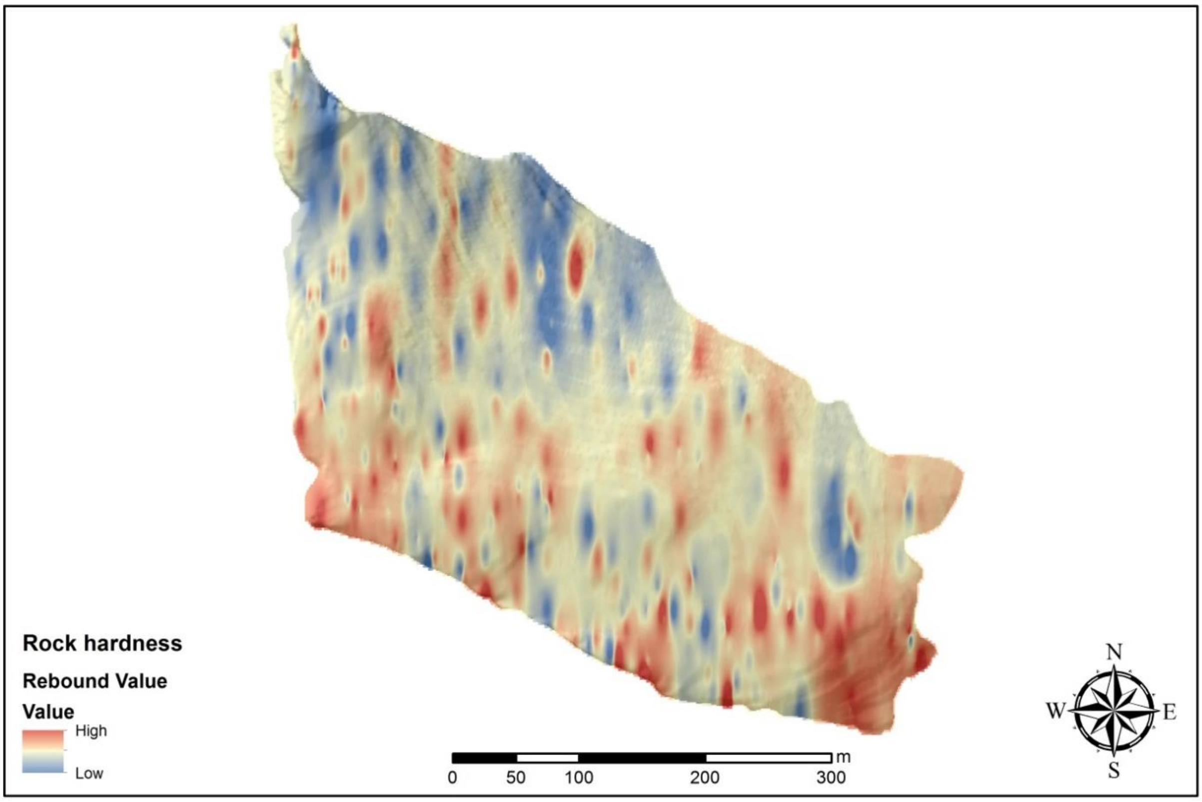

Figure 38: Interpolated rock hardness values on the Northern Buttress

Caruso *et al*. (2010) suggest that phylogeographic related processes (i.e. glacial events) have more influence on large-scale distributions of Antarctic anthropods than climatic and environmental conditions. Rock hardness can be used as a relative dating technique, operating under the premise that the degree of weathering (indicated by rock hardness) is related to the amount of time the surface has been exposed to weathering (Sumner *et al*., 2002; Matthews and Owen, 2008; Viles *et al*., 2011). This method has been applied as an approximation of relative ages on numerous geomorphological landforms (Viles *et al.* 2011). Betts and Latta (2000) used the Schmidt Hammer as a tool to assess relative age exposure of archaeological petroforms.

Rock hardness appears to have a broad pattern across the surface of the Northern Buttress. The blue areas, in Figure 38 above, are areas of relatively softer rock, whereas the red areas are relatively harder rock. The more northern part of the Northern Buttress appears to be softer than the more southern section, which could suggest a pattern of deglaciation when operating under the assumption that rock exposed for longer will be softer. This pattern is also present for lichen abundance, which will be discussed in objective four.

4.3.3 Temperature variability

Ambient air temperature is one of the determining factors for the survival of terrestrial Antarctic biota (Øvstedal and Lewis Smith, 2001). Within the summer period (December to February), air temperatures are known to rise above 0°C, but usually fall to below freezing again at night, which subjects biota to daily free-thaw cycles (Øvstedal and Lewis Smith, 2001). The summer period is when biota are most physiologically active; in the winter temperatures barely reach above 0°C, and biota are mostly covered by snow, thus they tend to remain dormant (Øvstedal and Lewis Smith, 2001). Air temperatures vary at the micro-, local-, and regional-scales, which could influence patterns of biodiversity. At the continental scale, biodiversity bares similar distributions to the different biogeographical zones, as discussed by Morgan *et al.* (2007), however there are notable differences at a much smaller scale. This study addresses air temperature differences within one region at the local and micro-climatic scales for a period of 15 days.

As discussed in the methodology section (Chapter 3), iButtons were placed across the surface of the Northern Buttress and at Robertskollen in order to get a short term insight into air temperature variation within the nunataks and between the nunataks. On the Northern Buttress, some of the iButtons were "paired" close to each other, one in a sheltered spot and the other in an unsheltered spot in order to quantify the role that local topography has on ambient air temperature. T-tests were conducted for each pair in order to test for significant differences in the temperatures from each population (n=2151); Table 3 below summaries the results. At the 95% level of significance there is a difference between three of the four pairs of iButtons. The graphs for each of these pairs are shown in Figure 51, Figure 52, Figure 53, and Figure 54 in Appendix A.

Table 3: Results from the paired "sheltered" and "unsheltered" iButtons on the Northern Buttress

Sheltered	Unsheltered	Sheltered Mean	Unsheltered Mean	df	p-value
iButton 7	iButton 9	-2.36864	-1.48156	4300	p<0.001
iButton 8	iButton 6	-3.42702	-3.36144	4300	p=0.601
iButton 10	iButton 4	-4.60530	-3.48685	4300	p<0.001
iButton 5	iButton 1	-2.12948	-1.66580	4300	p<0.001

At the local scale, temperature varied significantly across the surface of the Northern Buttress. The graph in Figure 39 shows the mean of the highest and lowest temperatures recorded at each time of the day on the Northern Buttress for the ten day period. It appears from the graph that at any one time there is an average of a four degree Celsius difference across the surface of the Northern Buttress. At the 95% level of confidence there is a highly significant difference ($p<0.001$) between the mean highest and lowest temperatures on the Northern Buttress.

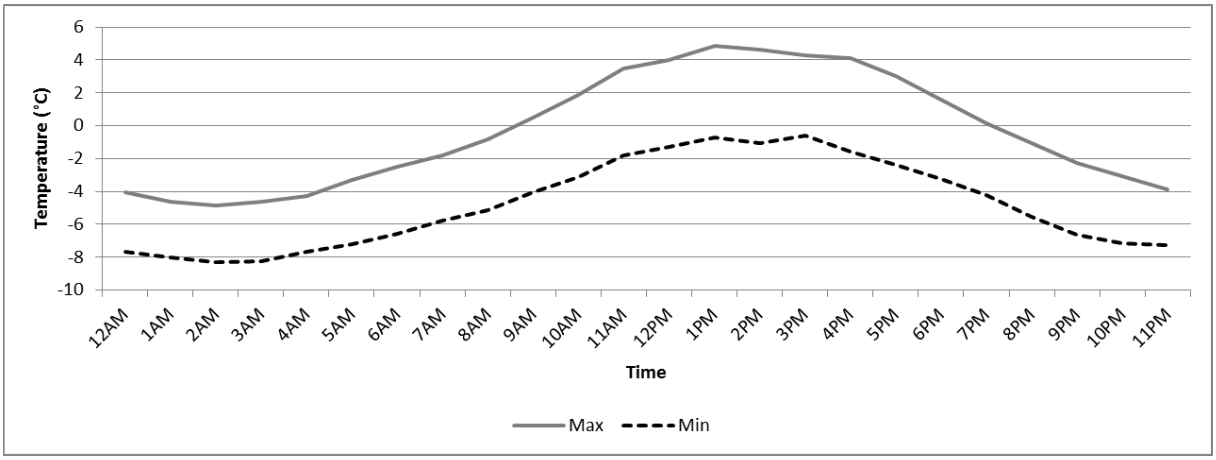

Figure 39: Mean maximum and minimum temperatures recorded per hour on the Northern Buttress

There appears to be spatial variations in temperature across the surface of the Northern Buttress, as shown in Figure 39, Figure 40, and Figure 41. There is a trend of decreasing temperature from west to east throughout the day, as shown in Figure 48, Figure 49, and Figure 50 in Appendix A. The mean warmest temperature (Figure 39) shows the south west corner to reach the highest temperatures (up to roughly 4°C), whereas the northern and eastern parts of the nunatak only reach an average high of approximately 0°C to 1°C. The mean minimum temperatures (Figure 41) and mean overall mean temperatures (Figure 42) bare a similar pattern of decreasing temperature from west to east, with the south west corner recording the highest temperatures on average. The relationship between the observed temperature patterns and lichen distribution and abundance will be discussed in objective four.

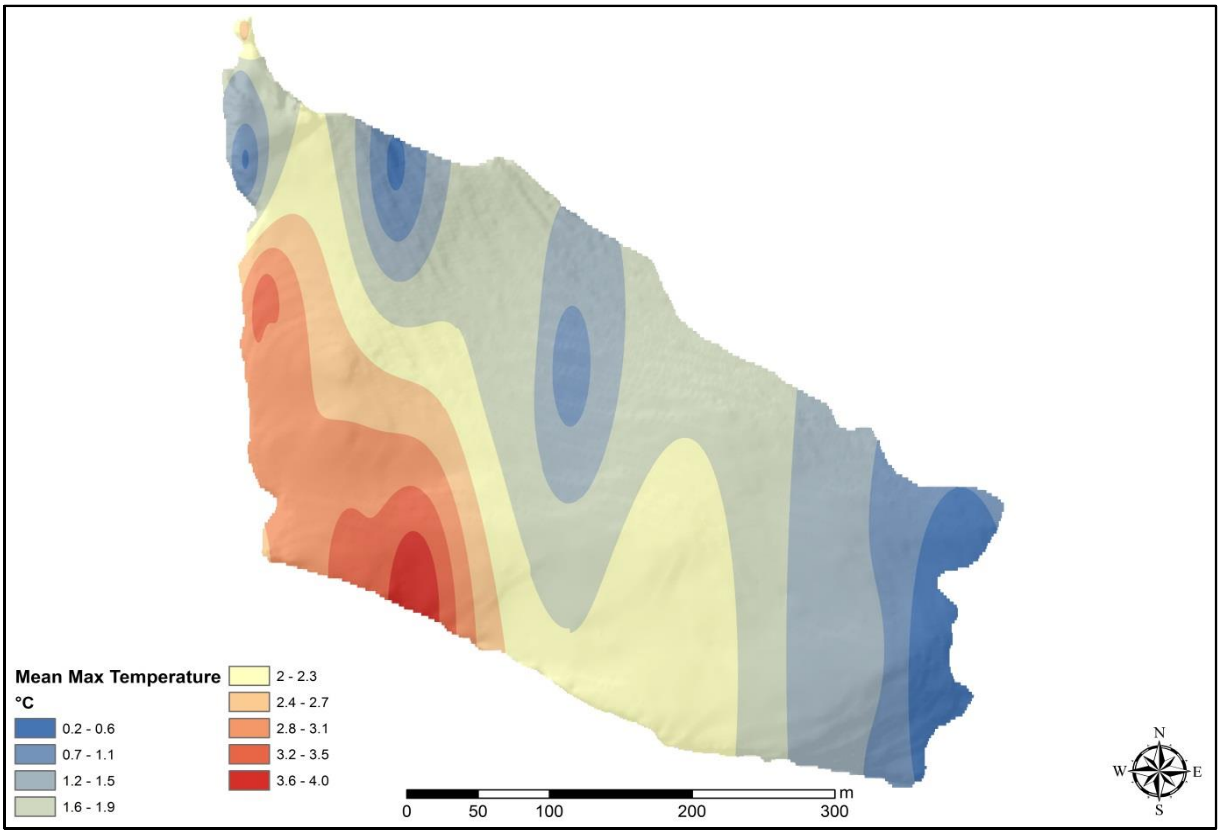

Figure 40: Interpolated mean daily maximum temperatures (°C) on the Northern Buttress between 09/01/2014 and 25/01/2014.

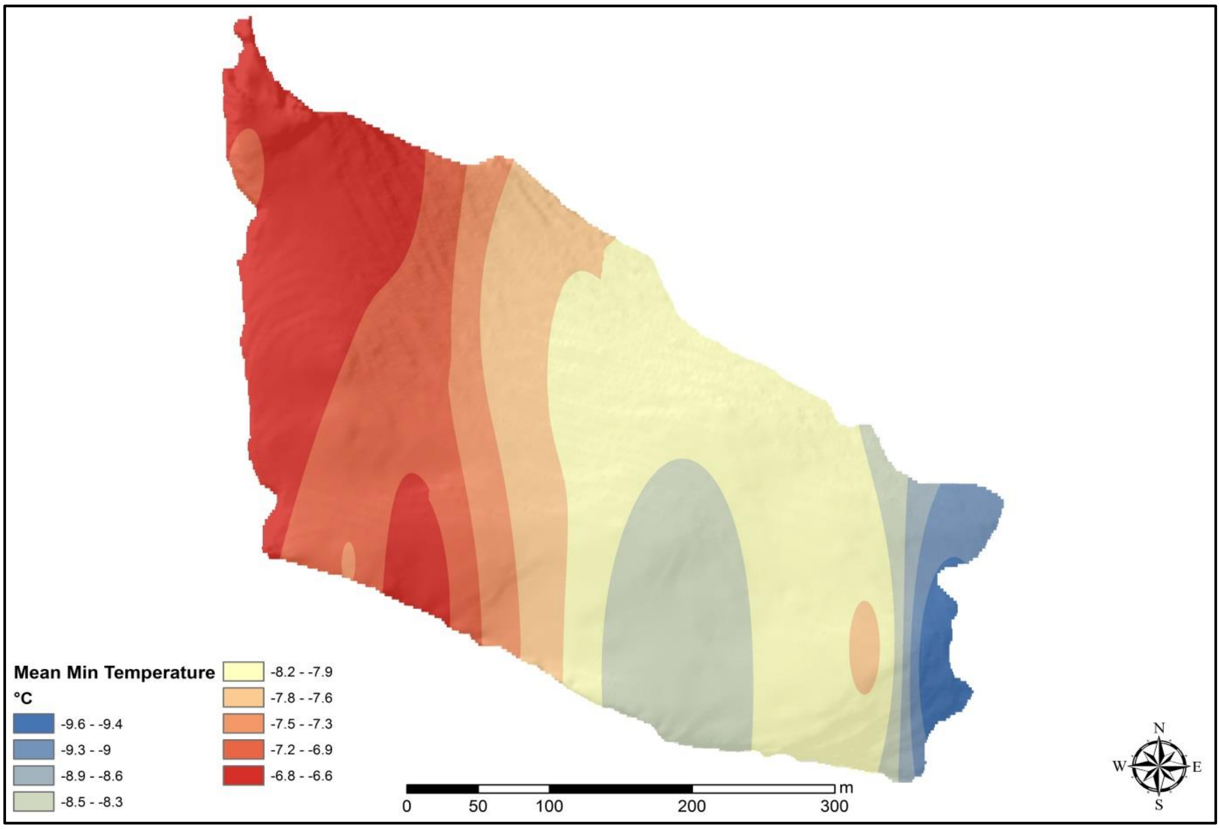

Figure 41: Interpolated mean daily minimum temperatures (°C) on the Northern Buttress between 09/01/2014 and 25/01/2014.

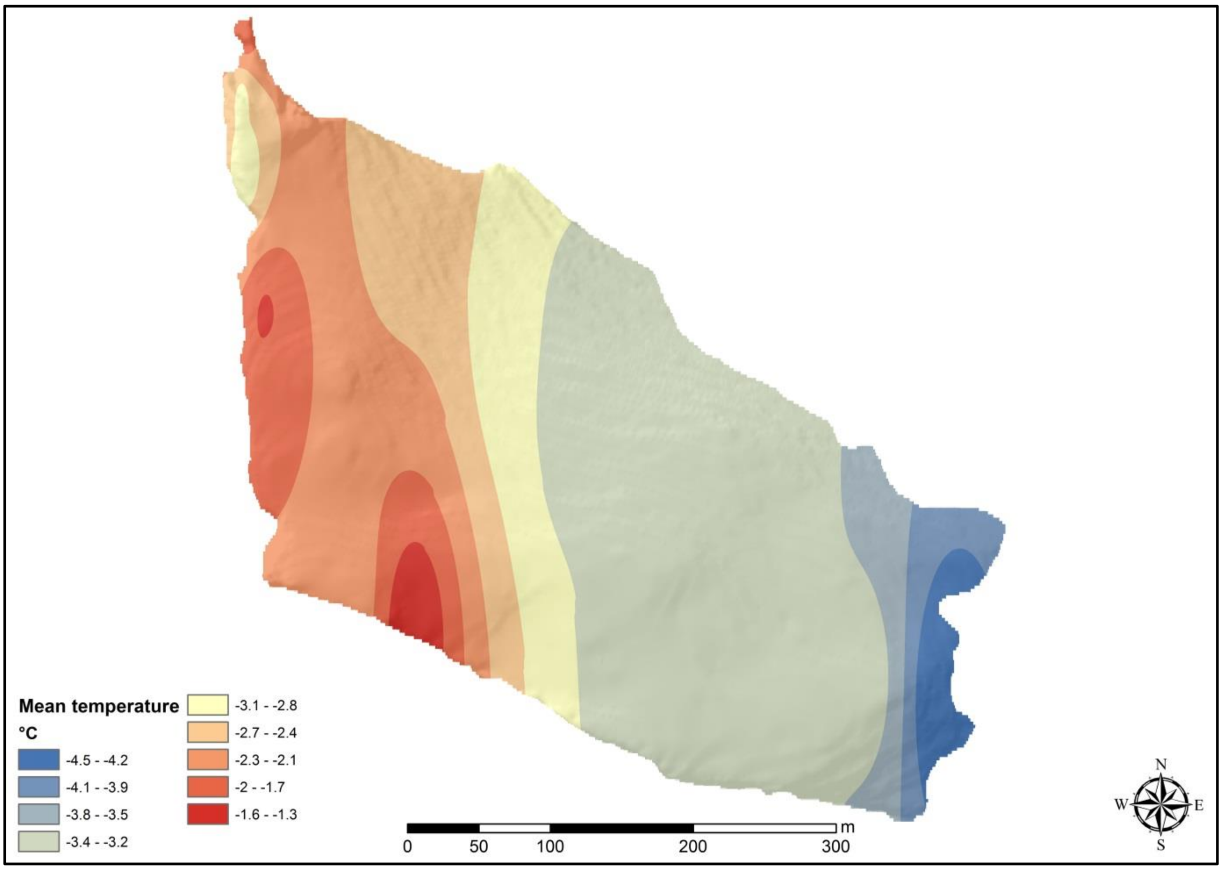

Figure 42: Interpolated mean daily temperatures (°C) on the Northern Buttress between 09/01/2014 and 25/01/2014.

4.3.4 Microtopography

It is well known that lichen colonise in weathering related microtopography (e.g. Chen *et al.*, 2000; De Los RíOs *et al.*, 2005); this is mainly thought to be due to the fact that water accumulates in these areas. During the 2012/2013 survey, all lichen occurrences were classed according to whether they were occurring in cracks, on rough surfaces (i.e. weathered faces), in pitting, on smaller rock (substrate), on the edge of rocks, or sheltered directly by other rock (as shown in Figure 43 below).

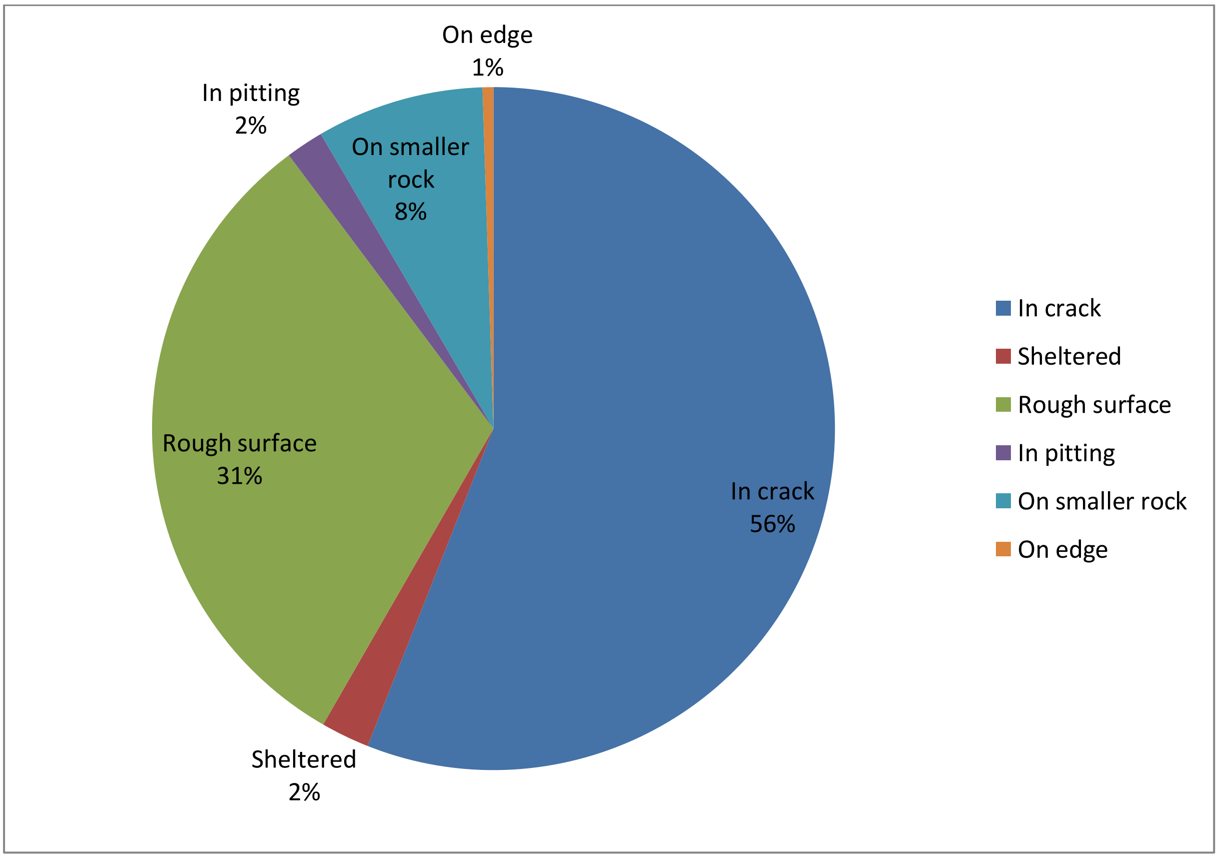

Figure 43: Graph of proportions of lichen occurring in associated weathering related micro-topography

Of the 394 lichen instances in the 2012/2013 survey, the majority (56%) of the lichen occurring in weathering related micro-topography were in cracks or fissures. One of the types of weathering processes acting on the Northern Buttress is granular disintegration (Hansen, 2013), which is most likely to provide ideal rough surfaces for lichen colonisation. Rough surfaces were the second most common weathering related micro-topography, with 31% of the observed lichen occurring on them. The rest of the types of weathering related micro-topography had a fairly negligible amount of lichen occurrences with only 51 instances between them.

4.4 Objective 4

Compare the patterns of lichen distribution and abundance to those of influencing environmental factors in order to gain a better understanding of their relationship with lichen establishment.

As demonstrated in objectives one to three, there are patterns of lichen distribution and abundance which are similar to that of specific environmental parameters. In order to test for statistical relationships, models were computed using lichen distribution (presence/absence data) and lichen abundance (lichen count data) as responses to a number of possible environmental predictors.

4.4.1 Model results

Lichen species distribution and overall distribution was modelled based on the 2009/2010 data (n=680) as a function of northness, eastness, slope, rock hardness and all the interactions between the terms. The results are summarised in Table 4 below:

Table 4: Lichen distribution models for the Northern Buttress

Lichen species	**Northness**	**Dip**	**Rock Hardness**	**Northness: Dip**	**Eastness: Dip**	**Northness : Rock Hardness**	**R^2**
Buellia species	*	***		*			0.07
Umbilicaria decussata			*				0.10
Usnea sphacelata							0.14
Acarospora gwynii	***	*		*	*		0.10
Lecanora expectans	*	***	.	.			0.09
Pseudephebe minuscula		**		*			0.09
Xanthoria elegans							-
Rhizocarpon geographicum		.				.	0.08
All species	***	***		*			0.08

Significance codes: $p <$ 0.001 ‘***’, 0.01‘**’, 0.05‘*’, 0.1‘.’

Based on the R^2 as a measure of goodness of fit, none of the models are a particularly good fit for the data, with them all explaining less than 14% of the variation present. The factors which were most commonly found to be significant were northness, dip, and the interaction between northness and dip.

A model based on lichen distribution for Robertskollen was not computed as most of the plots (14 of the 15) had lichen present, which meant there would not be a good representation of each response. Instead, a generalised linear model was run combining both the Northern Buttress and Robertskollen data from the iButton sample plots, with site as an added factor. The set of chosen predictors were rock hardness, northness, eastness, dip, minimum temperature, maximum temperature, and the interactions between the terms. The results from the spatially non-explicit generalised linear model are shown in Table 5.

Table 5: Results from the generalised linear model of lichen abundance on the Northern Buttress and at Robertskollen

Parameter	**Significance**
Rock hardness	***
Maximum temperature	*
Minimum temperature	***
Maximum temperature : Minimum temperature	.
Rock hardness : Minimum temperature	***

Significance codes: $p < 0.001$ ‘***’, 0.01‘**’, 0.05‘*’, 0.1‘.’

The fit of the model above is better than those of the lichen distribution models and explains over half (56%) of the variation in the data. The most significant factors acting as influences on lichen abundance were minimum temperature and rock hardness. In order to account for spatial autocorrelation, a spatially explicit SAR model was run on the same abundance data. The only factor which the SAR model found to be significant was minimum temperature ($p<0.1$); the Akaike Information Criterion value (AIC) for the SAR model was high, indicating a good fit for the data.

The reason for the apparent lack of a significant relationship between lichen distribution and the set of measured variables on the Northern Buttress is most likely due to the relatively consistent distribution of lichen across the nunatak, which does not appear to show any similarities to the locally heterogeneous environmental factors. Contrary to this, the models of lichen abundance have much better fits, which adds statistical support to the similar patterns of abundance and certain environmental parameters. The suggested reasons for each environmental having an influence or not on lichen distribution and abundance will be discussed in the section to follow.

4.4.2 Synthesis

As stated earlier, the aim of this project is to investigate the extent to which geomorphic features (landforms) and the ambient environment provide favourable habitats for lichen growth. This was achieved by:

1. investigating lichen species occurrences on the Northern Buttress,
2. comparing lichen distribution and abundance at the intra- and inter-nunatak scales,
3. measuring environmental factors which could act as controls to lichen colonisation,
4. and finally by comparing the patterns of lichen distribution and abundance to those of possible contributing environmental factors.

The following section combines the results from the four objectives and discusses them with respect to the overall aim of the research.

Dip and aspect of a rock surface directly control the amount of solar radiation received, and as a result also affect the amount of shelter, the rate of weathering and moisture presence (Pentecost, 1979); these are all important factors in determining lichen colonisation. In the Southern Hemisphere, the northern aspect receives more annual solar radiation than the southern aspect (Hansen, 2013). Table 6 from Hansen (2013) outlines the differences in received solar radiation per aspect for the Northern Buttress. Solar radiation is not only important in providing energy for photosynthesis, but it also has an effect on temperature, which has a positive influence on metabolic processes (Greene and Longton, 1970). Thus, in this case, the northern aspects would encourage plant growth more than the likes of southern aspects.

Table 6: Average solar radiation received per aspect on the Northern Buttress (Hansen, 2013:106).

Aspect	Average Solar Radiation Received (WH.m^{-2})
North	716 859
East	666 152
South	607 341
West	624 444
Top	686 885

Based on the distribution models, aspect is one of the influencing factors with regards to lichen distribution. Most of the lichen tended to colonise on northern aspects; however, a large portion of lichen were still found to colonise on southern aspects (Figure 37). Clast orientation is randomly orientated on the relatively flat surface of the Northern Buttress (Figure 35), thus topographical control can be ruled out as the reason for the observed preferential orientations of colonisation.

Figure 44 shows that the northern aspect is also favoured for lichen colonisation at Robertskollen. Contrary to the Northern Buttress, Cairn Peak and Ice Axe Peak at Robertskollen is predominantly north facing, thus local topography could play a role in prefered orientation (Figure 45 showing just Carin Peak north). Due to the favourable conditions related to northern aspects, this could explain at the local scale why Robertskollen has a greater abundance of lichens compared to that of the Northern Buttress. On average, the dip of rocks with lichen present was higher at Robertskollen than on the Northern Buttress (Figure 34 and Figure 45). Dip was also returned as an important factor with regards to lichen distribution; the reason for this is more than likely also due to received solar radiation, with steeper slopes receiving more concentrated insolation.

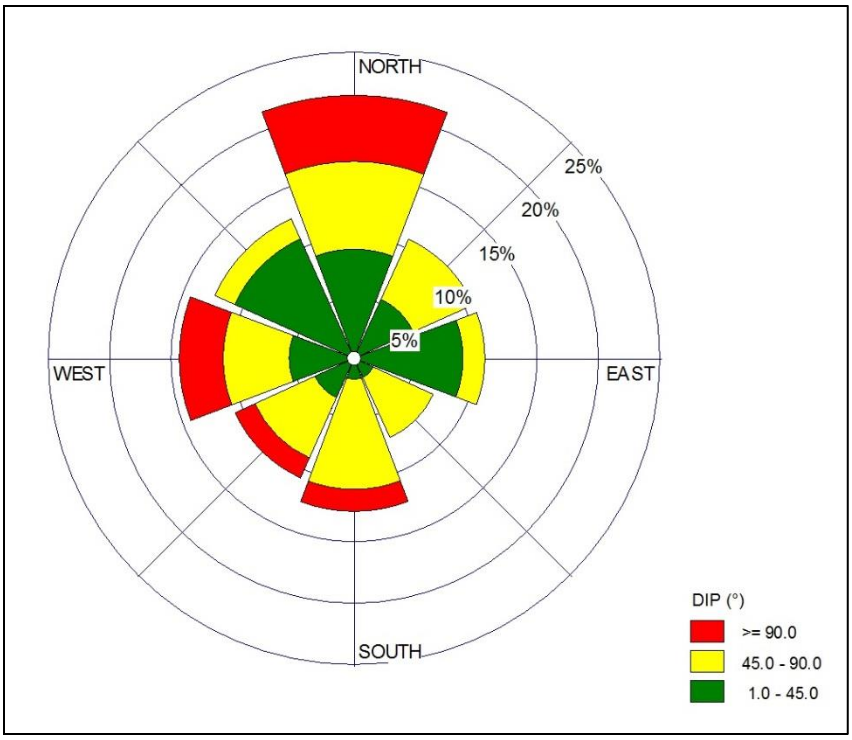

Figure 44: Rose diagram of aspect and dip of rock faces with lichen present at Robertskollen

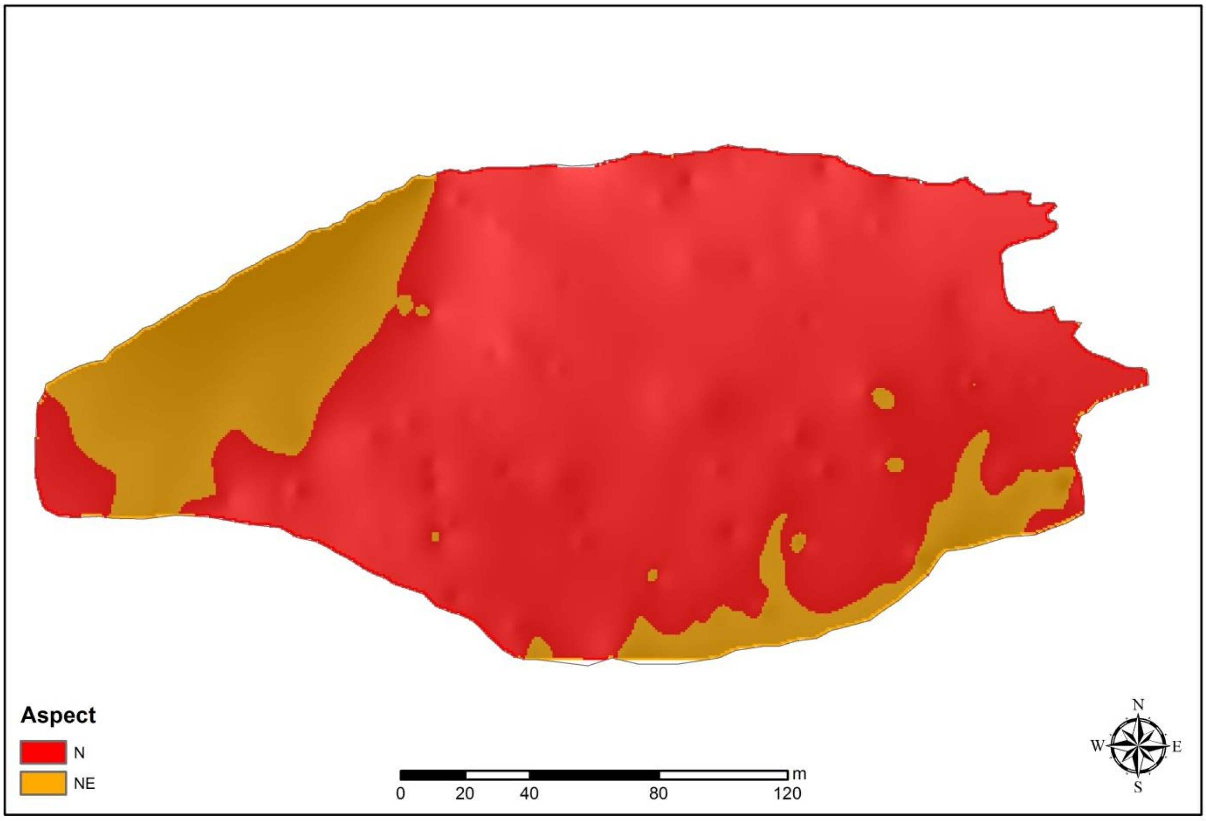

Figure 45: Interpolated aspect of Cairn Peak north at Robertskollen

Hansen (2013) found a relationship between aspect and rock hardness on the Northern Buttress; the highest rock hardness values were recorded on the southern sides, which also receive less radiation, whereas the top of the rocks had the lowest rock hardness values, followed by the northern aspects. Solar radiation plays a role in the weathering regime of rocks by processes of increased snow melt and a larger thermal regime, which may lead to thermal fatigue weathering (Hansen, 2013). Rock hardness was not a very significant factor in the lichen distribution models. However, it was found to be a highly significant factor in the GLM model of lichen abundance, with an increase in abundance associated with lower rock hardness values. This pattern can be seen in Figure 32 and Figure 33 of lichen abundance on the Northern Buttress, and Figure 38 of rock hardness on the Northern Buttress.

While lichens are often found on softer rock, this does not automatically mean that mean that the actual rock hardness is the reason for the relationship. Lichens are also known to contribute to the weathering of rock by both physical and chemical mechanisms (e.g. Chen *et al.*, 2000, Bjelland and Thorseth, 2002; Chen and Blume, 2002; Matthews and Owen, 2008; Zambell *et al.*, 2012), which means that the rock on which the lichens could be softer due to weathering processes induced by them. As lichen occurrence does not appear to be affected by rock hardness (based on visual representations and the GLM model results), one can propose that the similar pattern between lichen abundance and rock hardness is as a result of some other mechanism(s). Softer rock has been proposed as an indicator of surfaces which have been exposed for longer i.e. areas deglaciated earlier (Sumner *et al.*, 2002; Matthews and Owen, 2008; Shakesby *et al.*, 2011; Viles *et al.*, 2011). If the pattern of rock hardness is in fact indicating the pattern of deglaciation on the Northern Buttress, it would also explain the lichen abundance pattern. The longer a surface is exposed for, the more time lichen colonies would have to establish themselves and grow. Now that the entire surface has been deglaciated, there is lichen present on almost the entire surface of the Northern Buttress, which supports the model results that lichen occurrence does not appear to be affected by rock hardness. The only exception where there is a large area lacking lichen presence is on the north east corner of the Northern Buttress (see Figure 31). This zone coincides with where the ice matrix is most present as a form of clast support (Figure 36), which also supports the proposed pattern of deglaciation.

Lichens are very capable of surviving low temperatures, and have even been found to perform primary photosynthesis at temperatures as low as -15°C (Barták *et al.* 2007). This does not however rule temperature out as an important factor in influencing lichen distribution and abundance as it is important in controlling other environmental parameters. Minimum temperature (for the period that temperature was recorded) was found to be a significant factor by both the GLM and SAR models, with it being the only significant factor in the SAR model. The proposed reason why minimum temperature is more important than maximum temperature is that the minimum temperature is the limiting factor for other processes such as snow melt and thermal weathering.

A t-test based on the hypotheses below was conducted on mean temperatures for Robertskollen and the Northern Buttress.

H_o: *There is no significant difference in recorded temperatures at Robertskollen and on the Northern Buttress*

H_a: *There is a significant difference in recorded temperatures at Robertskollen and on the Northern Buttress*

At the 95% level of confidence the null hypothesis is rejected ($p<0.001$), and the conclusion that there is a significant difference between temperatures at Robertskollen and on the Northern Buttress. Figure 46 shows that although Robertskollen and the Northern Buttress have a very similar mean temperature profile, Robertskollen is on average roughly three to four degrees Celsius warmer than the Northern Buttress.

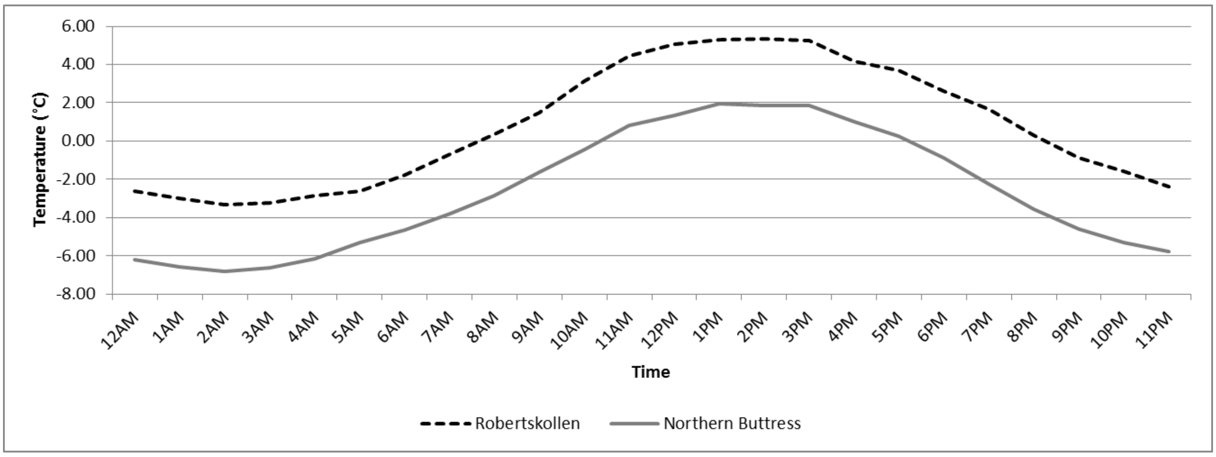

Figure 46: Graph of mean temperatures at Robertskollen and on the Northern Buttress

As previously stated, temperature is important in encouraging metabolic processes (Green and Longton, 1970). However, it does not act alone in influencing successful vegetation growth. One of the most important factors which is partly controlled by temperature, but was not measured by this study, is moisture availability. Kennedy (1993) suggests that water is in fact the primary limiting factor with regards to the presence, distribution, and abundance of life in Antarctica. There were fewer cases of meltwater found on the Northern Buttress compared to Robertskollen where it was more common and in greater volumes (see Figure 47), which could be due to Robertskollen receiving more precipitation than Vesleskarvet as Robertskollen is closer to the coast. Therefore, meltwater may also be a contributing factor to the greater abundance of lichens at Robertskollen compared to on the Northern Buttress.

Figure 47: Meltwater seeping down rocks at Robertskollen

Another factor which could have a positive influence on lichen abundance at Robertskollen compared to that of the Northern Buttress is ornithological products which contain important nutrients. Wasley *et al*. (2006) found that the productivity of Antarctic flora increased more positively to increased nutrients than to increased water. Concentrations of some important nutrients for plant growth (nitrogen, carbon, and potassium) were measured at Robertskollen by Ryan and Watkins (1989); they found that concentrations were significantly higher close to bird colonies and proposed that the presence of these elements has a direct effect on the abundance on Antarctic biota. Cocks *et al.* (1998) tested this hypothesis by comparing nitrogen and carbon concentrations in soils and plants on nunataks both with and without bird colonies. It was found that there was an increase in nitrogen at sites with breeding colonies, and evidence of the use of this nitrogen by the plants; there was however no significant difference found between carbon in the two different environments (Cocks *et al.* 1998). Robertskollen has a much higher presence of birds (roughly 600 pairs according to Ryan et al. (1989)), whereas there is no evidence indicating that birds are breeding at Vesleskarvet (Steele *et al*., 1994).

5 Conclusion

This investigation provides a baseline study which informs on environmental factors that act as influences on lichen distribution and abundance. Data such as these provide a useful reference that may be applied in further studies for predicting responses of lichen to climate change, as well as acting as a proxy for climate change. The present investigation established that microtopographical features, as well as microclimate do have an influence on lichen distribution and abundance. The distribution of lichen at the species level was found to be shaped by different environmental factors. In the case of the Northern Buttress of Vesleskarvet, rock hardness does not appear to act as a control on lichen occurrence as there is a more even distribution across the nunatak. Dip and aspect (north/south), which are random across the surface of the nunatak due to its autochthonous nature, were found to be the most important factors for lichen colonisation.

While rock hardness is an important factor in determining lichen abundance, this study also suggests the time a surface is exposed (*i.e.* not covered by snow and ice) may also be a control. The longer an area is exposed, the softer the rock should be and it also means that the longer the surface has been available for lichen establishment. Minimum temperature was found to be the most important factor in controlling lichen abundance; this is most probably due to it being a controlling factor to other environmental factors which have an influence on lichen growth. Lichen distribution was not found to be any different at the inter-nunatak scale, however lichen abundance was. This has been attributed to more favourable local topographical and climatic conditions at Robertskollen, compared to at Vesleskarvet.

In order to provide greater confidence to the theory that the relationship between rock hardness and lichen abundance is indicative of rock exposure time, lichen size of a single species could be measured across the surface of the nunatak. Lichens in the Antarctic are known to have slow growth rates (e.g. Sancho *et al.*, 2007; Allan Green *et al.*, 2012). Thus, a relative exposure time could be deduced by measuring the size of the thalli of a single species across the Northern Buttress. The *Acarospora gwynii* species would be suitable as it is the most abundant lichen on the Northern Buttress, and is easily identifiable.

Kappen (1998) states that lichen distribution at the scale of a single rock is determined by the chemical and mechanical properties of the substratum, the microclimatic conditions, and water availability. To extend on the present study, one could scale it down to the bolder scale and investigate the same environmental parameters as done by this study. Data from this project suggest aspect preference with regards to lichen colonisation, which has been suggested to be a result of increased insolation. However, the southern aspect is also well represented in the data, and receives the least amount of insolation. In order to investigate this more thoroughly, the thermal thermal spatial variability of rocks should be measured according to aspect throughout the day to get a greater understanding of how aspect influences the microenvironment. A combination of recording temperatures at regular intervals on each aspect of the boulder, as well as capturing thermal imagery over the surface of the boulder at specific times would prove very beneficial. These measurements should also be examined in conjunction with wind direction and wind speed data in order to establish whether or not aspect provides shelter at the boulder scale.

A novel way to visually investigate the connections between environmental factors and lichen occurrence at the boulder scale would be to create a model of a (few) selected boulder(s) using Structure from Motion (SfM) techniques. This will allow for specific parameters, such as rock hardness, lichen occurrence, temperature and microtopographical landforms, to be mapped on the surface of the boulder. A successful study done by Dwight (2012) applied a similar technique to investigate aspect control on rock hardness and lichen occurrence, with the exception that the model of the rock was created using a Differential Global Positioning System. By using SfM to create a model, there is the added advantage of having the model as a three-dimensional image, which will allow for finer scale mapping of lichens and microtopographical features.

Lichens are not only influenced by the surrounding environment, they also play a role in shaping it by weathering processes. It is generally accepted that lichens weather their rock substratum by both chemical and mechanical processes (Chen *et al*., 2000), however, these effects have not been studied sufficiently in the Antarctic (Chen and Blume, 2002). A study by Matthews and Owen (2008) found R-values to be much lower on recently exposed rocks (30-40 years) with lichen compared to those without. Rock hardness alone would not be considered a good indicator of weathering by lichen as there is no certainty with regards to the amount of time the rocks on the Northern Buttress have been exposed for, and the initial rapid weathering rates caused by lichen were found to decrease after a period of 40 years of colonisation (Matthews and Owen, 2008). Finer scale weathering impacts of lichen can be investigated by examining chemical composition changes with depth for rocks that have been colonised and those which are bare using Scanning Electron Microscopy (SEM), infra-red (IR) spectroscopy, electron microprobe and X-ray diffraction (XRD) (Acaso *et al*., 1990; Williamson *et al*., 1998).

In conclusion, this study has shown environmental factors do play a role in shaping lichen distribution and abundance. To further this research, it is suggested that a study is done noting the same environmental factors as the present study, but at the bolder scale to obtain a better understanding of processes acting on lichen establishment at a finer scale.

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Appendix A: Temperature variability on the Northern Buttress

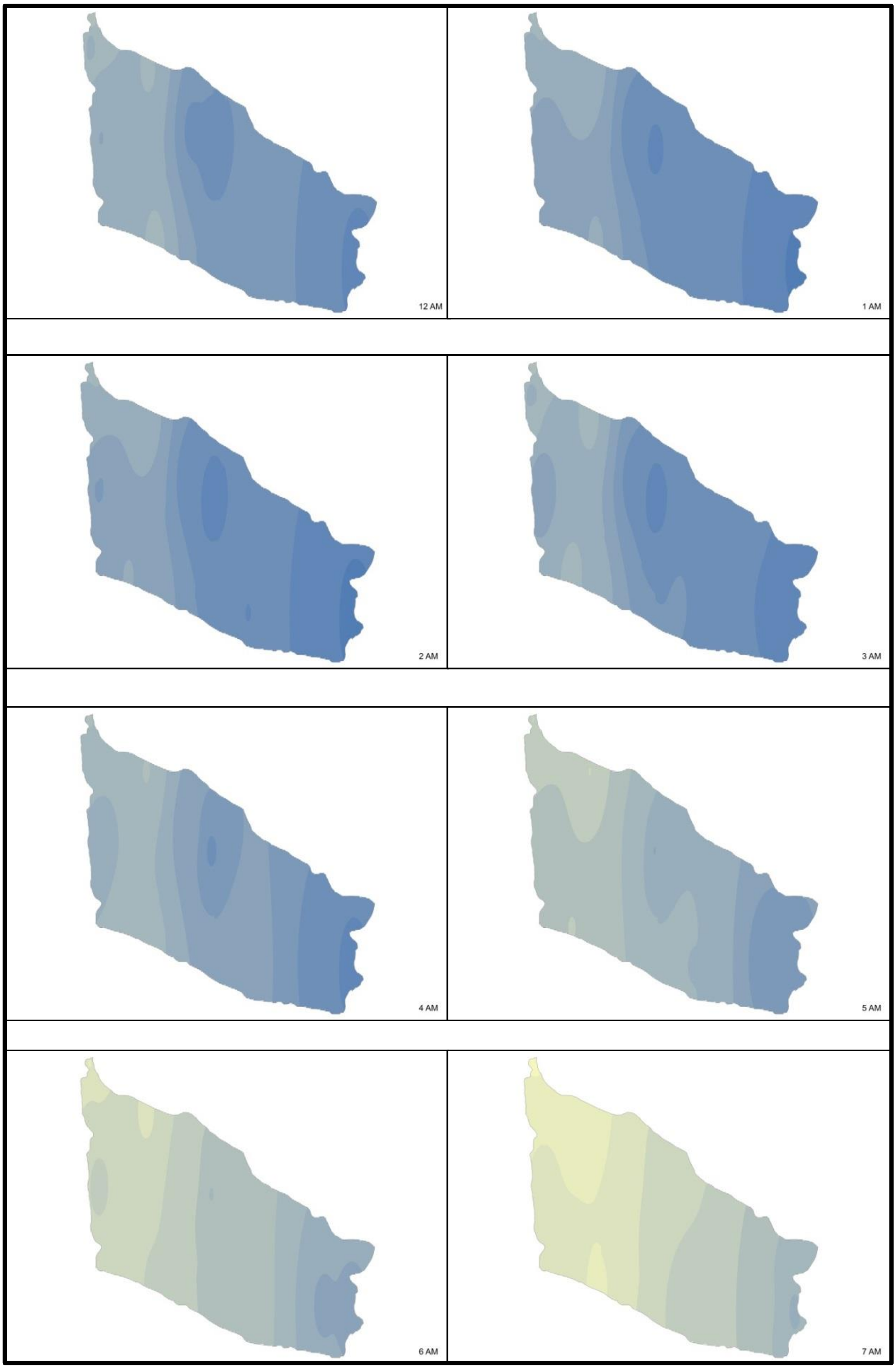

Figure 48: Interpolated mean daily temperatures (°C) on the Northern Buttress from 12 AM to 7 AM between 09/01/2014 and 25/01/2014.

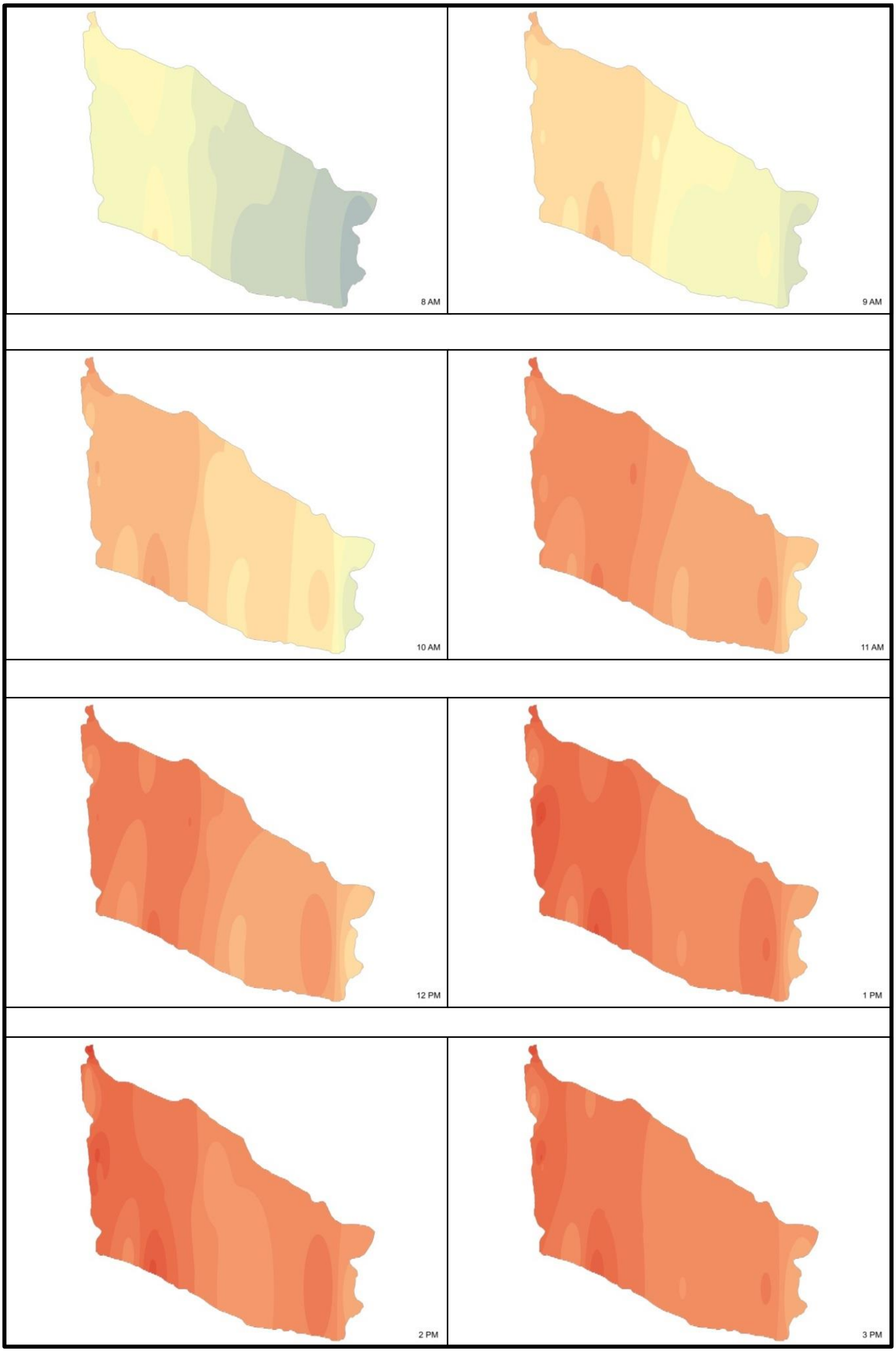

Figure 49: Interpolated mean daily temperatures (°C) on the Northern Buttress from 8 AM to 3 PM between 09/01/2014 and 25/01/2014.

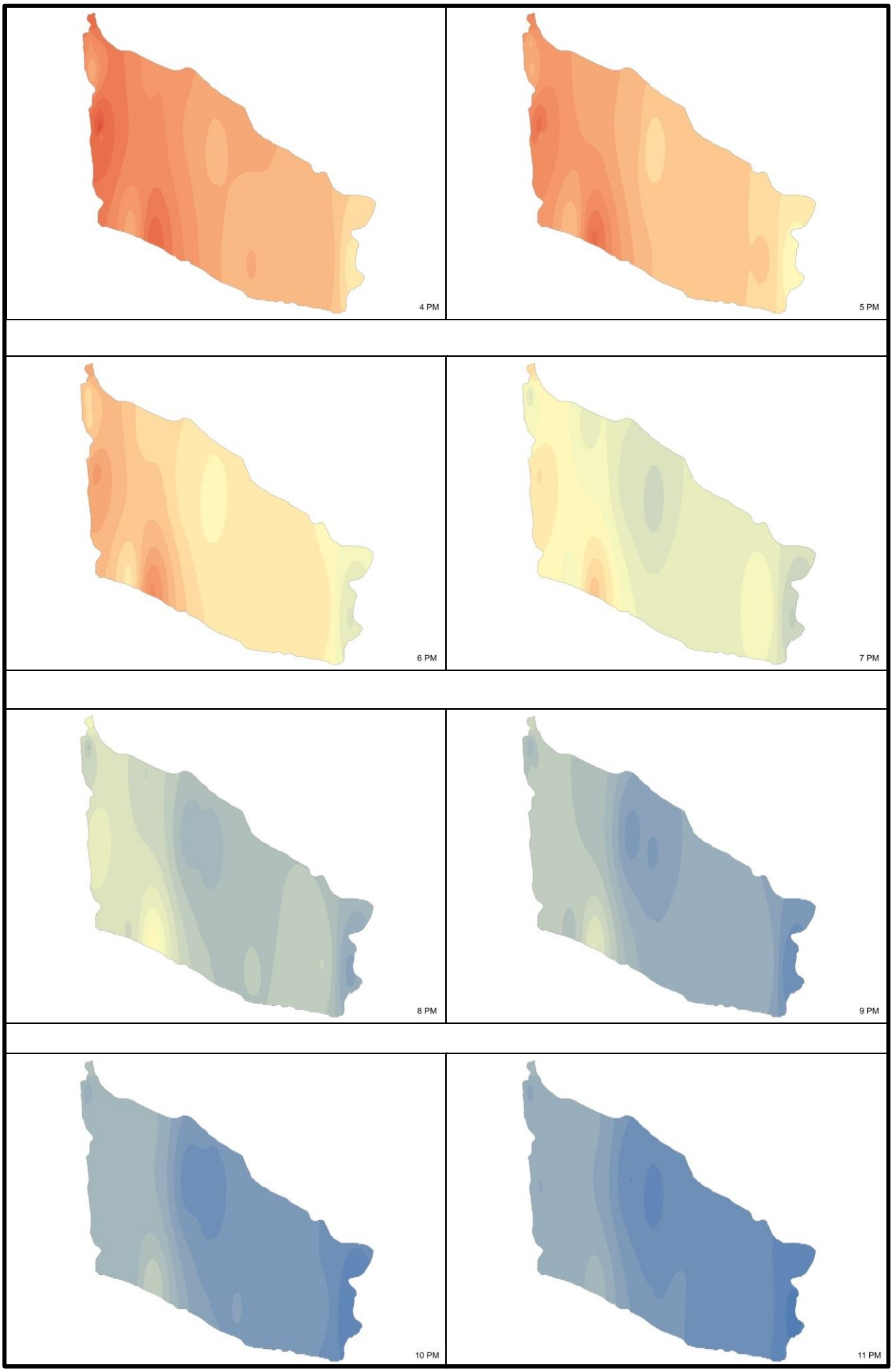

Figure 50: Interpolated mean daily temperatures (°C) on the Northern Buttress from 14 PM to 11 PM between 09/01/2014 and 25/01/2014.

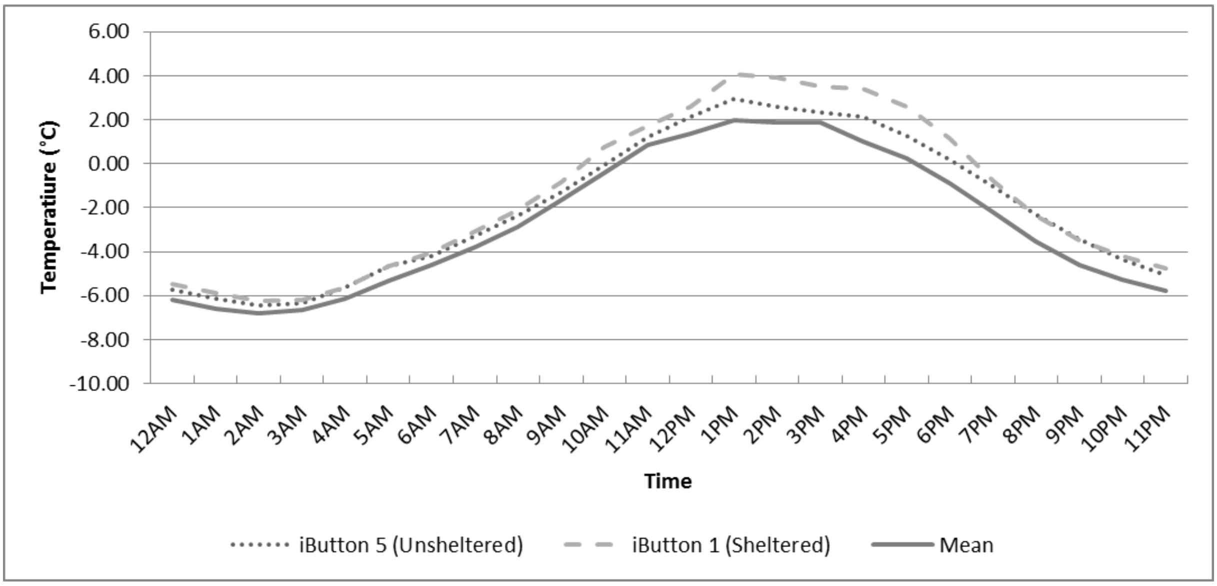

Figure 51: Mean daily temperatures (°C) of iButton 5 and iButton 1 on the Northern Buttress between 09/01/2014 and 25/01/2014.

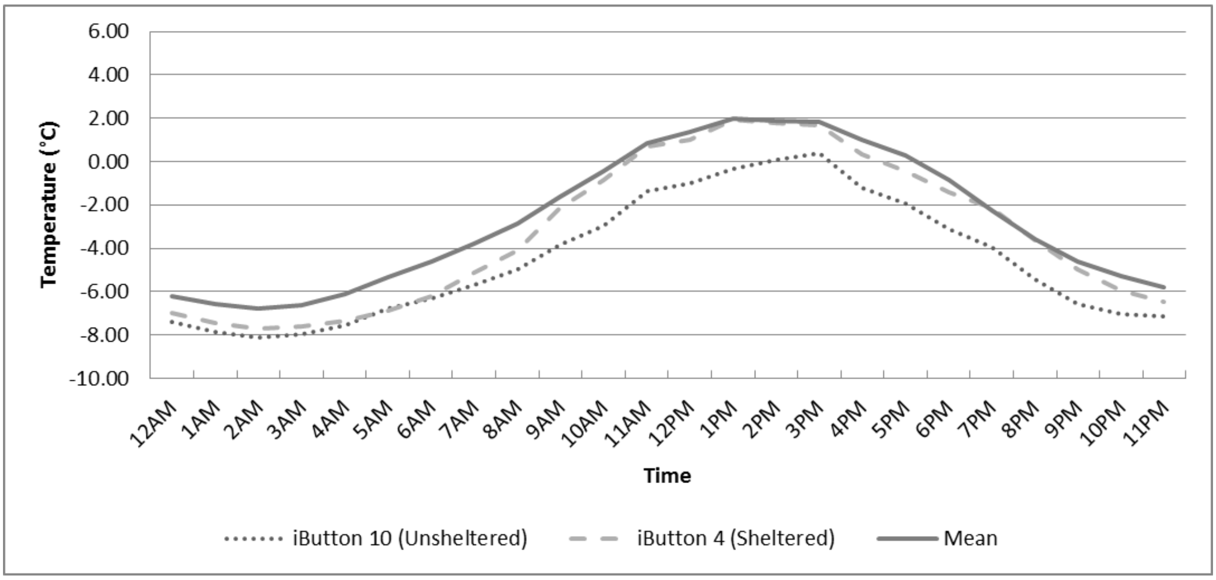

Figure 52: Mean daily temperatures (°C) of iButton 10 and iButton 4 on the Northern Buttress between 09/01/2014 and 25/01/2014.

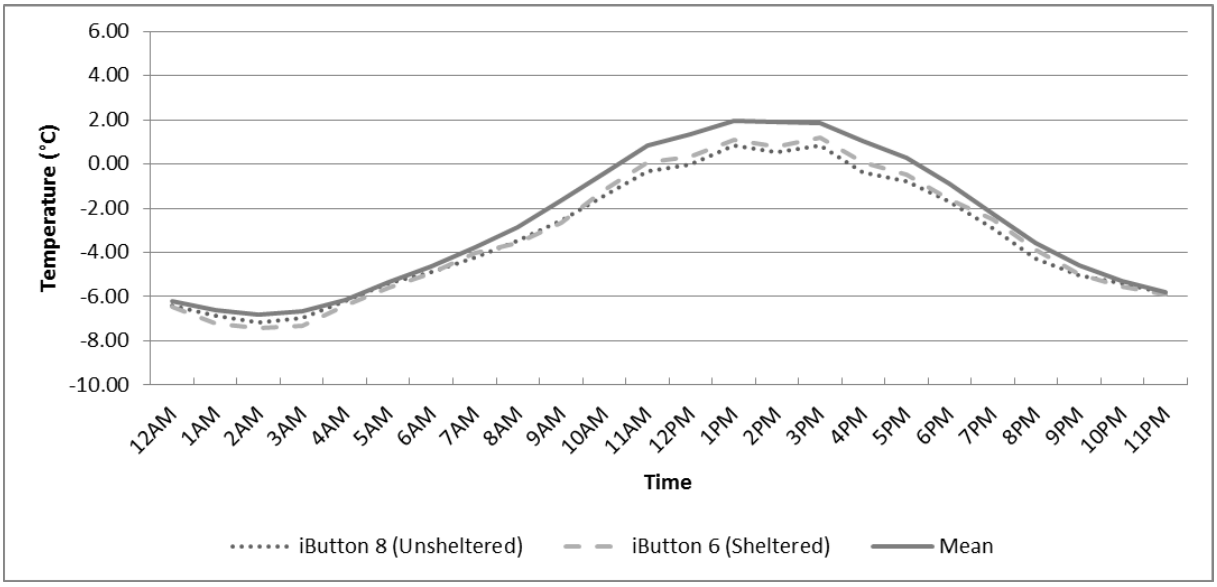

Figure 53: Mean daily temperatures (°C) of iButton 8 and iButton 6 on the Northern Buttress between 09/01/2014 and 25/01/2014.

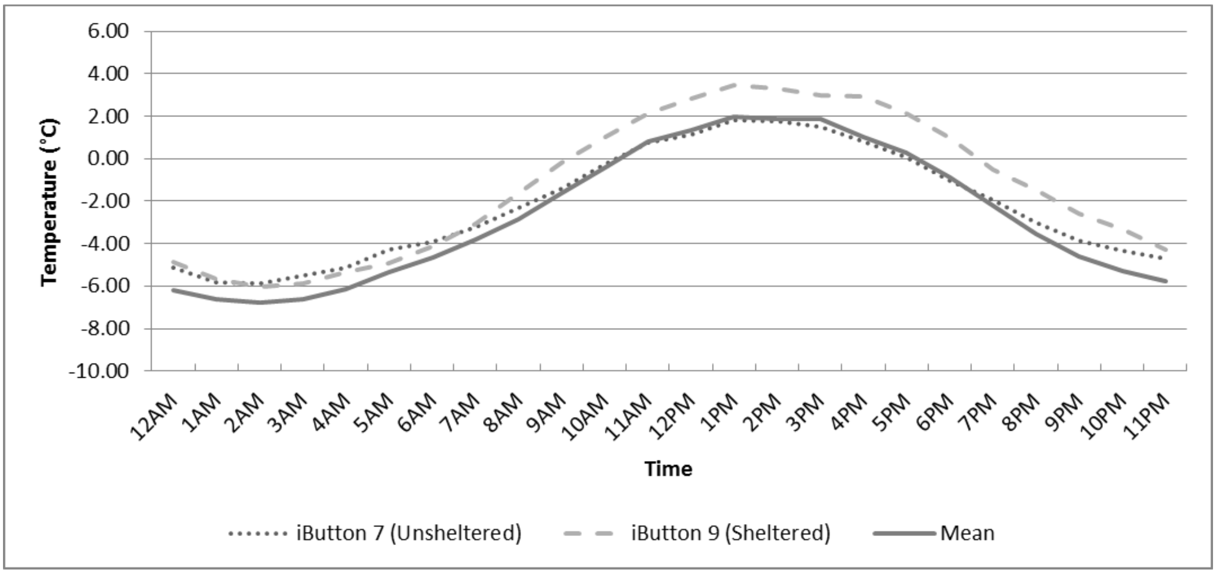

Figure 54: Mean daily temperatures (°C) of iButton 7 and iButton 9 on the Northern Buttress between 09/01/2014 and 25/01/2014.