Investigation of air and soil climate across the latitudinal and altitudinal gradient of the Ross Sea region of Antarctica

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Abstract

A soil climate station network in the Ross Sea region of Antarctica comprises; Cape Hallett (72.19°S, 2 m asl), Granite Harbour (77°S, 6 m asl), Victoria Valley (77.19°S, 408 m asl), Marble Point (77.25°S, 55 m asl), Bull Pass East (77.30°S, 833 m asl), Wright Valley (77.31°S, 155 m asl), Mt Fleming (77.32°S, 1690 m asl), Scott Base (77.50°S, 51 m asl), Minna Bluff (78.30°S, 28 m asl), and Darwin Glacier (79.50°S, 333 m asl). Variables measured include air and soil temperatures to 1.2 m depth, and wind speed and direction. The overall objectives of this study were to; investigate the trends in air and soil temperatures across latitudinal and altitudinal gradients from Cape Hallett (72°S) to Darwin Glacier (79.5°S), and from sea level to the edge of the Polar Plateau; quantify the cumulative number of days when air and soil temperatures were ≥0°C; and to analyse the wind data to characterise the wind regime at each site and to investigate storm events and diurnal patterns.

Mean annual air temperatures were, from warmest to coolest: Cape Hallett (-15.3°C), Granite Harbour (-16.6°C), Marble Point (-17.6°C), Darwin Glacier (-18.2°C), Minna Bluff (-18.3°C), Scott Base (-19.1°C), Wright Valley (-19.6°C), and Victoria Valley (-22.4°C). Two stations had a warming trend ($P<0.05$); Marble Point (in air, and in soil at 7.5 and 120 cm depth) and Granite Harbour (in soil at 5.5 cm depth). No significant trends of warming or cooling were observed at the Cape Hallett, Darwin Glacier, Minna Bluff, Scott Base, Wright Valley, Victoria Valley, or Mt Fleming sites. Shallow soil temperatures were warmer than air temperatures, apparently due to heating from solar radiation in summer, and snow insulation in winter.

The mean cumulative days/summer with air temperature ≥0°C ranged from: Wright Valley (33.3), Victoria Valley (22.3), Granite Harbour (10.4), Marble Point (9.7), Minna Bluff (7.6), Darwin Glacier (7.3), Scott Base (4.2), to Mt Fleming (0.0). In shallow soil (~5 cm depth), the mean cumulative number of days/summer with T≥0°C were: Wright Valley (69.8), Granite Harbour (69.6), Marble Point (55.5), Minna Bluff (52.8), Victoria Valley (50.2), Scott Base (34.6), Cape Hallett (32.2), to Mt Fleming (0.0). At the mid-depth soil (~20 cm depth), the overall cumulative numbers of days with T≥0°C were: Granite Harbour (65.5), Wright Valley (52.0), Marble Point (44.7), Minna Bluff (31.6), Cape Hallett (22.5), Scott Base (13.9), Victoria Valley (1.8), and Mt Fleming (0.0). There was no increasing or decreasing trend in the days with air or soil T≥0°C over the record period.

Mean annual wind speeds were: Darwin Glacier (45 kmhr^{-1}), Minna Bluff (42 kmhr^{-1}), Mt Fleming (29 kmhr^{-1}), Scott Base (17 kmhr^{-1}), Wright Valley (14 kmhr^{-1}), Marble Point (12 kmhr^{-1}), Victoria Valley (8 kmhr^{-1}), and Granite Harbour (7 kmhr^{-1}). The highest recorded mean hourly wind speed was 169 kmhr^{-1} at Minna Bluff in 2009. There was increasing wind speed with increased latitude (R^2=0.59), but no relationship between wind speed and altitude. Controls on wind speed and direction were likely to be a combination of altitude, latitude, local topography, and cyclonic storms.

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Chapter 1: Introduction

1.1 Why is Antarctic research important?

There is world-wide interest in the Antarctic climate and its relationship and response to global climate drivers. Viera *et al*. (2010) reported that "Antarctica contains 90% of the world's ice and exerts a predominant influence on the Southern Hemisphere and global atmospheric and cryospheric systems". Thus any change in the Antarctic climate may have far-reaching consequences.

The coldest mean permafrost temperature on Earth is likely to be in Antarctica (Viera *et al*. 2010), and in 2007 the International Panel for Climate Change (IPCC) predicted that by 2099 global temperatures could increase by as little as 1.1˚C or as much as 6.4˚C. Global temperature increase is expected to result in magnified climate change in the polar regions as the snow and ice melts (Convey *et al*. 2009). Melting reduces albedo by increasing darker portions of land relative to snow covered areas. Reduced albedo thus increases the land surfaces ability to absorb more radiation, exacerbating the heating process (Kane *et al*. 1991).

Support for the hypothesis that melting reduces albedo and leads to increased surface heating was highlighted by Turner *et al*. (2005), reporting that "the Antarctic Peninsula has experienced major warming over the last 50 years", however, others report that climatic warming over continental Antarctica is inconclusive, with periods of slight cooling and slight warming rendering the overall trend from 1998-2008 not statistically significant at the $P<0.05$ level in Southern Victoria Land (Guglielmin *et al*. 2011).

Little is known of soil climate in Antarctica and how it changes with altitudinal and latitudinal gradients. It is important to understand how the mechanisms of the Antarctic climate and subsurface thermal characteristics vary both spatially, and temporally, before trying to predict how the whole system will respond to global climate change. Longer records and more observations are needed to properly show any trends in inter-annual air temperatures (Adlam 2009; Zhou *et al*. 2009; Guglielmin *et al*. 2011). Eleven soil climate stations are installed in the Ross Sea region of Antarctica (Fig. 1.1), at a range of altitudes and latitudes, with a record period extending back to 1999. The soil climate stations form a network throughout the McMurdo Dry Valleys and surrounding area. Therefore, my research provides an opportunity to study Antarctic soil climate with more data than has ever before been available for both above-ground, and soil, climate parameters.

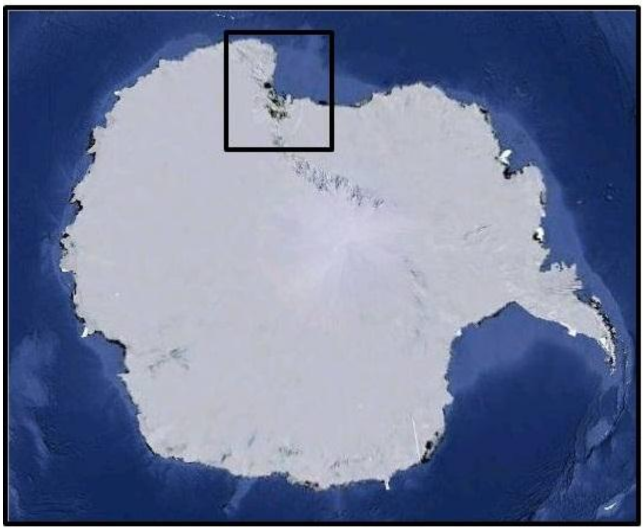

Fig. 1.1 The continent of Antarctica with the Ross Sea region, McMurdo Dry Valleys and surrounding areas where the soil climate stations are located highlighted by a black box.

My thesis utilises the data of K123 (http://www.antarcticanz.govt.nz/k123-environmental-protection-of-soils-in-the-ross-sea-region) supplemented with that from the Latitudinal Gradient Project (LGP) sites at Cape Hallett at 72.19˚S, and Darwin Glacier at 79.50˚S (www.lgp.aq).

1.2 Research objectives

The overall objective of my research was to investigate climate over the 12 year period from 2000-2011, both above-ground and within the soil, across a latitudinal gradient in the Ross Sea region of Antarctica and to analyse climate data parameters of importance to informing the Environmental Domains Analysis of Landcare Research.

The specific objectives of my research were to:

- investigate the trends in air and soil temperature across latitudinal and altitudinal gradients extending from Cape Hallett (72.19°S) to Darwin Glacier (79.5°S), and from sea level to the edge of the Polar Plateau,

- quantify the number of days with temperature ≥0°C at each site for air and soil, and

- analyse the wind data to characterise the wind regime at each site, and to investigate storm events and diurnal patterns.

Chapter 2: Literature review

2.1 Temperature trends

2.1.1 Background

The Earth's climate is of growing concern with focus on rising temperatures potentially leading to global sea level rise and increases in adverse weather conditions around the globe. Recognition of the strong link between the Earth's climate and surface conditions at high latitudes and the poles has long been realised (Justino *et al.* 2011). Increases in global surface air temperatures are predicted to be amplified in the polar regions due to enhanced feedback related to high albedo in the snow-covered polar regions (Comiso 2000).

The Antarctic continent and its surrounding ice sheets cover approximately 10% of the Earth's land surface area (Convey *et al.* 2009), making changes on the Antarctic continent of global consequence. Ice sheets and sea ice on and around Antarctica contain approximately 70-90% of the world's fresh water store (Convey *et al.* 2009, Justino *et al.* 2011), and so research into Antarctic, and global climate is essential to further understand Antarctic climate dynamics.

Ice covers over 99.6% of the continent and can be divided into three distinct glaciological zones; the East Antarctic Ice Sheet (EAIS), the West Antarctic Ice Sheet (WAIS), and the Antarctic Peninsula (Fig. 2.1).

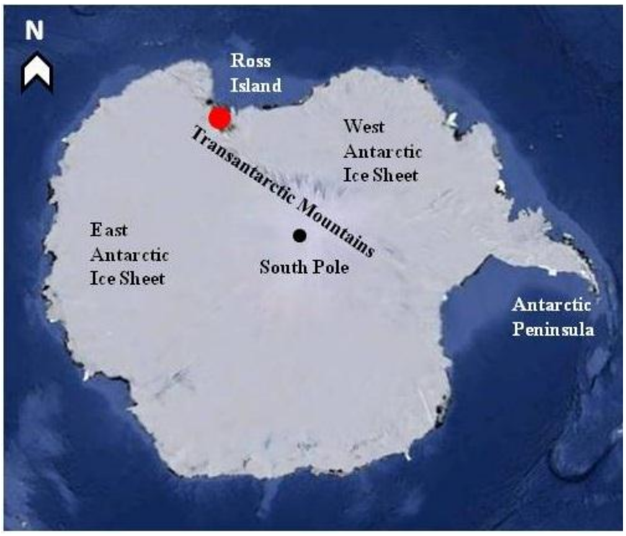

Fig. 2.1 Location map showing major features of the Antarctic continent (adapted from Google Earth).

The EAIS is at a higher altitude and contains the Polar Plateau, whilst the WAIS is at lower elevation. The two glaciological zones are separated by the Transantarctic Mountains. The Antarctic Peninsula is a thin spine of land ~70 km in width that extends north beyond the Antarctic Circle, and is apparently affected by oceanic climate processes more than those climatic factors affecting the rest of the continent (Monaghan & Bromwich 2008, Convey *et al.* 2009).

The Antarctic continent (with the exception of the Antarctic Peninsula) lies within the Antarctic Circle, and is therefore subject to 24 hours of daylight at the summer solstice in December, and 24 hours of darkness at the winter solstice in June (Convey *et al.* 2009).

Antarctica is a cold, remote continent, with extreme variations in climate. Permanent inhabitation is rare, and restricted to base locations, mainly around the continent edge. The inhospitable climate means that human exploration in Antarctica is a recent phenomenon, with only sporadic excursions to the interior of the continent during the first half of the twentieth century, with no record of consistent or long-term environmental data (Monaghan & Bromwich 2008, Convey *et al.* 2009). Antarctica is a cold desert, due to extremely low precipitation in the continental interior. Antarctica as a whole is the coldest, windiest and highest (mean altitude of 2000 m asl) continent on earth, with the coldest ever surface temperature recorded at the Russian Vostok station on the Polar Plateau of -89.28ºC (Convey *et al.* 2009).

From the latter half of the twentieth century to today, studies (e.g. Chapman & Walsh 2007 and Schneider *et al.* 2012) have shown warming patterns over parts of Antarctica, principally the Antarctic Peninsula and coastal regions of the continent. The sites of identified warming are biased towards climate station localities which are predominantly situated on the coast and Antarctic Peninsula (Monaghan & Bromwich 2008). Data from climate stations within the continent's interior are sparse and non-continuous (Chapman & Walsh 2007). Antarctic climate varies on a range of timescales from sub-annual through to orbital (Milankovitch cycles), and whilst isolated, is coupled to the global climate system (Convey *et al.* 2009).

The McMurdo Dry Valleys (Dry Valleys) region, whilst small in comparison to Antarctica as a whole, is the largest ice-free area on the Antarctic continent (Doran *et al.* 2002b, Bertler *et al.* 2004), and has an area approximating 4800 km^2 (Doran *et al.* 2002a). The Dry Valleys are located west of McMurdo Sound at the edge of the Transantarctic Mountains (Bertler *et al.* 2004).

2.1.2 Global trends

On average, the Earth's surface temperature has risen at a rate of 0.06°C per decade from satellite observations measured from 1979 – 2001, contrasting with an overall measured surface temperature increase of 0.25°C over the same time period (Lindzen & Giannitis 2002). Conversely, a global air temperature warming trend of 0.15 – 0.20°C per decade since the late 1970's to 2010 was reported by Hansen *et al*. (2010), whilst Comiso (2000) reported that global temperature records have had an overall increase of 0.57°C from 1961 to 1997, with a slightly larger increase in the Southern Hemisphere compared to the Northern Hemisphere.

Warming of the Earth's climate system have magnified effects at the polar regions and may be perceptible more rapidly at the poles than at the tropics (Convey *et al*. 2009). Amplified warming, as predicted in climate models, was apparent in the strong warming pattern of the Antarctic Peninsula during the second half of the twentieth century where warming was at a faster rate than at lower latitudes. Warming of the Antarctic Peninsula does not, however, match the spatial analysis of the Antarctic continent from 1966 to 2000 which indicates a slight net cooling (Doran *et al*. 2002b).

Warming in Antarctica has a seasonal pattern that matches the Northern Hemisphere landmasses, where warming is greatest in the winter and weakest from late spring through to the summer months (Chapman & Walsh 2007). Warming of the continent has not been found to be statistically significant, with cooling trends during the spring and summer months (Doran *et al.* 2002b). The McMurdo Dry Valleys, for the period 1986-2000, were found to be cooling at a rate of 0.7°C per decade with similar seasonal trends as continental Antarctica (Doran *et al.* 2002b).

Whilst the whole of Antarctica is sensitive to climate change, the Antarctic Peninsula in western Antarctica is most vulnerable as mean annual temperatures are already close to the melting point (0°C), and any further increase will exacerbate snow and ice melt (Comiso 2000). However, as mean annual air temperatures in the Ross Sea region are well below 0°C, small increases in temperature are not likely to have large impacts on ice and snow melt.

2.1.3 Circulation patterns

Atmospheric circulation patterns around and on the Antarctic continent contribute to Antarctic climate variability. For example, climatic patterns can migrate to Antarctica from the tropics by transportation across the ocean and through the atmosphere (Convey *et al.* 2009). El Niño Southern Oscillation (ENSO) can increase surface temperatures around the Admundsen and Bellinghausen Sea regions, reducing sea ice. Conversely, El Niño is correlated with reduced temperatures in the western Ross Sea and Weddel Sea region and increased sea ice extent. El Niño was not found to reflect cooling of regional temperatures, but acts to alter regional atmospheric circulation which leads to an apparent regional cooling (Bertler *et al.* 2004).

The Southern Hemisphere Annular Mode (SAM) is another example of climate variability that affects climate from the equator to the pole. SAM is a circumpolar wind pattern whose strength and intensity migrate between the mid-latitudes and the poles over a wide variety of timescales in a non-periodic manner (Convey *et* *al.* 2009). The SAM causes climatic variability over the Antarctic by altering geostrophic flow around the continent; weakening sensible heat exchange over the surface of the continent whilst simultaneously increasing warm NW winds over the Antarctic Peninsula. Whilst the cause of the SAM is unclear, the effect of the SAM on climate in Antarctica may be enhanced by depletion of the ozone hole (Monaghan *et al.* 2008). The greatest change in SAM recorded in Antarctica is during the summer and autumn months. Atmospheric circulation is at its strongest also during the summer and autumn months as the effects of the ozone hole move down through the atmosphere and with corresponding increases in atmospheric circulation around Antarctica at low enough levels to interfere with surface temperature patterns (Monaghan *et al.* 2008; Convey *et al.* 2009).

When the SAM is in a positive phase over continental Antarctica, the air pressure is lower and temperatures are cooler over the continent, but warmer over the Antarctic Peninsula (Monaghan & Bromwich 2008, Monaghan *et al.* 2008). The converse is true when the SAM is negative over the Antarctic. The SAM has become more positive over the last 50 years over the Antarctic coast, resulting in a continued drop in air pressure and may be contributing to the recorded small decrease in temperature over the continent (Convey *et al.* 2009).

2.1.4 Antarctic trends

Convey *et al.* (2009) reported that data gathered from automatic climate stations and satellite information, when interpolated into regions with sparse or no information (e.g. West Antarctica), revealed that the West Antarctic region shows the most significant warming (apart from the Antarctic Peninsula) of ~0.18°C per decade, with most warming occurring in the austral winter and spring months since the 1970’s (Schneider *et al.* 2012), and most negative trends (some cooling) in the austral summer and autumn in East Antarctica (Schneider *et al.* 2012). Convey *et al.* (2009) also reported that there had been slight cooling recorded on climate stations around East Antarctica since 1980, with a possible link to ozone depletion.

Whilst only slight to negligible cooling of the Antarctic continent, and warming of the Antarctic Peninsula has been identified (Schneider *et al.* 2012), results are based upon sparse climate stations preferentially located around the Antarctic continents edge and the Antarctic Peninsula, and microclimates caused by topography can result in adjacent stations recording conflicting climatic conditions (Comiso 2000, Schneider *et al.* 2012). Sparseness of climate station information also accounts for the ambiguity between authors of identified Antarctic climate trends. Comiso (2000) reported that trend results are meaningless if the record length is less than 10 years due to seasonal and decadal fluctuations.

Diurnal trends are most apparent in summer, despite 24 hour sunlight, with the greatest temperature gradient between 'night' and 'day' due to the angle of the sun in the sky, with continent-scale averaged temperature differences of about 5°C (Comiso 2000). The positioning and location (surrounding topography) of the climate stations have a strong influence on recorded temperatures, depending on ranges or mountains that may block the sun from the AWS for a significant amount of time. During winter, the temperature difference between 'night' and 'day' is almost zero (Comiso 2000). The coldest mean monthly air temperature occurred in September, indicating that there is a time lag for surface cooling. The warmest mean monthly air temperature occurred in January, indicating little to no lag time for surface heating, whilst a heating lag increases with depth below the surface (Comiso 2000).

2.1.5 McMurdo Dry Valleys temperature trends

The Dry Valleys range in elevation from near sea level to more than 2000 m ASL, and are termed a 'cold desert' due to low precipitation levels. Ephemeral streams, ice-covered lakes, glaciers, exposed bedrock and arid soils are all present (Doran *et al.* 2002a, 2002b).

Doran *et al.* (2002b) reported a mean annual temperature of -14°C at Lake Hoare, and -30°C at Lake Vida, a difference of 16°C over a distance of less than 100 km (Doran *et al.* 2002a). The Dry Valleys run perpendicular to the edge of the Polar Plateau and are adjacent to McMurdo Sound. Due to their location, the Dry Valleys are susceptible to multiple temperature regimes that impact the climate in the region. Relatively warm, humid air reaches the Dry Valleys from the Ross Sea region, cold dry air migrates from the East Antarctic Ice sheet, and air masses flow from the Ross Ice Shelf system which is at low elevation all interact with the

Dry Valleys. Thus, multiple temperature factors influence climate in the Dry Valleys (Bertler *et al.* 2004).

The Transantarctic Mountain range acts as an orographic barrier for further migration of weather systems. Therefore, any change in the three air mass transport systems outlined above will have an amplified effect on the Dry Valleys, making the Dry Valleys an excellent location for monitoring climatic changes (Bertler *et al.* 2004).

Wind is a strong climatic influence on temperatures at individual sites within the Dry Valleys, with distance to the coast and the dry adiabatic lapse rate being of less importance (Doran *et al.* 2002a, 2002b). Cooling trends in the Dry Valleys show significant correlation with increased clear-sky conditions whereby less cloud cover enables more long-wave radiation to be lost from the near-surface. A decrease in wind is also linked to decreasing temperatures as onshore winds during the summer, and katabatic wind patterns during the rest of the year transport relatively warmer air to the Dry Valleys. Katabatic wind patterns make the prediction of future mean annual temperatures in the Dry Valleys difficult based on geographical positioning alone (Doran *et al.* 2002a, 2002b).

There is an east-west temperature gradient in the Dry Valleys during the summer, and the Dry Valleys experience warmer summers and cooler winters than McMurdo Station on Ross Island (~60 km away). There is a south-north progression in mean annual temperature relationships of the Dry Valleys: Taylor Valley>Wright Valley>Victoria Valley from 1985-2000 (Doran *et al.* 2002a). Correlations between air and soil temperatures with altitude were reported by Adlam (2009), however, no strong link between latitude and temperature patterns was reported by Adlam (2009).

Victoria Valley is bowl-shaped, as is Wright Valley, with their lowest points in the centre of the valleys. Both valleys have drainage pathways at higher altitudes where katabatics can flow downhill into the valley and not completely through the valley. Air within the Victoria and Wright valley basins therefore receive less katabatic warming than Taylor Valley, and Lake Vida in Victoria Valley commonly reaches temperatures below -50°C (Doran *et al.* 2002a).

A network of soil climate stations was installed throughout the McMurdo Dry Valleys in 1986 by the Long-Term Ecological Research (LTER) project. Data from the McMurdo Dry Valley stations contributed to the conclusion that Antarctica was cooling (Doran *et al.* 2002a). The soil climate station data showed cooling with a seasonal signature of 0.7°C per decade (Doran *et al.* 2002a). Adlam (2009) analysed data from automatic soil climate stations within the McMurdo Dry Valleys region from 1999 to 2007 for air and soil temperature measurements and found no significant warming or cooling temperature trend.

A climate station positioned at Lake Hoare indicated that seasonally averaged near-surface temperature decreased by 0.7°C per decade from 1986 to 1999. Winter and spring showed the smallest decrease; conversely, autumn and summer showed the largest decrease in air temperatures compared to other seasons. Seasonally averaged wind speeds correlated with a seasonal decrease with the near-surface temperatures for 1986-1999 (Doran *et al.* 2002b).

2.1.6 Surface station data

Antarctic station data is collected by either automatic or manned climate stations. AWS's are more likely to fail due to adverse and extreme weather conditions, and with no-one to conduct repairs, months, to years of data can be lost. Manned climate stations, therefore, tend to be more accurate. The cost of maintaining a constant presence in Antarctica is substantial, and so automatic climate stations are being installed to compliment the manned sites. The lower relative cost of automatic climate stations means that more sites can be installed and a greater coverage gathered (Comiso 2000).

Soil temperature measurements from climate stations may sometimes need careful interpretation. Snow cover over the ground at a climate station may insulate the underlying soil and act as a buffer against changing air temperatures (Guglielmin 2004).

2.1.7 Satellite data

Satellite data provides a way of gathering information over the vast interior of the Antarctic continent where there are few or no stations that can collect climate information. However, satellite information, at present, is strongly biased towards clear-sky conditions which are generally cooler and can therefore give misrepresentative readings (Comiso 2000).

2.1.8 Timescale

The time-period for data collection is vital for interpretation of the data. Trends analysed over the Antarctic continent beginning prior to 1965 (to 2002) are found to be generally positive, that is, show a warming trend (Monaghan & Bromwich 2008). After 1965 (to 2002), temperature trends are mostly negative (cooling) (Monaghan & Bromwich 2008). Thus, there appears to be decadal variability overlying shorter time-scale annual-seasonal variability. Comiso (2000) reports that the mean annual temperatures from 21 stations covering Antarctica over 45 years revealed that 17 stations had positive (warming) trends, whilst only four had negative trends. In contrast, the same stations over a shorter, 20 year period, recorded that only nine stations had a positive trend whilst the remaining 12 had negative trends. From these trend analyses, Comiso (2000) put forward that trend analyses fluctuate significantly for periods of less than 10 years, have some fluctuation for 10-20 year periods, and are generally stable for timescales over 20 years.

In Antarctica, many climate stations have only recently been installed and therefore long-term trends are not yet available. Whilst time scales of analyses vary, the data collection time period is important when considering temperature trends in Antarctic data (Doran *et al.* 2002b).

2.2 Wind patterns

2.2.1 Introduction

Winds in Antarctica are not always small isolated events, Antarctic winds have been linked to controlling climate in the continent, moving ice and snow around the ground surface, opening polynyas and altering the Southern Ocean composition (Renfrew & Anderson 2006).

The ice surface of Antarctica absorbs long-wave solar radiation, and radiates thermal energy back to the atmosphere. This thermal energy is responsible for an almost constant temperature inversion over the continent (Parish 1988). The temperature inversion develops over gently sloping interior continental terrain and forms a sloped-inversion pressure gradient force. The pressure gradient force is the main driver for Antarctic slope flows, and results in Antarctic wind flows having high ($\geq$0.80) directional consistency values and high wind speeds (Parish & Bromwich 1986, King 1989) and results in almost year-round katabatics flowing off the Antarctic continent (Baines & Fraedrich 1989).

In addition to radiational cooling and pressure gradient forces, the surrounding topography and orographic features are important in controlling the frequency and direction of near-surface winds (Parish & Bromwich 1986, Argentini *et al.* 1995, Monaghan *et al.* 2005). Topographic control is highlighted by large areas of air flow confluence at the continental exterior which are marked by scouring of the ice and snow, polynyas in the sea ice and sastrugi patterns in snow. Converging air produces an anomalously large air supply which intensifies katabatic flows (Liu & Bromwich 1997).

The strong persistent surface winds of Antarctica, whilst unique to the continent, are not isolated on a global scale. The surface winds are part of a thermally direct circulation that moves equator-ward and links to equator-ward surface winds (Liu & Bromwich 1997). The surface winds in Antarctica are not thought to be large-scale, or to generate synoptic systems (Baines & Fraedrich 1989).

2.2.2 On-ground or satellite observations

Satellite surface wind observations are able to cover large spatial areas, over terrain that would be otherwise logistically inaccessible (Bromwich 1989a, King *et al.* 1998). However, satellite observations are restricted to clear-sky conditions (Comiso 2000) which can impose a significant bias on the reportable results. The benefit of satellite wind observations using thermal infrared imagery (TIR) increases when a polar-orbiting satellite data is combined with automatic weather station (AWS) data that is collected in-situ at individual locations (King *et al.* 1998).

AWS are generally able to collect detailed year-round data including surface winds. Many equipment failures are encountered due to the exceptionally harsh Antarctic climate; however, AWS data are the primary data source for katabatic flow studies (Renfrew & Anderson 2006). A significant limitation for the use of AWS data in katabatic wind flow studies was reported by Renfrew & Anderson (2006) as the height of the AWS station, usually not exceeding 3 m. This height restriction limits wind observational studies to the near-surface winds only.

2.2.3 What is a katabatic wind?

"Katabatic" is the term used to describe winds flows caused by radiative cooling on ice slopes of near-surface air that develops a near-surface inversion layer (Bromwich *et al.* 1994, Argentini *et al.* 1995, Davolio & Buzzi 2002, Parish & Cassano 2003b). Katabatic winds are intense winds that are topographically channelled and converge over steep coastal slopes. In narrow glacial valleys, the enhanced supply of cold dense air is a key feature of katabatic winds (Bromwich *et al.* 1994, Davolio & Buzzi 2002).

Winds in Antarctica tend to be gravity driven, forming on the high Polar Plateau and descending down to the coastal margins at the edge of the continent. Katabatic winds flow downslope but are not necessarily a downslope flow (Parish & Cassano 2003, Knuth & Cassano 2011). Downslope and katabatic winds are often mistaken, yet it is important that the two flows are differentiated.

Katabatic flow has been described as that which flows downslope as a mass of radiatively cooled air that is denser than surrounding air masses (Parish & Cassano 2003). Due to the domed topography of the Antarctic continental interior (Renfrew & Anderson 2006), radiative cooling is reported by Renfrew & Anderson (2006) and Knuth & Cassano (2011) to be greatest during the winter as thermal energy is lost from the ground surface in the form of long-wave radiation (Parish & Bromwich 1989, Renfrew & Anderson 2006). Cooling of the snow surface generates a strong surface temperature inversion which induces a pressure gradient force directed downslope to a lower pressure area. General down-slope flow is characterised by not having the radiatively cooled, dense pocket of air, and can be generated by a number of factors, including storm events (Parish & Cassano 2003).

Katabatic flows descending from the Polar Plateau are also identified by increased air temperature, despite having a lower bulk air temperature from radiational cooling due to significant mixing of the turbulent air above and decreased humidity linked with fast wind speeds. The relatively slow progression speeds of katabatic events moving through a region are a further indicator of high air turbulence within the flow. The swift onset and decay of katabatic flows are not reflected in air temperatures. Air temperatures that have increased due to the katabatic passage can remain elevated for days following the wind event (King *et al.* 1998, Doran *et al.* 2002a, Nylen *et al.* 2004).

Parish & Cassano (2001) made it clear in their report that it is not possible to determine whether a flow is downslope or katabatic from wind measurements alone, whilst Knuth & Cassano (2011) stated that knowledge of the thermodynamic evolution of Antarctica's near surface air is needed to sufficiently identify katabatic flows, which isn't possible from current limited surface wind speed data.

Katabatic winds have long been reported (for example, Kodama & Wendler 1986, Parish 1988, Bromwich *et al.* 1994, Bromwich & Liu 1996, Davilo & Buzzi 2002) to be a significant wind feature in Antarctica's lower atmosphere. Katabatic winds have been found to dominate coastal margins (Davilo & Buzzi 2002) where internal continental air drainage converges in channels near the coast and flows out to sea, where the fastest persistent strong flows are often observed (Bromwich *et al.* 1994, Davilo & Buzzi 2002).

Katabatic flows cause strong winds blowing down off the high continental interior down to the coast that have been reported (Renfrew & Anderson 2006) to be a contributor in the formation of polynyas – areas of open water in an otherwise frozen water body – which impact on the thermohaline circulation and water mass movements in the southern coastal ocean.

Kodama & Wendler (1986) stated, when referring to the importance of katabatic flows in Antarctica that they didn't know of any other single meteorological parameter that could impart a continental-scale effect on the climate like the Antarctic katabatic wind flows do. Katabatic winds are also reputed to play an important role in the meteorology of the high southern latitudes and contribute to southern hemisphere atmospheric circulation (Liu & Bromwich 1997, Renfrew & Anderson 2006).

Katabatic winds are strongly influenced by ice topography and the orientation of the continental interior (Bromwich *et al.* 1990, Bromwich *et al.* 1994). Cooling of katabatic air masses causes a density differentiation between the katabatic and surrounding air. The denser katabatic air flows downslope, driven by the sloped-inversion force (Davolio & Buzzi 2002) as a pressure gradient force is established down the sloping terrain (Parish & Cassano 2003b).

Katabatic flows, once initiated, do not always flow consistently. Sudden decay of katabatic winds at one location followed by the continuation of wind flow further down-slope is termed a katabatic jump, or Lowes Phenomenon, and was observed by Doran *et al.* (2002a) in the McMurdo Dry Valleys during wind investigation from 1986-2000. Katabatic wind decay is often associated with a rapid air pressure change (Gallee *et al.* 1996).

2.2.4 Foehn winds

Foehn winds result from the modification of air flow from topographic barriers such as mountains. Wind modification in the lee of mountain ranges generates strong foehn winds with rapid air temperature rises. Speirs *et al.* (2010) reported that strong warm foehn wind events are a regular occurrence in the McMurdo Dry Valleys, and can have a strong impact on landscape forming processes within the valleys (Speirs *et al.* 2010). At the time of writing, I have found no other scientific investigation into foehn winds in the McMurdo Dry Valleys

Foehn winds in the McMurdo Dry Valleys were reported by Speirs *et al.* (2010) as south-westerly winds with speeds over 5 ms^{-1} and an air temperature warming of at least 1°C per hour and a corresponding drop of relative humidity of more than 5% per hour.

2.2.5 Summer and winter winds

Summertime katabatic wind events are less frequent, and exert less control on weather patterns than those during the winter months, when katabatic winds are most frequent (Doran *et al.* 2002a, Nylen *et al.* 2004). Due to the reduced number of katabatics and storms during summer, air temperatures generally track a predictable pattern following the dry adiabatic lapse rate, with air temperatures increasing approximately 1°C for every 1 km that the air moves inland. The air flows also cool at the dry adiabatic lapse rate as the air masses increase in elevation (Doran *et al.* 2002a). Onshore winds dominate during summer bringing airflows through the McMurdo Dry Valleys (Doran *et al.* 2002a).

Summer katabatic wind events increase by 3% for every 10 km progression up valley towards the ice sheet, whilst wintertime wind events were reported to increase by 14% for every 10 km progression up valley towards the ice sheet (Nylen *et al.* 2004). A 13 year record at Lake Hoare from 1989-2001 reported by Nylen *et al.* (2004) found that the frequency of katabatic wind events was lowest during summer (December) with katabatics recorded only 4% of the time compared to 26% in winter (July) for the same record period. A higher percentage of strong winter-time wind events were reported by Knuth & Cassano (2011) in the Terra Nova Bay region for the record period 1993-2007, with winter experiencing 68% of the annual strong wind events compared with only 4% in the summer. Average summertime katabatic wind speeds were also reported to be slower (6.5 ms^{-1}) than wind events during winter (9.0 ms^{-1}) (Nylen *et al.* 2004). Katabatic winds were determined by Nylen *et al.* (2004) as being strong unidirectional winds.

Wintertime katabatic surface wind circulation was reported to be strongest during the winter months when surface cooling is greatest (King *et al.* 1998, Knuth & Cassano 2011), and wind patterns show high directional consistency related to katabatic wind flow (Parish & Cassano 2003). Winter wind speeds were reported to be high and generally consistent once established from mid-February (Bromwich 1989b), and katabatics in the Terra Nova Bay region were found to be well defined between the months of January and June (Bromwich 1989b). However, Doran *et al.* (2002a) reported that strong katabatic winds are not uniform across all areas, causing large spatial variations in mean annual temperatures due to localised temperature warming from katabatic wind events such as in the McMurdo Dry Valleys.

Wintertime wind events were reported (Nylen *et al.* 2004) to increase local air temperatures by as much as 30°C. Winter katabatics were reported to have a large controlling factor on winter air temperatures, with a 1% increase in katabatic wind activity increasing local air temperatures by 1°C, a rate that exceeds dry adiabatic lapse rates and overrides topographic and elevation effects (Nylen *et al.* 2004).

Knuth & Cassano (2011), reported an anomalously large number of strong wind events (≥20 ms^{-1}) in the Terra Nova Bay region during September 2009, with 39% of winds classed as strong compared to 14% of strong wind events recorded during the month of September between 1993-2007.

Whilst most published literature reports the wintertime maximum occurrence of katabatic winds, Speirs *et al.* (2010) reported that foehn wind events were more common during winter months, possibly due to a decrease in synoptic activity during the summer in the Ross Sea region.

2.2.6 Diurnal wind speed variations

Parish *et al.* (1993) reported that during the summer, katabatic wind speeds decreased at mid-day. However, an earlier report by Bromwich (1989b) stated that during late summer (February), automatic weather stations recorded maximum diurnal wind speeds at about 6 am, with minimum wind speeds at 7 pm for the Terra Nova Bay area 1984-1985. Bromwich (1989b) also reported that the fastest wind speeds occurred at the same time the lowest air temperatures were recorded, but there was an offset of approximately 4 hours between the maximum air temperature and minimum wind speed.

2.2.7 Winds in the Ross Sea region and McMurdo Dry Valleys

In the Ross Sea region, Bromwich *et al.* (1994) reported that katabatic airflows originated mainly from glaciers flowing through the Transantarctic Mountains from East Antarctica, with Byrd Glacier having the greatest contribution, and from West Antarctica. However, Speirs *et al.* (2010) suggested that winds in the McMurdo Dry Valleys are actually predominantly foehn winds, and originate from topographically modified south-westerly air flow originating from higher levels. Speirs *et al.* (2010) also proposed that foehn winds in the McMurdo Dry

Valleys are caused by cyclonic activity over the Ross Sea and subsequent strong winds in the Transantarctic Mountains.

Katabatic winds in the Ross Sea region were found to be able to cover large distances (>1000 km) with favourable synoptic conditions (Bromwich *et al.* 1992). The persistence of katabatic winds over long distances in the Ross Sea region was reported by Bromwich *et al.* (1994) calculated from 24 hour clear-sky wintertime numerical simulations. The katabatics were fed and sustained by cold interior air drainage to the coast and had important impacts on the airflow patterns over the Ross Ice Shelf which lies adjacent to the Transantarctic Mountains, and affects the McMurdo Dry Valleys climate (Nylen *et al.* 2004).

Despite the katabatics having similar origins, the response of each of the Dry Valleys varies with wind strength, time, and thermal characteristics. Therefore, accurately predicting the behaviour, onset, and decay of katabatic wind events in the McMurdo Dry Valleys, and throughout Antarctica, with the added component of often complex local topography changing and funnelling winds from a number of directions, is difficult (Davolio & Buzzi 2002). For example, between 1986 and 2000 the wind in the Wright Valley had bimodal directional components with light prevailing winds having coastal origins and flowing up-valley from McMurdo Sound. Stronger katabatics in the Wright Valley however flow down-valley from the Polar Plateau to the south-west (Doran *et al.* 2002a).

Doran *et al.* (2002a) hypothesised that as Victoria Valley, the northern-most of the McMurdo Dry Valleys, is slightly bowl-shaped, as with Wright Valley, the topography facilitates the formation of a pool of cold air to settle into the valley resulting in air temperatures dropping to below -50°C during winter. This cold cell of air remains in the valley floor and is only disrupted or mixed by strong katabatic or storm winds that can destroy the strong temperature inversion. Speirs *et al.* (2010) put forward an alternative hypothesis for sudden strong temperature changes in the Dry Valleys; they suggested that the sudden onset of foehn winds can increase air temperatures by as much as 40°C within a few hours during winter. Speirs *et al.* (2010) explained the rapid and extreme temperature rise as foehn air flow displacing cold stable air in the valley floors with adiabatically warmed air from higher levels.

The presence of hydraulic jumps in katabatic wind patterns within the Dry Valleys has also been postulated to be the result of foehn wind reaching down-valley sites before up-valley sites due to wind flow deflection through mountain passes and by the sharp-angled valleys themselves (Speirs *et al.* 2010).

Katabatics in the McMurdo Dry Valleys also play a role in maintaining the Dry Valleys as an extreme polar desert (Fountain *et al.* 2010).

2.3 Summary and conclusion

Contradictions in the presence, and amount, of warming or cooling over the Antarctic continent are found throughout the published literature, resulting from the use of different sampling methods, time-scales, locations, and sparseness of available data. Despite ambiguity in temperature results between authors, there is a strong underlying theme behind their research; it is widely accepted that any global climate warming is likely to be amplified at the poles, and as Antarctica stores 70 to 90% of the world's fresh water in ice, warming, and subsequent melting of the ice would have global consequences.

Adlam (2009) reported no short-term warming or cooling temperature trends within the Ross Sea region. My research builds upon Adlam's work to incorporate climate data to 2011 with the aim of providing more comprehensive knowledge of short-term air and soil temperature trends in the Ross Sea region of Antarctica.

Much ambiguity surrounds wind behaviour and causes for wind events in and around the Antarctic continent. Four main wind types are identified in the literature; katabatic, foehn, down-slope (gravity), and storms, but clear definition on classifications are generally unavailable. My research will aim to characterise the general wind pattern behaviour throughout the Ross Sea region, over seasonal and annual time-frames, and will also look at storm events.

Chapter 3: Site descriptions and Bull Pass East site installation

3.1 Introduction

This chapter gives site descriptions of the soil climate station network. Site and soil descriptions for Cape Hallett and Darwin Glacier are provided as they have not previously been published. Methods of data collection are included, along with installation information for the Bull Pass East site, which was established in January 2012. A brief overview of maintenance works conducted during the January 2012 fieldwork is also provided.

3.2 Soil climate station locations

Eleven soil climate stations (Fig. 3.1 & Table 3.1) are situated to provide coverage of the range of soil/landscape positions in the ice-free regions of the Ross Sea region of Antarctica.

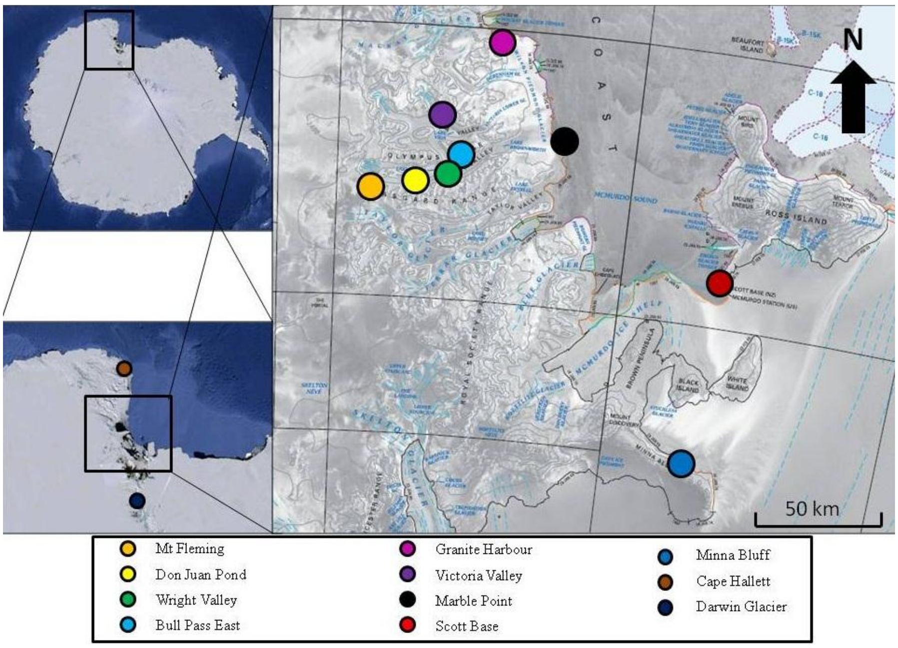

Fig. 3.1 Location map of soil climate stations in the Ross Sea region. Base map from Ferrigno *et al*. (2010) and Google Earth.

The automated soil climate stations (Table 3.1) collect data on soil temperature, soil water content, air temperature, relative humidity, wind speed and direction, solar radiation and soil electrical conductivity. Measurements for above-ground variables are taken every 10 minutes, while soil variables are taken every 20 minutes. Data are averaged and recorded over hourly intervals. The data are stored on Campbell data loggers at site and downloaded annually.

Table 3.1 Location and elevation (m ASL) information for the 11 automated soil climate stations in the McMurdo Sound region.

Station	Latitude (°S)	Longitude (°E)	Elevation (m asl)	Installed
Darwin Glacier	79°50'11.3"	159°19'12.2"	333.0	Nov 2004
Minna Bluff	78°30'41.6"	166°45'58.3"	28.4	Jan 2003
Scott Base	77°50'53.9"	166°45'38.1"	50.9	Jan 1999
Don Juan Pond	77°34'26.0"	161°14'19.6"	734.3	Jan 2011
Mt Fleming	77°32'42.8"	160°17'24.6"	1689.5	Jan 2002
Wright Valley	77°31'06.2"	161°51'55.7"	155.1	Jan 1999
Marble Point	77°25'10.5"	163°40'57.1"	55.2	Jan 1999
Victoria Valley	77°19'51.4	161°36'02.5"	408.1	Jan 1999
Granite Harbour	77°00'23.5"	162°31'32.8"	6.0	Jan 2003
Bull Pass East	77°30'7.9"	162°03'53.2"	832.7	Jan 2012
Cape Hallett	72°19'	170°16'	2.0	Jan 2002

3.3 Methods

3.3.1 Introduction

Data for 2011 were downloaded from the 10 soil climate stations within the Ross Sea region of Antarctica in January 2012. Data from Victoria Valley, Wright Valley, Scott Base, Granite Harbour, Marble Point, Minna Bluff, Mt Fleming and Don Juan Pond were collected by the author and Dr Cathy Seybold (USDA). Data from Cape Hallett and Brown Hills, Darwin Glacier, were provided by Dr I. Hawes.

Data from the data logger at each soil climate station were downloaded onto hand-held computers then transformed to MS Excel 2007 format. Data from 2011 were collated with previous data extending back to 1999 by Dr Cathy Seybold. The full datasets are available at www.lgp.aq and www.nrcs.usda.gov.

3.3.2 Instrumentation

Air temperature was measured using the following sensors: Campbell 109 air temperature probe (Don Juan Pond, Victoria Valley), Campbell 107 air temperature sensors (Granite Harbour, Marble Point, Minna Bluff, Mt Fleming, and Cape Hallett), Vaisala HMP 45C air temperature sensor (Scott Base), Vaisala HMP 155 (Darwin Glacier), and Campbell RM Young RTD air temperature probe (Wright Valley). Air temperature was measured at heights of between 2 and 3 m above the ground surface.

Soil temperature was measured using an MRC (Measurement Research Corporation) soil temperature probe at Victoria Valley, Don Juan Pond, Granite Harbour, Marble Point, Minna Bluff, Scott Base and Wright Valley. Campbell Scientific 107B temperature probes were used at Cape Hallett, and Campbell 107 soil temperature sensors were used at Mt Fleming. Temperature data at the Darwin Glacier station were collected using hydra-probe sensors (Stevens Water Monitoring Systems, Portland, Oregon).

Wind speeds and directions were measured using an RM Young wind sensor at Don Juan Pond, Granite Harbour, Marble Point, Minna Bluff, Mt Fleming, Scott Base, and Wright Valley, Bull Pass East, Cape Hallett. At the Darwin Glacier site, a Vector W200P (wind vane) and a A100LM (anemometer) were used. Wind speeds and directions were measured at the Victoria Valley site using a MetOne wind sensor.

Data were recorded on: Campbell CR1000 data-loggers (Don Juan Pond), Campbell CR10 data-loggers (Cape Hallett), or Campbell CR-10X-2M-XT data-loggers (Granite Harbour, Marble Point, Minna Bluff, Mt Fleming, Scott Base, Wright Valley, Darwin Glacier and Victoria Valley).

3.3.3 Data analysis

MS Excel 2007, Statistica and Grapher software were used for data manipulation, graphing and statistical analysis.

Data files were acquired and stored in Excel format. All available data for each site was collated into one large file. Once all stations had been collated, the relevant data were selected and transferred to smaller, topic-specific files. Pivot tables were created to enable statistical analysis for each site and to identify missing and/or 'bad' data. 'Bad' data was determined to be that which fell outside the realm of natural weather conditions, such as recordings of -102.2°C air temperature at Victoria Valley in November 2008. Therefore, temperatures that were exceptionally high or low, and sudden very high wind speeds that could not be explained by passing storms or weather events were removed from the data set. These were determined by examining all temperature and wind speed ranges for the sites and identifying outliers. The outliers were then examined in hourly increments to see if they were part of a storm or weather event. If the values were deemed too extreme, and most likely to be caused by equipment malfunction or human intervention during maintenance visits, then the values were removed from the dataset.

As an arbitrary guideline, it was decided that data missing for a period of five days or less was to be interpolated, and the monthly and yearly averages still considered valid. Data missing for periods longer than five days were left as missing data and thus the mean annual data could not be determined for that year. This arbitrary cut-off point was used to reduce the amount of data lost for analysis and to reduce the amount of any possible bias created by assuming that the missing data was the same as the data on either side of the gaps.

3.4 Site descriptions

3.4.1 Cape Hallett

The soil climate station at Cape Hallett is located on a low-lying ridge adjacent to the shoreline (Fig. 3.2a) on the inland side of the Endisto Inlet. The ground surface is a pebbly substrate with sub-angular to sub-rounded rocks generally <10 cm in diameter (M.R. Balks, pers. comm.) (Fig. 3.2b).

Fig. 3.2 Cape Hallett soil climate station site. (a) View of the automatic weather station. (b) Desert pavement (photographs: M.R. Balks).

The Cape Hallett soil climate station was installed on the 15th January 2004 on the east side of a low mound. Desert pavement is basalt dominated sand and gravels.

Five soil horizons were identified (Fig. 3.3) and soil characteristics described on the 14th January 2004 (Table 3.2). The site was not under active melt, nor had flowing water, but the soil was moist at the time of sampling (M.R. Balks, pers. comm.).

Table 3.2 Soil profile description for Cape Hallett soil climate station (data provided by M.R. Balks).

Described by:	Dr M.R. Balks
Date:	January 14th 2004
Location:	72° 19' S 170° 16' E
Elevation:	2 m
Site description:	On crest of beach ridge at edge of Endisto Inlet. About 10 m from south of ice edge and about 200 m north of base of adjacent steep hill site. This site is close enough to the hill to be shaded for a few hours each night in summer
Slope:	5-10°
Moisture regime:	Dry near surface, moist at depth
Vegetation:	None seen
USDA classification:	None assigned
Parent material:	Sub-rounded, beach deposited, locally-derived scoriacieous basalt. Fresh and decomposed penguin guano, penguin remains and penguin nest stones

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..Table 3.2 continued..

Weathering stage:	I (no evidence of chemical weathering)
Depth to ice-cemented ground:	~40 cm
Soil depth (cm)	**Soil Description**
5-0:	Desert pavement. Reddish black (YR3/1) and dark reddish brown (10YR 3/3) lithochrome stony, gravelly, loamy sand. Some salt present. Sharp irregular boundary,
0-5:	Brown (7.5YR 4/4) stony, gravelly, loamy sand. Common penguin guano and remains. No salts visible. Diffuse smooth boundary,
5-15:	Brown (7.5YR 4/4) stony gravel. No salts. Abundant penguin bone remains. Sharp irregular boundary,
15-30:	Brownish (10YR 3/2) dark, moist, iron-sand. Few penguin feathers. No salts visible. Smooth distinct boundary,
30-80+:	Reddish black (2.5YR 2/1) gravelly coarse iron-sand. Very moist and ice cemented below 40 cm depth.

Fig. 3.3 Desert pavement and soil profile at Cape Hallett soil climate station site (Photograph: M.R. Balks).

3.4.2 Granite Harbour

The soil climate station at Granite Harbour is located on the shoreline of Granite Harbour on a narrow sloping boulder surface with a steep hillside to the south of the station. The site has a sheltered microclimate which may impact on temperature and wind measurements at the site (Figs. 3.1, 3.4). The Mackay Glacier flows into the harbour from the west and terminates at the sea ice. The shoreline boulders are dominated by clasts >50 cm mixed with smaller (~10 cm) clasts and sand-sized fines (Fig. 3.4). The soil description for the Granite Harbour site is included in Seybold *et al.* (2010).

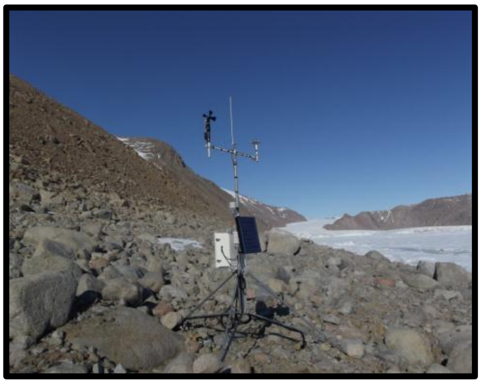

Fig. 3.4 Granite Harbour soil climate station situated on a boulder colluvial foot-slope/lateral moraine adjacent to a steep hillside (view looking west).

During the maintenance visit on the 21st January 2012, the entire bay was covered with sea ice, although some pressure ridges and melt pools were visible. On the shoreline there were small widely spaced snow patches, and abundant mosses. Weather on the day of data collection was fine and sunny with little-to-no breeze. The soil climate station required only one battery change (out of three installed), and the wind sensor was updated. There were no evident footprints remaining from the data collection team visit of the previous year, and the ground surface appeared natural and undisturbed.

3.4.3 Victoria Valley

The soil climate station at Victoria Valley is situated on the valley floor east of the Victoria Glacier terminus and Lake Victoria (Fig. 3.5a). The valley floor is covered with patterned ground with low centred polygons and cracks. The site is also utilised by the University of Washington, measuring the expansion cracks and generating time-lapse images of snow cover over the site area. The desert pavement comprises stony gravel, predominantly <10 cm in diameter, and rarely >30 cm (Fig. 3.5b). Soil description is in Seybold *et al.* (2010).

Fig. 3.5 Victoria Valley soil climate station (a) view of the soil climate station with Victoria Glacier in the background (view looking west). (b) Desert pavement.

Minimum air temperatures were not recorded at the Victoria Valley site between 2000 and 2010 due to winter temperatures that were lower than the measurement capacity of the temperature probe. Mean annual air temperatures were therefore unable to be calculated. Maximum air temperatures were not affected. In January 2011, a new air temperature sensor was installed which was able to record lower temperatures. Soil temperatures at Victoria Valley, available for the entire recording period (2000-2011) were not affected.

On the day of data download (21st January 2012) there were no snow patches visible within the vicinity of the site, and the day was fine with a moderate breeze flowing down-valley over Victoria Glacier. Minimal maintenance of the site was required, with replacement of only one battery. There were no footprints evident from last year’s maintenance trip.

3.4.4 Marble Point

The Marble Point soil climate station is located on a low-lying rock outcrop at the terminus of the Wilson Piedmont Glacier at the coast edge (Fig. 3.6a). The bare sections of ground consisted of close-knit angular rocks interspersed with gravelly sand (Fig. 3.6b). The soil had relatively high moisture content at the time of the visit due to active snow-melt at the site. A soil description for the Marble Point site is included in Seybold *et al.* (2010).

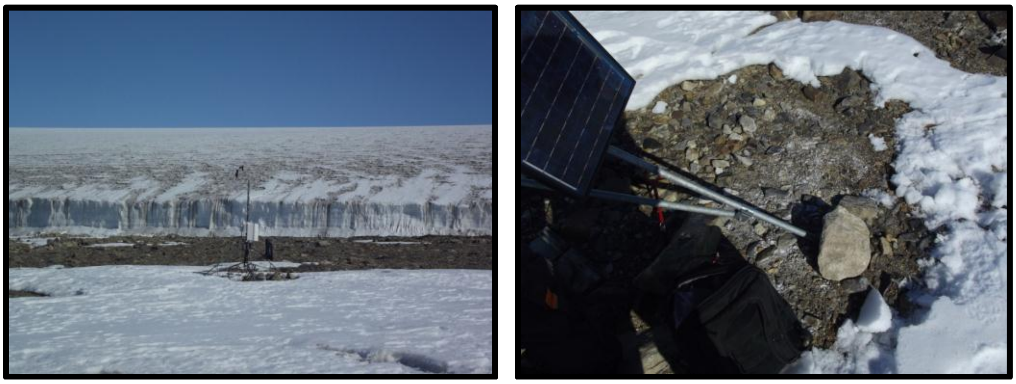

Fig. 3.6 Marble Point soil climate station. (a) View of the soil climate station with the Wilson Piedmont Glacier in the background. (b) Partially snow-covered desert pavement beneath and around the soil climate station.

There was extensive snow cover at the Marble Point site at the time of visit (21st January 2012), covering some of the sensors. Maintenance undertaken at the Marble Point site included changing one battery and replacing the wind sensor. A new data logger was also installed, and the rest of the equipment appeared to be in good working order. There was no evidence of footprints or human activity from previous visits.

3.4.5 Wright Valley

The Wright Valley soil climate station (Fig. 3.7a) is located on the floor of Wright Valley, slightly to the east of the Bull Pass intersection through the Olympus Range, and east of Lake Vanda. Steep valley walls arise either side of the site, so that the station is exposed to wind channelling along the valley floor from the east and west. The Wright Valley site is rarely snow-covered. The desert pavement consisted of large (>15 cm) clasts, smaller gravel-sized clasts (<5 cm) and sand-size fines (Fig. 3.7b). Footprints were easily made in the vicinity of the soil climate station as the material beneath the desert pavement was a fine silt-dominated powder that was easily compressed, so care was taken to walk on the boulders as much as possible. The soil description for the Wright Valley soil climate station site is provided in Seybold *et al.* (2010).

Fig. 3.7 Wright Valley soil climate station site. (a) View of the soil climate station site looking east. (b) Desert pavement in the vicinity of the soil climate station.

The weather on the day of data collection (20th January 2012) was clear and fine with an easterly wind blowing up-valley. Maintenance at the site involved changing one battery, swapping the data logger for a new one, and installing guide ropes to the soil climate station frame. The guide ropes stabilise the triangle-framed station during strong winds. The systems hard drive within the data box attached to the soil climate station frame was also changed. Despite the ease with which the desert pavement was disturbed, there were no visible footprints remaining at the site from the previous year's maintenance visit.

3.4.6 Mt Fleming

The Mt Fleming soil climate station is the highest elevation station within the Ross Sea region network at 1689 m ASL. The site is located within a cirque adjacent to the Airdevronsix Ice Fall and Upper Wright Glacier at the edge of the Polar Plateau (Fig. 3.8a). The ground surface was dominated by large boulders >30 cm in diameter interspersed with smaller rocks and gravel. The rocks displayed cavernous weathering (by wind-blown particles) and some fracturing (Fig. 3.8b). A soil description for the Mt Fleming soil climate station site is provided in Seybold *et al.* (2010).

Fig. 3.8 Mt Fleming soil climate station at the head of the Wright Valley. (a) View of the soil climate station. (b) Desert pavement with fractured rocks (foot for rough scale).

Winter air temperatures consistently dropped below the recording capabilities of the air temperature sensor until 2010 when a new sensor was installed. Therefore, mean annual air temperatures were not available until 2011.

The Mt Fleming site was extremely windy on the day of data collection (20^{th} January 2012), when wind speed averaged ~62 $kmhr^{-1}$. The air temperature during the maintenance visit was the lowest experienced while visiting the network in 2012 (-14°C). No footprints or other evidence of human activity from previous visits was visible.

Snow patches were evident on the ground surface, with extensive snow and ice cover mantling the cirque ridges and overflowing from the back of the cirque rim into the basin. Towards the head of the Wright Valley, the Airdevronsix Ice Fall flowed downslope merging into the Upper Wright Glacier.

The Mt Fleming soil climate station required maintenance to change one battery. The Trimble handheld computer could not tolerate the low air temperatures, so a laptop computer was used to download the previous year's climate data from the station.

3.4.7 Don Juan Pond

The Don Juan Pond automatic soil climate station is located on a ledge within the southern arm of the Wright Valley wall at 734 m ASL above the hyper-saline Don Juan Pond (Fig. 3.9). The Don Juan Pond soil climate station was installed in January 2011. Desert pavement at the site is predominantly rough and uneven with volcanic rocks (dolerite).

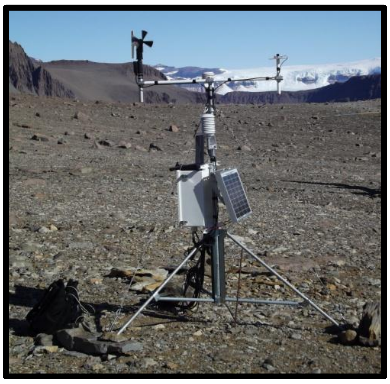

Fig. 3.9 Soil climate station located on a ledge above Don Juan Pond in the Wright Valley. Looking west towards the Upper Wright Glacier and Airdevronsix Ice Fall (in the background).

On downloading the data from the Don Juan Pond site it was noted that the station software ceased collecting data in July of 2011. All equipment at the site appeared to be in working order; however, due to the system failure, data for the previous year was only collected until 7 pm on the 12th July 2011, following installation on the 11th January 2011. Due to system failure the data collection flash drive hardware was removed (for inspection and manual download back at Scott Base) and replaced with a new card. No other maintenance was required.

The weather at the Don Juan Pond site on the day of data collection (20th January 2012) was fine with weak easterly winds blowing up-valley. There was no evidence of human disturbance at this site from last year's site installation and the site of excavation to install soil sensors was no longer distinguishable from the wider landscape. In the vicinity of the soil climate station there were small, widely spaced ice patches and rare areas of running water. A soil and site description is given below (Table 3.3).

Table 3.3 Soil profile description for the Don Juan Pond soil climate station (Data provided by Dr Cathy Seybold).

Described by:	Malcolm McLeod and Cathy Seybold
Date:	January 11, 2011
Location:	77º 34' 26.1'' S 161º 14' 19.8'' E
Elevation:	728 m
Site description:	In the upper Wright Valley on a mountain ridge on the south side of the south fork of the Wright Valley above Don Juan Pond. The surface is flattened (could be under snow in winter) and was snow free. The area has moderately developed polygons that are about 10 m x 10 m. The patterned ground cracks are about 30 cm wide and dominated by stony material. Pedon is in middle of a patterned ground polygon
Slope:	5%, north facing slope 0º
Geomorphic description:	Toe slope in bowl shaped ridge on side of mountain valley. Colluvial fan over glacial till
Moisture regime:	Arrid (torric) moisture regime
Natural drainage class:	Well drained
Vegetation:	None
USDA classification:	Sandy-skeletal, mixed, hypergellic Typic Haplorthel.
Parent material:	Granite dominated with some dolerite till
Weathering stage:	II
Depth to ice-cemented ground:	24 cm
Coherence:	120 cm
Oxidation:	0
Ghosts:	0
Salts:	1 cm
Soil horizon (depth in cm):	**Soil description:**
Cn1 (0-1):	Desert pavement, weathered, polished and some pitted boulders and gravels with yellowish brown (10YR 5/4 moist) coarse sand (5% of surface); single grain; loose, non-cemented, non-sticky and non-plastic; non effervescent (1N-HCl); very few salt/carbonate accumulations under stones; surface boulders (65 mm to 2 m) cover about 15% of surface, cobles cover about 25% of surface, and gravels cover about 55% of

..Continued on following page..

..Table 3.3 continued..

	surface; fragment kinds are 85% granite, 10% dolerite; surface is flattened; abrupt smooth boundary.
Cn2 (1-24):	Light yellowish brown (2.5Y 6/3 moist) stony sand; single grain; loose, non-cemented, non-sticky, and non-plastic; non effervescent (1N-HCl); 15% stones and 5% cobbles; clear wavy boundary.
2Cfm1 (24-70):	30% Yellowish brown (10YR 5/5 moist) and 70% strong brown (7.5YR 4/6 moist) very gravelly sand; single grain; loose, frozen, non-sticky and non-plastic; non effervescent (1N-HCl); 5% stones, 10% cobbles and 40% gravel; oxidized surfaces; gradual wavy boundary.
2Cfm2 (70-120):	Yellowish brown (10YR 5/5 dry) very gravelly sand; single grain; loose, frozen, non-sticky and non-plastic; non effervescent (1N-HCl); 5% stones, 15% cobbles and 35% gravel; oxidized surfaces.

3.4.8 Scott Base

The Scott Base soil climate station is located approximately 200 m upslope from Scott Base, on a south-facing blocky basaltic lava flow (Fig. 3.10). The ground consists of basaltic lava blocks averaging 10-50 cm in diameter, interspersed with sand-sized fines and gravel. A soil description for the Scott Base site is included in Seybold *et al.* (2010).

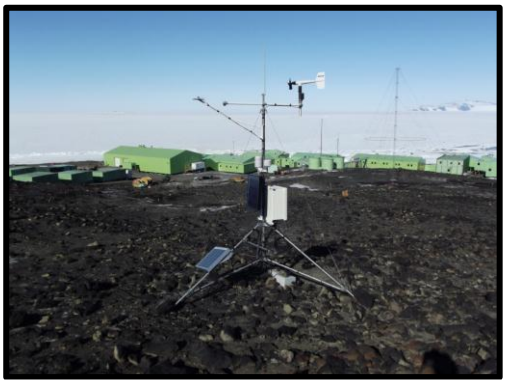

Fig. 3.10 Scott Base soil climate station located upslope from Scott Base (in the background).

The Scott Base soil climate station had periods of missing air temperature data. In January 2002 (1^{st} – 14^{th}), a sensor change rendered two weeks of air temperature data unusable. Missing and bad data at Scott Base was replaced using data from the nearby NIWA managed weather station (http://www.cliflo.niwa.co.nz). Air temperature data were similar at both the Scott Base and NIWA sites; therefore, due to the utilisation of NIWA data from the Cliflo database (http://cliflo.niwa.co.nz/), a complete air temperature record for the Scott Base soil climate station was able to be constructed.

There was little to no snow cover at and around the Scott Base soil climate station at the time of the visit (21st January 2012). All equipment was working with one battery change and new globes installed on the net radiometer. Despite the close proximity to Scott Base, there were no visible footprints or signs of human activity around the soil climate station site.

3.4.9 Minna Bluff

The Minna Bluff soil climate station is located on an area of till that extends from the face of Minna Bluff to the edge of the Ross Sea in front of Minna Bluff (Fig. 3.11). The site was strewn with a mixture of basaltic boulders with smaller gravels and fines making up the desert pavement. The topography of the site is low-rising and hummocky, with patterned ground evident. A soil description for the Minna Bluff site is included in Seybold *et al.* (2010).

Fig. 3.11 Minna Bluff soil climate station with the snow-covered "bluff" in the background.

During the maintenance visit (14th January 2012) small isolated patches of snow remained in the area surrounding the station. There was no obvious disturbance of the desert pavement around the station.

Strong persistent winds are common at Minna Bluff, and the site's guide ropes had been worked loose. Wire and tape was used to secure the guide rope fastenings. The wind sensor was replaced, as was one of the batteries.

Wind data for the years 2003-2008 at this site were unusable due to high winds repeatedly damaging the wind sensors.

3.4.10 Darwin Glacier (Brown Hills)

The Darwin Glacier soil climate station is located in an east-west trending valley on glacial till (Fig. 3.12). The site is located inland with seasonal snow cover. Darwin Glacier is the southern-most soil climate station within the network and was established under the LGP program.

Soil temperature vitel probes at the Darwin Glacier soil climate station are installed at 5 and 10 cm depth.

Fig. 3.12 Darwin Glacier soil climate station (photograph: I. Hawes).

3.5 Bull Pass East site installation

3.5.1 Introduction

To increase the coverage of soil climate stations to include the McMurdo Dry Valley walls a site was selected in the Wright Valley and a soil climate station was installed in January 2012.

With the installation of the new site, the Wright Valley is now monitored along its length from Mt Fleming at the head of the valley to the Bull Pass East soil climate station on the northern side, with the Don Juan Pond site on the southern side and the Wright Valley floor site (Fig. 3.1). No data was available from the Bull Pass East station for inclusion in analysis undertaken for this thesis.

3.5.2 Site location

The Bull Pass East site is located at 832 m ASL on the northern edge of the Wright Valley wall about 1 km east of Bull Pass (Fig. 3.13). The site was on a south-facing slope with predominantly granitic and basaltic desert pavement rocks. The site ridge is backed by peaks of the Olympus Range which supply colluvial sediments to the Bull Pass East site ridge.

Fig. 3.13 Site location on the northern wall of the Wright Valley adjacent to the Bull Pass intersection. Image adapted from googlemaps.co.nz.

3.5.3 Geological setting and site description

Wright Valley was likely formed by glacial movement in the Miocene (15 mya.), identified by transported sediments in ice cores, and subsequently subjected to uplift and glacial invasions since the late Pliocene (Campbell & Claridge 1978). Analysis of glacio-marine diamicton deposits revealed that the Wright Valley had been a fjord multiple times (Turnbull *et al.* 1994).

The Wright Valley is one of three large ice-free “dry valleys” that receive minimal precipitation (Campbell & Claridge 1987), however, the Bull Pass East site, at 832 m asl, receives more precipitation in the form of snow than the valley floor. The Wright Valley is part of East Antarctica which was once part of Gondwanaland. Similarities in geology are found both in the East Antarctic region and Australia, South America and Africa (Campbell & Claridge 1987). The geology consists of Precambrian basement sedimentary rocks metamorphosed to granites and gneisses, and intrusive basaltic and granitic rocks (Campbell & Claridge 1987, Turnbull *et al.* 1994).

Overlying the Precambrian basement is the Ross Supergroup, a folded, thick synclinal group of weakly metamorphosed greywackes and argillites, limestones and conglomerates. Correlatives of the Ross Supergroup outcrops are found amongst areas further north and south, along the coast of the Ross Ice Shelf and coastal South Victoria Land where the McMurdo Dry Valleys are located (Campbell & Claridge 1987).

The Beacon Supergroup is predominantly a quartzose sandstone, dated as Devonian in the Ross Sea region by Turnbull *et al.* (1994). Basaltic volcanism intrudes through these deposits within the McMurdo Dry Valleys region (Campbell & Claridge 1987). Basaltic intrusive rocks, the Ferrar Group, are of Early to Middle Jurassic age and thick horizontal sills intruded into both basement and overlying rocks (Campbell & Claridge 1987). The Ferrar Dolerites are the youngest rocks identified in East Antarctica, however, younger fossils of Cretaceous and Early Tertiary age have been found in raised sections of the McMurdo Sound region. The presence of Cretaceous and early Tertiary aged fossils indicates that younger rocks are possibly present beneath ice and snow cover (Campbell & Claridge 1987).

There was a distinct desert pavement of clasts ~2-5 cm in diameter of rock types ranging from granite to basalt. The Bull Pass East site is predominantly covered with ventifacts (wind/ice carved rocks), ranging in size from <10 cm to ≥ 2 m (Fig. 3.14 a). A large portion (~75%) of sand-sized fines also covered the ground surface (Fig. 3.14 b).

Fig. 3.14 Bull Pass East installation site. (a) Ventifacts surrounding the installation site. (b) Desert pavement.

3.5.4 Equipment

The soil climate station frame is a 2 m high Campbell CM6 tripod structure with one white box containing wiring and fittings to attach solar radiation, wind direction and speed, temperature, and humidity sensors and a solar panel attached to data-loggers (Table 3.4).

Table 3.4 Summary of equipment installed at Bull Pass East in January 2012 (information provided by Dr Cathy Seybold).

Quantity	Description
1	Campbell CR1000 datalogger
1	Campbell NL115 storage flash card module
2	Campbell BP24 24-amp-hr YUASA battery
1	Campbell CH100 charger/regulator
1	Campbell MSX-20 solar panel.
1	Campbell ENC 16/18 enclosure
1	Campbell CM6 2-m tower
8	Hydra-probe soil moisture/temperature sensors, analog 2.5 volt
6	Campbell 107 soil temperature sensors
1	MRC soil temperature probe
2	Campbell CS215 RH and temperature probe
1	Campbell 109 air temperature probe w/radiation shield
1	Licor LI200X pyranometer solar radiation sensor w/leveling fixture and mounting arm
1	RM Young wind sensor
1	Campbell HMP45C relative humidity and radiation shield

3.5.5 Installation process

A soil pit was excavated to install the temperature probes and soil sensors. The overlying desert pavement was removed and placed on a sheet to be returned when work was completed. Underlying soil was then excavated using a hand shovel to 1.2 m depth and also placed upon a sheet to reduce disturbance of the surrounding area and ensure that all material was returned to the hole (Fig. 3.15a). A jackhammer was used to assist breaking up the underlying soil and boulders (Fig. 3.15b) and was used to speed up the digging process. No ice-cemented material was found at this site to a depth of 1.2 m.

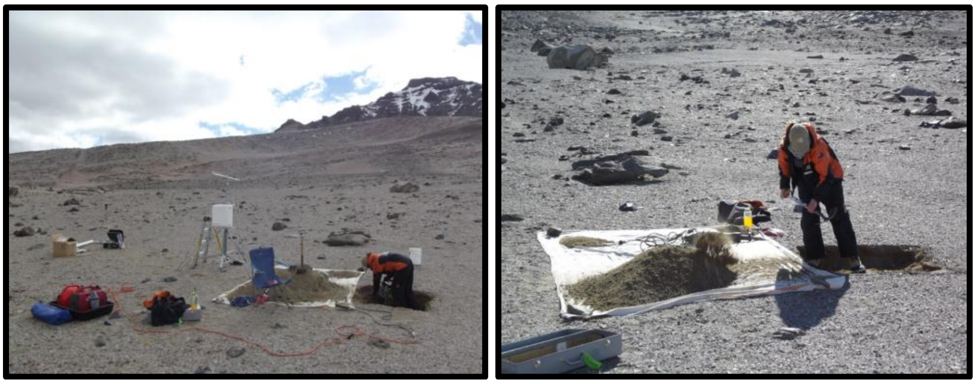

Fig. 3.15 Bull Pass East installation work. (a) Removing the desert pavement and digging the soil sensor pit with desert pavement separated from the main body of sediment. (b) Using a jackhammer to assist digging the hole. The soil climate station is under construction in the centre of image (a).

The soil climate station was installed on-site including wiring and sensor set-up (Fig. 3.16).

Fig. 3.16 Dr Cathy Seybold constructing the soil climate station at Bull Pass East adjacent to the soil sensor pit.

Four soil horizons were identified, and the soil profile was described (Table 3.5) (Figs. 3.17 a-c). Samples were taken of each soil horizon (four horizons including the desert pavement) and returned to the University of Waikato for future analysis.

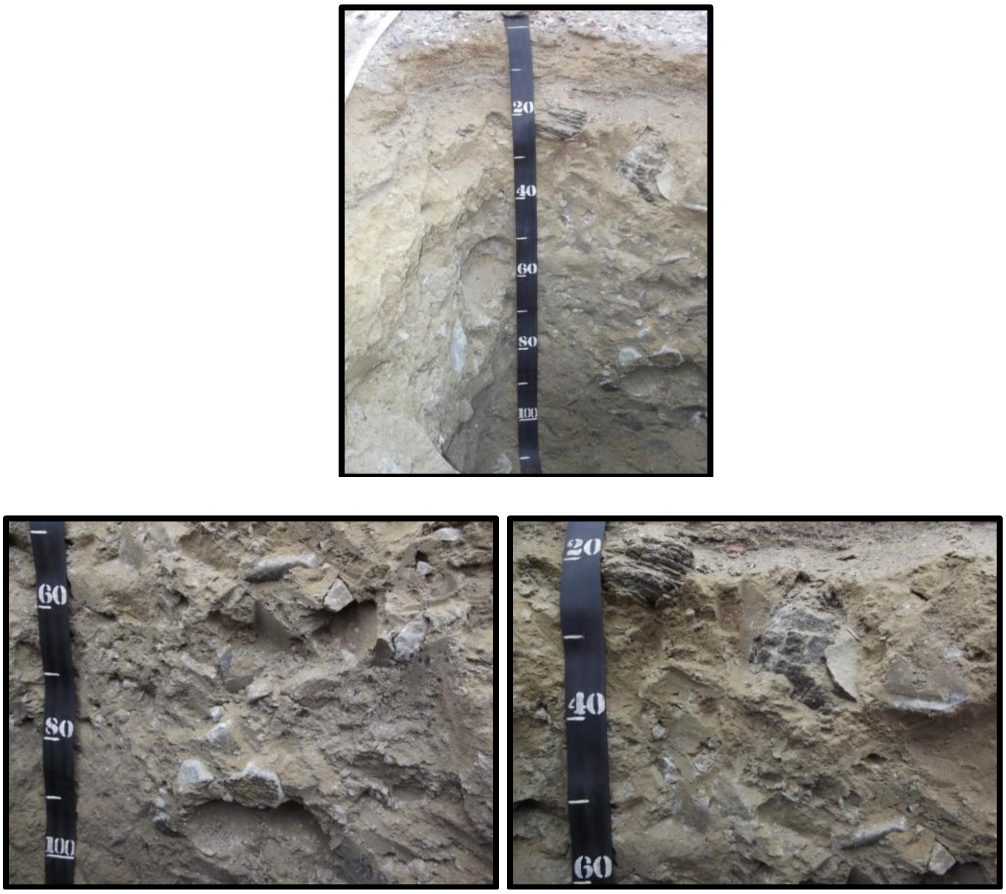

Fig. 3.17 Bull Pass East soil profile. (a) Overall soil profile (measurements in cm). (b) Close-up of 15-60 cm of soil profile. (c) Close-up of 50-100 cm of the soil profile.

Table 3.5 Soil profile description of Bull Pass East soil climate station.

Described by:	Cathy Seybold & Holly Goddard
Date:	17th January 2012
Location:	77º 30’ 07.9’’ S 162º 03’ 53.1’’ E
Elevation:	832 m asl
Site description:	The site is on a ridge east of Bull Pass looking over the Wright Valley (of the McMurdo Dry Valleys in Antarctica).
Slope:	5%, south-facing slope
Geomorphic description:	Toe slope in bowl-shaped ridge on side of mountain valley
Moisture regime:	Aridic (torric) moisture regime
Natural drainage class:	Well drained
Vegetation:	None
USDA classification:	Sandy-skeletal, mixed, hypergellic Typic Haplorthels

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..Table 3.5 continued..

Parent material:	Aeolian over colluvial material
Weathering stage:	IV
Depth to ice-cemented ground:	> 120 cm (did not encounter any ice cement)
Depth to permafrost:	Yet to be determined from soil climate station data
Coherence:	120 cm
Oxidation:	0
Ghosts:	0
Salts:	0 cm
Soil horizon (depth cm):	**Soil description:**
C1 (0-1):	Desert pavement, weathered, polished, and some pitted stones and gravels with 50% grey (10YR 6/1 dry) and 50% (10YR 2/1 dry) coarse sand (5% of surface); single grain; loose, non-cemented, non-sticky and non-plastic; non effervescent (1N-HCl); surface stones (65 mm to 2 m) cover about 5% of the surface, cobbles cover about 5% of the surface, and gravels cover about 85% of the surface; fragment kinds are 85% granite, 10% dolerite; abrupt smooth boundary.
C2 (1-23):	Light olive brown (2.5YR 5/4 dry) gravelly coarse sand; single grain; loose, non-cemented, non-sticky, and non-plastic; non effervescent (1N-HCl); 5% stones and 20% gravel; non-oxidised; finely stratified throughout; 0.7% by weight water content; clear smooth boundary.
C2k (23-79):	Light olive brown (10YR 5/3 moist) very gravelly fine sand; massive; very friable, non-sticky and non-plastic; slightly effervescent (1N-HCl); 15% stones, 15% cobbles, and 20% gravel; non-oxidised; 4.0% by weight water content; gradual, wavy boundary.
2C (79-120):	Greyish brown (10YR 5/2 moist) very gravelly sand; non-oxidised, massive; very friable, non-sticky and non-plastic; non effervescent (1N-HCl); 15% stones, 10% cobbles and 25% gravel, non-oxidised; 5.8% by weight water content.

The MRC (Measurement Research Corporation) probe was installed within the soil pit to 1.2 m depth (Fig. 3.18a). The pit was then in-filled, with Campbell 107 soil temperature sensors installed at depths of 2, 10, 25, 35, 50 and 75 cm. Hydra-probe soil moisture and temperature sensors were installed at 2, 10, 25 and 50 cm depths (Fig. 3.18b).

The soil surface was then restored with the original desert pavement material to return the sites appearance as close as possible to that before works began. Evidence of work at the site remained in the form of footprints, and a slight discolouration in the sediment compared to the surrounding area as all wires were buried beneath the surface, becoming visible only at the climate station (Fig. 3.19a). A year after installation no evidence remained of disturbance caused by site installation and desert pavement had returned to a non-disturbed state (Fraser Morgan pers. comms.).

Fig. 3.18 MRC probe and soil temperature sensor installation at Bull Pass East. (a) Installation of the MRC probe to 1.2 m depth. (b) Re-filling the soil pit after installing the MRC probe, Campbell 107 soil temperature sensors and hydra-probe sensors.

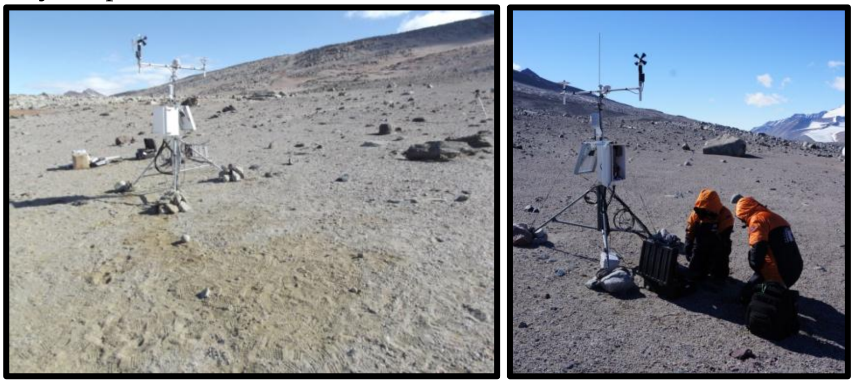

Fig. 3.19 Fully installed Bull Pass East soil climate station. (a) Just after site installation completion. (b) Site one year on with no surface disturbance evident from previous year (photo by Fraser Morgan).

3.5.6 Site and weather conditions during fieldwork – 16th- 20th January 2012

Damp patches were evident in surface depressions, presumably from recent ice/snow melt or salt-rich hydroscopic soils retaining moisture.

Weather was generally sunny with light breezes, and air temperatures were between 0°C and -5°C. Weather conditions worsened on the evening of the 18th and all day of the 19th January, with thick fog at the mouth of the valley and within the valley floor. Light snow fell above ~1200 m, and clouds increased, reducing visibility. Conditions improved and returned to sunny and calm on the 20th January with light winds.

3.6 Summary and conclusion

The Ross Sea region soil climate station network consists of eleven sites (from north to south): Cape Hallett (72.19°S), Granite Harbour (77.00°S), Victoria Valley (77.19°S), Marble Point (77.25°S), Bull Pass East (77.30°S), Wright Valley (77.31°S), Mt Fleming 77.32°S), Don Juan Pond (77.34°S), Scott Base (77.50°S), Minna Bluff (78.30°S), and Darwin Glacier (79.50°S). The soil climate station at Don Juan Pond was established in January 2011, and the Bull Pass East site was installed in January 2012. No climate data was available for the inclusion within this research for the Bull Pass East soil climate station.

Each soil climate station measured air temperature and soil temperatures extending down to 1.2 m depth, and wind speeds and directions between 2-3 m above the ground surface. Other variables such as relative humidity of the air and soil, conductivity of the soil, soil moisture, and solar radiation were recorded at each station but not included within this research.

A brief site description and site conditions at time of visit are included for each soil climate station. Full soil descriptions are included for the Don Juan Pond, Cape Hallett, and Bull Pass East site. Site installation information, including equipment used is detailed for the Bull Pass East site, installed in January 2012.

The Cape Hallett, Granite Harbour, Victoria Valley, Marble Point, Bull Pass East, Wright Valley, Mt Fleming, Don Juan Pond, Scott Base, Minna Bluff, and Darwin Glacier soil climate stations have unique and often challenging environments. The soil climate stations record air and soil climate at various points throughout the McMurdo Dry Valleys and wider Ross Sea region.

Chapter 4: Air and soil temperatures across latitudinal and altitudinal gradients

4.1 Introduction

Air temperatures and soil temperatures at two depths; 5-10 cm (shallow soil depth), and 75-120 cm (deep soil depth), are reported from 1999-2011 at up to 10 soil climate station sites in the Ross Sea region of Antarctica, extending from Cape Hallett in the north to Darwin Glacier in the south.

The objectives of this chapter were to investigate the temperatures at the various sites to identify any significant increasing or decreasing temperature trend in air and soil measurements, and to examine relationships between temperature and latitude or altitude across the range of Latitudinal Gradient Project sites from Cape Hallett to Darwin Glacier.

4.2 Temperature ranges and extremes

4.2.1 Temperature range with depth

The mean annual temperatures for the available data were calculated by taking the mean temperatures for each year at the Victoria Valley, Wright Valley, Mt Fleming, Minna Bluff, Marble Point, Granite Harbour, Scott Base, Cape Hallett, and Darwin Glacier sites for air, shallow soil and deep soil measurements (Table 4.1). Victoria Valley, Wright Valley, Mt Fleming, Marble Point and Cape Hallett sites all had similar mean annual temperatures from air through to deep soil (Table 4.1), with temperature differences from air through to deep soil all within ± 1°C. The site at Granite Harbour had the largest temperature difference (2.8°C) between mean annual air and mean annual deep soil (88 cm depth) during its operating period 2003-2011 (Table 4.1).

Table 4.1 Mean annual temperatures, ranges and extremes for air, shallow soil (5-10 cm depth), and deep soil (75-120 cm depth) over the recording period.

Stations	Recording period	MAT for period of data (°C)	MAT range (°C)	Warmest temp (°c)	Coldest temp (°c)	Temp range (°c)	Warmest MAT (°C)	Coldest MAT (°C)
Victoria Valley								
air	2000-2011	-22.4*	N/A	10.8	-54.2*	65*	-22.4*	-22.4*
8 cm soil	2000-2011	-22.9	3.6	14.8	-55.3	70.1	-21.3	-24.9
120 cm soil	2000-2011	-22.7	1.9	-7.9	-36.5	28.6	-21.6	-23.6
Wright Valley								
air	2000-2011	-19.6	3.5	11.9	-53.2	65.2	-17.6	-21.1
8 cm soil	2000-2011	-19.8	3.3	15.5	-53.0	68.5	-17.8	-21.1
120 cm soil	2000-2011	-19.5	2.0	-6.2	-31.7	25.5	-18.3	-20.3
Mt Fleming								
air	2006-2011	N/A	N/A	-2.2	N/A	N/A	N/A	N/A
8 cm soil	2006-2011	-23.3	1.4	0.2	-40.5	40.7	-22.5	-23.9
75 cm soil	2006-2011	-23.4	1.1	-11.3	-32.0	20.7	-22.7	-23.8
Granite Harbour								
air	2003-2011	-16.6	3.1	6.9	-43.4	50.2	-15.0	-18.1
6 cm soil	2003-2011	-14.4	2.1	18.3	-41.2	59.5	-13.2	-15.3
88 cm soil	2003-2011	-13.2	1.9	2.7	-30.0	32.7	-12.6	-14.5
Marble Point								
air	2004-2011	-17.6	3.2	6.1	-43.2	49.3	-16.1	-19.5
8 cm soil	2000-2011	-18.2	1.8	17.7	-45.8	63.5	-17.4	-19.2
120 cm soil	2000-2011	-18.2	2.1	-4.2	-31.8	27.7	-17.1	-19.2
Scott Base								
air	1999-2011	-19.1	4.7	6.0	-48.0	54.0	-16.1	-20.8
9 cm soil	1999-2011	-18.0	3.0	11.3	-42.3	53.6	-16.4	-19.5
116 cm soil	1999-2011	-17.9	2.6	-3.2	-31.2	28.0	-16.6	-19.2
Minna Bluff								
air	2007-2011	-18.3	1.6	4.8	-46.6	51.4	-17.3	-18.8
5 cm soil	2007-2011	-16.3	1.6	17.4	-48.9	66.3	-15.3	-16.9
112 cm soil	2007-2011	-16.4	1.2	-4.9	-28.6	23.7	-15.7	-16.8
Don Juan Pond								
air	2011	N/A	N/A	2.5	-34.0	36.4	N/A	N/A
5 cm soil	2011	N/A	N/A	10.5	-35.1	45.6	N/A	N/A
120 cm soil	2011	N/A	N/A	-3.3	-25.8	22.5	N/A	N/A
Cape Hallett								
air	2004-2005	-15.3	2.4	5.2	-43.5	48.7	-14.1	-16.6
7 cm soil	2004-2005	-16.1	N/A	14.4	-43.2	57.7	-16.1	-16.1
99 cm soil	2004-2005	-15.4	N/A	-2.4	-28.0	25.6	-15.4	-15.4
Darwin Glacier								
air	2005-2007	-18.2	1.3	4.7	-39.9	44.5	-17.5	-18.8
10 cm soil	2005-2007	N/A	N/A	13.8	-13.9	27.7	N/A	N/A
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

MAT = mean annual temperature
* = For 2011 only (after sensor replaced)
N/A = no data available

4.2.2 Air temperatures

By comparing the mean annual air temperatures for each sites entire recording period, the soil climate stations ordered from warmest to coolest (Table 4.1) were: Cape Hallett (-15.3°C), Granite Harbour (-16.6°C), Marble Point (-17.6°C), Darwin Glacier (-18.2°C), Minna Bluff (-18.3°C), Scott Base (-19.1°C), Wright Valley (-19.6°C), and Victoria Valley (-22.4°C).

The warmest air temperature measured at any site over the recording period from 1999-2011 of +11.9°C was recorded in the Wright Valley site in January 2002 (Table 4.1). The coldest air temperature, -54.2°C was recorded at Victoria Valley in July 2011 (the only year for which minimum air temperatures were available for the Victoria Valley soil climate station).

Overall, the minimum temperatures were recorded at most sites in 2005 (Granite Harbour, Marble Point and Cape Hallett) (Table 4.1). Maximum air temperatures in 2010 were the highest recorded at three stations (Victoria Valley, Marble Point, and Scott Base).

Thus, Wright Valley exhibited the greatest variation in air temperatures with a range of 65.1°C between the highest and lowest air temperatures recorded between 1999 and 2011 (Table 4.1).

Air temperatures at Victoria Valley dropped below the measurement capability of the sensor, thus minimum and annual air temperatures for the Victoria Valley site could not be calculated until the 2011 year following sensor replacement in 2010.

4.2.3 Shallow soil temperatures

The mean annual shallow soil (5-10 cm soil depth) temperatures for each site (Table 4.1) over the entire recording period ranged from highest to lowest: Granite Harbour (-14.4°C), Cape Hallett (-16.1°C), Minna Bluff (-16.3°C), Scott Base (-18.0°C), Marble Point (-18.2°C), Wright Valley (-19.8°C), Victoria Valley (-22.9°C), and Mt Fleming (-23.3°C).

The coldest recorded shallow soil temperature at 5-10 cm depth was at the Victoria Valley soil climate station in July 2004 with a shallow soil temperature of -55.3°C. The warmest shallow soil temperature recorded was +18.3°C at Granite Harbour in December 2008 (Table 4.1).

The station with the greatest range in shallow soil temperature over the recording period was Victoria Valley with a range of 70.1°C from 1999 to 2011 (Table 4.1). Mt Fleming had the smallest shallow soil temperature range of 40.7°C, with winter temperatures corresponding with other stations, but cooler summer temperatures when compared with the other sites.

The warmest shallow soil temperatures (Table 4.1) were recorded in 2001 when three soil climate stations (Wright Valley, Marble Point, and Scott Base) had their highest shallow soil temperature. The coldest shallow soil temperatures were recorded in 2004 at three stations (Victoria Valley, Wright Valley, and Marble Point).

4.2.4 Deep soil temperatures

By comparing the mean annual deep soil (75-120 cm soil depth) temperatures for each sites entire recording period, the soil climate stations ordered from warmest to coolest (Table 4.1) were: Granite Harbour (-13.2°C), Cape Hallett (-15.4°C), Minna Bluff (-16.4°C), Scott Base (-17.9°C), Marble Point (-18.2°C), Wright Valley (-19.5°C), Victoria Valley (-22.7°C), and Mt Fleming (-23.4°C).

Temperature ranges for soil temperatures at depths of 75-120 cm were considerably narrower than those for air and shallow soil depths (Table 4.1). The widest deep soil temperature range for all sites, over the entire recording period from 1999-2011, was 32.7°C at Granite Harbour. Mt Fleming had the narrowest deep soil temperature range at 20.7°C.

The warmest deep soil temperature was +2.7°C at Granite Harbour in December 2010. The coldest deep soil temperature was -36.5°C at Victoria Valley in August and September 2008.

Most sites (Victoria Valley, Mt Fleming, Granite Harbour and Scott Base) had their coldest year for deep soil temperatures in 2008. Two of the four operational stations (Victoria Valley and Wright Valley) had their warmest deep soil temperature in 2002.

4.3 Annual temperature variability

4.3.1 Introduction

Mean annual temperatures for individual years for air, shallow soil, and deep soil for 2000-2011 showed similar patterns (Fig. 4.1a-c). Inter-annual variation and temperature range decreased with depth.

4.3.2 Mean annual air temperature

The same general pattern of warmer and cooler years was evident across all stations (Fig. 4.1a). Cape Hallett recorded the warmest mean annual temperature of -14.1°C, whilst Mt Fleming had the coldest mean annual air temperature -23.2°C.

4.3.3 Mean annual shallow soil temperature

Mean annual shallow soil temperatures showed a greater range of temperature between stations (Fig. 4.1b) than mean annual air temperatures. All stations showed corresponding peaks and troughs in temperature indicating that differences between years were consistent across the whole region. The warmest mean annual shallow soil temperature was -13.2°C recorded at Granite Harbour. The coldest mean annual shallow soil temperature was -24.9°C at Victoria Valley.

Relatively cooler mean annual shallow soil temperatures were recorded in 2002 and 2006 (except at Scott Base in 2002 and Granite Harbour in 2006). The warmest mean annual shallow soil temperatures were recorded in 2003, 2007 and 2011 except for Marble Point in 2007 which recorded a higher temperature in 2008.

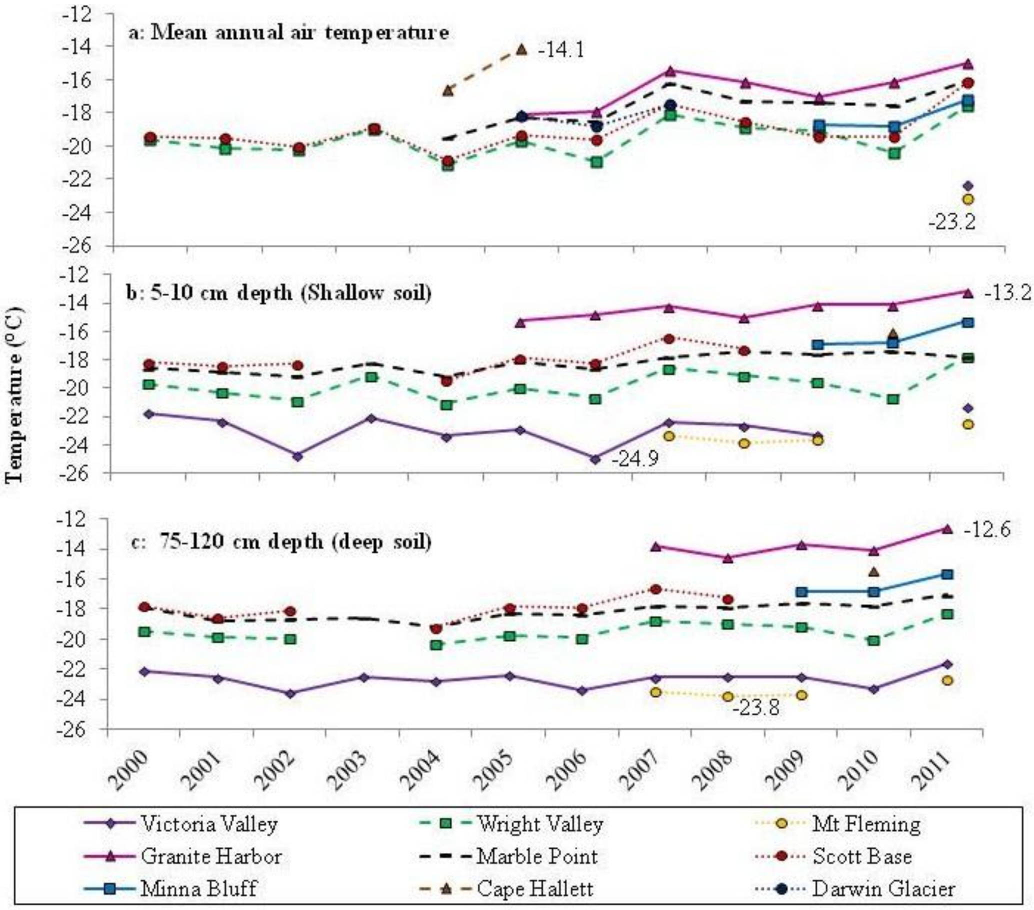

Fig. 4.1 Mean annual temperatures for individual years, for all soil climate stations from 1999-2011. a: air, b: 5-10 cm soil, c: 75-120 cm soil.

4.3.4 Mean annual deep soil temperature

Stations showed general similarities in temperature trends over the years, with distinct differences in temperature between sites (Fig. 4.1c).

Granite Harbour recorded the warmest deep soil mean annual temperature of -12.6°C. Mt Fleming recorded the coldest deep soil mean annual temperature of -23.7°C.

4.4 Mean annual temperatures: 12 month moving averages

Twelve month moving averages were applied using monthly mean air and soil temperatures (Fig. 4.2 a-c) to avoid the effects of arbitrary January-December annual boundaries.

Calculated 12 month moving average mean annual data (Fig. 4.2 a-c) revealed the same general pattern as standard mean annual measurements (Fig.4.1 a-c) with increased detail of data between the arbitrary January-December year. The moving average calculated mean annual data for 12 months centred on each month, so, for example, the data point for August 2002 air temperature is calculated by taking the mean of all data from March 2002 - February 2003.

4.4.1 Mean annual air temperature: 12 month moving average

Twelve month moving average data for air (Fig. 4.2a) revealed a warm period between January 2007 and December 2008 across all sites, indicating that the winter of 2007 and summer of 2008 were warm compared to other years on record.

A trough in air temperatures in 2010 was evidence of a cool 2010 winter at Cape Hallett and Wright Valley, and to a lesser degree at Scott Base.

4.4.2 Mean annual shallow soil temperature: 12 month moving average

Twelve month moving average data for shallow soil showed a wider range of temperatures between sites than was evident for air temperature (Fig. 4.2b). All sites exhibited similar patterns in temperature.

Relatively lower temperatures were recorded in 2002 at all sites (Fig 4.2b). Relatively lower temperatures were also recorded in 2006, particularly at Victoria Valley, and to a lesser extent at the other sites, and in 2010 at Wright Valley and Cape Hallett. Temperature peaks were sharper and shorter than the temperature lows. Mean annual shallow soil data recorded a peak at all sites in 2003 and 2011.

Granite Harbour had the “noisiest” data with sharp peaks and troughs throughout the record from 2004-2011. The 2002 temperature low had the greatest impact at the Victoria Valley site, where the largest and longest temperature decrease was recorded (Fig. 4.2b).

4.4.3 Mean annual deep soil temperature: 12 month moving average

Deep soil measurements (Fig. 4.2c) had less variability in temperature than was evident at shallow soil depths. January 2002 to January 2003 showed the deepest temperature trough, with Victoria Valley decreasing from -22.2°C to -24.3°C, Wright Valley decreasing from -19.4°C to -21.6°C, and Marble Point decreasing from -18.1°C to -19.4°C. A smaller trough was recorded in 2010. Victoria Valley recorded a further shallow trough in 2006, only slightly visible at the other sites.

Temperature peaks were difficult to identify at deep soil depths, but a definite peak in 2011 was recorded at all locations. A relatively warmer winter in 2003 was seen following the 2002 temperature trough. There was a time lag between the maximum and minimum temperatures from air to deep soil.

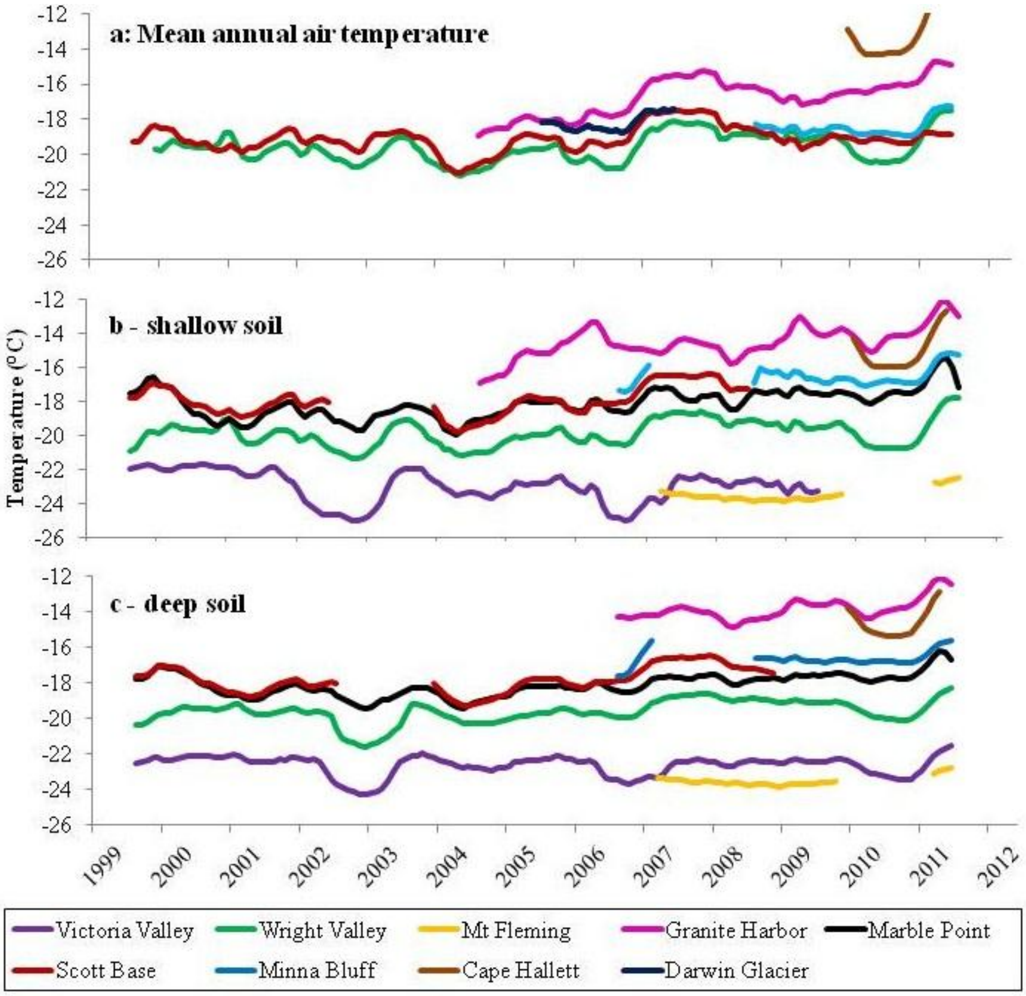

Fig. 4.2 Mean annual temperatures: 12 month moving average. a: air, b: 5-10 cm soil, c: 75-120 cm soil.

4.5 Trends in mean annual air and soil temperatures

4.5.1 Mean annual air temperature trend

In assessing temperature trends, time records with three or less annual data points were not included as the results showed misleadingly high R^2 values and low

P values. Wright Valley and Scott Base had the longest continuous records available and also the lowest R^2 values (Fig. 4.3).

There was a trend of increasing air temperature over time at Marble Point ($P<0.05$) with an apparent increase in mean annual temperature of 2.9°C between 2004 and 2011 (Fig. 4.3).

Wright Valley and Scott Base air temperature data had lower R^2 and higher P values than other stations, indicating that changes in air temperature were not statistically significant at the $P<0.05$ level (Fig 4.3). Both the Wright Valley and Scott Base sites had been operational since 1999 through to 2011, and therefore, gave a longer measurement of temperature trends over time than Granite Harbour or Marble Point.

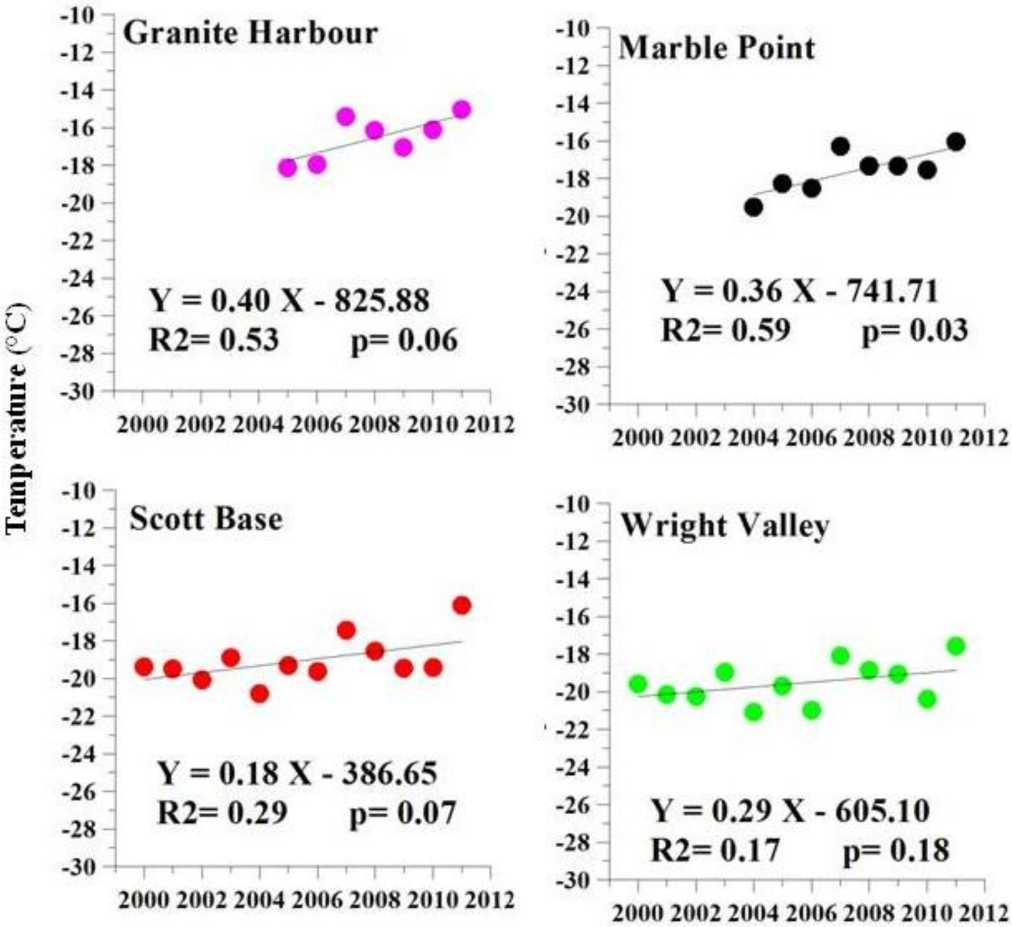

Fig. 4.3 Mean annual air temperatures with R^2, P values and regression equations.

4.5.2 Mean annual shallow soil temperature trend

At shallow soil depths warming trends were evident at Marble Point ($P<0.01$) and Granite Harbour ($P<0.02$). There were no significant trends at Mt Fleming, Scott Base, Victoria Valley or Wright Valley (Fig. 4.4).

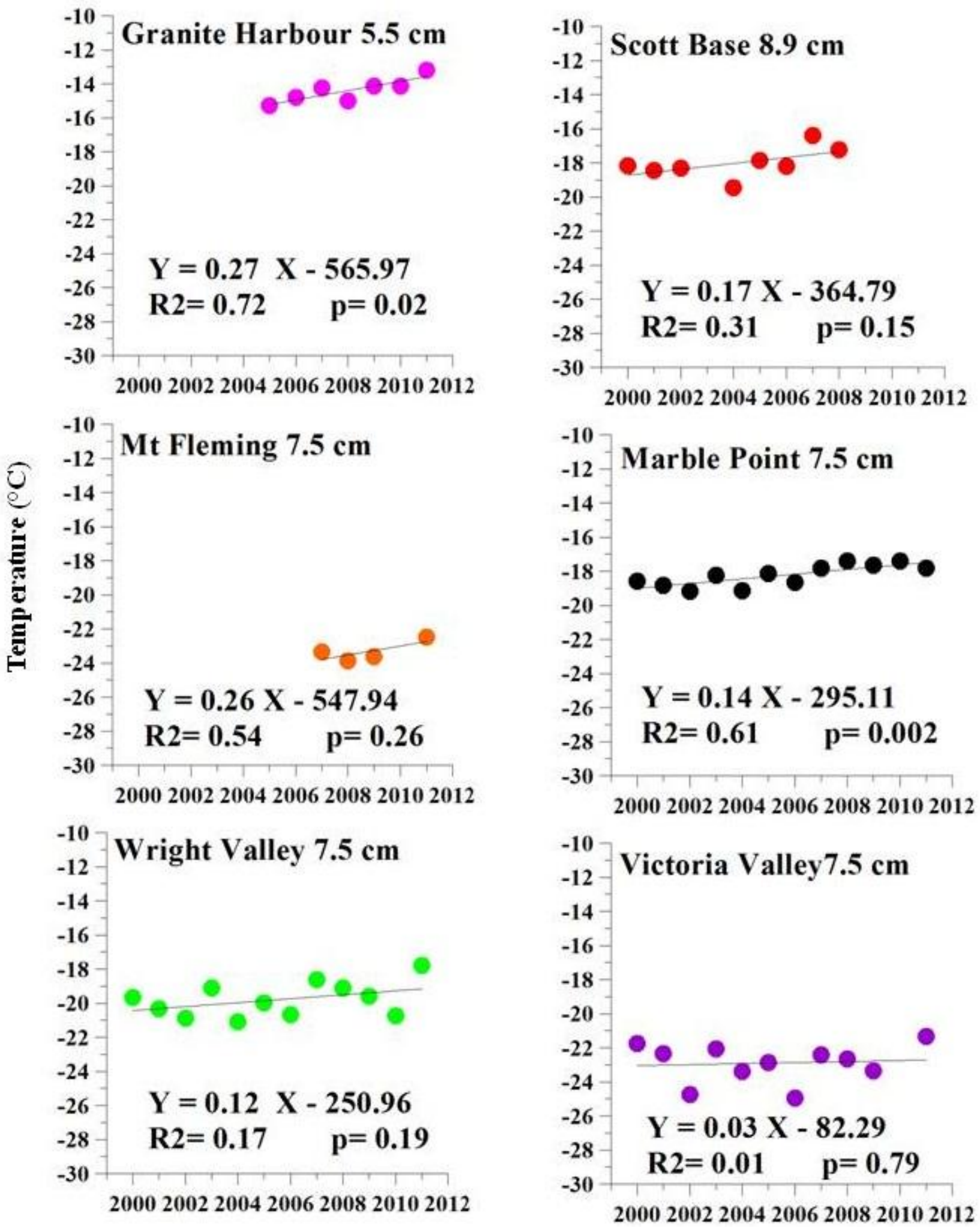

Fig. 4.4 Mean annual shallow soil temperatures with R^2, P values and regression equation.

4.5.3 Mean annual deep soil temperature trend

A statistically significant warming trend (P=0.01) was identified in deep soil measurements at Marble Point over the recording period (2000-2011). There was no significant warming trend in deep soil at Granite Harbour, Mt Fleming, Scott Base, Victoria Valley or Wright Valley over the recording period (Fig.4.5).

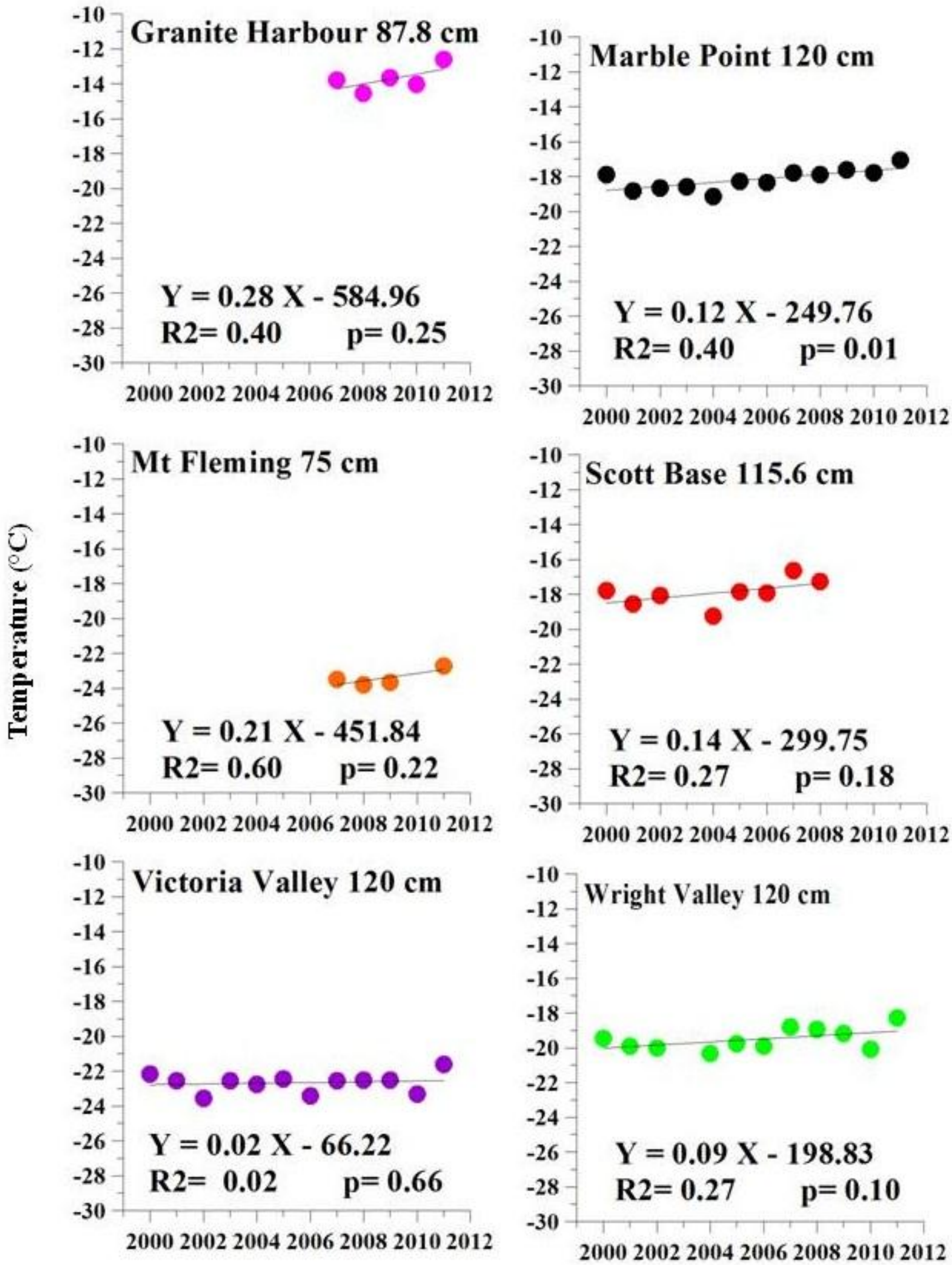

Fig. 4.5 Mean annual deep soil temperatures (75-120 cm) with R_2, P values and regression equations.

4.6 Monthly temperature trends

4.6.1 Introduction

Mean monthly data for air, shallow soil, and deep soil, were investigated to provide a more detailed view of temperatures over the recording period showing seasonal variability. Sites were categorised into coastal and inland sections.

Thirty-one day moving averages were applied to present monthly data, but were not found to yield more information than mean monthly data, and were not presented here.

4.6.2 Mean monthly air temperatures

Mean monthly air temperatures at inland sites (Victoria Valley, Wright Valley, Mt Fleming, Darwin Glacier, and Don Juan Pond) (Fig. 4.6a) showed a similar seasonal pattern across the sites. Conversely, the warmest summer (January) air temperatures were consistently recorded at Wright Valley. The coldest recorded mean monthly winter air temperature was recorded in 2001 at Wright Valley. The warmest mean monthly winter air temperature at all sites within the network was recorded in 2007 at Wright Valley.

Mean monthly air temperatures at coastal sites (Minna Bluff, Marble Point, Granite Harbour, Cape Hallett, and Scott Base) had a narrower temperature spread than at inland sites (Fig. 4.7a). Relatively warmer and cooler years were more obvious for coastal, than for inland air temperatures, with cooler winter temperatures recorded in 1999, 2001, 2004, 2006 and 2008 at Scott Base (and Minna Bluff in 2008). The effects of cooler winter air temperatures for coastal sites were also evident in mean annual and moving average air temperatures (Figs. 4.1a & 4.2a). Summer mean monthly coastal air temperatures had less inter-annual variation than for colder winter temperatures. The warmest summer mean monthly coastal air temperature (0.97°C) was recorded at Granite Harbour in 2005.

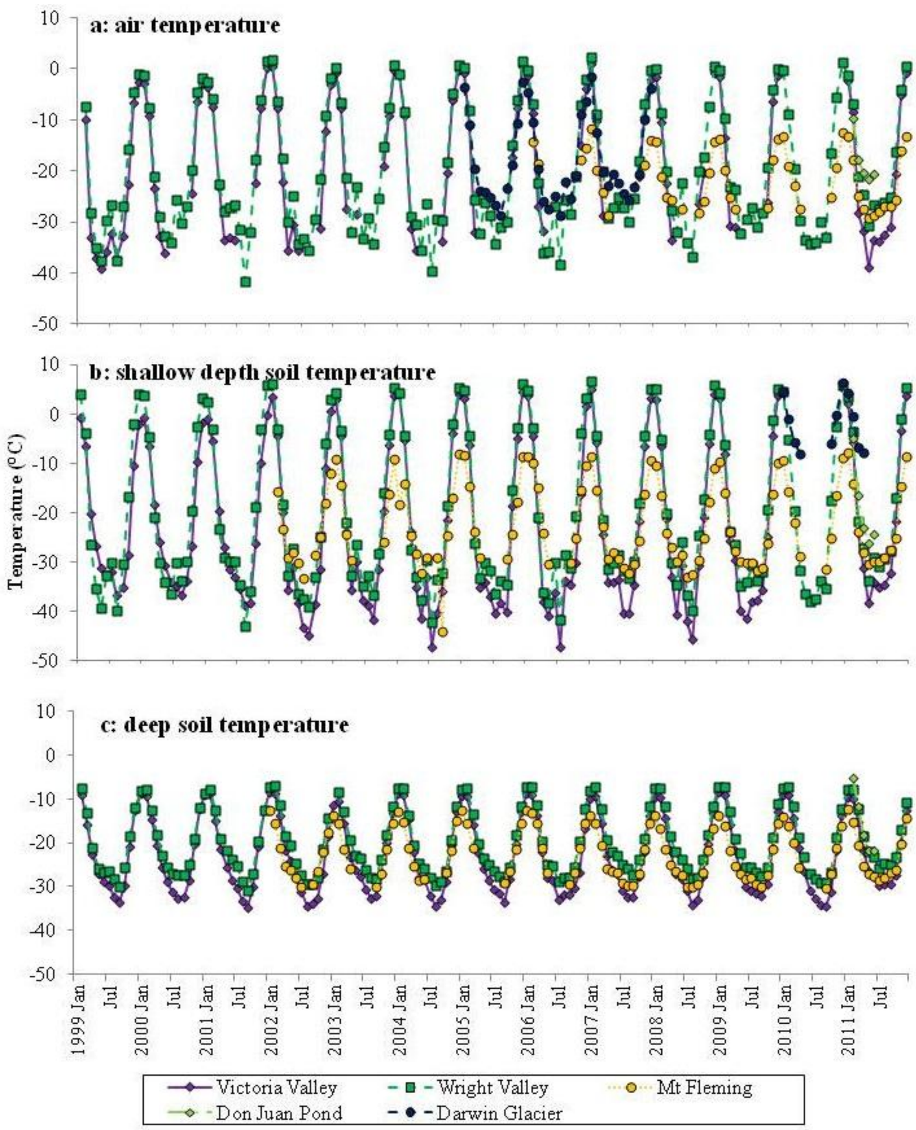

Fig. 4.6 Mean monthly temperatures for inland sites (i.e. Victoria Valley, Wright Valley, Mt Fleming, Don Juan Pond and Darwin Glacier). a: air, b: shallow soil (5-10 cm depth), c: deep soil (75-120 cm depth).

4.6.3 Mean monthly shallow soil temperatures

Mean monthly shallow soil temperatures at inland sites showed similar seasonal patterns across the stations (Fig. 4.6b). Temperature range for monthly shallow soil temperatures was greater than for air temperatures. Victoria Valley generally experienced the coldest winter temperatures at shallow soil depth, whilst Wright Valley had the warmest recorded shallow soil inland summer temperatures. The winters (July) of 2002, 2004, 2006 and 2008 had relatively colder shallow soil temperatures than other years at Victoria Valley.

Coastal sites (Fig.4.7b) had less temperature spread compared to the inland sites for mean monthly shallow soil temperatures. Relatively colder winters (July) were recorded in 2001, 2002, 2004, 2006 and 2008 at Marble Point and Minna Bluff. Granite Harbour recorded the warmest mean monthly shallow soil temperature in January 2005. The warmest winter coastal shallow soil mean monthly temperatures were recorded at all stations in July 2011.

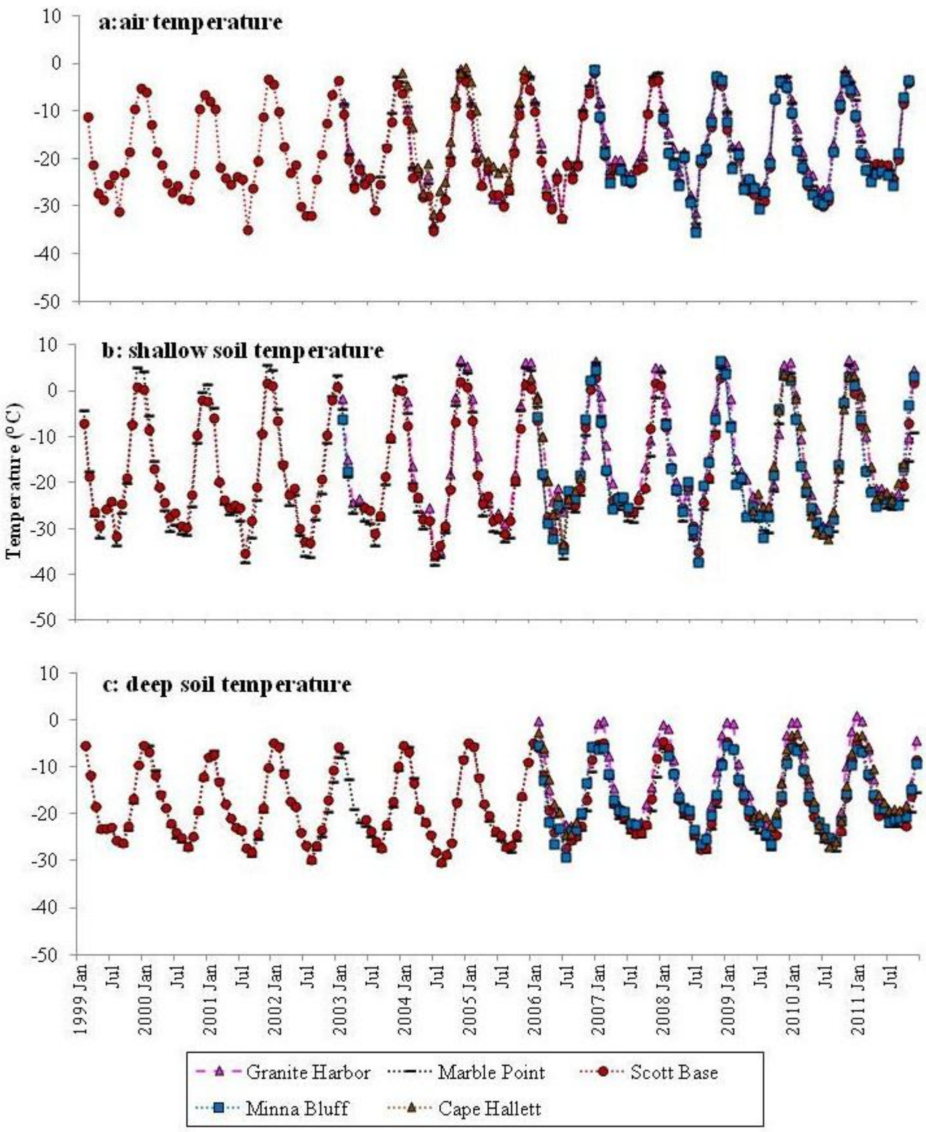

Fig. 4.7 Mean monthly air and soil temperatures for coastal sites (i.e. Granite Harbour, Marble Point, Scott Base, Minna Bluff and Cape Hallett). a: air, b: shallow soil (5-10 cm depth), c: deep soil (75-120 cm depth).

4.6.4 Mean monthly deep soil temperatures

Victoria Valley consistently recorded the coldest winter mean monthly inland deep soil temperatures (Fig. 4.6c). Warmest summer mean monthly deep soil inland temperatures were consistently recorded at Wright Valley, except for February 2011 when the Don Juan Pond soil climate station was installed and recorded the warmest deep soil mean monthly temperatures (-5.3°C).

Mean monthly deep soil temperatures at coastal sites (Fig. 4.7c) had narrower temperature spreads than air and shallow soil measurements. Cape Hallett consistently recorded the warmest summer mean monthly deep soil coastal temperatures from 2006 to 2011. Deep soil temperatures in summer 2011 (January) were the warmest over the recording period for Cape Hallett, whilst deep soil coastal temperatures were the coldest in July 2004 at Marble Point. The warmest coastal deep soil winter temperatures were recorded at all sites in July 2011.

4.6.5 Mean monthly air temperatures for January 2007 - December 2008: 31 day moving average

Graphing a 31 day moving average over a 2 year period made it clearer to see temperature patterns and differences between stations that were hard to identify in the longer period mean annual graphs. Data were categorised into coastal and inland stations (Figs. 4.8 & 4.9).

Both coastal and inland air temperature sites responded in similar ways (Fig. 4.8a & 4.9a) to changing seasons with a rapid decrease in temperature from February through to mid-late April (both 2007 and 2008). Coupled with the rapid temperature drop was an increase in temperature variability across all sites between mid March and mid October.

Warmer temperatures, visible at coastal and inland stations, occurred from mid-late September, to January. During the summer months especially, and also spring/autumn months (late October through mid March), temperature fluctuations were reduced compared to winter months, with each station following the same peak pattern, with higher/lower temperatures depending on the station's location. The summer temperature peak occurred in late December - early January 2008 at all sites. Increased temperature variability resumed from Mid March 2008 onwards (Fig. 4.8a & 4.9a).

4.6.6 Mean monthly shallow soil temperatures for January 2007 – December 2008: 31 day moving average

Inland shallow soil temperatures showed that Mt Fleming cooled most rapidly after summer and took longer to warm after winter for 2007 and 2008 than other sites (Fig.4.8b). Victoria Valley and Wright Valley had similar temperature patterns, whilst the Mt Fleming site had a flattened temperature pattern relative to the Victoria and Wright Valley sites (Fig. 4.8b).

In the coastal shallow soil temperature data, Granite Harbour was the warmest site in the summer of 2007-2008 from mid December 2007 through to early February 2008 (Fig. 4.9b). The lowest winter temperatures at all coastal sites occurred between August and September 2008 (Fig. 4.9b). The summer peak was narrower than the winter low, recording maximum temperatures in early January 2008 before decreasing rapidly. The shallow soil temperatures during winter 2008 were colder than for the 2007 winter for coastal stations.

4.6.7 Mean monthly deep soil temperatures for January 2007 – December 2008: 31 day moving average

The moving average showed smooth transitions through the seasons from 2007-2008 for deep soil temperatures in coastal and inland locations (Fig. 4.8c & 4.9c). The stations had an almost steady pattern most of the time, with most fluctuations in temperature occurring in winter 2008 (June-August).

Inland deep soil temperatures over both 2007 and 2008 showed little variation (Fig. 4.8c), with a relatively cooler winter trough in 2008. The deep soil temperatures at Mt Fleming are relatively warmer in winter and cooler in summer than Wright and Victoria Valley.

The 2008 winter soil temperatures were lower from February to September 2008 than the 2007 winter for coastal sites (Fig. 4.9c). Granite Harbour deep soil temperatures were consistently warmer than other coastal sites during the observation period.

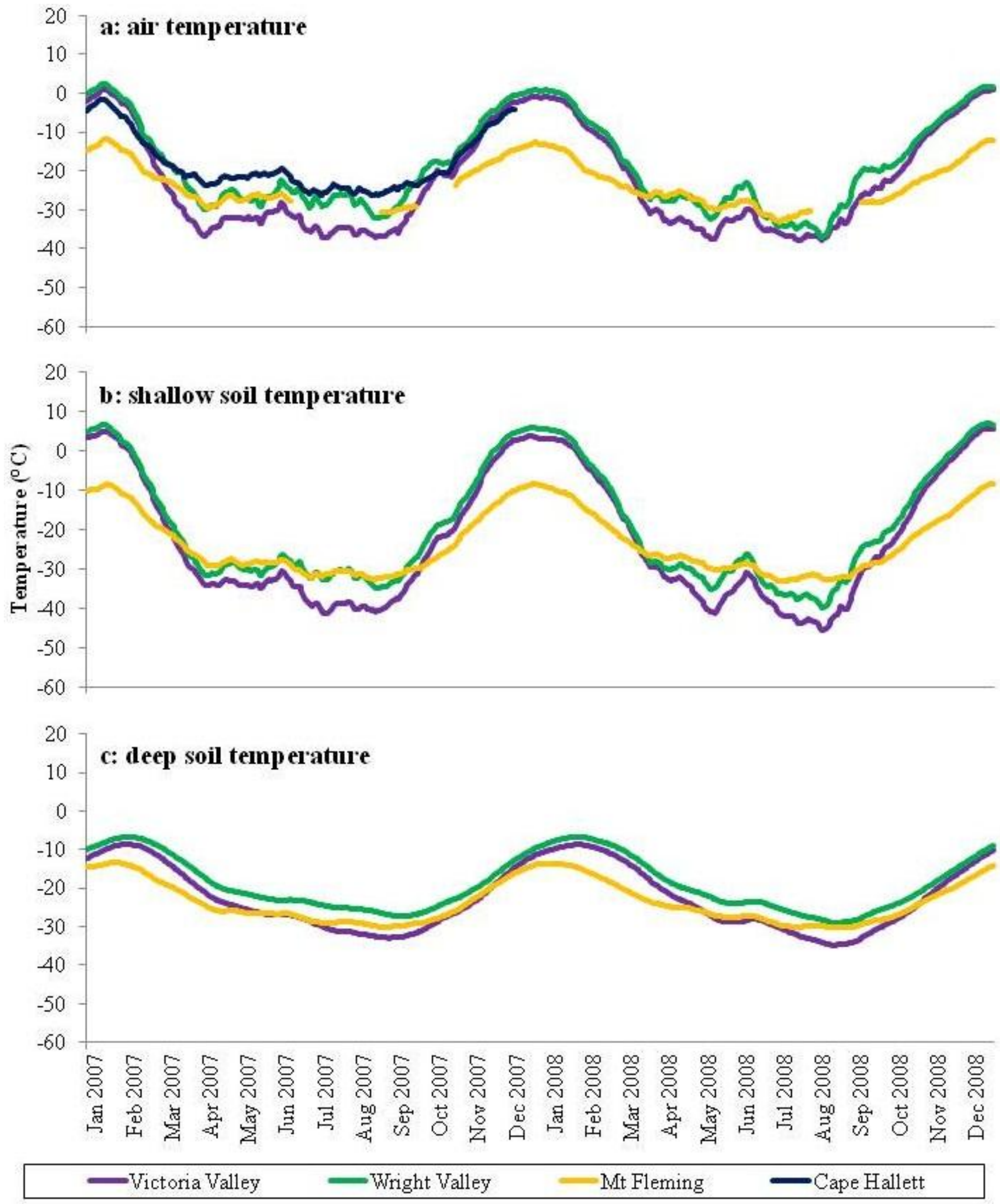

Fig. 4.8 24 month mean monthly air and soil temperatures for inland sites (i.e. Victoria Valley, Wright Valley, Mt Fleming and Cape Hallett) from January 2007 – December 2008 (31 day moving average). a: air, b: 5-10 cm soil, c: 75-120 cm soil.

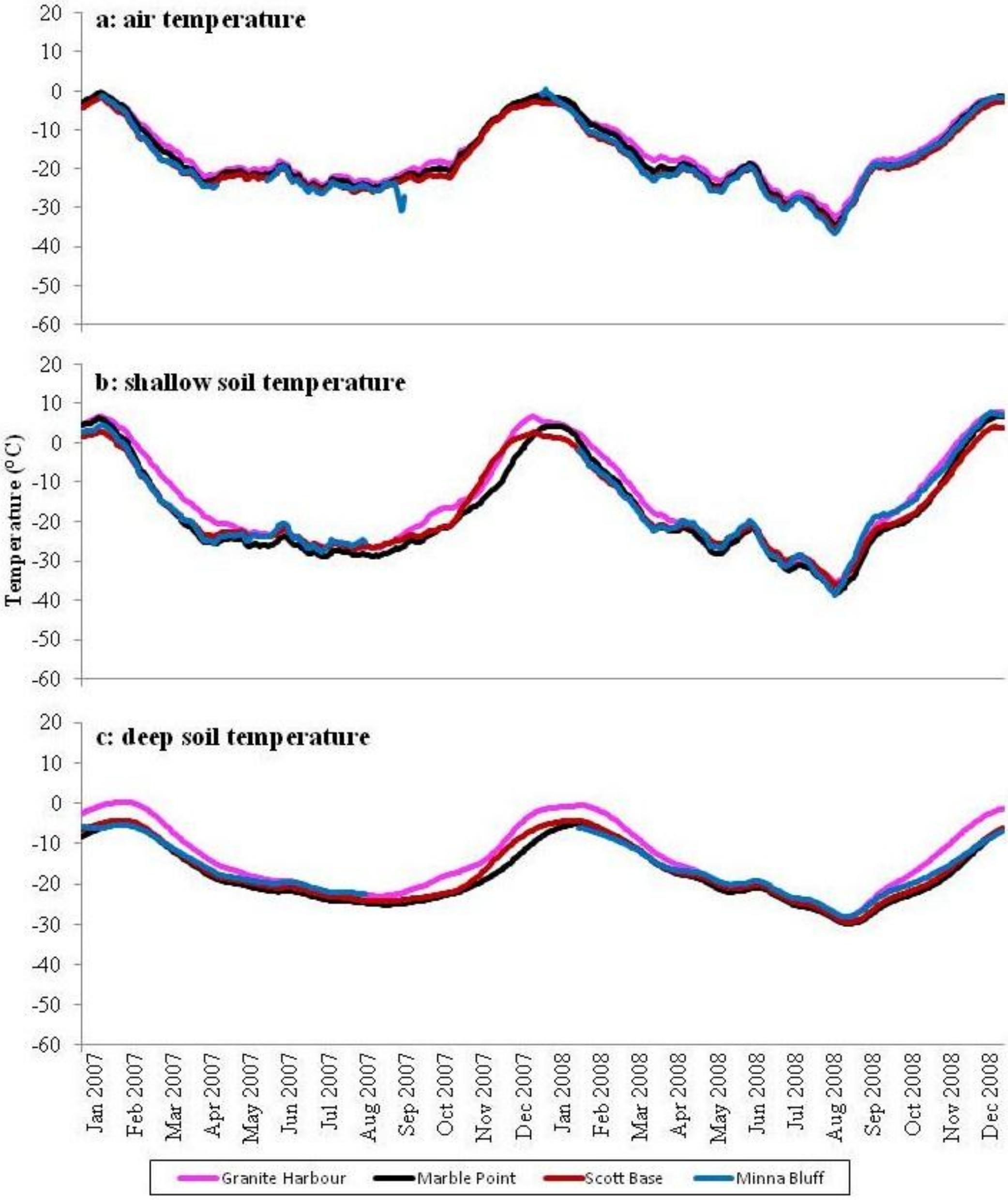

Fig. 4.9 24 month mean monthly air and soil temperatures for coastal sites (i.e. Granite Harbour, Marble Point, Scott Base and Minna Bluff) from January 2007 – December 2008 (31 day moving average). a: air, b: 5-10 cm soil, c: 75-120 cm soil.

4.7 Seasonal temperatures for 2010 – 2011

4.7.1 Introduction

Mean daily data for air, shallow soil, and deep soil measurements were categorised into coastal and inland sites, and by season for comparison of temperature characteristics.

4.7.2 Spring temperatures

Inland air temperatures (Fig. 4.10a) had sharply defined temperature variations with distinct peaks and troughs representing warmer and cooler periods. Temperatures increased from September to early November before levelling from mid November. Coastal air temperatures (Fig. 4.11a) showed the same variable but increasing temperature trend as inland air temperatures through the spring period.

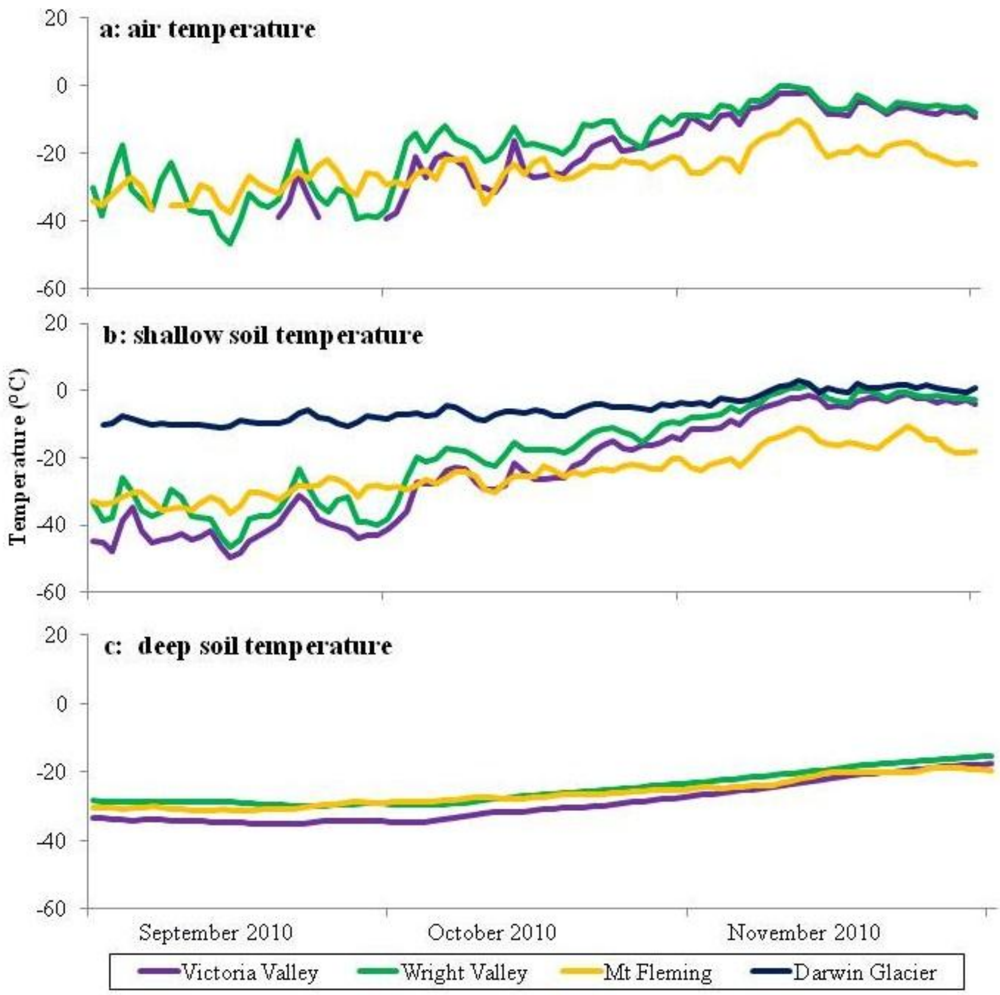

Fig. 4.10 Mean daily temperatures in springtime (Sep-Nov) for inland sites (Victoria Valley, Wright Valley, Mt Fleming and Darwin Glacier) in 2010. a: air; b: 5-10 cm soil depth; c: 75-120 cm soil depth.

Shallow soil temperatures at inland and coastal sites had a gentler and more undulating pattern in temperature fluctuations (Fig. 4.10b & Fig. 4.11b) than air temperature data, with longer peaks and troughs than those for air temperatures. Shallow soil temperatures at inland sites were lower at the beginning of spring than the air temperatures (Fig. 4.10a-b). The Darwin Glacier site had an almost steady-state temperature pattern for shallow soil through the spring season, probably due to snow cover insulating the ground surface (Guglielmin 2004). For the remaining inland shallow soil sites, temperatures steadily increased to the end of November, with temperatures levelling off only at the end of spring.

There were fluctuations in temperature both over time at each station, and between stations for shallow soils for both inland and coastal sites during September 2010, which decreased from mid October 2010 (Fig. 4.10b & Fig. 4.11b).

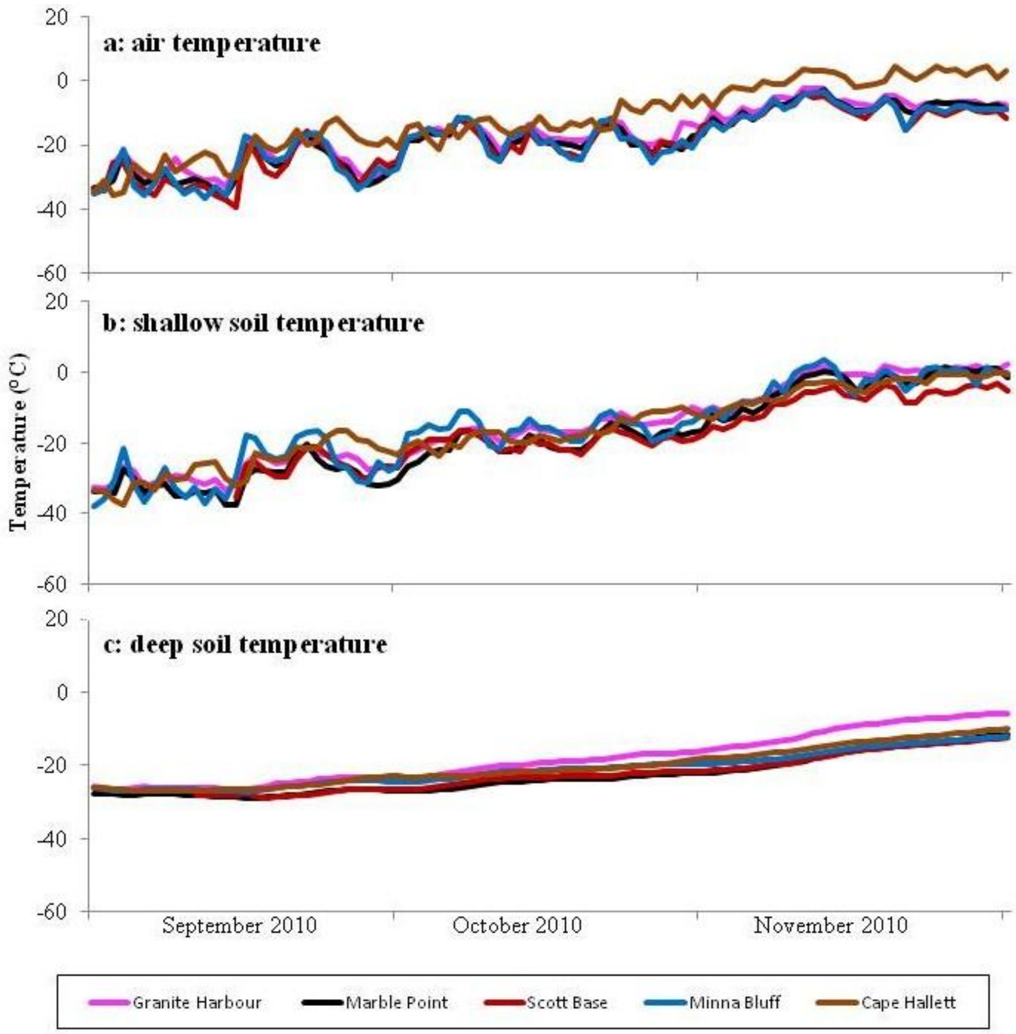

Fig. 4.11 Mean daily temperatures in springtime (Sep-Nov) for coastal sites (Granite Harbour, Marble Point, Scott Base, Minna Bluff and Cape Hallett) in 2010. a: air; b: 5-10 cm soil depth; c: 75-120 cm soil depth.

Deep soil temperature measurements for spring were flattened with few peaks and troughs, and showed an almost laminar increase in temperature from early to late spring 2010 for both inland and coastal sites (Fig. 4.10c & Fig. 4.11c). Deep soil temperatures in spring at coastal sites were warmer at the end of spring than inland deep soil temperatures for the same time. Temperature increase for deep soil inland sites began from early-mid October 2010 (Fig. 4.10c), whilst the onset of deep soil spring temperature increase for coastal sites began earlier (in mid September 2010) (Fig. 4.11c).

4.7.3 Summer temperatures

Mean daily summer inland air temperatures increased at the beginning of December before levelling off from mid December, and remained almost steady until mid January 2011 (Fig. 4.12a). Mean daily summer coastal air temperatures had a small temperature increase at the beginning of December then remained steady until mid-late January, after which they began to gradually decrease (Fig. 4.13a).

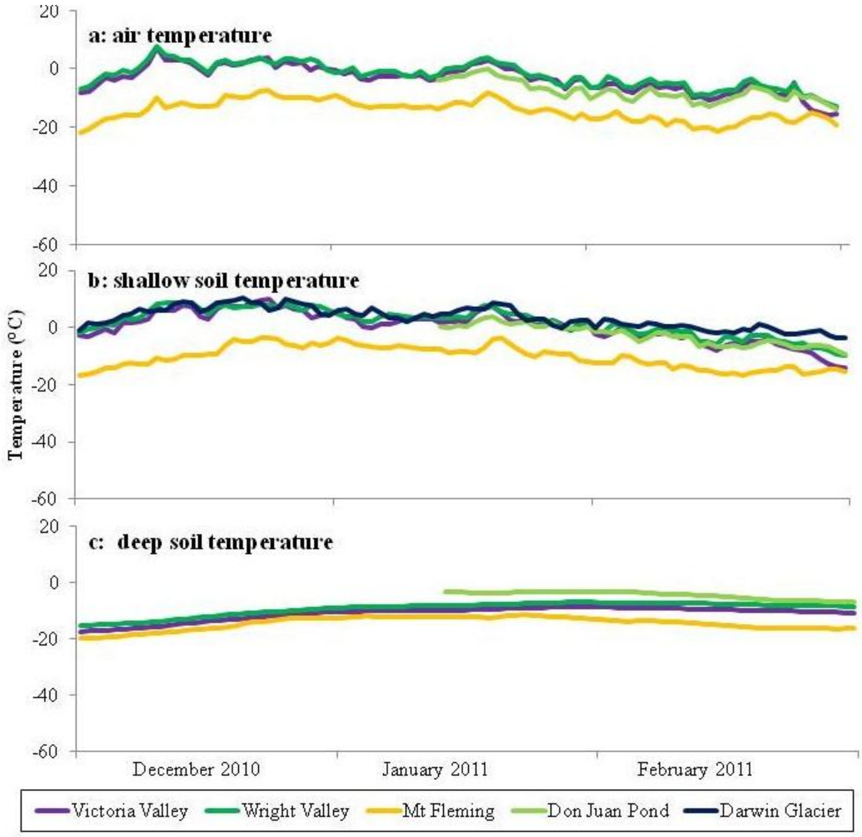

Fig. 4.12 Mean daily temperatures in summertime (Dec-Feb) at inland sites (Victoria Valley, Wright Valley, Mt Fleming, Don Juan Pond and Darwin Glacier) in 2010/2011. a: air; b: 5-10 cm soil depth; c: 75-120 cm soil depth.

In mid January 2011 a short temperature peak was recorded at all sites at both coastal and inland locations before temperatures began to decrease to the end of February 2011 (Fig. 4.12a & Fig. 4.13a). All sites at coastal and inland locations had similar air temperatures during summer except for inland site Mt Fleming which was consistently colder (Fig. 4.12a).

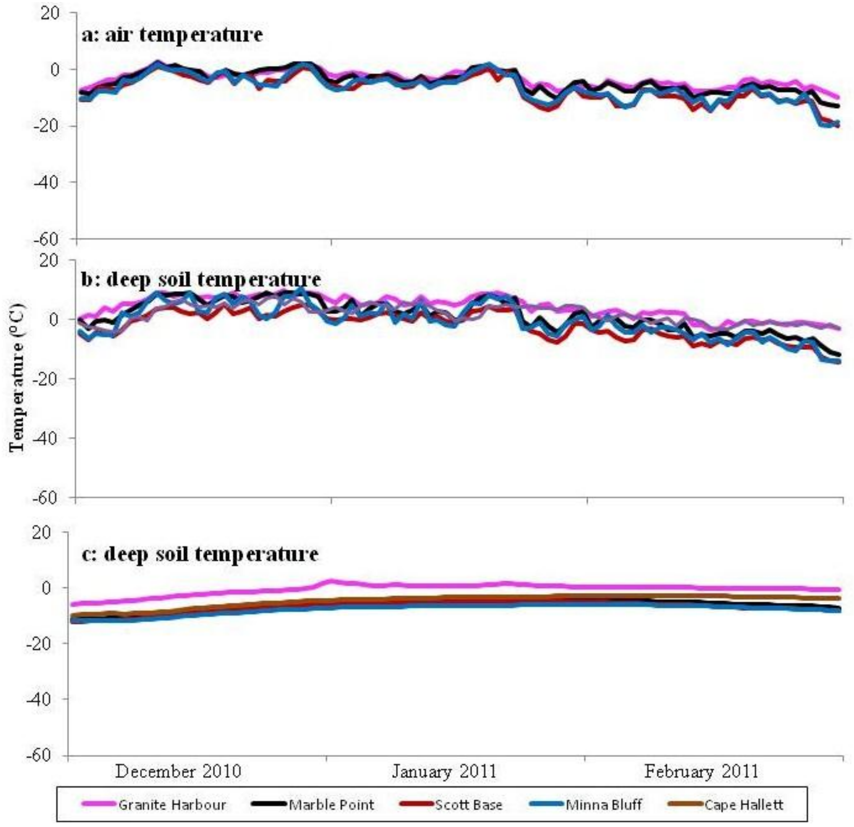

Fig. 4.13 Mean daily temperatures in summertime (Dec-Feb) at coastal sites (Granite Harbour, Marble Point, Scott Base, Minna Bluff and Cape Hallett) in 2010/2011. a: air; b: 5-10 cm soil depth; c: 75-120 cm soil depth.

Mean daily temperatures for shallow soils in coastal and inland sites had a later and broader temperature peak for the summer months of December 2010 – February 2011 than for other seasons (Fig. 4.12b & Fig. 4.13b). Inland shallow soil temperatures had higher temperature variability compared to inland air temperatures. Coastal shallow soil summer temperatures had greater temperature variability than coastal air temperatures for summer months (Fig. 4.13b). Mt Fleming had lower summer shallow soil temperatures than other inland sites. Shallow soil summer temperatures began to decrease from mid January 2011 for both coastal and inland sites (Fig. 4.12b & Fig. 4.13b).

Deep soil summer mean daily temperature measurements gradually increased at both coastal and inland sites (Fig. 4.12c & Fig. 4.13c) with maximum temperatures attained early January. Both inland and coastal sites showed a temperature plateau from early January through to the end of February with the exception of Mt Fleming and Don Juan Pond (Fig. 4.12c), which began to decrease in temperature from mid-late January 2011. Granite Harbour had an anomalous peak in the summer coastal deep soil temperatures (Fig. 4.13c) in late December – early January. Granite Harbour consistently had the warmest deep soil temperatures for summer months in 2011 (Fig. 4.13c).

4.7.4 Autumn temperatures

During autumn 2011, mean daily air temperatures became erratic, with large peaks and troughs from late March 2011 to the end of May 2011. Temperature spread and fluctuations were greater for inland sites than coastal sites (Fig. 4.14a & Fig. 4.15a). Despite the large temperature swings, the overall air temperature for autumn 2011 decreased slowly.

Inland shallow soil autumn temperatures decreased from the beginning of March to the end of May 2011 with distinct peaks and troughs (Fig. 4.14b). Darwin Glacier shallow soil temperatures were warmer and more even than other inland sites with a near-stable temperature pattern from March to the end of May 2011 (Fig. 4.14b). Coastal autumn shallow soil temperatures showed the same pattern as inland sites. Shallow soil coastal temperatures had a greater spread and exhibited more fluctuations than coastal air temperatures during the autumn season (Fig. 4.15b).

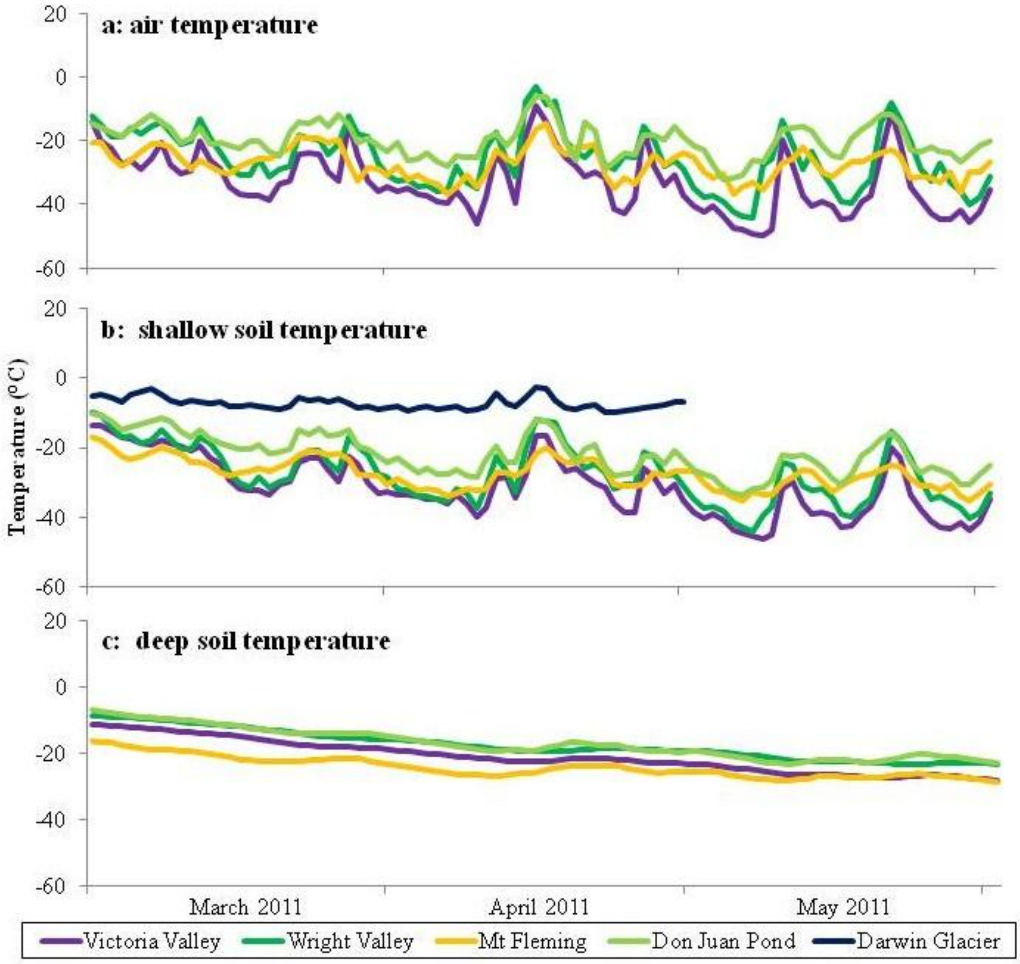

Fig. 4.14 Mean daily temperatures in autumn (Mar-May) at inland sites (Victoria Valley, Wright Valley, Mt Fleming, Don Juan Pond and Darwin Glacier) in 2011. a: air; b: 5-10 cm soil depth; c: 75-120 cm soil depth.

Deep soil autumn temperature measurements for inland and coastal sites showed a gradual decrease in temperature from the start to end of autumn (Fig. 4.14c & Fig. 4.15c). Inland deep soil autumn temperatures began at a cooler temperature than the coastal sites and the inland sites had cooled more than the coastal sites by the end of autumn 2011.

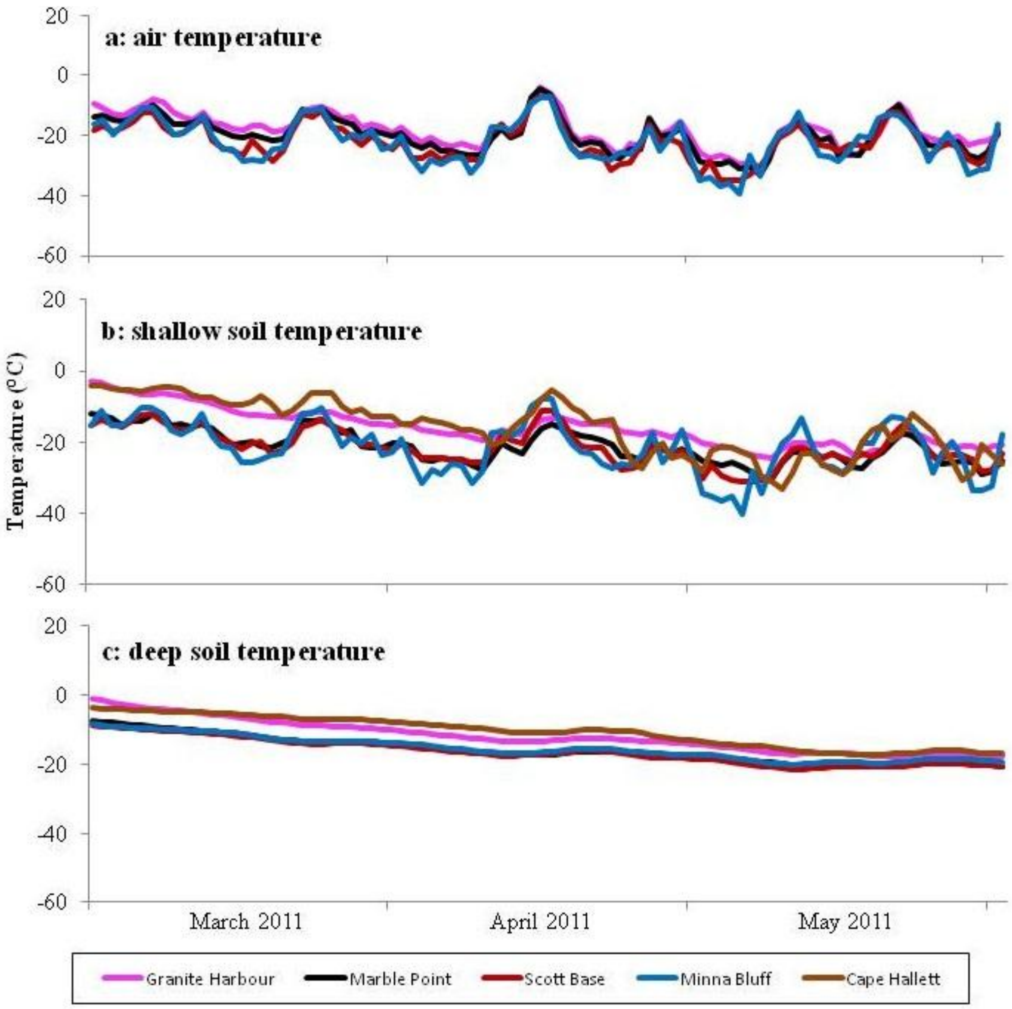

Fig. 4.15 Mean daily temperatures in autumn (Mar-May) at coastal sites (Granite Harbour, Marble Point, Scott Base, Minna Bluff and Cape Hallett) in 2011. a: air; b: 5-10 cm soil depth; c: 75-120 cm soil depth.

4.7.5 Winter temperatures

Mean daily inland winter air temperatures (Fig.4.16a) showed large temperature fluctuations. Victoria Valley consistently recorded the coldest mean daily air temperatures from June 2011 – August 2011. No one site had distinctive warmest winter temperatures. Mean daily coastal winter air temperatures (Fig. 4.17a) had little temperature range between stations and overall had fewer temperature fluctuations during the winter months than the inland sites. Whilst temperatures fluctuated during the winter season, there was no temperature increase or decrease from the onset to end of winter for inland and coastal sites. Strong peaks of air temperatures in both coastal and inland sites probably indicated the passage of regional storms, katabatic, or foehn wind events (Fig. 4.16a & Fig. 4.17a).

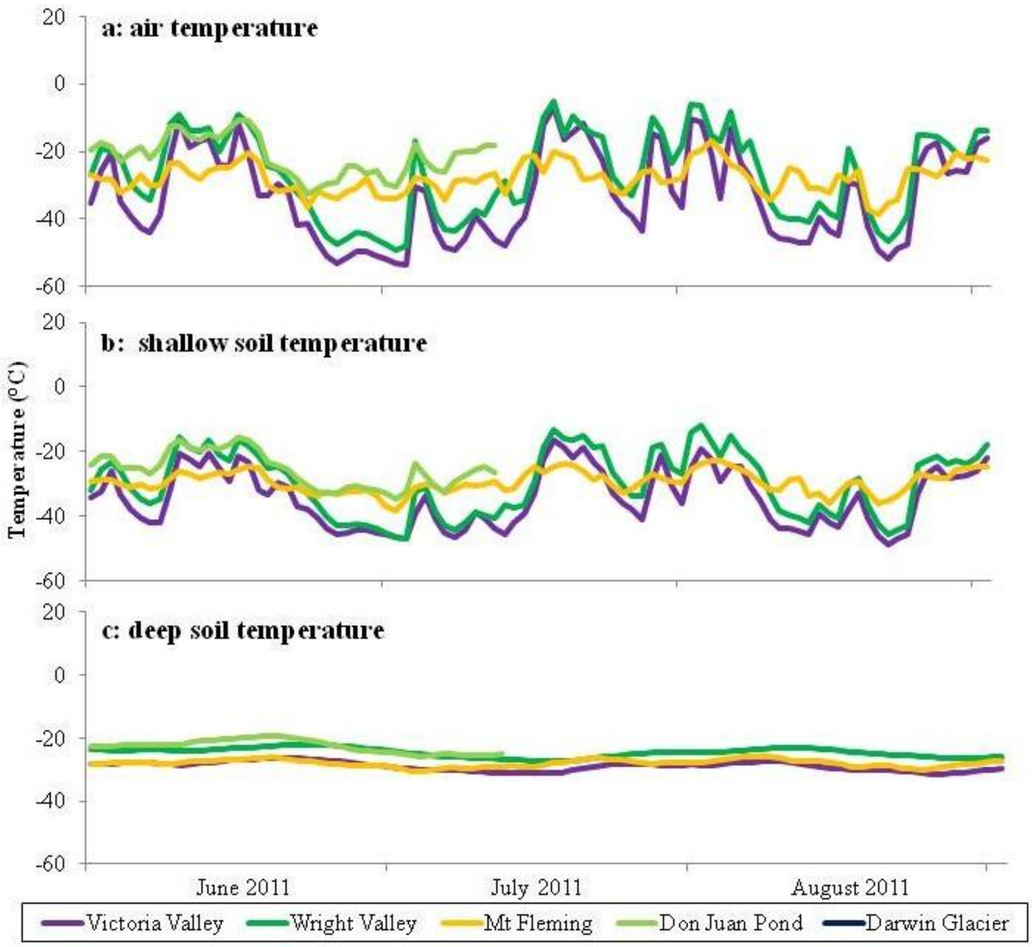

Fig. 4.16 Mean daily temperatures in wintertime (Jun-Aug) at inland sites (Victoria Valley, Wright Valley, Mt Fleming, Don Juan Pond and Darwin Glacier) in 2011. a: air; b: 5-10 cm soil depth; c: 75-120 cm soil depth.

Mean daily shallow soil winter temperatures for inland sites had lower temperature variability than inland site winter air temperatures (Fig. 4.16a-b). Conversely, shallow soil winter temperatures for coastal sites had higher temperature range and variability compared to coastal winter air temperatures (Fig. 4.17a-b). Temperature peaks and troughs in winter temperatures were less defined, and more prolonged in shallow soil temperatures for both inland and coastal locations than air temperatures, with coastal sites being more dampened presumably due to snow cover.

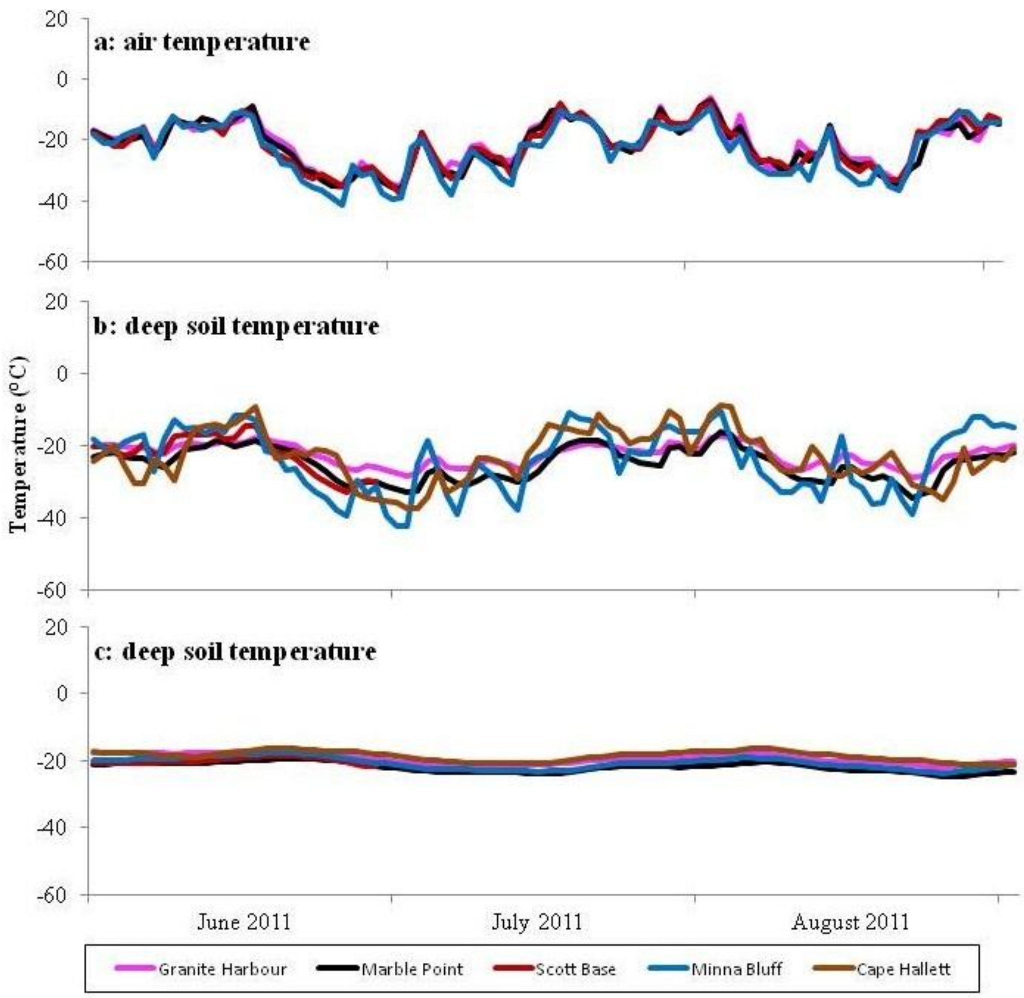

Fig. 4.17 Mean daily temperatures in wintertime (Jun-Aug) at coastal sites (Granite Harbour, Marble Point, Scott Base, Minna Bluff, and Cape Hallett) in 2011. a: air; b: 5-10 cm soil depth; c: 75-120 cm soil depth.

Deep soil winter temperature measurements for inland and coastal sites were near linear, with two gentle peaks evidence of slight warming at depth during the winter months (Fig. 4.16c & Fig. 4.17c). Temperatures remained steady over the winter 2011 season at both inland and coastal sites, with inland temperatures slightly colder than coastal locations.

4.8 Discussion

4.8.1 Station comparison

All the soil climate stations generally followed the same temperature patterns of warmer and cooler years with differences between stations relating to site localities. On both annual and seasonal scales, cold or warm events at one station were generally recorded at the other sites to a greater or lesser degree. Some discrepancies were visible however between stations, as only two of the 10 stations in the network recorded a warming trend (Marble Point both air and soil, and Granite Harbour at shallow soil) whilst no significant warming or cooling trend was recorded at the other six stations with longer records. For a region as large as the Ross Sea region, recordings from only six stations cannot viably represent the whole area. As time progresses, more stations can be incorporated into the results as the records increase.

The soil climate station at Granite Harbour was located on a sheltered north-facing harbour edge with a warm microclimate created by direct sun and melt-water sub-surface flow from the adjacent hillside through the highly porous, bouldery soil. Melt-water conducts energy into the soil giving higher soil temperatures at depth than would occur without the consistent melt-water flow. Thus deep soil temperature measurements for Granite Harbour were considered anomalously high, and not considered typical of the wider area. Due to the atypical site (through water flow) that led to the high deep soil temperature measurement at Granite Harbour, the statistically significant warming trend identified in the deep soil measurements at Granite Harbour was not considered likely to be representative of the wider area. The impact of surrounding topography sheltering sites, and leading to conflicting climatic conditions between neighbouring stations was reported in previously published literature by Comiso (2000) and Schneider *et al.* (2012).

4.8.2 Latitude and altitude

Soil climate sites within the network ranged from near sea level to 1670 m ASL and from ~72°S to ~79°S. Across the latitudinal gradient the northernmost soil climate station was Cape Hallett (72°19’). The southernmost station was Darwin Glacier (79°50’). Neither Darwin Glacier nor Cape Hallett stations had continuous extended air temperature records. Cape Hallett’s (72°19’) warmest air temperature was +5.19°C, whilst the warmest air temperature recorded at Darwin Glacier (79°50’) was similar (+4.67°C).

Doran *et al.* (2002a) reported a south-north progression in mean annual near surface air temperature in the Dry Valleys: Taylor Valley>Wright Valley>Victoria Valley from 1985-2000. Taylor Valley was not a site that was utilised in this dataset, and Victoria Valley suffered equipment failure during winter months from 1999-2010 so direct comparison cannot be made. However, within the network used for this analysis, a north-south progression was not found in the mean annual deep soil temperatures, with Cape Hallett>Minna Bluff>Scott Base>Marble Point>Wright Valley>Victoria Valley>Mt Fleming. Overall mean annual air temperatures for air and soil plotted in a latitudinal transect confirmed that latitude alone was not the main controlling factor on temperature (Fig. 4.18). Air and soil plots are closely coupled for each site, but no distinct gradation from south to north was evident. A south-north gradation was reported in previous work within the Ross Sea region by Adlam (2009).

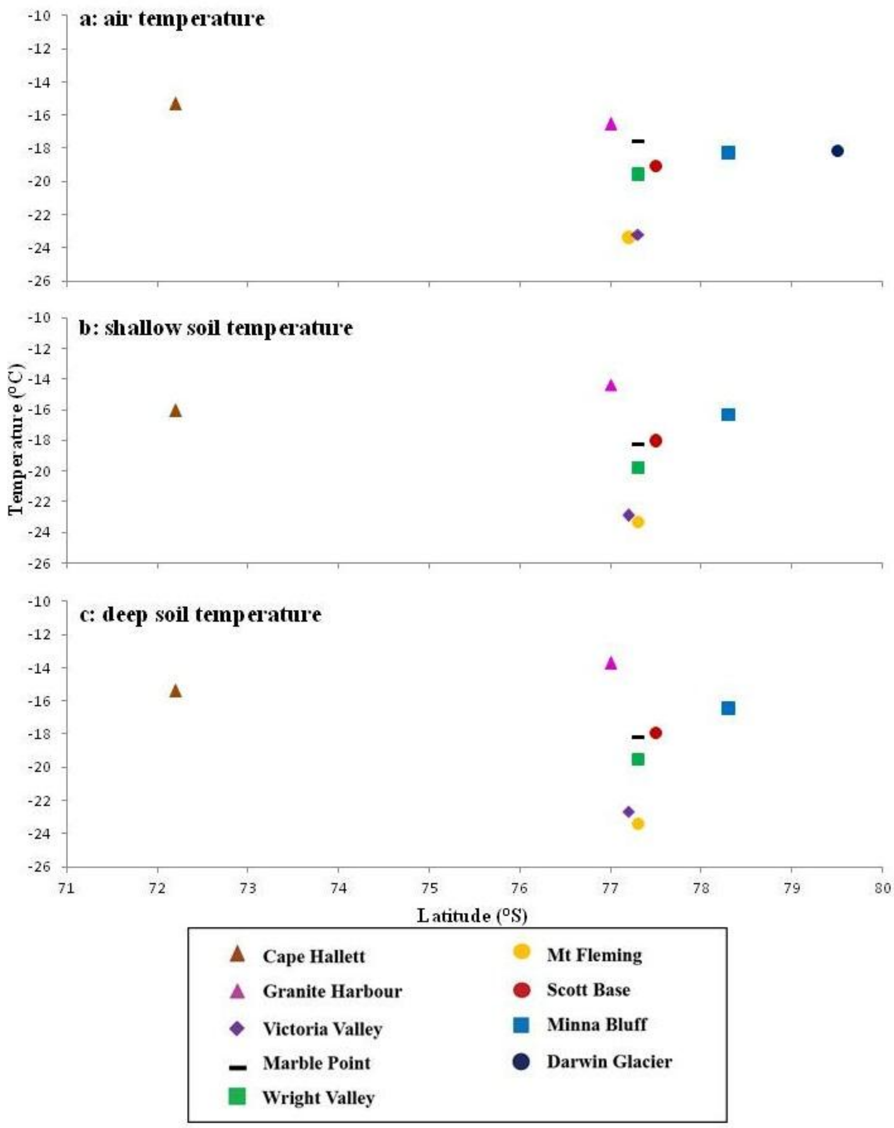

Fig. 4.18 Overall mean annual temperatures vs. latitude for a: air, b: shallow soil (5-10 cm depth) and c: deep soil (75-120 cm depth).

Data was categorised into coastal and inland sites for analysis, but no latitudinal trend was evident and the data were not included here. When plotted on a latitudinal gradient, the overall mean annual air and soil temperature pattern for all stations showed the same pattern from air through to deep soil (Fig. 4.18a-c) with Cape Hallett being the warmest site for air and soil (and the most northern site). However there was no significant linear trend of decreasing temperature with increasing latitude.

Variation in air temperatures at increasing elevations indicated that temperatures were controlled by multiple factors, not elevation alone. Other variables controlling temperature included latitude, and may include aspect and topography – the direction the station is facing and the surrounding topography which may act to block sunlight, and therefore warmth, from reaching the sensors.

Altitude had a strong control on temperature patterns at the soil climate stations within the Ross Sea region, reported also by Adlam (2009) in a previous study of the Ross Sea region of Antarctica. Soil climate station location may have influenced temperature, with differences in temperature regimes observed between inland and coastal sites.

When ranked according to station elevation (Fig. 4.19), a decreasing temperature trend with increasing elevation was evident in the overall mean annual air, and soil temperature data. A greater temperature decrease with increasing altitude was recorded in the deep soil temperatures than air and shallow soil depths, where atmospheric temperature fluctuations had a smaller impact.

Data was categorised into coastal and inland sites to identify any differences in temperature patterns with location. Both inland and coastal sites had similar temperature patterns.

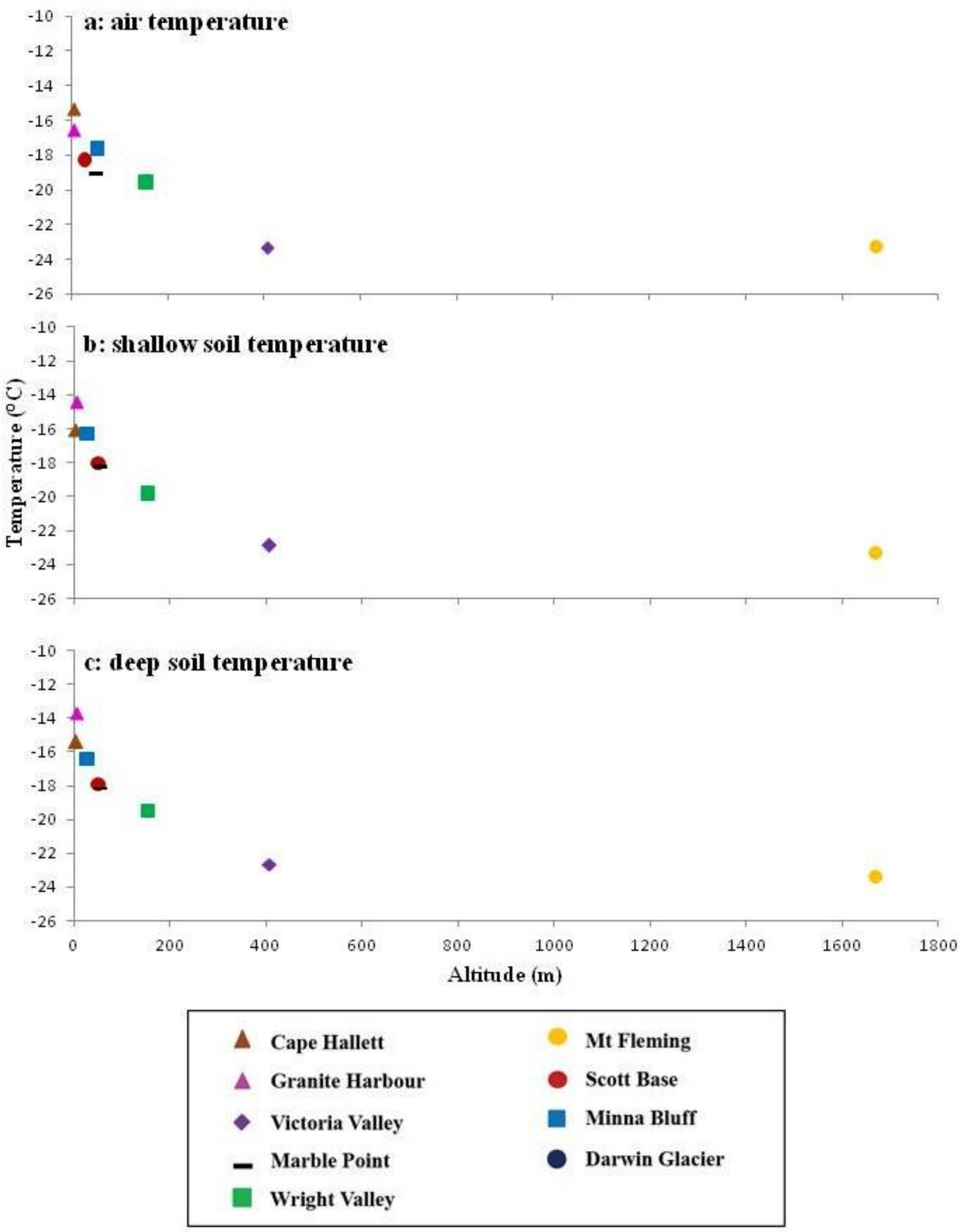

Fig. 4.19 Overall mean annual temperatures vs. altitude for a: air, b: shallow soil (5-10 cm depth) and c: deep soil (75-120 cm depth).

4.8.3 Air and soil temperature trends

Air temperatures were the most variable of the temperature measurements, with highs and lows reflecting seasonal patterns, however, shallow soils reached higher temperatures than those recorded with the air sensors. Higher shallow soil temperatures than air temperatures was likely due to solar radiation warming the soil surface and penetrating to the sensors beneath the surface causing warmer temperatures than those found in the air (Adlam 2009). Deep soil measurements were the least variable due to the soil profile acting as a buffer and insulator against diurnal, and seasonal, variability. Shallow and deep soil temperature measurements may also have been buffered by ice/snow cover insulating the soil profile from atmospheric conditions (Guglielmin 2004). Shallow soil temperatures were also hotter than air temperatures due to direct solar radiation.

Adlam (2009) reported that all deep soil mean annual temperature measurements over the recording period 1999-2007 were warmer than mean annual air measurements for the same period. However, using collected data from 2000 – 2011 (same data as Adlam 2009 extended to 2011), it was found that only four of the 10 soil climate stations recorded warmer deep soil temperatures than air: Wright Valley (0.1°C warmer), Granite Harbour (3.4°C), Scott Base (1.2°C) and Minna Bluff (1.9°C). Three of the sites analysed had colder mean annual deep soil temperatures compared to mean annual air temperatures: Victoria Valley (0.3°C cooler), Marble Point (0.6°C) and Cape Hallett (0.1°C). The remaining three sites (Mt Fleming, Darwin Glacier and Don Juan Pond) did not have sufficient data for analysis. Adlam (2009) classed deep soil measurements as 75-105 cm depth, whilst soil depth classification for this analysis was 75-120 cm depth. Therefore, some differences in findings may be linked to the different depth range used.

Up to 2001 the Antarctic Peninsula was warming at a significant rate, and the continental interior of Antarctica was experiencing net cooling (Doran *et al.* 2002b). The Victoria Valley, Wright Valley, Mt Fleming, Scott Base, Granite Harbour, Minna Bluff and Marble Point sites were previously investigated by Adlam (2009) who reported no statistically significant warming trend over the recording period 1999-2007. Investigation of all sites and all depths indicated that whilst there was definite seasonality and inter-annual variability between 1999 – 2011, there was a reliable warming signature in both air and shallow soil at only one site, Marble Point, ($P<0.05$). A P value of 0.01 coupled with an R^2 of 0.40 was identified at Marble Point.

The significance level and R^2 value at Marble Point was strongest in the shallow soil depths, indicating that warming is greatest in the shallow soil depths (7.5 cm) at the Marble Point soil climate station site. Warming at the Marble Point site may be an early indicator of a longer term warming trend that could become apparent at other coastal and inland sites over time.

Turner *et al.* (2005) reported that the near surface air temperature was cooling at an insignificant rate over the Antarctic continent from the 1950’s to 2000. The Long Term Ecological Research (LTER) project installed automatic climate stations (AWS) in the McMurdo Dry Valleys to record air temperatures. Measurements recorded a strong cooling of 0.7°C per decade from 1986 over a 14 year period (Doran *et al.* 2002a & 2002b). No significant cooling was evident in my data, concurring with Turner *et al.* (2005).

The McMurdo Dry Valleys are subject to multiple temperature regimes (Bertler *et al.* 2004) that create complications in determining simple warming and cooling trends within my data. As only one site, Marble Point, was identified to be warming for air and soil temperature measurements at the 95% confidence interval ($P<0.05$), I conclude that there is no general warming trend for air temperature in the Ross Sea region. However, the site at Marble Point may be warming. Site microclimate is an important factor at climate stations (Comiso 2000, Schneider *et al.* 2012). Further investigation of the Marble Point site is needed to determine the cause for warming and to determine whether this is a longer-term trend or just a short-term effect.

Mean annual data with 12 month moving averages applied to shallow soil temperatures revealed greater seasonal variability in shallow soil temperatures between annual points than for air temperatures (Fig. 4.2b), suggesting a strong influence of solar radiation warming the soil surface and increasing shallow soil temperatures above ambient air temperatures. Despite greater variability and fluctuations between annual points, the annual means with 12 month moving averages indicated that soil temperatures may give better representation for identifying temperature trends as solar radiation, storm events and cloudy conditions impact less on temperature measurements and may give better indication of overall temperature trends, however, snow, clear skies, and shady hills will impact soil temperatures.

A 31 day moving average applied to 24 month mean "monthly" (31 day) soil temperatures (Fig. 4.7b) revealed a cyclic trend with much less winter variability than the same analysis applied to air temperatures (Fig. 4.7a). Reduced winter variability in shallow and deep soils compared to air temperatures was likely due to no diurnal radiative heating, and at times, snow insulating the soil from air temperature fluctuations. The shallow soil moving average revealed a clearer picture of the longer-term (annual and inter-annual) temperature pattern, with broad winter low temperatures interspersed with rapid increases (and decreases) entering into summer months from spring, and from summer months into autumn.

Seasonal data for air and soil temperatures (Figs. 4.10-4.17) showed that summer months were the least variable in temperature, whilst autumn and winter showed greatest temperature fluctuations. Spring was a season of generally strong temperature increase.

Strong coupling between air and soil temperatures was visible at all sites, with corresponding peaks and troughs in the data over time. A temperature lag was evident as deep soil temperatures were reported to be the warmest in autumn and winter seasons (Figs. 4.14-4.17) due to warming during the spring and summer months being only slowly transmitted down to the 75-120 cm depth range.

Diurnal and seasonal variability were dampened out with depth, leaving only large-scale temperature variables such as summer and winter in the deep soil depth range (75-120 cm). The "noise" that affected mainly air temperature was removed and underlying trends were visible. Therefore, for temperature analysis, I would suggest using deep soil measurements at 75-120 cm depth to determine warming or cooling trends in the data.

4.8.4 Limitations to the study

4.8.4.1 Timescale

This study used up to 11 years of near-continuous air and soil temperature data (Table 4.1) Whilst only two sites reported significant warming trends, it is possible that this data is only a snapshot in a larger-scale pattern that is not yet visible due to the lack of long-term data for the network. In order to better determine the presence or absence of temporal trends, a longer dataset is needed.

A time period of less than 10 years will not give viable results, between 10-20 years is still subject to cyclic variability, whereas >20 years is termed "stable" Comiso (2000), and is the advised recommended minimum time period to use if possible.

4.8.4.2 Data continuity and reliability (equipment failure)

A problem with the temperature data was equipment failure. Failure occurred through mechanical breakdown, temperature extremes extending beyond the capabilities of the equipment, and through human interference. Human interference was generally the result of maintenance performed disturbing the equipment resulting in false temperature readings. For example, the air temperature sensor at Scott Base in January 2002 produced unusable readings for two weeks due to maintenance on a solar radiation cover which, when removed, resulted in temperature recordings that were abnormally high.

Equipment compatibility was an issue at the Victoria Valley and Mt Fleming sites, as winter temperatures dropped below the measurement capabilities of the air temperature sensors. The temperature sensors were not updated until the January 2010 season. The soil climate station at Scott Base also had prolonged gaps in air temperature data. However, air temperature data for Scott Base was retrieved from a nearby climate station run by NIWA and downloaded with permission from www.clifo.niwa.nz.

An important tool to determine the causes of mechanical or equipment failure was the metadata files for each station. Within the metadata files, reports are documented of works performed at each site. Therefore, unexpected recordings could be checked with the metadata file to determine if works were being undertaken at that time, and the data could then be removed.

4.8.4.3 Analysis techniques

Straight line regression has been used for this analysis, but is possibly not the best option to use. Climatic trends in the Antarctic may not be following a simple upward or downward progression (increasing/decreasing temperatures), but may actually be on a cyclic shift over time. However, as no obvious pattern was visible when data was graphed, a simple straight line regression was determined to be sufficient to give results. Had there been any evidence of cyclicity in the data, then other forms of regression analysis could have been investigated.

4.9 Conclusions

The mean annual air temperatures for each sites entire recording period ordered from warmest to coolest (Table 4.1) were: Cape Hallett (-15.3°C), Granite Harbour (-16.6°C), Marble Point (-17.6°C), Darwin Glacier (-18.2°C), Minna Bluff (-18.3°C), Scott Base (-19.1°C), Wright Valley (-19.6°C), and Victoria Valley (-22.4°C).

The mean annual shallow soil (5-10 cm soil depth) temperatures for each site (Table 4.1) over the entire recording period ranged from highest to lowest: Granite Harbour (-14.4°C), Cape Hallett (-16.1°C), Minna Bluff (-16.3°C), Scott Base (-18.0°C), Marble Point (-18.2°C), Wright Valley (-19.8°C), Victoria Valley (-22.9°C), and Mt Fleming (-23.3°C).

The mean annual deep soil (75-120 cm soil depth) temperatures, ordered from warmest to coolest (Table 4.1) were: Granite Harbour (-13.2°C), Cape Hallett (-15.4°C), Minna Bluff (-16.4°C), Scott Base (-17.9°C), Marble Point (-18.2°C), Wright Valley (-19.5°C), Victoria Valley (-22.7°C), and Mt Fleming (-23.4°C).

Two (Marble Point and Granite Harbour) out of the ten sites measured showed evidence for warming over the measurement period. Air and soil temperature measurements showed that there was an increase ($P<0.05$) in mean annual air temperatures for Marble Point between 2004 and 2011 ($R^2=0.59$); mean annual shallow soil (5-10 cm) temperatures from 1999 to 2011 ($R^2=0.61$); and mean annual deep soil (75-120 cm) temperatures from 1999 to 2011 ($R^2=0.40$). A temperature increase was also measured at Granite Harbour for shallow soil temperatures from 2005 to 2011 ($P=0.02$). No statistically significant warming or cooling trend was identified at any other site over the recording period of 1999 to 2011. Application of moving averages to mean annual (12 month) and mean monthly (31 day) temperature data were explained, and revealed the same trends found using mean annual measurements.

Both sites with evidence of warming (Marble Point and Granite Harbour) were on the coast of the Antarctic mainland in relatively close proximity.

Investigation of air and soil temperature trends over an altitudinal and latitudinal transect from 1999 to 2011 agrees with much of the published literature for continent-wide Antarctic research which state that Antarctic continent cooling was not statistically significant whilst the Antarctic Peninsula was widely accepted to be warming.

The McMurdo Dry Valleys are a unique climate in that they are the largest ice-free region of Antarctica, and as such, are likely affected by different climatic patterns than the continent as a whole. Thus, it is suggested that these results act as a guide for the McMurdo Dry Valleys and Ross Sea region only, and cannot be extrapolated to a wider region.

“Warmer” years (2003 and 2011), and “cooler” years (2002, 2006 and 2010), were observed and are considered to be part of natural variability and not necessarily indicative of climate change.

A longer dataset is needed to identify the presence or absence of long-term temperature trends in the Ross Sea region of Antarctica.

Chapter 5: Cumulative days above freezing for soil climate stations in the Ross Sea region

5.1 Introduction

The numbers of days at or above freezing were calculated for each soil climate station for air, ~5, ~20 and ~75 cm soil depths for the summer months November to February. The soil depths were selected to give a span of the soil profile at as many common depths as possible, the soil profile at the Mt Fleming site extended to 75 cm depth, and thus this was the maximum depth selected for comparison. Full datasets are included in appendix 1.

The objective of this chapter was to quantify the cumulative number of days where T ≥0°C for air and soil. Time with T ≥0°C is important as that denotes the period when liquid moisture could potentially be available within the soil to support microbial activity.

5.2 Methods

Cumulative days at or above freezing for each soil climate station at each depth (air, ~5, ~20 and ~75 cm) were calculated for the summer period (November – February) using the mean hourly temperature data. If more than five consecutive days were missing then that summers data was discarded.

Cumulative days data included temperature measurements at 0°C. Mean hourly measurements with T≥0°C were totalled then divided by 24 (hours in a day) to get the cumulative number of "days" with T ≥0°C for each summer period.

5.3 Results

The overall mean number of cumulative days per summer with T≥0°C for air ranged from highest to lowest from (Table 5.1): Wright Valley (33.3), Victoria Valley (22.3), Granite Harbour (10.4), Marble Point (9.7), Minna Bluff (7.6), Darwin Glacier (7.3), Scott Base (4.2) to Mt Fleming (0.0).

Table 5.1 Cumulative days per summer with T≥0°C at each soil climate station for air, and ~5, ~20 and ~75 cm soil depths.

	Years of measurement	Air		~5 cm		~20 cm		~75 cm	
		mean	SD	mean	SD	mean	SD	mean	SD
Wright Valley	1999-2011	33.3	6.0	69.8	5.5	52.0	8.3	0.0	0.0
Victoria Valley	1999-2011	22.3	7.4	50.2	15.9	1.8	3.5	0.0	0.0
Mt Fleming	2002-2011[a]	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Granite Harbour	2004-2011[b]	10.4	3.5	69.6	9.0	65.5	8.0	28.9	19.8
Marble Point	1999-2011[c]	9.7	3.6	55.5	10.9	44.7	13.2	0.0	0.0
Scott Base	1999-2011	4.2	2.6	34.6	8.8	13.9	9.0	0.0	0.0
Minna Bluff	2006-2011[d]	7.6	1.6	52.8	4.4	31.6	18.0	0.0	0.0
Cape Hallett	2004-2011[e]	n/a	n/a	32.2	0.1	22.5	0.7	n/a	n/a
Darwin Glacier	2005-2011[f]	7.3	0.3	n/a	n/a	n/a	n/a		

[a]Mt Fleming air 2006-2011
[b]Granite Harbour 77 cm 2007-2011
[c]Marble Point air 2003-2011
[d]Minna Bluff air 2008-2011, no data 2007/2008
[e]Cape Hallett 2004/2005 only air, 68 cm 2009/2010 only
[f]Darwin Glacier 2005/2006 & 2006-2007 air only, 5 & 20 cm 2010/2011 only

For the shallow soil interval (~5 cm depth), the mean cumulative number of days per summer with T≥0°C ranged (from highest to lowest) from (Table 5.1): Wright Valley (69.8), Granite Harbour (69.6), Marble Point (55.5), Minna Bluff (52.8), Victoria Valley (50.2), Scott Base (34.6), Cape Hallett (32.2) to Mt Fleming (0.0).

At the mid-depth soil (~20 cm depth) interval, the overall mean cumulative number of days where T≥0°C ranged (from highest to lowest) from (Table 5.1): Granite Harbour (65.5), Wright Valley (52.0), Marble Point (44.7), Minna Bluff (31.6), Cape Hallett (22.5), Scott Base (13.9), Victoria Valley (1.8) to Mt Fleming (0.0).

Granite Harbour was the only site to have any cumulative days per summer with deep soil (~75 cm depth) T≥0°C, with an overall mean of 28.9 days (Table 5.1).

The number of cumulative days with T≥0°C for air, ~5, ~20, and ~75 cm soil depths in each summer season varied across the sites (Table 5.1). The highest number of cumulative days with T≥0°C for air and ~5 cm soil depth were at the

Wright Valley site. The highest number of cumulative days with T ≥0°C for ~20 cm soil depth and ~75 cm soil depth were at the Granite Harbour site (Table 5.1).

The Wright Valley, Victoria Valley, Marble Point and Scott Base sites have the longest records for all measurement depths (1999-2011). Only the Wright Valley, Victoria Valley and Scott Base soil climate stations had consecutive annual measurements over the recording period, the remaining sites had some missing data (Table 5.1).

The Granite Harbour site was the only site to record any days with T≥0°C for ~75 cm soil depth (Table 5.1). The Victoria Valley site had the greatest between-season variability over the recording period for air and ~5 cm soil depths. The Minna Bluff site had the greatest between-season variability for ~20 cm soil depth measurements. The Granite Harbour site was the only site with any days with T≥0°C at ~75 cm soil depth.

There was marked variability between summers across all sites (Figs. 5.1-5.3). The summers of 2000/2001 and 2002/2003 were both interpreted as cooler summers, with 2000/2001 being the summer with the least number of cumulative days at or above freezing at all depths (Figs. 5.1-5.3). The highest numbers of days with air T≥0°C over the years of record was in the summer of 2001/2002 for the Victoria Valley (32.7), Wright Valley (41.8), and Scott Base (8.6) sites. Other stations did not have air temperature data for the 2001/2002 summer (Figs. 5.1-5.3).

The Mt Fleming site had only 0.3 days with T≥0°C at ~5 cm soil during the 2010/2011 summer season over the stations entire recording period. Thus, a graph of the Mt Fleming site air and soil data was not included in this chapter (Appendix 1, Table 1.2).

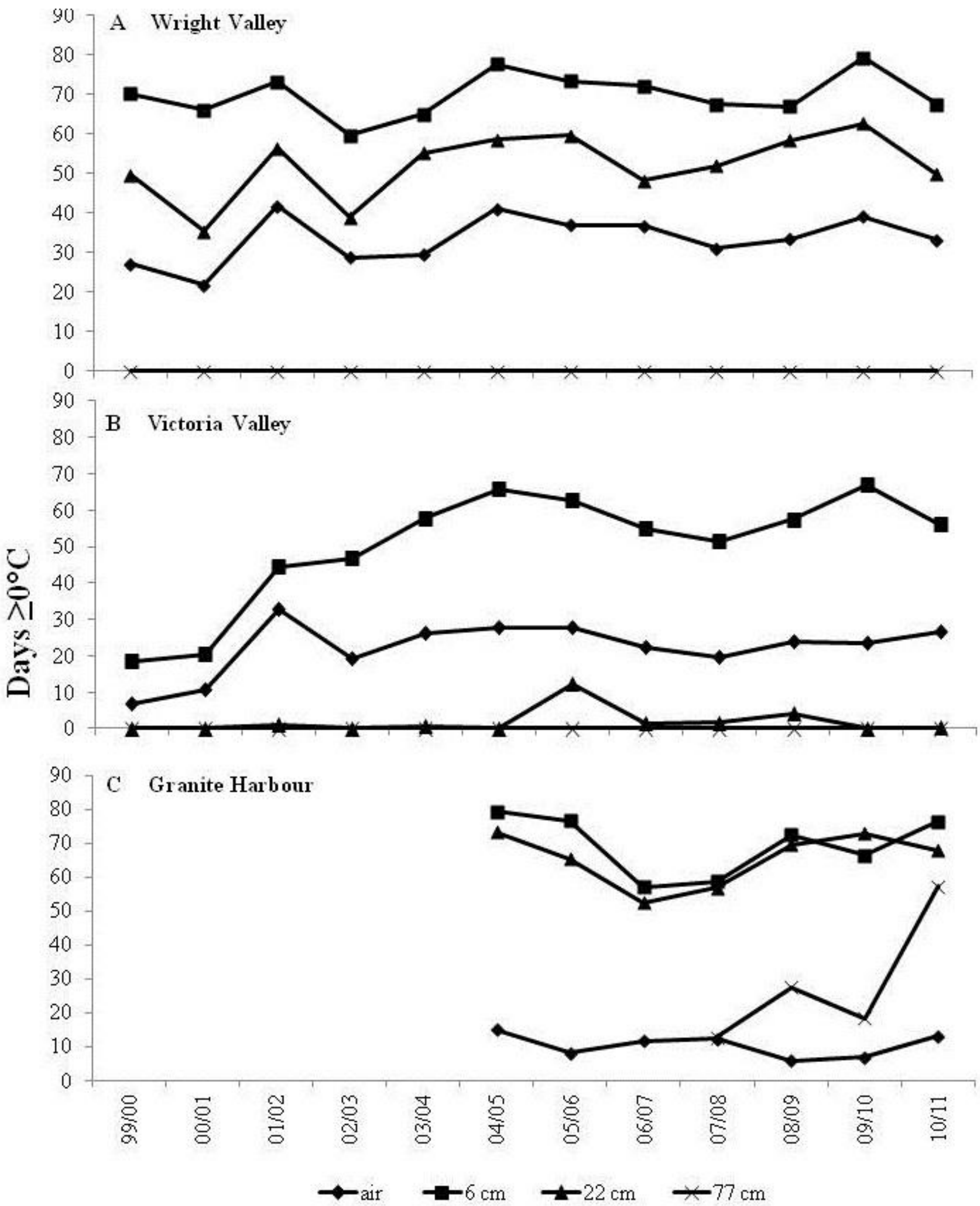

Fig. 5.1 Cumulative days with T≥0°C for summers from 1999-2011 for air, ~5 cm soil depth, ~20 cm soil depth and ~75 cm soil depth at A: Wright Valley, B: Victoria Valley, and C: Granite Harbour.

Air temperature had lower inter-annual variability and lower numbers of days with T≥0°C than ~5 cm soil temperature data at all sites. The greatest number of days with T≥0°C was generally at the ~5 cm soil depth. The only time the ~5 cm soil depth number of days with T≥0°C was exceeded was at the Granite Harbour site in the summer of 2009/2010 when the ~20 cm soil depth measurements were above 0°C for longer (Figs. 5.1-5.3).

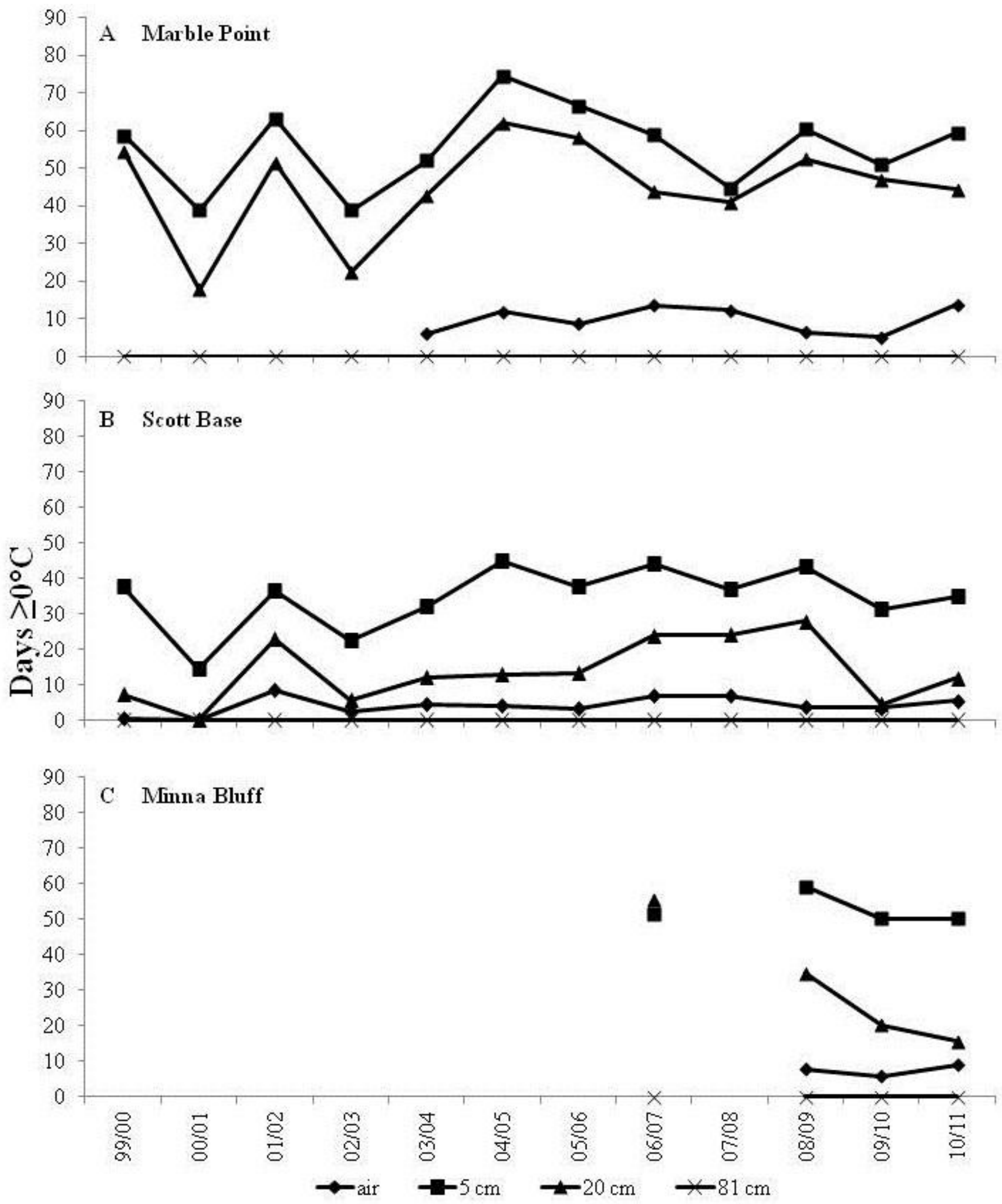

Fig. 5.2 Cumulative days with T≥0°C for summers from 1999-2011 for air, ~5 cm soil depth, ~20 cm soil depth and ~75 cm soil depth at A: Marble Point, B: Scott Base, and C: Minna Bluff.

The longest period with mean cumulative air temperatures (T≥0°C) were at the Wright Valley (41.8 days) and Victoria Valley (32.7 days) sites.

The Wright Valley site had the greatest mean number of days with ~20 cm T≥0°C (624 total days from 1999/2000 to 2010/2011) during the summer seasons. The Granite Harbour site also had a high numbers of days with ~20 cm T≥0°C (458.4 days per summer) over the recording period 2004/2005 to 2010/2011.

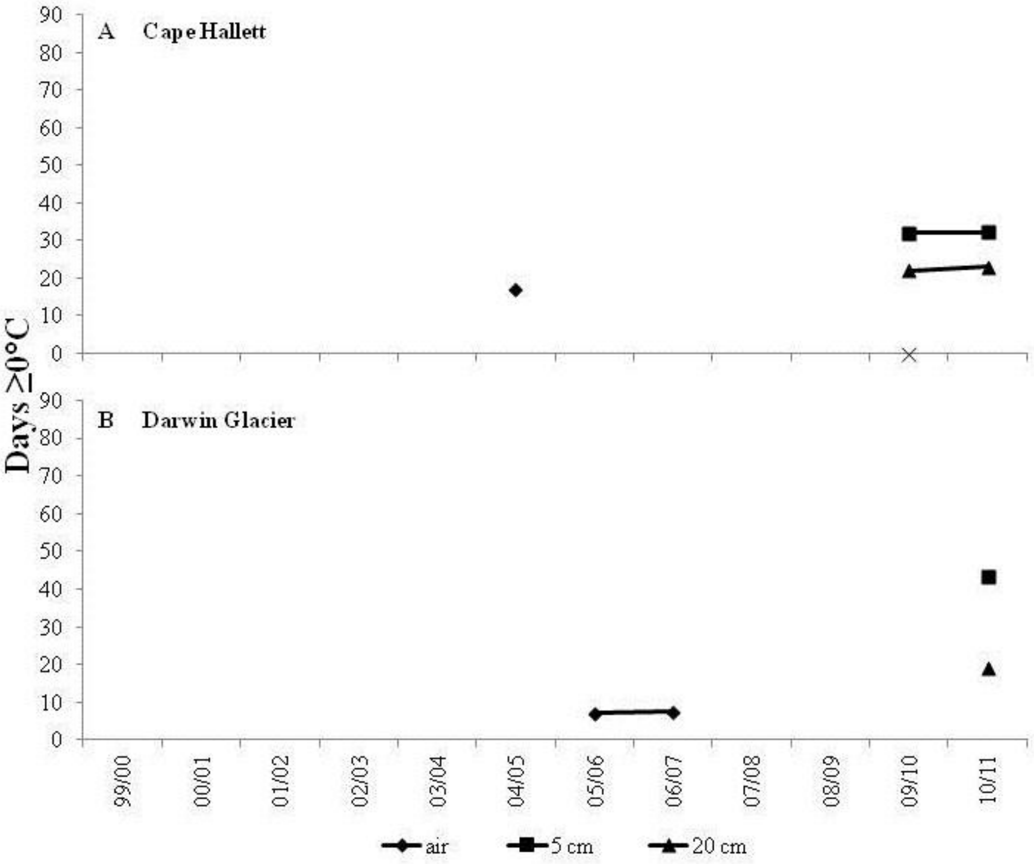

Fig. 5.3 Cumulative days with T≥0°C for summers from 1999/2000 to 2010/2011 for; air, ~5 cm soil depth, ~20 cm soil depth and ~75 cm soil depth at A: Cape Hallett, and B: Darwin Glacier.

A slight peak in the number of days with T≥0°C was recorded in the summer of 2009/2010 for ~20 cm soil depth, with the greatest number of days with T ≥0°C recorded at the Wright Valley (62.5 days) and Granite Harbour (72.9 days) sites. The Victoria Valley, Marble Point, Scott Base and Minna Bluff sites had fewer days with T≥0°C in the 2009/2010 summer than the previous 2008/2009 summer (Figs. 5.1-5.3).

Relatively higher numbers of days with air T≥0°C were recorded in the summer of 2005/2006 at the Wright Valley and Victoria Valley sites, with both sites recording their second highest number of days with air T≥0°C during the 2005/2006 summer. However other soil climate stations did not have a high number of cumulative days when T≥0°C for the summer of 2005/2006 (Figs. 5.1-5.3).

The 2000/2001 summer at the Wright Valley site had a peak in the cumulative number of days when shallow soil (~5 cm depth) T≥0°C, with the lowest number of days with ~5 cm T ≥0°C recorded in the same summer at the Scott Base and Marble Point sites (Figs. 5.1-5.3).

At ~75 cm soil depth, Granite Harbour (Fig. 5.1c) was the only site with cumulative days where soil temperatures ≥0°C over the recording period (Figs. 5.1- 5.3). The highest cumulative days with ~75 cm T≥0°C for the Granite Harbour site was in the 2010/2011 summer with 57.2 cumulative days (Appendix 1, Table 1.4). No cumulative days with deep soil (~75 cm depth) T≥0°C were recorded in the summers of 2004/2005 or 2007/2008 at the Granite Harbour site, a pattern which is not seen in shallower soil depths and air temperature measurements for the Granite Harbour site (Fig. 5.1c).

No days with air T≥0°C were observed at the Scott Base site during the 2000/2001 summer season (Fig. 5.2b). The Victoria Valley site also had a relatively low number of days with air T≥0°C for 2000/2001 (Fig. 5.1b) but the number was slightly greater than the 1999/2000 summer.

At the Marble Point and Scott Base sites, fewer days with ~5 cm depth T≥0°C were recorded in the summer of 2002/2003, but not at other recording sites (Figs. 5.1- 5.3). Fewer days with ~5 cm T≥0°C were observed (Figs. 5.1-5.3) in the summer of 2007/2008 at all sites (Wright Valley, Victoria Valley, Granite Harbour, Marble Point, and Scott Base) relative to other recording years.

The Victoria Valley site soil temperatures at ~20 cm depth did not reach zero between the summer months of December 1999 to February 2005, or in the summer of 2009/2010. The ~20 cm soil depth temperatures at Scott Base did not attain temperatures ≥0°C during the summer of 2000/2001.

5.4 Discussion

The mid-depth soil (~20 cm depth) had the greatest between-season variability in cumulative days with T≥0°C across all stations. Overall, shallow soil depths (~5 cm) recorded the most days at or above freezing with all sites (except Mt Fleming) recording more than ten cumulative days ≥0°C per year.

All stations that were active had a peak in the number of days at or above freezing in the summer of 2001/2002, indicating that the 2001/2002 summer season was relatively warmer than other years on record. The sites with increased number of days at or above freezing may have had liquid water for some time. Liquid water is important within the soil profile for the possible presence and survival of micro-organisms and lichens/mosses.

Granite Harbour was the only site with T≥0°C for ~75 cm soil depth (Figs. 5.1-5.3), thus indicating that the Granite Harbour site was subject to extraordinary microclimate circumstances. The influx of melt-water percolating down through the soil profile from the adjacent hillside was the likely source of energy being conducted to depth at the Granite Harbour site.

The descending orders of the number of cumulative days with T≥0°C for air and soil measurements do not follow the same order throughout the profile. This is likely due to the varying hours of sunlight each soil climate station receives during the Antarctic summer months, which will in turn, be a function of the site placement in respect to surrounding topography. Soil climate stations situated away from topographical highs will receive more summer sunlight hours than a site located at the foot of a bluff.

Soil moisture availability, as well as other factors such as nutrients and pH are limiting factors on microbial growth in Antarctic soils (Aislabie *et al.* 2011). Whilst bacteria can survive with sustained absences of available liquid water within the soil, for example, during winter, bacterial population size and bacterial growth is enhanced when soil moisture is available (Aislabie *et al.* 2011). Soil moisture acts to increase connectivity within the soil and thereby reduce spatial isolation between bacterial colonies, and increase nutrient transportation (Aislabie *et al.* 2009). Thus, changes in the time period when liquid water is available within a soil profile can impact microbial life.

There were no statistically significant increasing or decreasing trends relating to the number of days with T≥0°C in the air and soil summer temperature data, and there was a strong inter-annual variability at all sites (except ~75 cm soil depth).

Whilst Chapter 4 of this thesis reported a statistically significant warming trend in air, shallow soil (5-10 cm) and deep soil (75-120 cm) at the Marble Point site, no significant increasing trend was found in the number of days with T≥0°C for the Marble Point site during the summer season, suggesting that whilst the air and soil temperatures may, for the recording period 1999-2011 have been increasing, the temperature increase was sufficiently below zero to prevent an increase in days above zero degrees centigrade.

5.5 Summary and conclusions

The cumulative number of days where T≥0°C were calculated for each soil climate station (Table 5.1) over summer months (November to February) for air, shallow soil (~5 cm depth), mid-depth soil (~20 cm depth), and deep soil (~75 cm depth).

The overall mean number of cumulative days per summer with T≥0°C for air ranged from highest to lowest from (Table 5.1): Wright Valley (33.3), Victoria Valley (22.3), Granite Harbour (10.4), Marble Point (9.7), Minna Bluff (7.6), Darwin Glacier (7.3), Scott Base (4.2) to Mt Fleming (0.0).

For the shallow soil interval (~5 cm depth), the mean cumulative number of days per summer with T≥0°C ranged (from highest to lowest) from (Table 5.1): Wright Valley (69.8), Granite Harbour (69.6), Marble Point (55.5), Minna Bluff (52.8), Victoria Valley (50.2), Scott Base (34.6), Cape Hallett (32.2) to Mt Fleming (0.0).

At the mid-depth soil (~20 cm depth) interval, the overall mean cumulative number of days where T≥0°C ranged (from highest to lowest) from (Table 5.1): Granite Harbour (65.5), Wright Valley (52.0), Marble Point (44.7), Minna Bluff (31.6), Cape Hallett (22.5), Scott Base (13.9), Victoria Valley (1.8) to Mt Fleming (0.0).

Granite Harbour was the only site to have any cumulative days per summer with deep soil (~75 cm depth) T≥0°C, with an overall mean of 28.9 days.

There was marked between-summer variability in the cumulative days T≥0°C for air and all depths over the recording period from 1999/2000 to the 2010/2011 summer.

There was no overall increasing or decreasing trends in the number of days where T≥0°C over the time period recorded.

Soil surface temperatures (~5 cm) had more days with T≥0°C than air, and the cumulative number of days where T≥0°C decreased and became less variable with depth.

Mt Fleming was the only site to record zero days at or above freezing for air, ~20 and ~75 cm soil depth summer temperature measurements. At ~5 cm soil depth Mt Fleming only attained T≥0°C for a few hours in the 2010/2011 summer with 0.3 days recorded.

The Granite Harbour site had the highest mean number of days per summer at or above freezing for mid and deep soil summer temperature measurements, probably due to melt-water flow in the subsurface at the Granite Harbour site at the base of a steep north-facing slope.

The number of days when soil T≥0°C can impact on the duration of time that liquid water is available within the soil profile, which, in turn, can act as a control on the presence and size of microbial populations within the soil.

Chapter 6: Wind patterns in the Ross Sea region

6.1 Introduction

Wind speeds and directions are reported from eight soil climate stations in the Ross Sea region of Antarctica, from Granite Harbour in the north to Darwin Glacier in the south. Wind data records extend from 2000 to 2011.

The objectives of this chapter were to analyse the wind data to characterise the wind regime at each site and to investigate storm events and diurnal patterns.

Wind speeds were recorded every 10 minutes and averaged hourly. Thus, maximum wind speeds were maximum mean hourly wind speeds. Wind speed and direction data were formatted in excel and graphed using Grapher software. Wind speeds were reported in $kmhr^{-1}$ for easier interpretation. Wind speed and direction circular plots were constructed using mean hourly data for each site for each year.

6.2 Wind speeds and directions

Mean annual wind speeds and maximum annual wind speeds varied between stations over the recording period 2000-2011 (Table 6.1). Mean annual wind speeds ranged from lowest to highest: Granite Harbour (7 $kmhr^{-1}$), Victoria Valley (8 $kmhr^{-1}$), Marble Point (12 $kmhr^{-1}$), Wright Valley (14 $kmhr^{-1}$), Scott Base (17 $kmhr^{-1}$), Mt Fleming (29 $kmhr^{-1}$), Minna Bluff (42 $kmhr^{-1}$), and Darwin Glacier (45 $kmhr^{-}$1).

The Darwin Glacier site generally had the highest mean annual wind speeds, with the highest recorded mean annual wind speed of 47 $kmhr^{-1}$ (2007). The Granite Harbour site had the lowest mean annual wind speed of 6 $kmhr^{-1}$ (2004-2007). The Darwin Glacier and Minna Bluff sites had the strongest recorded maximum wind speeds. The Minna Bluff site had the greatest maximum mean hourly wind speed (169 $kmhr^{-1}$), in 2009 (Table 6.1).

The sites with lower mean annual wind speeds (Granite Harbour, Victoria Valley, Marble Point, and Wright Valley) had little between-year variation in mean annual wind speed over the years of record (std.dev. <3 kmhr^{-1}, Table 6.1). Sites with higher wind speeds (Mt Fleming, Scott Base, Minna Bluff and Darwin Glacier) had greater inter-annual variation in wind speeds.

Table 6.1 Mean annual and maximum annual* wind speeds in kmhr^{-1} for soil climate station network from 2000 to 2011.

Year	Granite Harbour		Victoria Valley		Marble Point		Wright Valley		Mt Fleming		Scott Base		Minna Bluff		Darwin Glacier	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
2000			8	51	12	59	15	70			18	93				
2001			8	61			14	69			17	88				
2002			7	55	11	60	13	71			18	93				
2003			9	65	13	79	14	65			19	100				
2004	6	86	9	65	11	86	14	71			15	134				
2005	6	35	9	59	12	68	15	83			18	109	33	146	46	128
2006	6	37	7	68	12	68	12	70			17	91	64	306	45	115
2007	6	51	9	70	13	61	14	78	36	118	18	105			47	130
2008	7	61	9	63			14	70	37	105	17	91			46	135
2009	12	81	8	58			14	70	47	127	18	115	45	169		
2010	7	53	8	55	12	65	13	67			14	79	32	119	44	132
2011	7	43	8	62	13	62	14	65	34	98	18	91	34	141	43	127
Overall Mean and Max	**7**	**86**	**8**	**70**	**12**	**86**	**14**	**83**	**39**	**127**	**17**	**134**	**42**	**306**	**45**	**135**
Standard Dev.	**2**	**19**	**1**	**6**	**1**	**9**	**1**	**5**	**6**	**13**	**1**	**15**	**14**	**75**	**1**	**7**

* Mean annuals and maximums calculated from hourly averages.

The highest maximum annual wind speeds for Granite Harbour, Marble Point, and Scott Base were in 2004. Victoria Valley and Wright Valley had high maximum wind speeds for 2004 (Table 6.1). The maximum wind speed at both Granite Harbour and Marble Point was 86 kmhr^{-1} and occurred on the 24th August 2004 at both sites. The highest mean hourly wind speed at Victoria Valley (65 kmhr^{-1}) also occurred on the 24th August 2004. The maximum mean hourly wind speed at Scott Base in 2004 (134 kmhr^{-1}) was on the 16th May and was an extreme storm event resulting in damage to the Scott Base research site ("Snow, ice and 200km/h winds" 2004). The maximum wind speed at Wright Valley (71 kmhr^{-1}) was on the 8th June 2004.

There was a general increase in mean annual wind speed with increasing latitude across the soil climate station sites (Table 6.1). The Granite Harbour site generally experienced the lowest mean annual wind speeds except in 2009.

6.3 Wind patterns in 2011

Mean annual wind directions had little to no inter-annual variation over the recording period 2000-2011 (Full set of wind rose plots in Appendix 2). Thus 2011 was used as a representative year for closer analysis as most stations were operational during 2011. Predominant wind directions varied between sites (Figs. 6.1 & 6.2).

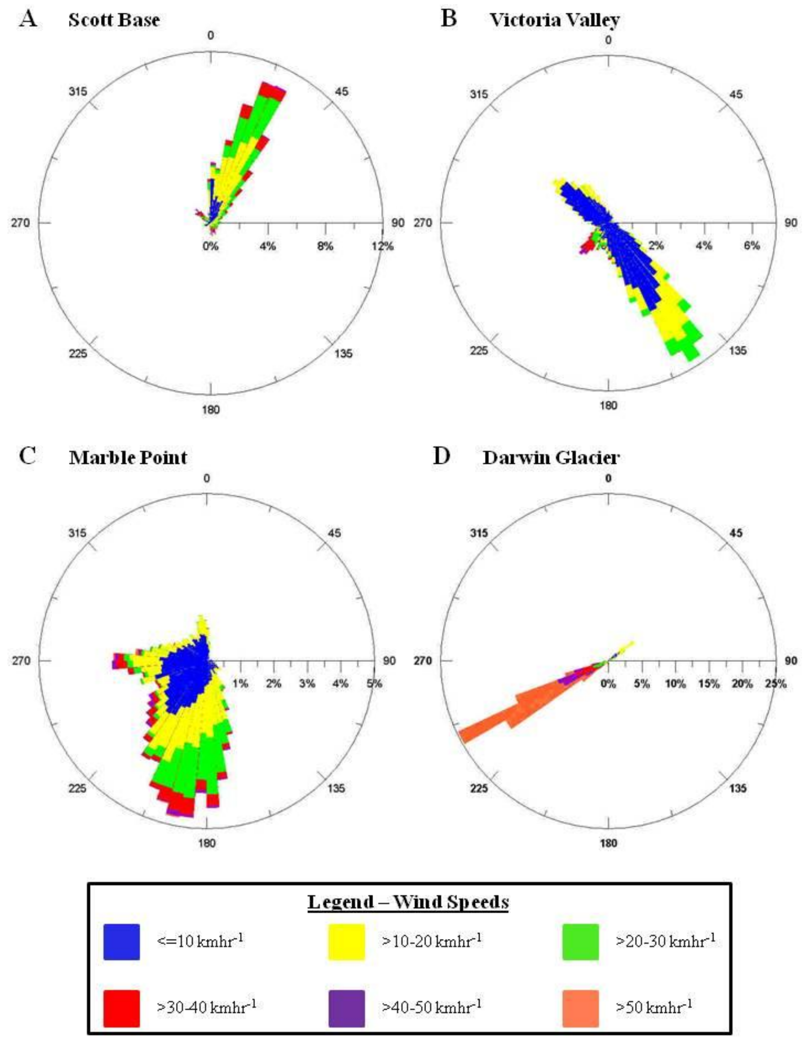

Fig. 6.1 Hourly wind speed (kmhr^{-1}) and direction (degrees) measurements for 2011 at A: Scott Base, B: Victoria Valley, C: Marble Point, and D: Darwin Glacier. Circumference shows the direction the wind is blowing from. The radius axis gives the percent of time the wind is blowing from a particular direction (the radius scale is not the same on all graphs).

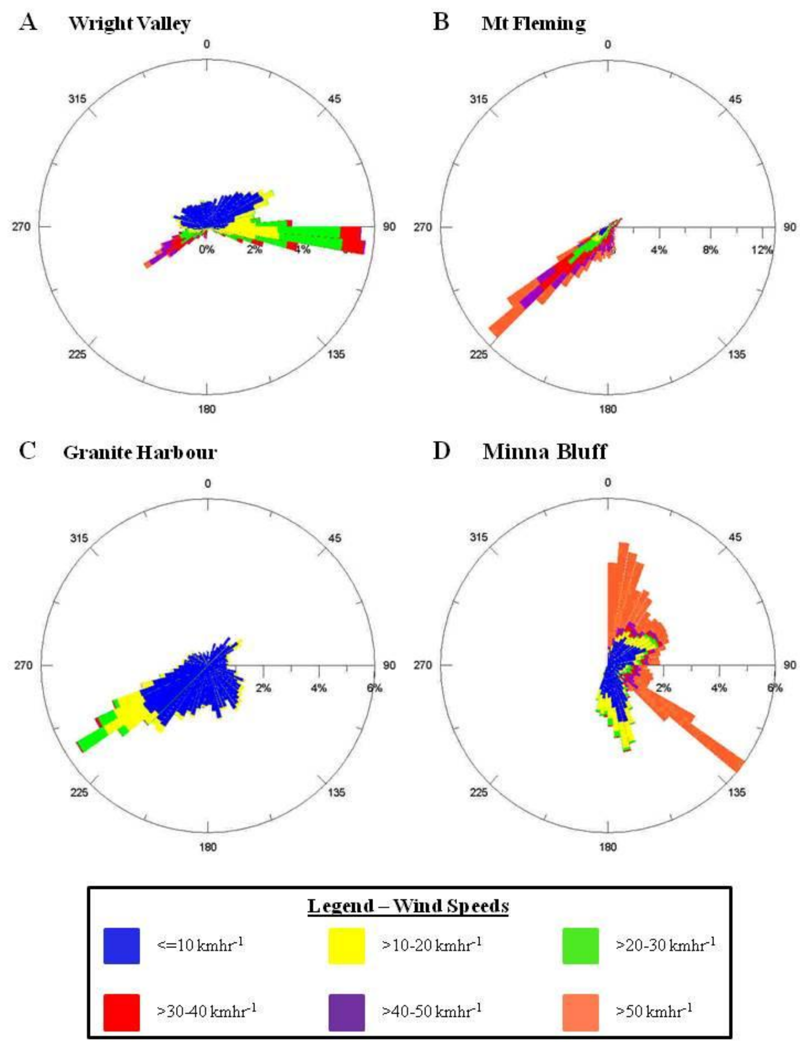

Fig. 6.2 Hourly wind speed ($kmhr^{-1}$) and direction (degrees) measurements for 2011 at A: Wright Valley, B: Mt Fleming, C: Granite Harbour, and D: Minna Bluff. The radius axis gives the percent of time the wind is blowing from a particular direction (the radius scale is not the same on all graphs).

Scott Base (Fig. 6.1a) had a dominantly NNE wind direction with very little variation. For the Victoria Valley site, winds were dominantly from the SE and NW (Fig. 6.1b). At the Marble Point site winds generally came from the SSW or W (Fig. 6.1c), and at Darwin Glacier (Fig. 6.1d) winds came dominantly from the WSW. The prevailing wind direction for the soil climate station at Wright Valley (Fig. 6.2a) was from the E, whilst at the Mt Fleming site, dominant and strong winds came from the SE (Fig.6.2b). At the Granite Harbour site (Fig. 6.2c) the winds predominantly came from the WSW. The site at Minna Bluff (Fig. 6.2d) had only three full years of record, with strong prevailing winds coming from

NNE and SE directions. At Minna Bluff gentler winds came mainly from the S or NW.

Of all the stations, in 2011 Darwin Glacier experienced the strongest, most consistent, unidirectional winds with dominant wind direction from the SW (Fig. 6.1d). The most southerly stations (Darwin Glacier, Scott Base and Mt Fleming) had the most unidirectional winds (Figs. 6.1 & 6.2).

Strong winds (≥30 $kmhr^{-1}$) came solely from the SW direction at the Victoria Valley, Darwin Glacier, Mt Fleming and Granite Harbour sites (Figs. 6.1b,d & 6.2b,c). At Wright Valley (Fig. 6.2a), strong winds came from a SW and E direction. Marble Point had a wide directional spread of high wind speeds from W-S (Fig. 6.1c). Scott Base (Fig. 6.1a) had strong winds from the NE, whilst Minna Bluff had strong winds from the N-NE and SE directions (Fig. 6.2d).

Weaker winds (<30 $kmhr^{-1}$) were more variable than the strong winds at the Victoria Valley, Marble Point, Wright Valley, and Granite Harbour sites (Figs. 6.1b,c & 6.2a,c). The Granite Harbour site had weak multi-directional winds, with a slightly greater frequency of winds originating from the SE (Fig. 6.2c). Weak winds at Victoria Valley had a bi-directional pattern from NW-SE (Fig. 6.1b). Weak winds at Wright Valley flowed from the same direction as strong winds, but also over a wide directional range from W to NE (Fig. 6.2a).

For the Scott Base, Darwin Glacier and Mt Fleming sites, weak winds originated from the same general direction as strong winds during the 2011 year. At the Marble Point and Minna Bluff sites weak winds originated from the same direction as strong winds, and also had southerly component (Figs. 6.1 & 6.2).

6.4 Wind speeds and directions throughout the year 2011

6.4.1 Air temperature and wind speed changes over three month intervals

Hourly wind data for 2011 was split into three-month intervals beginning with January. Wind patterns varied between all sites during the January to March period (Figs. 6.3 to 6.6).

Granite Harbour had the weakest wind speeds and least variability over all seasons in 2011 (Figs. 6.3a, 6.4a, 6.5a & 6.6a). Mt Fleming and Minna Bluff had the most extreme wind patterns, with wind speeds at Minna Bluff exceeding 140 kmhr^{-1} in the July-September season (Fig. 6.5c). High speed wind events recorded at the Victoria Valley station were also evident at the Wright Valley and Marble Point sites (Figs. 6.3d-f, 6.4d-f, 6.5d-f, & 6.6d-f). Some Scott Base high-speed wind events coincided with strong winds at the Victoria Valley, Wright Valley and Marble Point sites (Figs. 6.3 – 6.6).

Wind speeds at the Victoria Valley and Wright Valley sites decreased markedly on the 25th February 2011 (Fig. 6.3d-e). Low winds were then interspersed with short-term high speed wind events until mid-October 2011 when wind at both the Wright and Victoria Valleys increased in speed (Fig. 6.6d-e). The Marble Point site had a similar pattern to the Wright and Victoria Valley sites, with higher background winds (Figs. 6.3f, 6.4f, 6.5f & 6.6f). All other sites had a gradual increase in wind speed and variability from January – March 2011.

The sunset for the austral winter was on the 24th April 2011 (http://www.timeanddate.com) in the McMurdo region. Wind speed and air temperature data were examined for the week surrounding the final sunset (21st - 28th April 2011). There was no identifiable change in air temperature or wind speed correlating with the sunset at any site.

The greatest frequency of high speed wind events occurred between July and September 2011 at all sites (Fig. 6.5). An increase in background wind speeds at the Wright Valley site was evident in the July to September 2011 time period (Fig. 6.5e) but no change in wind patterns was observed at the other sites between July and September 2011.

The sun rose above the horizon for the first time in the Ross Sea region on the 19th August 2011 for 44 minutes, with daylight time increasing every day until the sun stayed permanently above the horizon for the austral summer on the 24th October 2011 (http://www.timeanddate.com). Wind speeds did not show a change with the rise of the sun in August (Fig. 6.5), however, a change in wind behaviour to a diurnal pattern was observed around the 24th October at the Wright Valley and

Victoria Valley sites. However, there was no marked change at the Mt Fleming, Marble Point, Minna Bluff, Scott Base and Granite Harbour sites over the August to October 2011 period (Fig. 6.6).

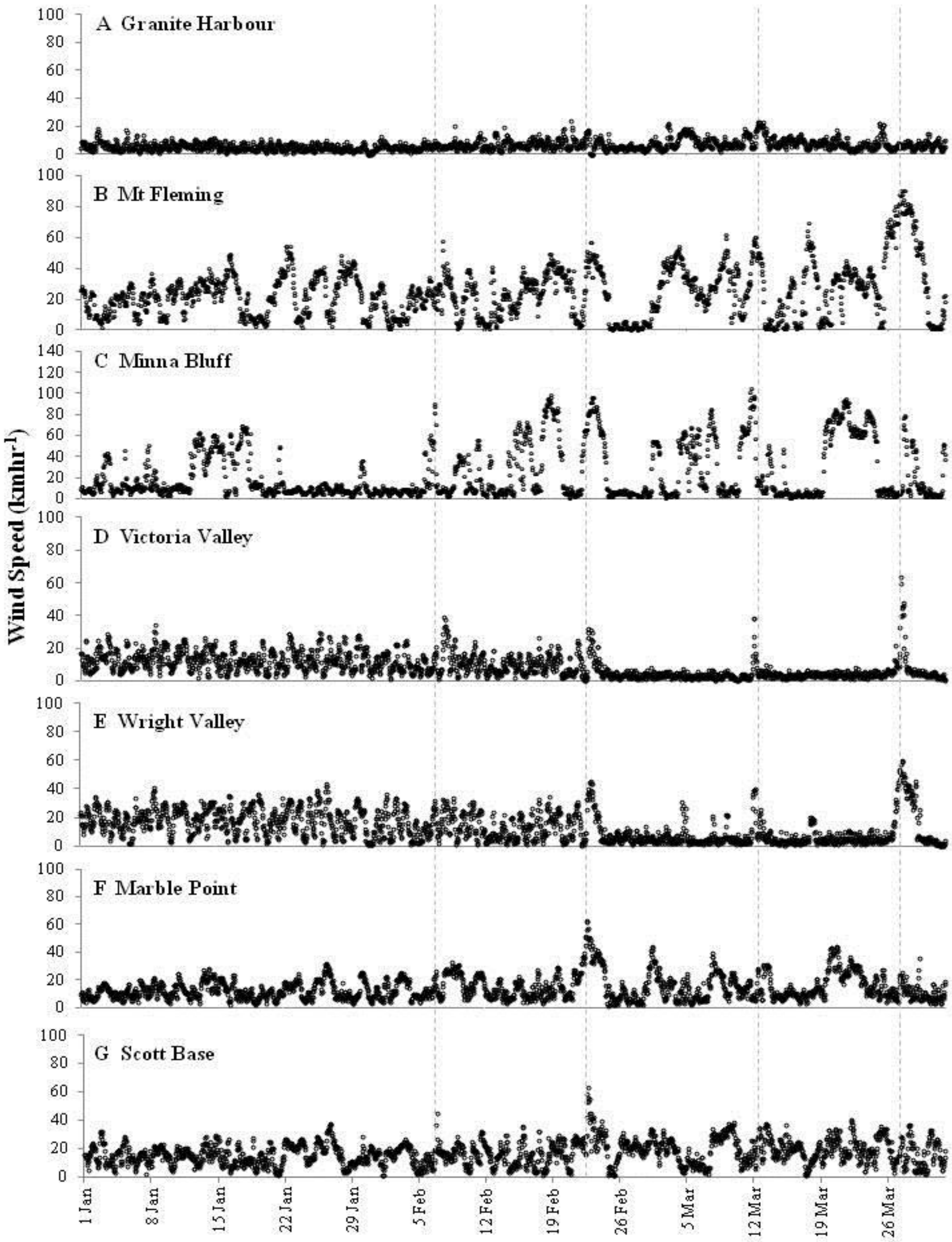

Fig. 6.3 Mean hourly wind speeds (kmhr^{-1}) for 1 January – 31 March 2011. A: Granite Harbour, B: Mt Fleming, C: Minna Bluff, D: Victoria Valley, E: Wright Valley, F: Marble Point, G: Scott Base. Note vertical scale for Minna Bluff is different from other sites. High wind events are highlighted by grey vertical dashed lines.

Wind speed patterns changed from low-speed to moderate/fast winds (30-40 kmhr^{-1}) at the Victoria Valley and Wright Valley sites on the 15th October 2011 (Fig. 6.6d,e). Winds at the Marble Point site also became faster and more consistent, but without the marked change of the Wright Valley and Victoria Valley sites (Fig. 6.6f). No change in wind pattern during the October – December 2011 period was evident at the other sites.

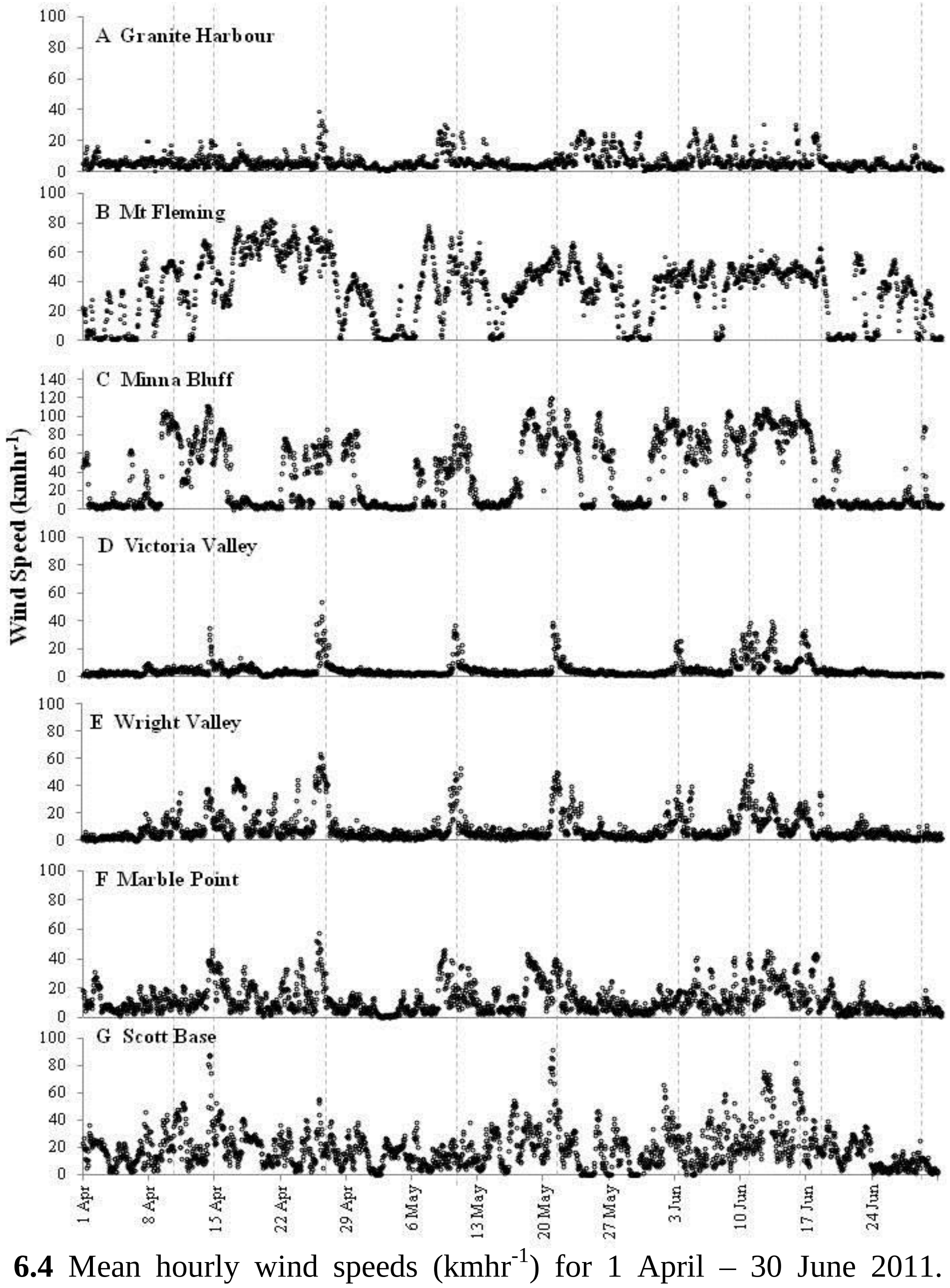

Fig. 6.4 Mean hourly wind speeds (kmhr^{-1}) for 1 April – 30 June 2011. A: Granite Harbour, B: Mt Fleming, C: Minna Bluff, D: Victoria Valley, E: Wright Valley, F: Marble Point, G: Scott Base. Note vertical scale for Minna Bluff is different from other sites to accommodate higher hourly wind speeds. High wind events are highlighted by grey vertical dashed lines. N.B. vertical scale is same for all graphs except Minna Bluff.

Whilst some high speed wind events were localised and observed at few sites, there were many high speed wind events throughout 2011 that were observed at most, if not all sites (Figs. 6.3 – 6.6).

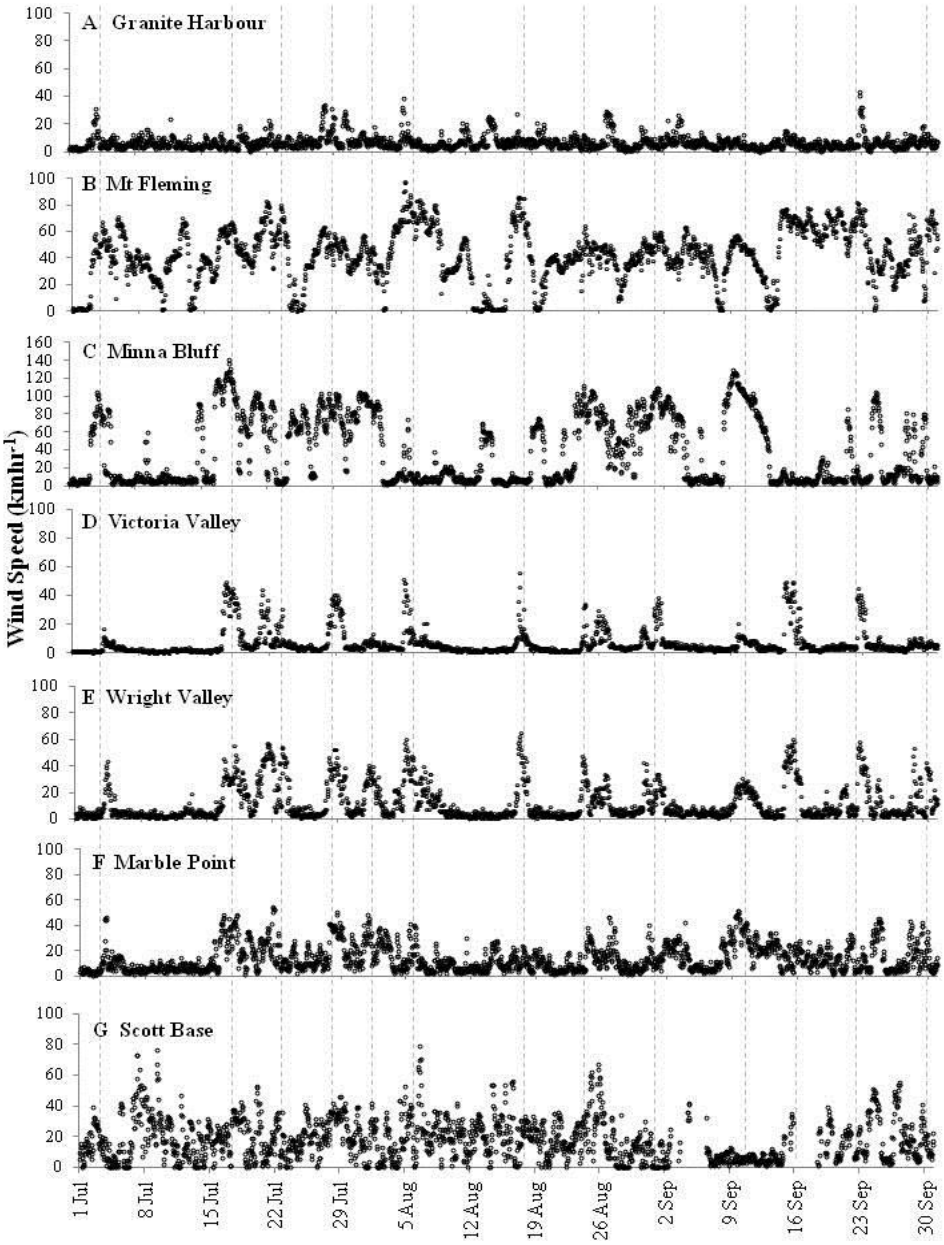

Fig. 6.5 Mean hourly wind speeds (kmhr^{-1}) for 1 July – 30 September 2011. A: Granite Harbour, B: Mt Fleming, C: Minna Bluff, D: Victoria Valley, E: Wright Valley, F: Marble Point, G: Scott Base. Note vertical scale for Minna Bluff is different from other sites. High wind events are highlighted by grey vertical dashed lines.

Many smaller wind events occured across all sites, the strongest link was between the Victoria Valley, Wright Valley and Marble Point sites, where most high speed wind events seen at one site were also recorded at the other two sites. During October-December 2011 the Granite Harbour, Minna Bluff, Scott Base and Mt Fleming sites did not have any major high speed wind events recorded at all sites at the same or similar time.

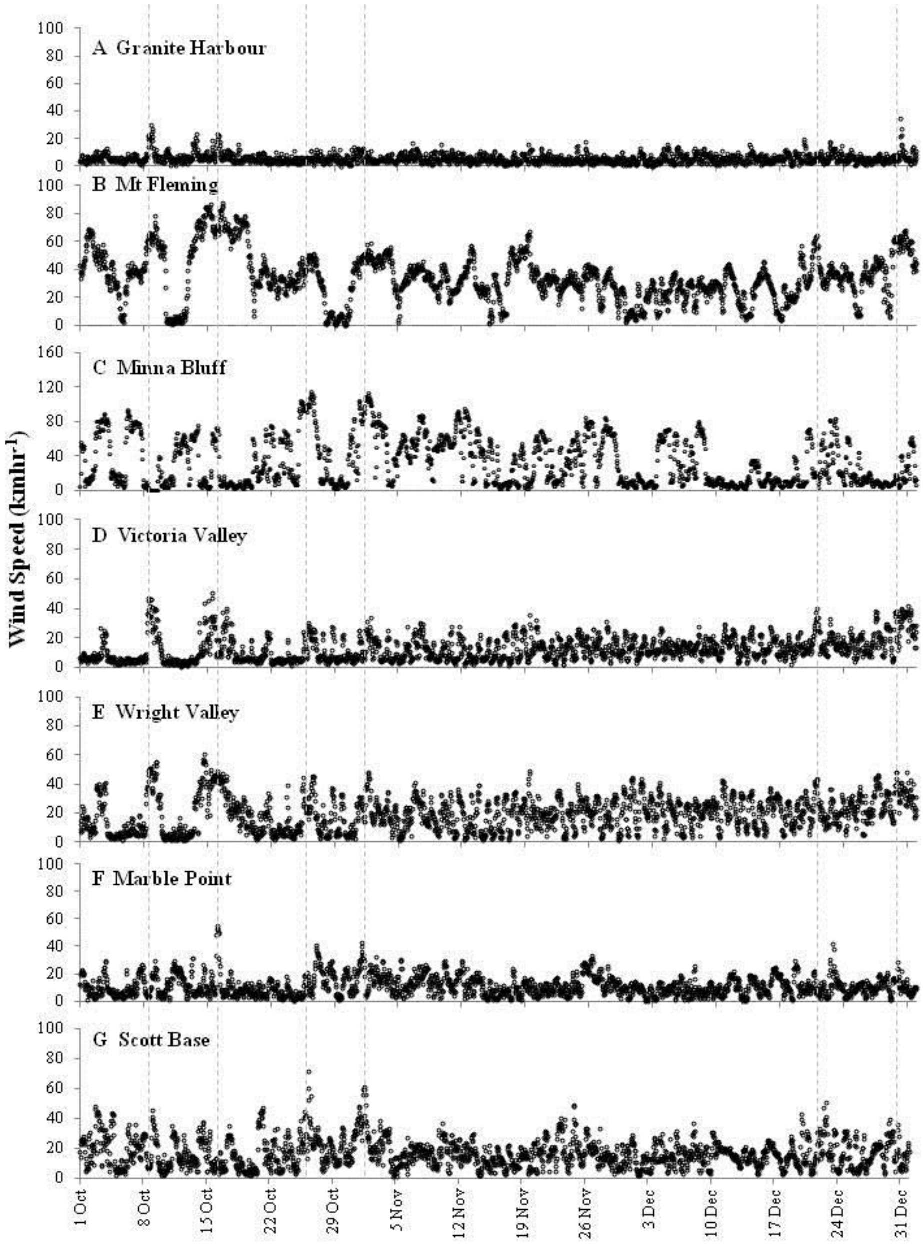

Fig. 6.6 Mean hourly wind speeds (kmhr^{-1}) for 1 October – 31 December 2011. A: Granite Harbour, B: Mt Fleming, C: Minna Bluff, D: Victoria Valley, E: Wright Valley, F: Marble Point, G: Scott Base. Note vertical scale for Minna Bluff is different from other sites. High wind events are highlighted by grey vertical dashed lines.

6.4.2 Summer 2011 diurnal patterns

A summer week (5th-11th January 2011) was used to observe diurnal wind speed and air temperature patterns across the soil climate station network (Figs. 6.7 & 6.8).

There was diurnal wind speed variability at the Granite Harbour, Darwin Glacier, Victoria Valley, Wright Valley and Minna Bluff sites (Figs. 6.7 & 6.8), with strongest wind speeds occurring late afternoon. The coastal Marble Point and Scott Base sites had only weak, or no, diurnal variability in wind speed.

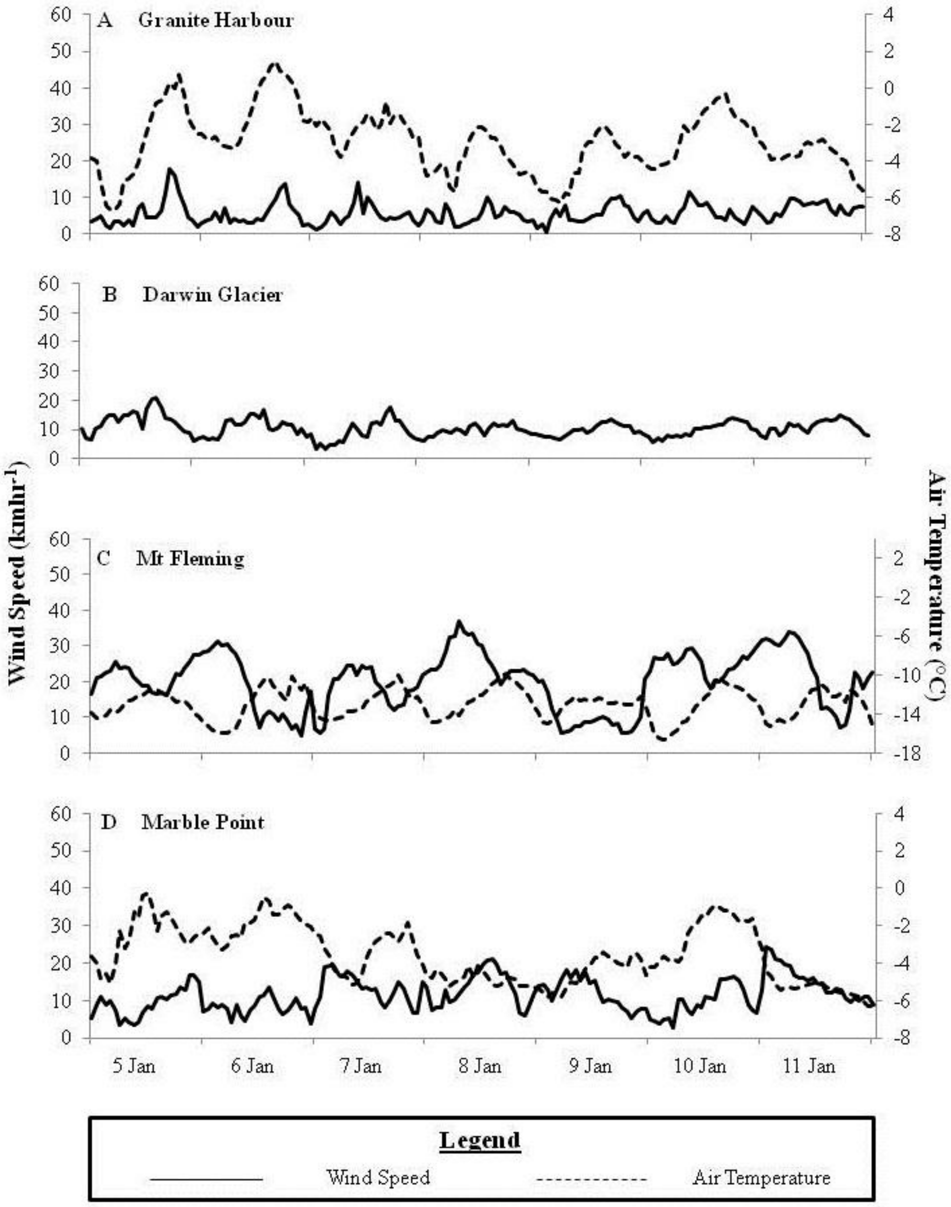

Fig. 6.7 Hourly averaged wind speed and air temperature for 5th January to 11th January 2011. A: Granite Harbour, B: Darwin Glacier, C: Mt Fleming and D: Marble Point (no air temperature data was available for Darwin Glacier).

Air temperatures followed a similar pattern to wind speed with the warmest temperatures in the afternoon at the Granite Harbour, Victoria Valley and Wright Valley sites (Figs. 6.7 & 6.8). Granite Harbour, Victoria Valley and Wright Valley had the warmest air temperatures during the selected week, whilst Minna Bluff had the highest wind speeds (Figs. 6.7 & 6.8). Minna Bluff had two short high-speed wind events on the 5th January, and the evening of the 7th January 2011 (Fig. 6.8d). No other sites had high speed wind events in the week investigated.

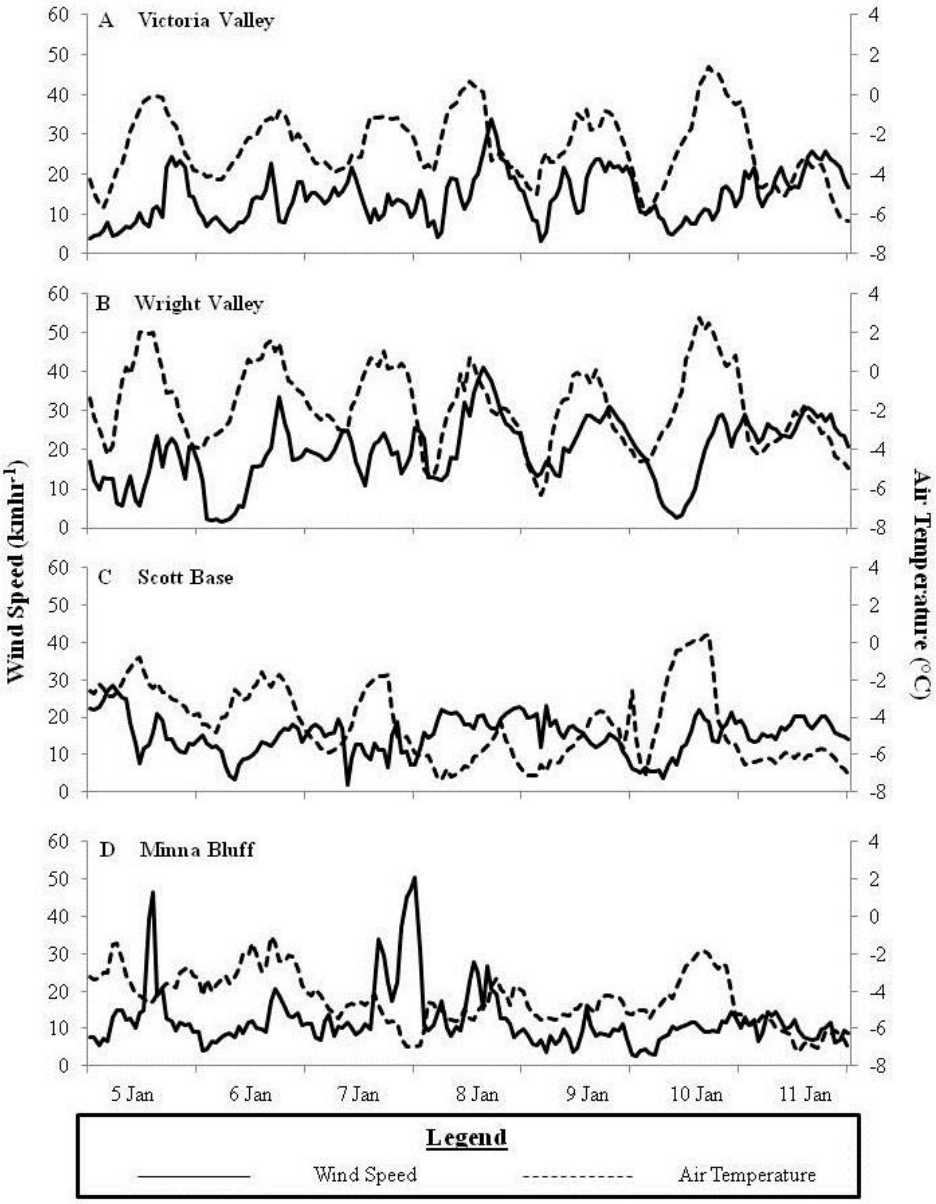

Fig. 6.8 Hourly averaged wind speed and air temperature for 5th January to 11th January 2011. A: Victoria Valley, B: Wright Valley, C: Scott Base and D: Minna Bluff.

6.5 Prevailing wind directions – summer and winter

Mean hourly wind directions are shown for the 2009 winter (June-August) and 2009/2010 summer (December-February) at each soil climate station in the network (Table 6.2). There was some variation in wind direction between the summer and winter months at three sites (Granite Harbour, Marble Point, Wright

Valley, and Scott Base), but wind direction was the same in winter and summer at Victoria Valley, Mt Fleming, and Minna Bluff. No winter 2009 wind data was available for the Darwin Glacier site. In general, wind directions had greater variability in summer than in winter months (Figs. 6.9 – 6.11).

Table 6.2 Prevailing summer (December – January) and winter (June – July) wind directions for each climate station for winter 2009 and summer 2009/2010.

	Wind Direction (true N)	
Station	**Winter 09**	**Summer 09-10**
Granite Harbour	SW/SE	WSW/NE
Victoria Valley	NW/SE	NW/SE
Marble Point	W/SSW	SSE
Wright Valley	SW/NE	W
Mt Fleming	SW	SW
Scott Base	E	NE
Minna Bluff	SE	SE
Darwin Glacier		NE

The Granite Harbour, Victoria Valley, Marble Point and Wright Valley sites had bi-directional dominant wind directions during the 2009 winter, although none had the same bi-directional orientation (Table 6.2). In the summer of 2009/2010, only the Granite Harbour and Victoria Valley sites had bi-directional dominant wind directions (Table 6.2).

Wind speeds were higher during winter 2009 than in the summer of 2009/2010 at all sites except the Victoria and Wright Valley sites (Fig. 6.9c,d & 6.10a,b).

During winter 2009, strong winds at Wright Valley predominantly came from the SW with weaker winds flowing from SW to NE (Fig. 6.10a). In summer 2009/2010 strong winds at the Wright Valley site still came from the SW, but less frequently than during winter. The main summer wind flow came from the E (Fig. 6.10b).

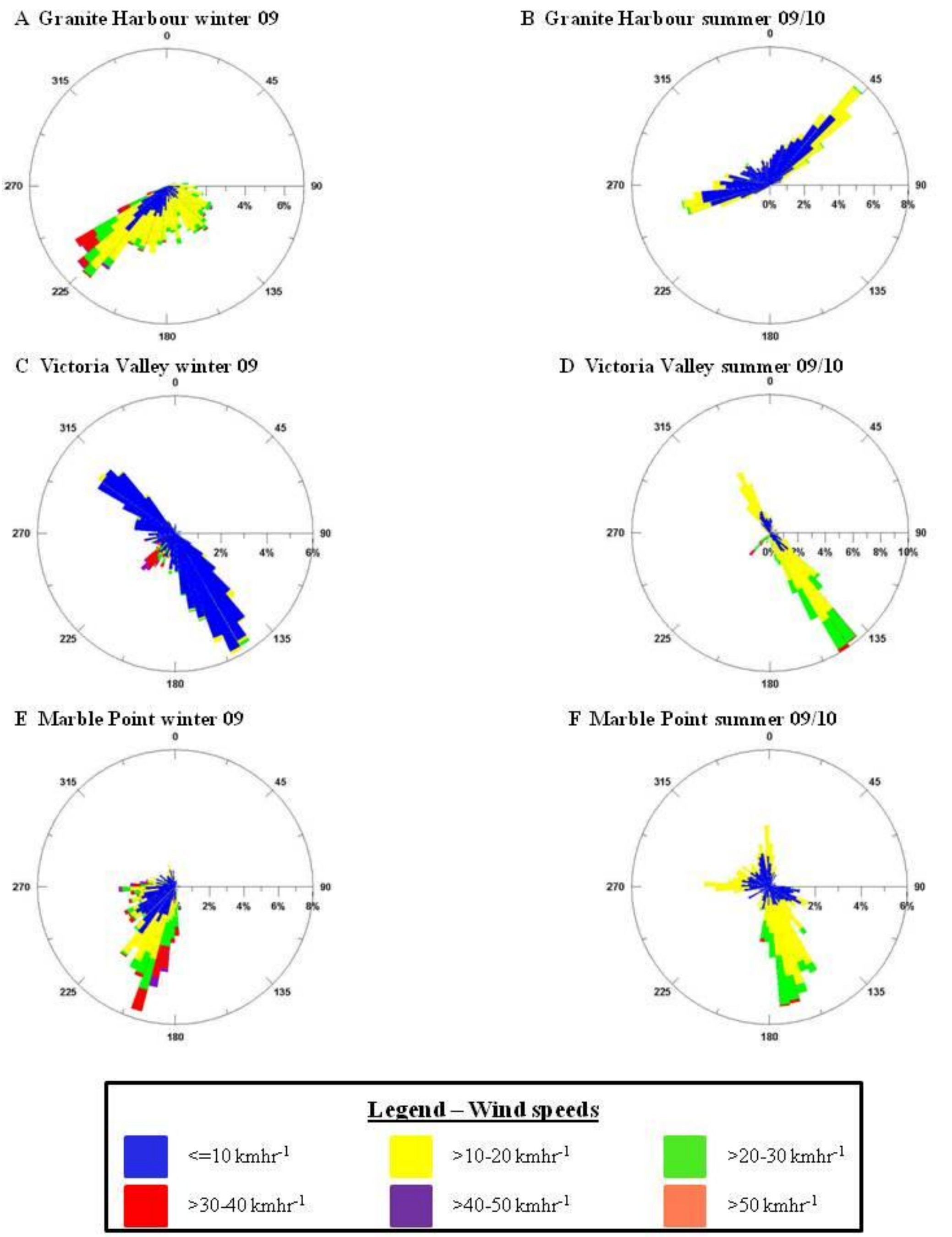

Fig. 6.9 Winter 2009 and summer 2009/2010 mean hourly wind speeds and directions. A&B: Granite Harbour, C&D: Victoria Valley, E&F: Marble Point.

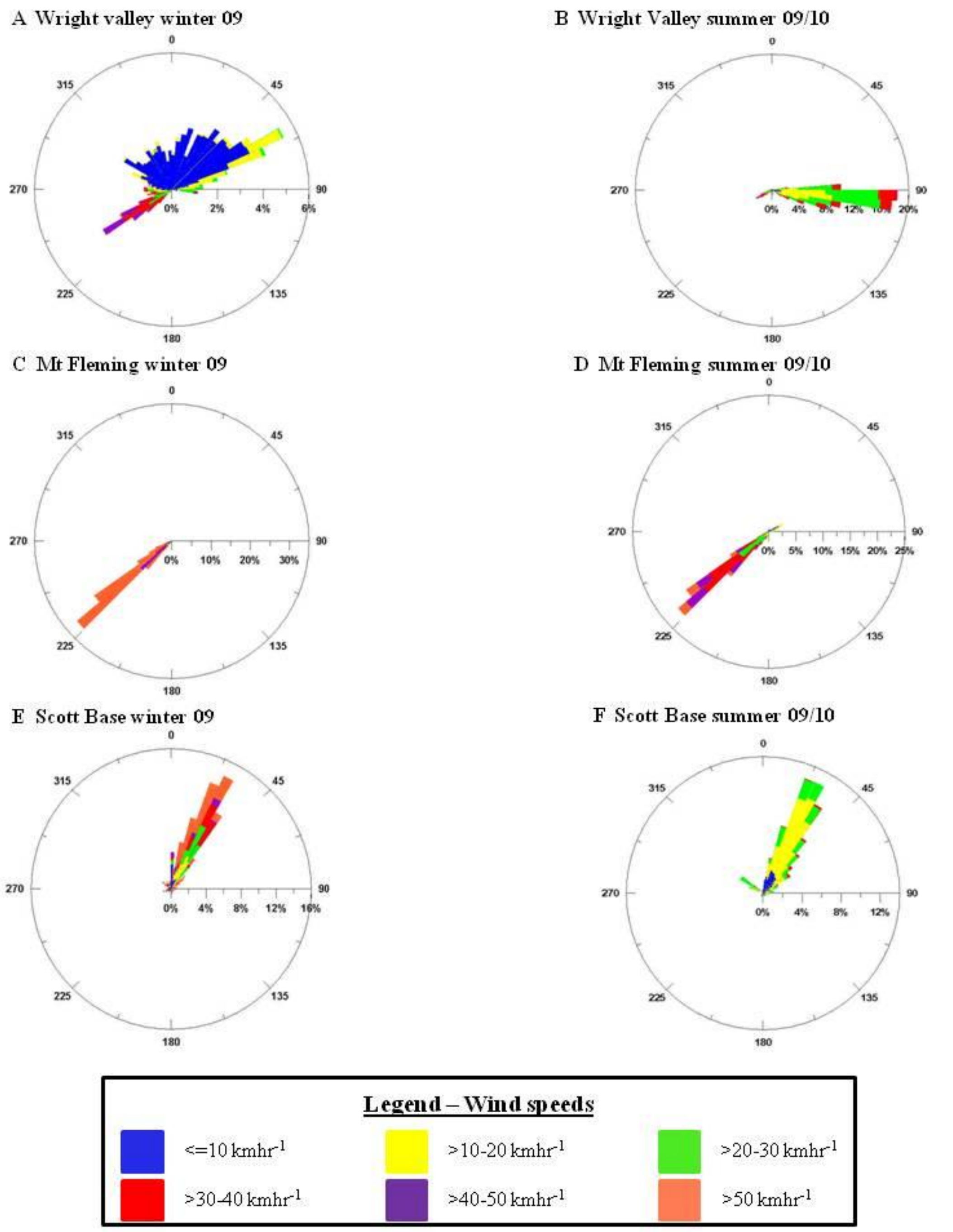

Fig. 6.10 Winter 2009 and summer 2009/2010 mean hourly wind speeds and directions. A&B: Wright Valley, C&D: Mt Fleming, E&F: Scott Base.

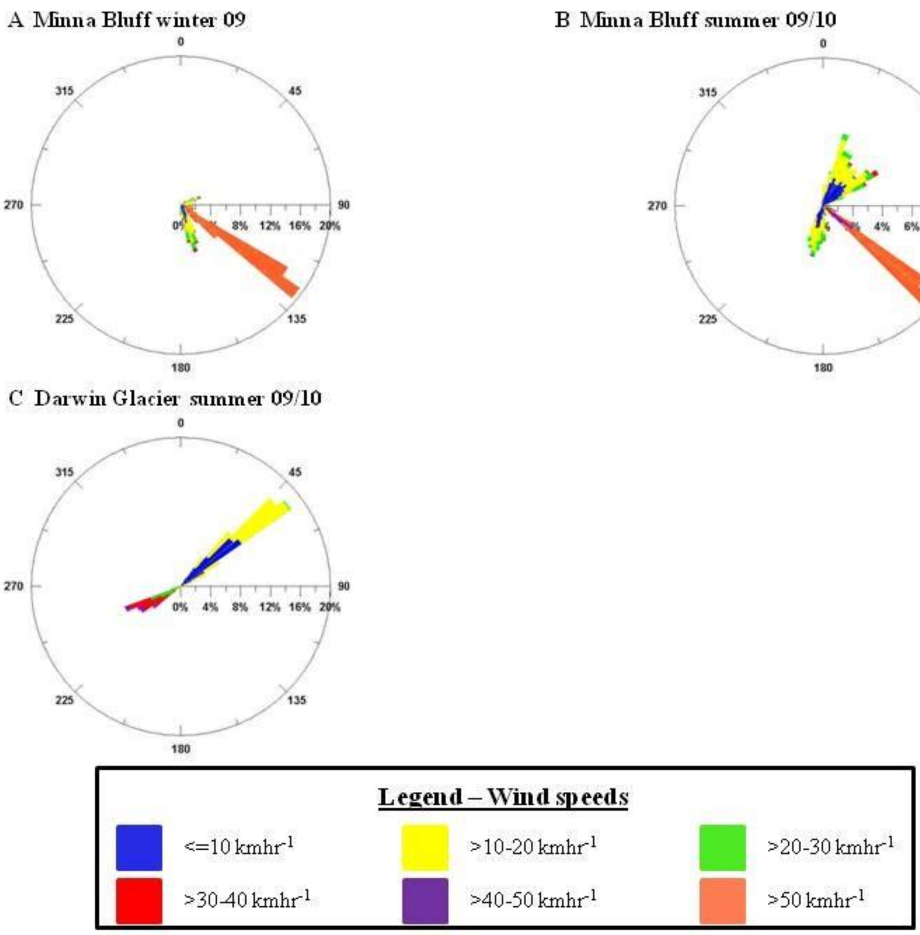

Fig. 6.11 Winter 2009 and summer 2009/2010 mean hourly wind speeds and directions. A&B: Minna Bluff, C: Darwin Glacier (winter 2009 wind data was not available for Darwin Glacier).

6.6 Storm progression 4th-10th August 2011

A high speed wind event was identified over the 4th – 10th August 2011 at all sites within the network (Figs. 6.12 – 6.15). Air temperature and wind speed were graphed with a wind rose showing wind speeds and direction for each site detailing wind directions for the 4th – 10th August 2011.

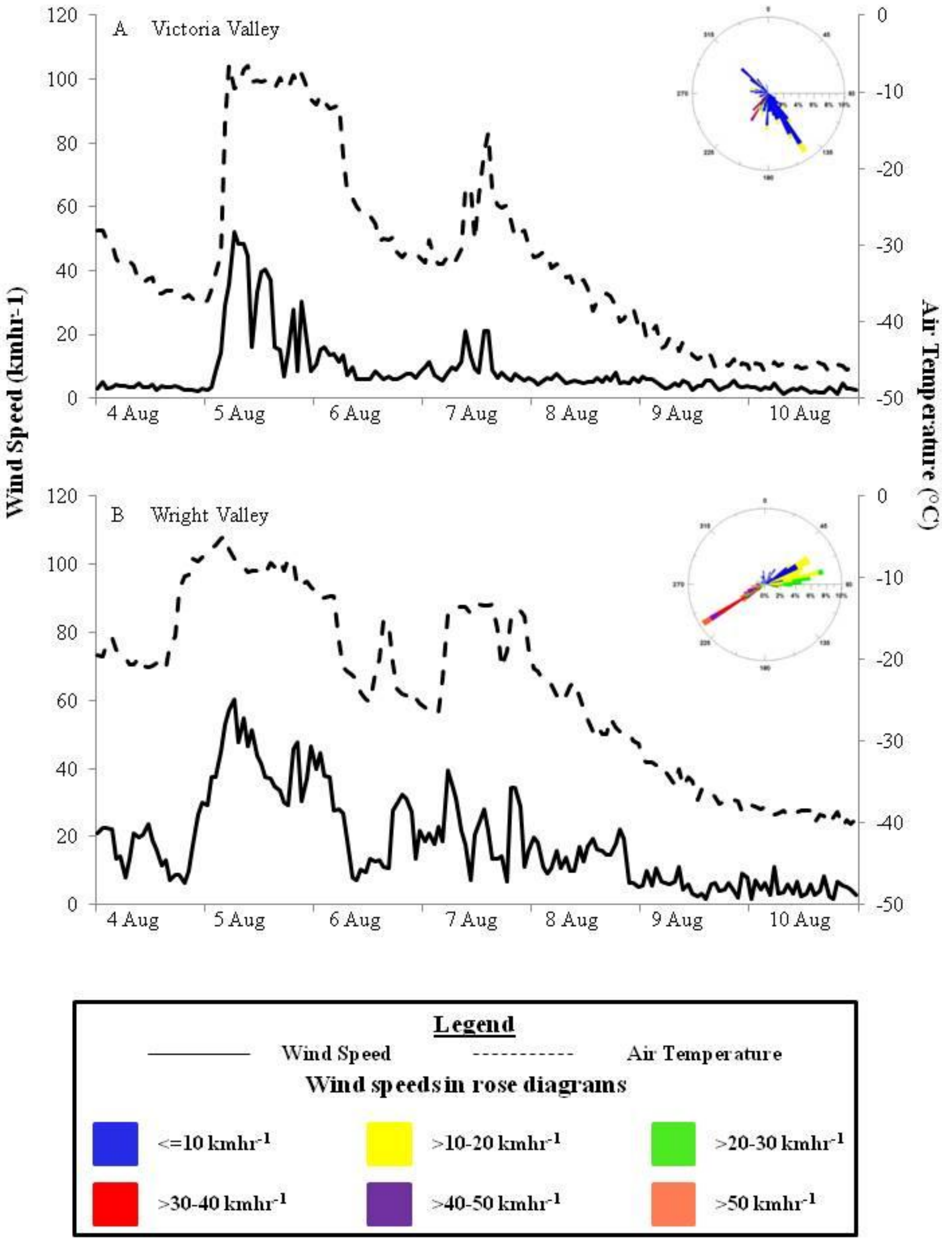

Fig. 6.12 Winter storm event with wind speed (kmhr^{-1}) and air temperature (°C) vs. time (4th August 2011 – 10th August 2011) for A: Victoria Valley, and B: Wright Valley.

Sharp increases in wind speed and air temperature occurred in the early morning of the 5th August 2011 at the Victoria Valley site (Fig. 6.12a). At the Wright Valley site, high wind speed and temperature increase onset began slightly earlier, with winds and air temperatures increasing in the evening of the 4th August 2011 (Fig. 6.12b). Conditions at the Mt Fleming site were already windy compared to other sites before the 5th August 2011, although there was a further peak in wind speed at mid-morning on the 5th August (Fig. 6.13a).

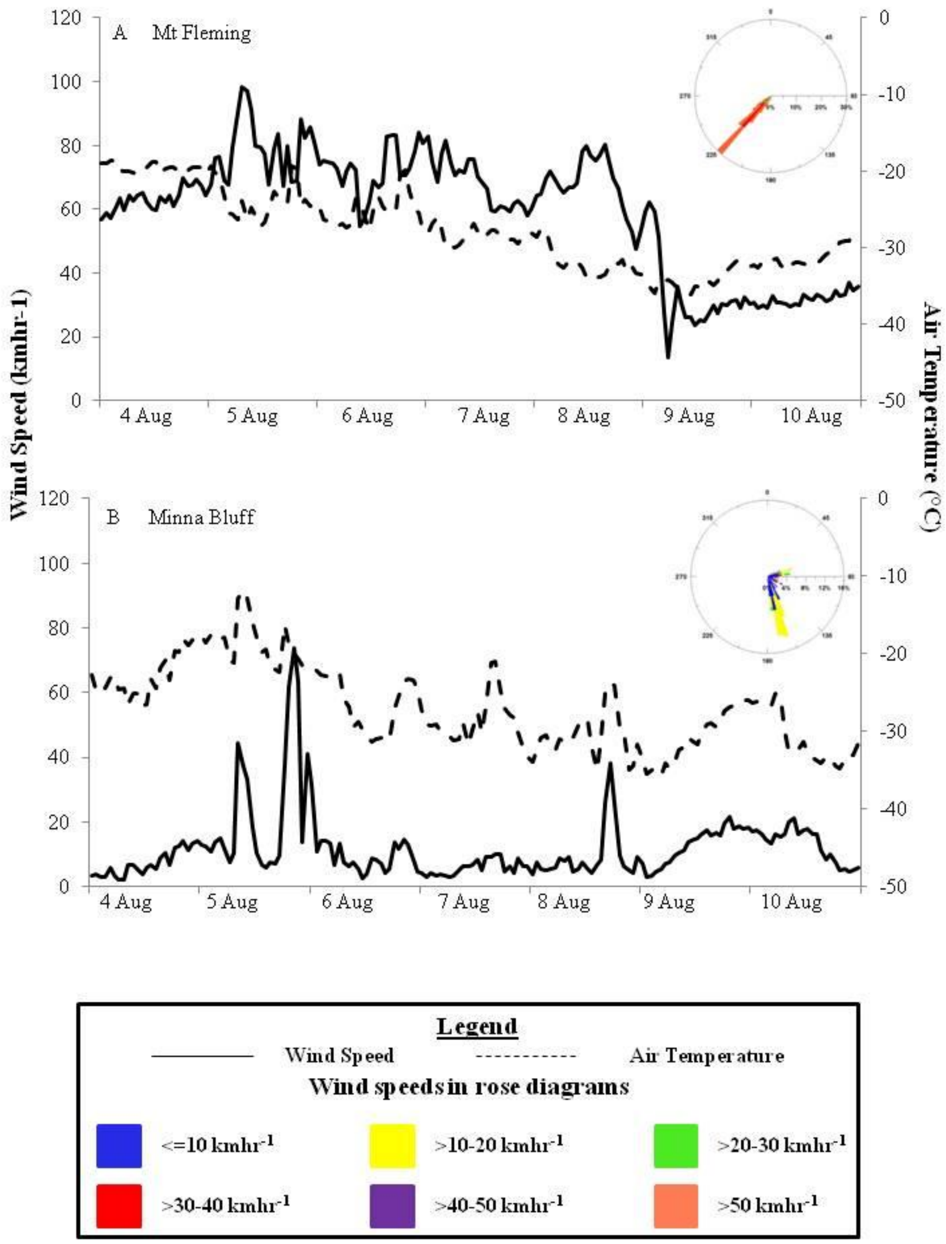

Fig. 6.13 Winter storm event with wind speed (kmhr^{-1}) and air temperature (°C) vs. time (4th August 2011 – 10th August 2011) for A: Mt Fleming, and B: Minna Bluff.

At the Minna Bluff site, there were two sharp spikes in wind speed on the 5th and 6th of August 2011 (Fig. 6.13b), with small corresponding increases in air temperature relative to the Wright Valley and Victoria Valley sites (Fig. 6.12a & b). The high speed wind event occurred at both the Granite Harbour and Marble Point sites (Fig. 6.14a & b) in the morning of the 5th August 2011. The site at Marble Point had two consecutive wind speed peaks, in the morning of the 5th August, and in the late evening of the same day (Fig. 6.14b). Air temperature at the Granite Harbour site had a greater increase with wind onset compared to the Marble Point site.

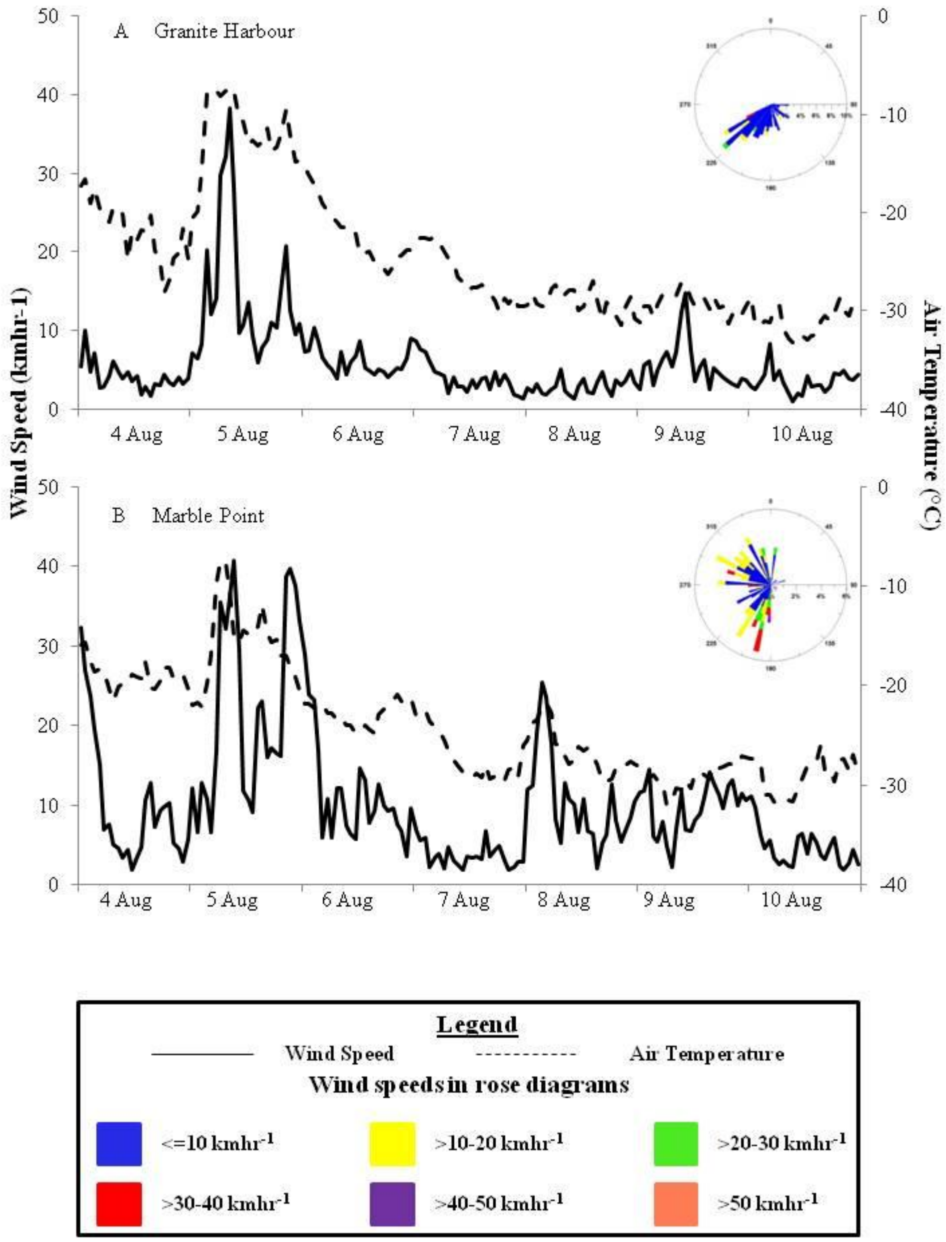

Fig. 6.14 Winter storm event with wind speed (kmhr^{-1}) and air temperature (°C) vs. time (4th August 2011 – 10th August 2011) for A: Granite Harbour, and B: Marble Point.

Winds at the Scott Base site were erratic with multiple wind events over the week of the 4th – 10th August 2011. A high speed wind event was identified on the morning of the 5th August (Fig. 6.15) which correlated with the wind event identified at the Victoria Valley, Wright Valley, Mt Fleming, Minna Bluff, Granite Harbour, and Marble Point sites. A peak in air temperature during the wind event was also observed in the Scott Base site data (Fig. 6.15).

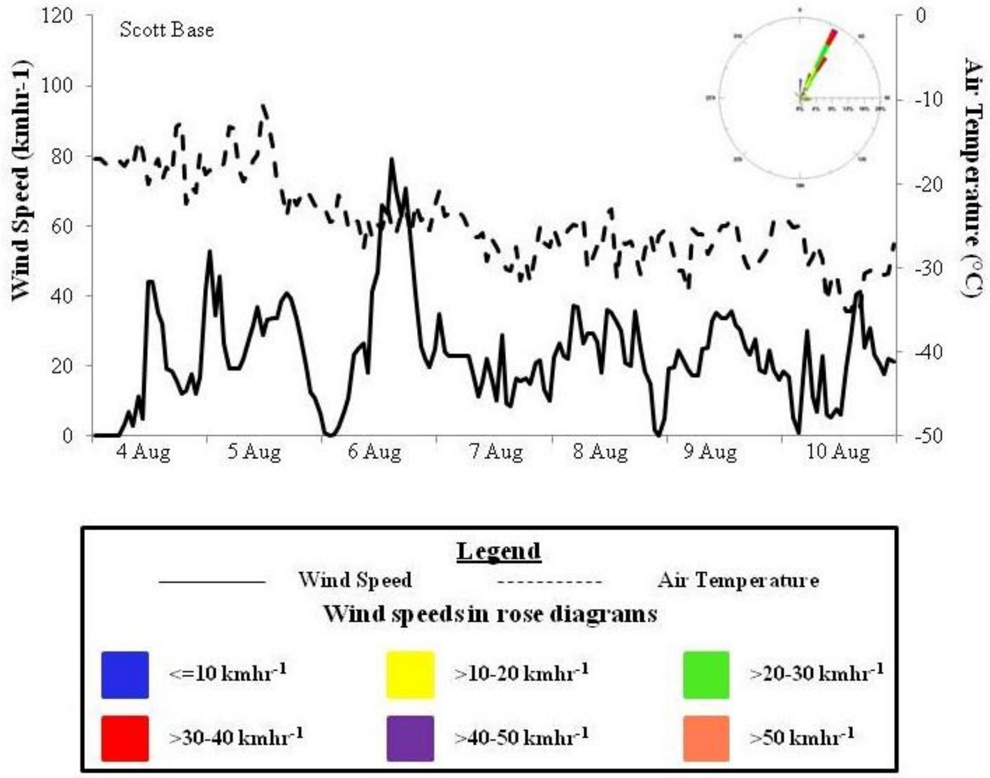

Fig. 6.15 Winter storm event with wind speed (kmhr^{-1}) and air temperature (°C) vs. time (4th August 2011 – 10th August 2011) for Scott Base.

The high speed wind event, identified as a sharp peak in wind speed was a short-term event, lasting less than 24 hours at the Victoria Valley, Wright Valley, Mt Fleming, Minna Bluff, Granite Harbour and Marble Point sites. Wind speeds at the Wright Valley site increased again in the morning of the 6th August before slowing to background speeds around midday on the 6th August (Fig. 6.12b).

High speed wind directions came from the SW for the Victoria Valley, Wright Valley and Mt Fleming sites (Figs. 6.12a & b, Fig. 6.13a). At Minna Bluff, strong winds came from an E direction (Fig. 6.13b), whilst at the Marble Point site, strong winds came from the S/SSW (Fig. 6.14b). Strong winds at the Scott Base site came from the NE (Fig. 6.15). Thus, strong winds were not unidirectional across all sites, although winds from the S-SW were dominant.

6.7 Storm progression 15th-21st August 2011

A high speed wind event was identified in the Victoria Valley on the 17th August 2011. A week either side of the wind event (15th-21st August) was graphed for each station along with air temperature and a corresponding wind rose plot for the same period was included for wind direction comparison (Figs. 6.16 - 6.19).

The high speed wind event was visible as a peak in both wind speed and air temperature at the Victoria Valley site at about midday on the 17th August 2011. The increased wind speed peaked rapidly then decreased again over a couple of hours (Fig. 6.16a). Air temperature at the Victoria Valley site increased sharply at the wind onset but decreased at a slower rate than the wind speed, with air temperatures returning to pre-wind event levels over a period of two to three days (Fig. 6.16a).

At the Wright Valley site, the wind event onset was slightly earlier than other sites, starting in the early hours of the morning on the 17th August 2011 and continuing until the early hours of the 18th August 2011 (Fig. 6.16b). Air temperatures increased with the onset of the wind event, decreasing back to pre-wind event temperatures by midday on the 19th August 2011 (Fig. 6.16b).

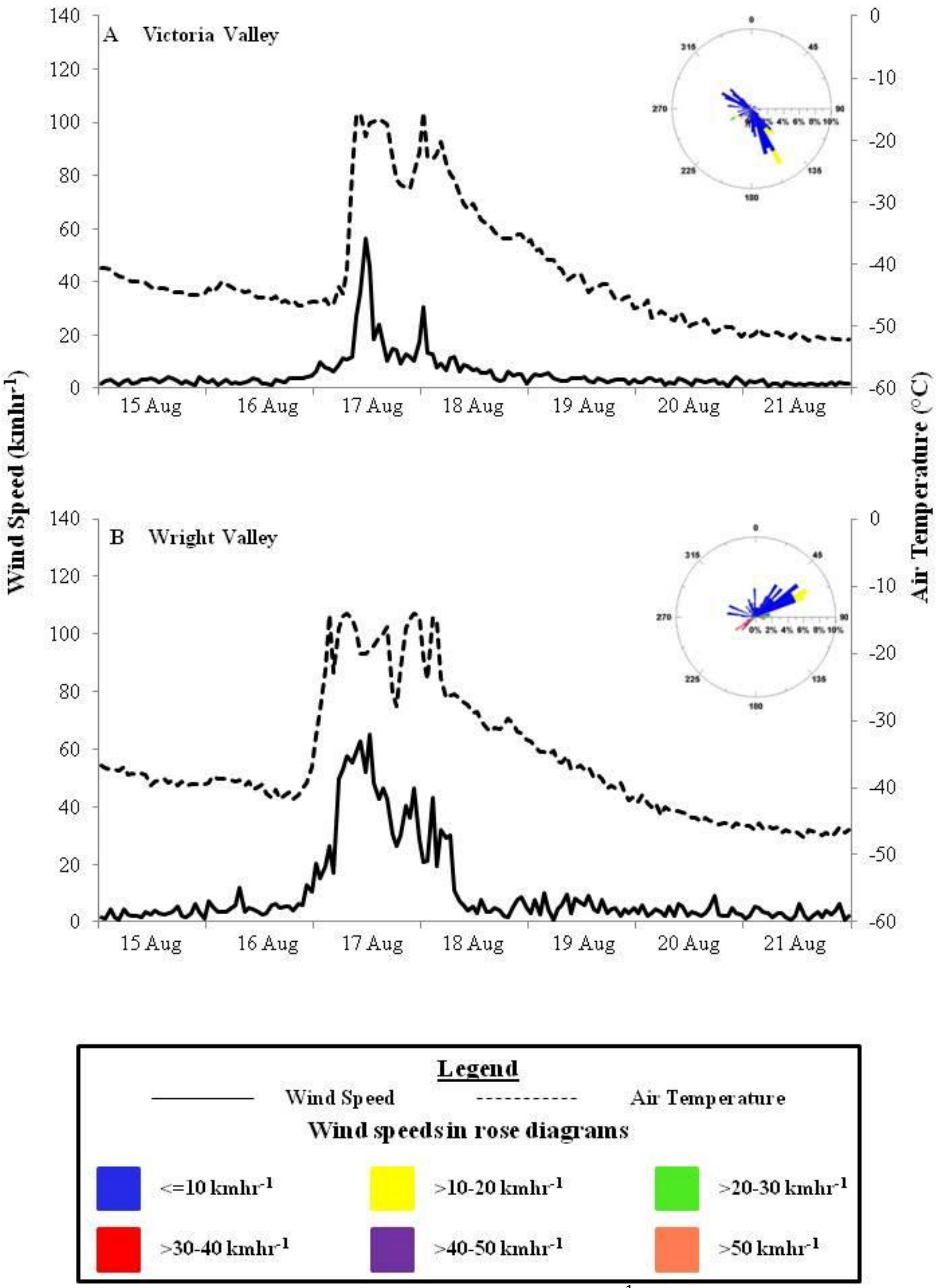

Fig. 6.16 Winter storm event with wind speed (kmhr^{-1}) and air temperature (°C) vs. time (15th August 2011 – 21st August 2011) for A: Victoria Valley, and B: Wright Valley.

The site at Mt Fleming had more prolonged high wind speeds than the Wright Valley and Victoria Valley sites, starting in the morning of August 16th 2011 and ceasing in the evening of the 19th August 2011 (Fig. 6.17a). Air temperature at Mt Fleming did not follow the same pattern as the Victoria Valley and Wright Valley sites, with no discernible sharp increase in temperature with the onset of the high speed wind event. There was a decrease in air temperature following the decay of the wind event in the evening of the 18th August 2011 to the morning of the 19th August 2011, before air temperatures began to slowly increase again (Fig. 6.17a).

The site at Minna Bluff had a delayed high speed wind event compared to the other sites, with a sharp increase in wind speeds in the evening of the 18th August 2011 and decaying by midday on the 20th August 2011 (Fig. 6.17b). There was a slight increase (8.9°C) in air temperature over the wind event time period, with a small (relative to Victoria Valley and Wright Valley) drop in air temperature (10.3°C) following the wind event (Fig. 6.17b).

At the Scott Base site two sharp short-term peaks in wind speed and air temperature were observed on the 15th and 16th August. Both the wind speed and air temperature dropped rapidly following wind onset at the Scott Base site (Fig. 6.19).

The Granite Harbour and Marble Point sites did not experience a high speed wind event or increased air temperature during the week 15th – 21st August 2011 (Fig. 6.18). However, small air temperature increases followed a similar pattern to wind speed at the Granite Harbour and Marble Point sites (Fig. 6.18).

Wind directions for the sites that experienced a high speed wind event (Victoria Valley, Wright Valley, Mt Fleming and Minna Bluff) were generally from the SW except for Minna Bluff where the high speed wind came from the NE, and at the Scott Base site where the strong winds came from the NW (Figs. 6.16b, 6.17b, 6.18a & 6.19).

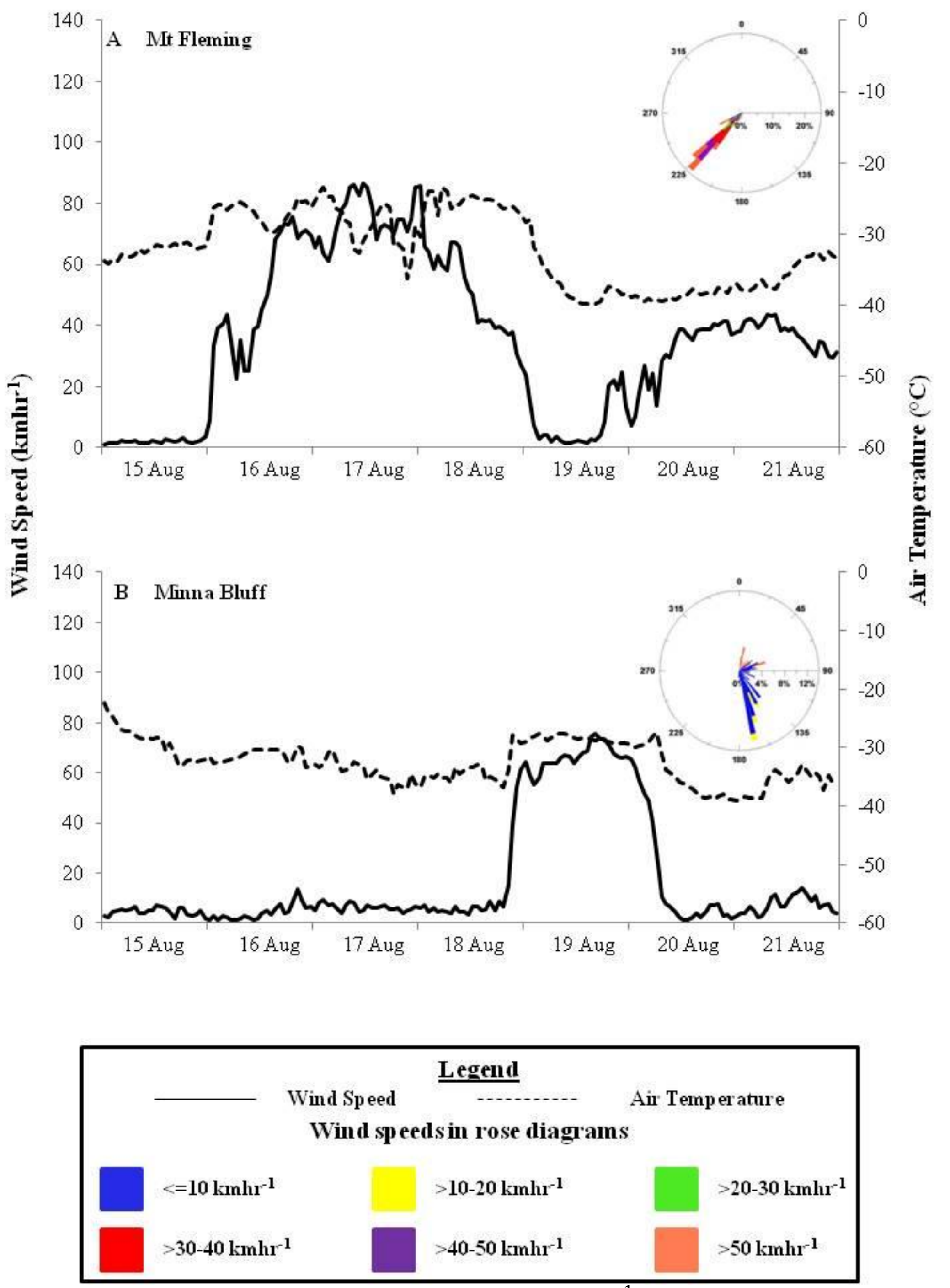

Fig. 6.17 Winter storm event with wind speed (kmhr^{-1}) and air temperature (°C) vs. time (15th August 2011 – 21st August 2011) for A: Mt Fleming, and B: Minna Bluff.

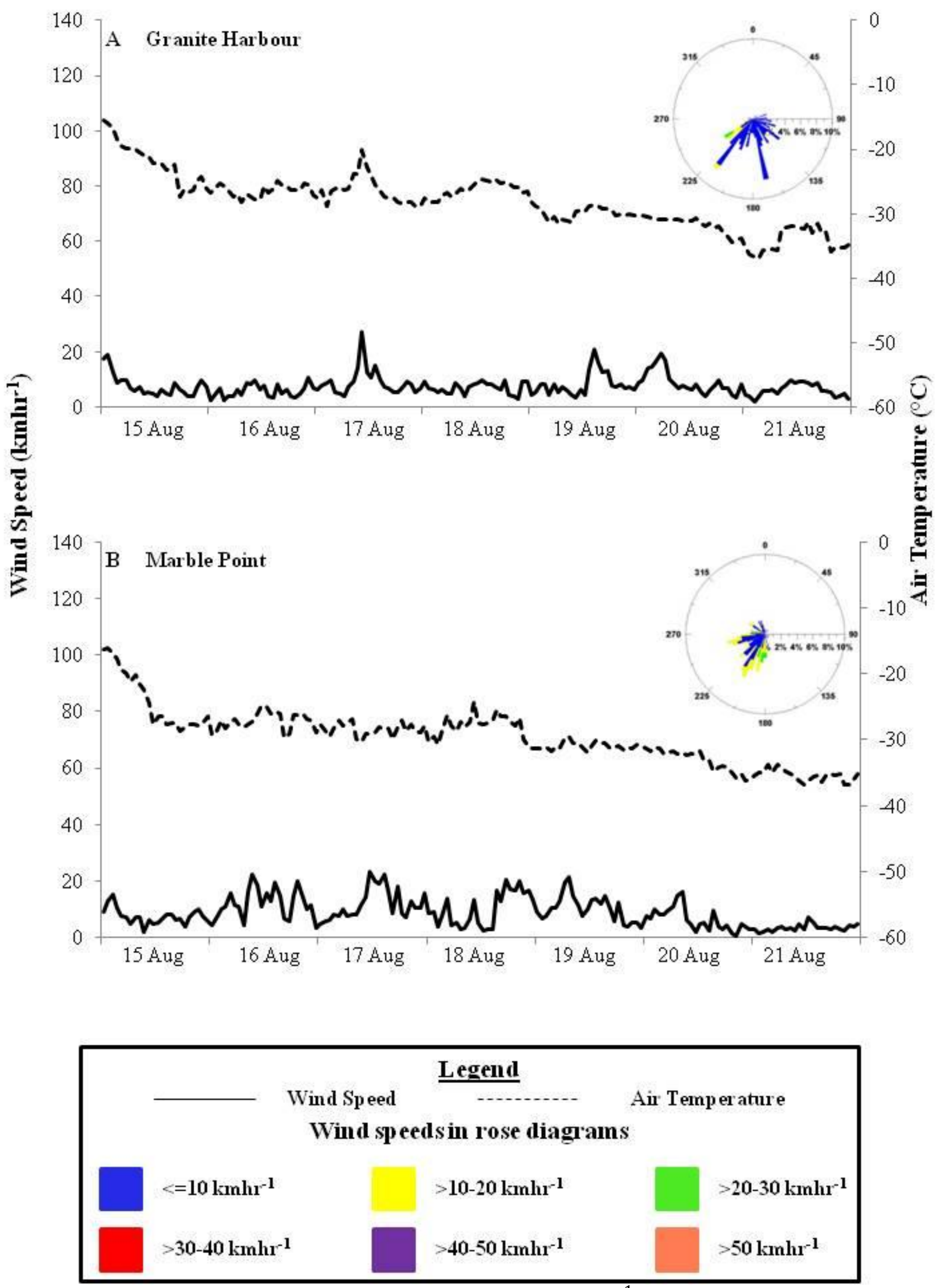

Fig. 6.18 Winter storm event with wind speed (kmhr^{-1}) and air temperature (°C) vs. time (15th August 2011 – 21st August 2011) for A: Granite Harbour, and B: Marble Point.

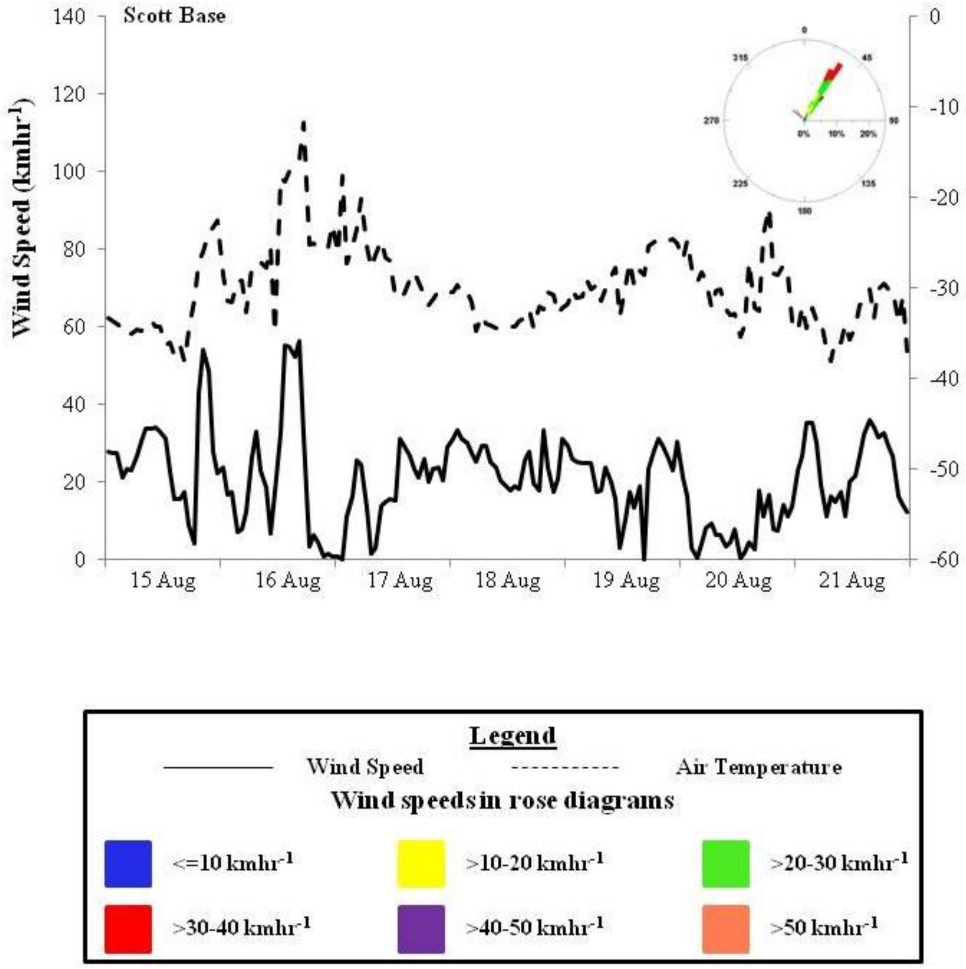

Fig. 6.19 Winter storm event with wind speed (kmhr^{-1}) and air temperature (°C) vs. time (15th August 2011 – 21st August 2011) for Scott Base.

6.8 Discussion

6.8.1 Which station was the windiest?

Davolio & Buzzi (2002) (Terra Nova Bay) and Bromwich *et al.* (1994) (Siple Coast and Ross Ice Shelf) reported that the fastest, most persistent winds were found at coastal margins in Antarctica as the air-flows converge in valleys and are channelled out to sea. However, in the Ross Sea region, this was not the case. The site with the highest mean wind speed (45 kmhr^{-1}) in this study, Darwin Glacier, was not a coastal site, and was in fact at approximately 300 m ASL in a glacial-till dominated valley, and also the most southerly site. Other particularly windy sites were Mt Fleming (on the margin of the Polar Plateau), and Minna Bluff which borders the Ross Ice Shelf. Granite Harbour, a coastal site, had the lowest mean annual wind speed (7 kmhr^{-1}). However, Granite Harbour is sheltered by a large steep hillside immediately south of the climate station, and therefore, has a different micro-climate from other coastal sites (Marble Point and Scott Base) in this study (Table 6.1).

6.8.2 Is there a correlation between altitude or latitude and wind speed?

There was no significant relationship between altitude and wind speed (Fig. 6.20a). There was a moderate relationship between latitude and wind speed (Fig. 6.20b), however topographic variation is also likely to be a key factor (Davolio & Buzzi 2002).

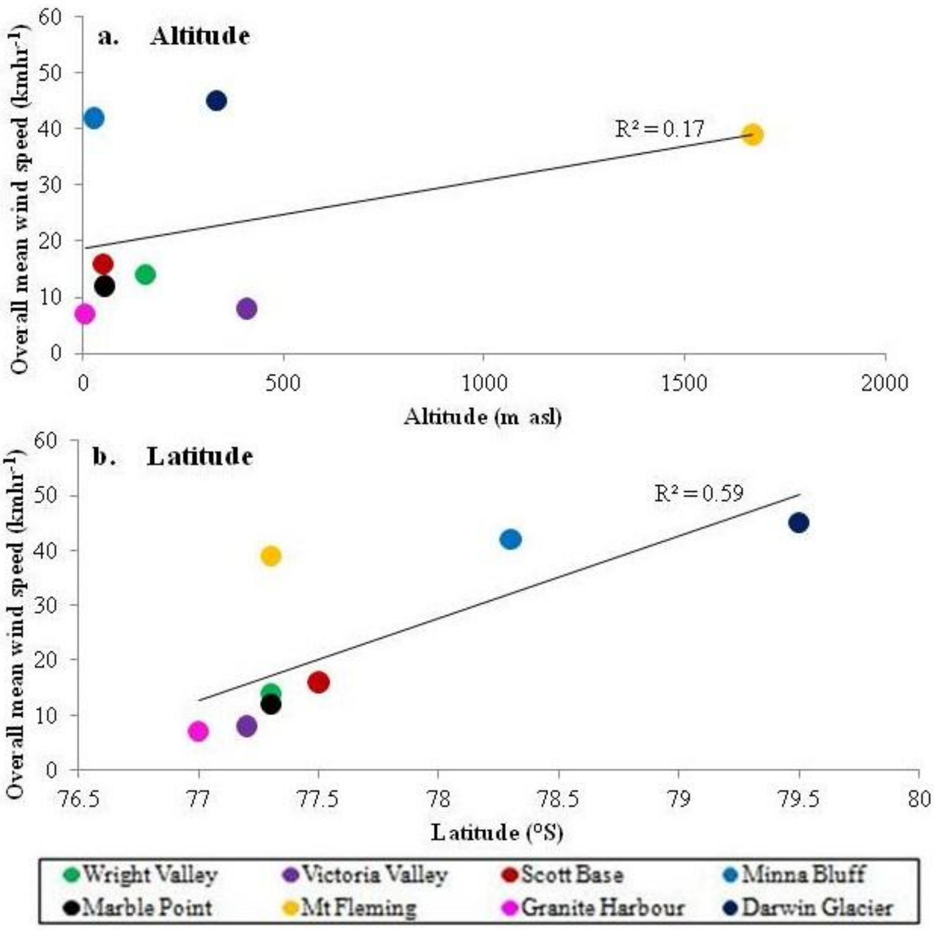

Fig. 6.20 Mean hourly wind speeds (kmhr^{-1}) vs. a. altitude (m ASL), and b. latitude (°S) for all sites.

Mt Fleming, Minna Bluff and Darwin Glacier had higher overall mean wind speeds than the other sites (Fig.6.20).

6.8.3 The influence of topographic barriers on wind speed and direction

The Victoria Valley and Wright Valley sites both had moderate overall mean wind speeds. The Mt Fleming site, at the head of the Wright Valley (Fig. 6.21), had much higher wind speeds than the Wright Valley site, with an overall mean wind speed of 39 $kmhr^{-1}$. The Mt Fleming, Wright Valley and Victoria Valley stations are relatively close together (the distance between Mt Fleming and Wright Valley sites is 40 km), yet there was a marked difference in wind speeds and direction between sites. The higher wind speeds at Mt Fleming from the SSE are likely linked to topography and elevation (Fig. 6.21). Winds flow unrestricted over the high Polar Plateau, before descending into lower elevations via topographically constrained channels. Due to the exposed nature of the Mt Fleming site adjacent to the Polar Plateau, there is no deflection or barrier for the strong south polar winds to encounter before reaching the Mt Fleming site.

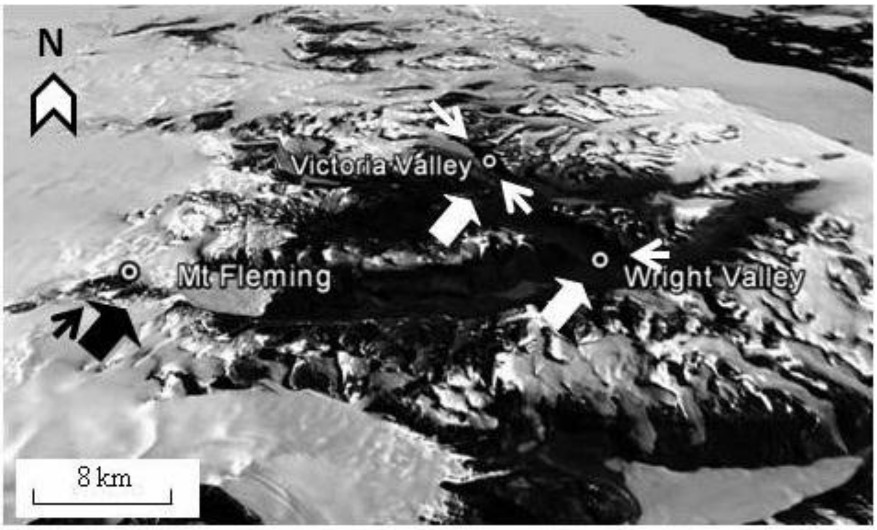

Fig. 6.21 Topographic view of Mt Fleming, Wright Valley and Victoria Valley facing north (image adapted from Google Earth). Thick arrows indicate strong wind directions, and thin arrows indicate prevailing wind directions.

Both the Wright and Victoria Valley sites (Fig. 6.21), are located on valley floors in low-lying topographic depressions. Doran *et al.* (2002a) reported that in winter the depressions enable pools of cold air to form that remain until strong winds flow through to disturb them, and support for their statement was seen in my winter wind speed data for both the Wright and Victoria Valley sites. Winter air temperatures at Victoria Valley dropped regularly below -40°C, before rapidly increasing (by up to 34°C in 15 hours, April 2011) with strong wind events. Between wind events, air temperatures and wind speeds were low. Conversely, in summer, radiative heating of the ground prevented the formation of cool air inversion.

Speirs *et al.* (2010) stated that the winds in the McMurdo Dry Valleys are dominantly foehn winds not katabatics. Foehn winds are formed in the lee of mountain ranges (in this case, the Transantarctic Mountains) and Speirs *et al.* (2010) classified foehn winds in the McMurdo Dry Valleys as those which are faster than 5 ms^{-1} from the south-west, warmed air temperatures at a rate of 1°C per hour, and increased relative humidity by at least 5%. The dominant annual wind direction at Wright Valley was SSE (Fig. 6.18). At the Victoria Valley site, the dominant wind direction was from the SSW, likely channelled from Wright Valley, through Bull Pass and over to the Victoria Valley soil climate station. The SSW direction of winds in Victoria Valley may indicate a topographic or foehn origin as stipulated by Speirs *et al*. (2010).

Minna Bluff experienced high wind speeds, and is situated at the foot of an exposed ridge extending from the Antarctic continental coastline (Fig. 6.22). I thought that the bluff to the south of the soil climate station would act as a barrier to winds and provide a topographic shelter to the site. Measurements showed that the dominant winds reaching the Minna Bluff site originated from the SW, thus flowing parallel to Minna Bluff.

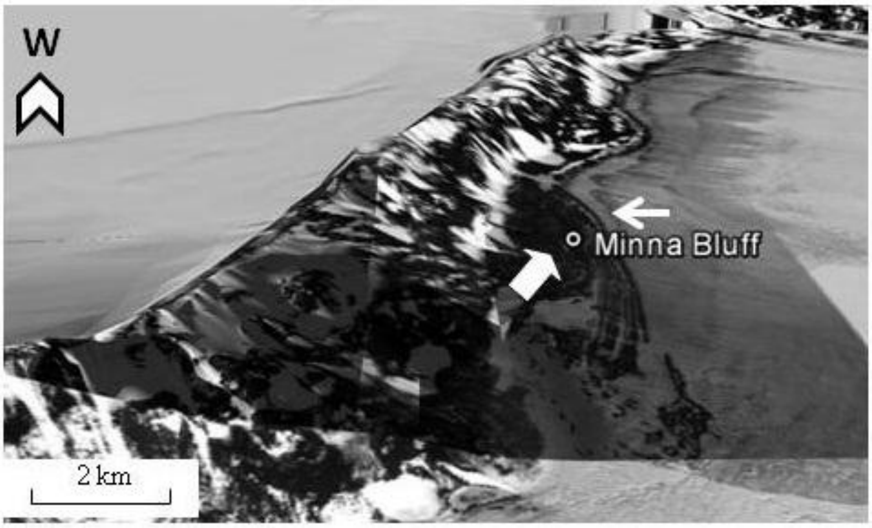

Fig. 6.22 Topographic view of the Minna Bluff site facing west (image adapted from Google Earth). Thick arrow indicates strong wind directions, and thin arrow indicates prevailing wind directions.

The site at Granite Harbour is sheltered by a steep hillside directly south of the station (Fig. 6.23). Further south of Granite Harbour are irregular mountain tops and the McMurdo Dry Valleys which may act to dissipate strong winds before they reach the Granite Harbour site (Fig. 6.23). Despite the southerly barrier to strong winds, the dominant wind direction for the Granite Harbour site was from the SW.

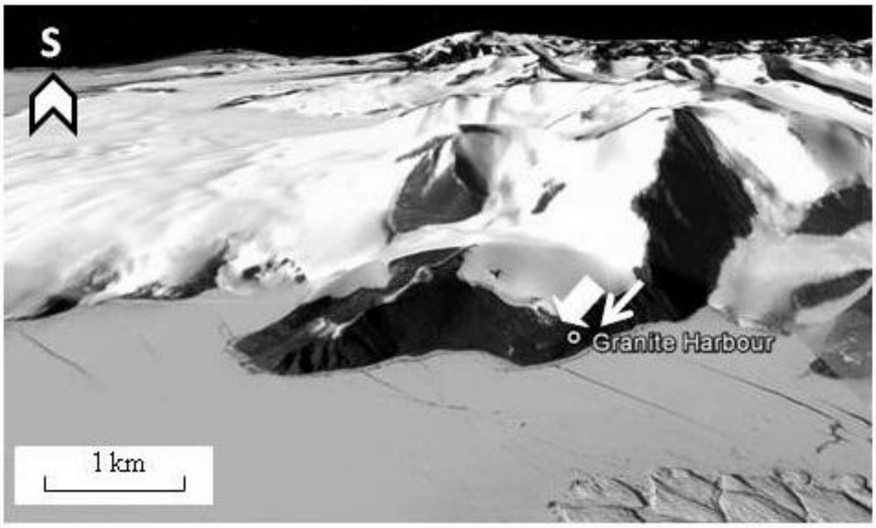

Fig. 6.23 Topographic view of the Granite Harbour soil climate station facing south (image adapted from Google Earth). Thick arrow indicates strong wind directions, and thin arrow indicates prevailing wind directions.

The Darwin Glacier climate station was located in an east-west trending valley (Fig. 6.24), which, if following the same pattern as the Victoria and Wright

Valley, then the site would be relatively sheltered and should have experienced moderate not high winds. The Darwin Glacier site was the southernmost of the station network and the windiest except for one extreme wind event at Minna Bluff in 2009. The dominant wind direction at the Darwin Glacier site was from the SW (Fig. 6.24).

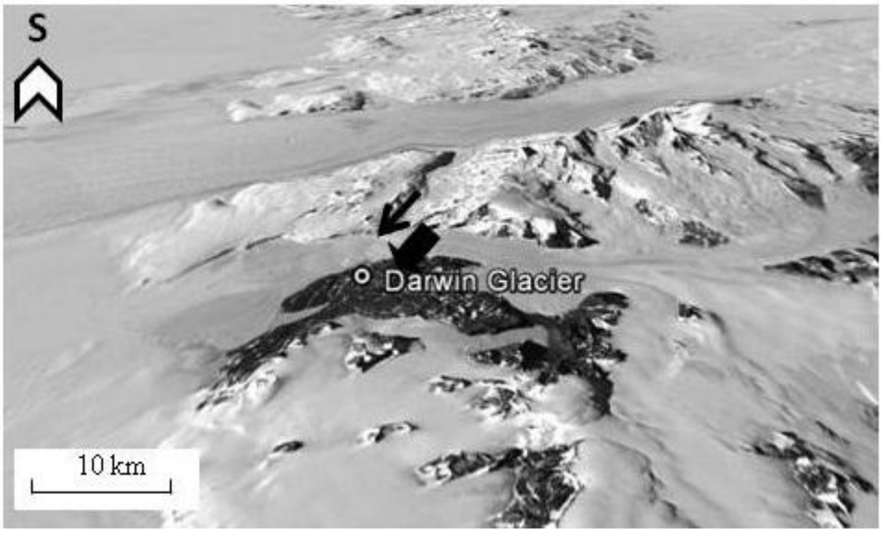

Fig. 6.24 Topographic view of the Darwin Glacier soil climate station facing south (image adapted from Google Earth). Thick arrow indicates strong wind directions, and thin arrow indicates prevailing wind directions.

The Scott Base soil climate station site is located on Ross Island on Hutt Point. The station is adjacent to the coast, and winds predominantly come from a NNE direction (Fig. 6.25). Southerly winds are not dominant, despite an open expanse of Ross Ice Shelf to the south of the station. The NNE wind flow may result from katabatic outflow off Ross Island. Strong winds generally arrive at the Scott Base site from the NW (Fig. 6.25).

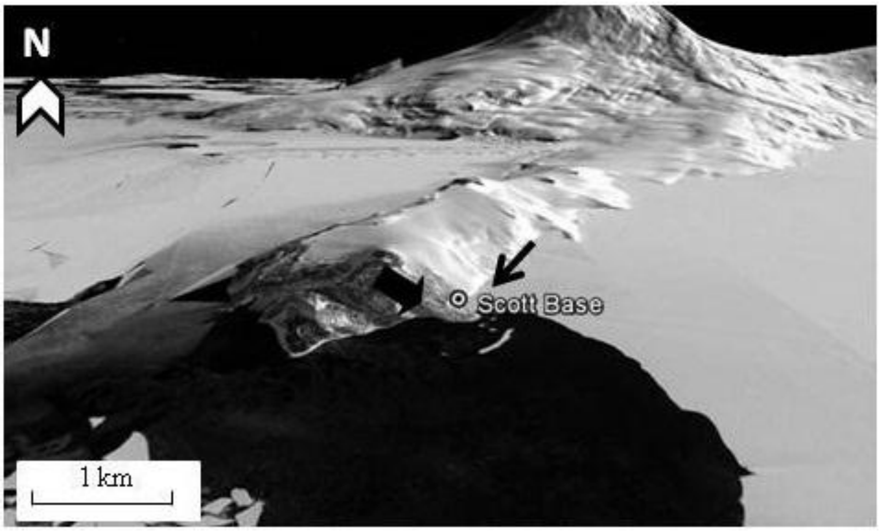

Fig. 6.25 Topographic view of the soil climate station site at Scott Base, facing north (image adapted from Google Earth). Thick arrow indicates strong wind directions, and thin arrow indicates prevailing wind directions.

Marble Point is a coastal site to the east of the McMurdo Dry Valleys (Fig. 6.26). The site is exposed on its coastal side, backed by the Wilson Piedmont Glacier and the McMurdo Dry Valleys. The prevailing wind direction at Marble Point was from the SSW and SSE, suggesting that wind flow predominantly came towards the Marble Point site down along the coast during summer and from more inland during winter (Fig. 6.26).

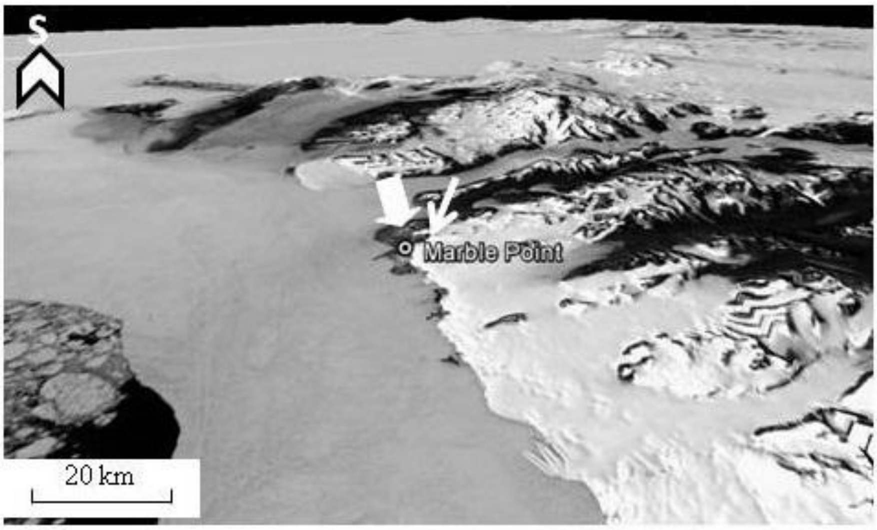

Fig. 6.26 Topographic view of Marble Point facing south (image adapted from Google Earth). Thick arrow indicates strong wind directions, and thin arrow indicates prevailing wind directions.

Speirs *et al.* (2010) observed a SW origin foehn wind pattern in the McMurdo Dry Valleys. I observed that strong winds at the Victoria Valley and Wright Valley sites were predominantly from the SW. The only other two sites within the network that had a SW prevailing wind direction were Darwin Glacier and Marble Point. It is suggested that strong winds in the McMurdo Dry Valleys may be of foehn origin, but at the Granite Harbour, Scott Base, Minna Bluff, and Mt Fleming sites in the Ross Sea region of Antarctica prevailing winds were generally formed by gravity-driven katabatic or downslope wind flows.

Whilst wind directions at each station showed little inter-annual variation, there was marked variability between stations (Fig. 6.27). The differences suggest that whilst most strong winds in the Ross Sea region originated from the South Pole and Polar Plateau (not including cyclonic storm events), the persistent wind directions were altered before reaching the soil climate station sites. The differences in prevailing wind directions may have been due to topographical constraints or weather systems, altering wind flow.

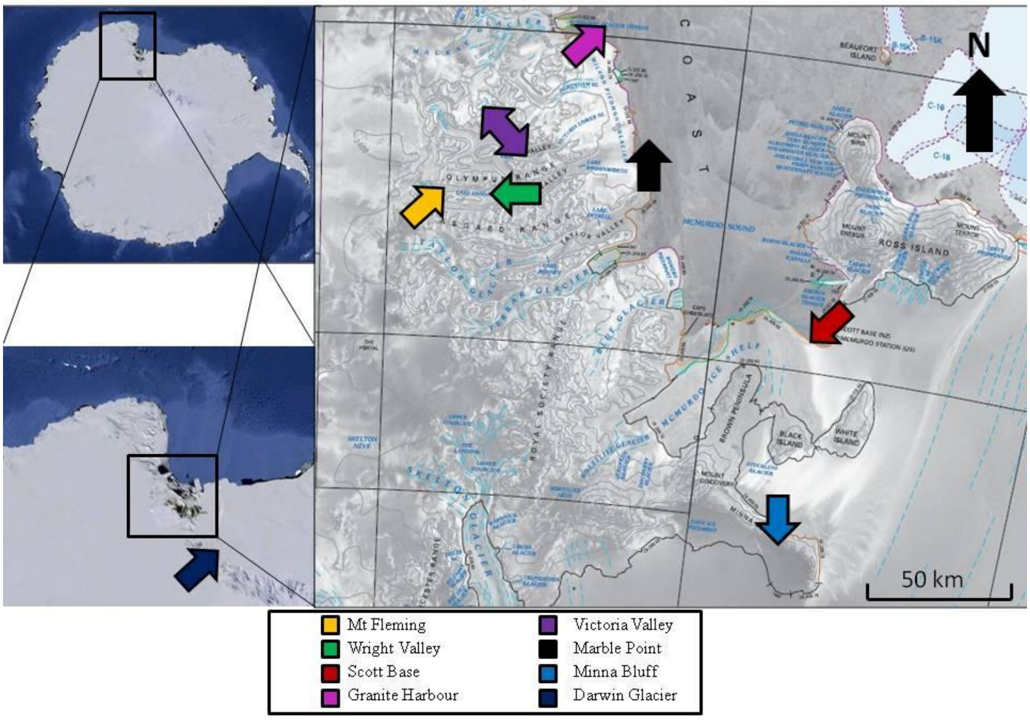

Fig. 6.27 Prevailing wind directions at each site with arrows indicating wind direction.

6.8.4 Are winter storms evident at all stations?

It was not possible to acquire localised isobar maps of the Ross Sea region which were desired to highlight the presence and location of storm events for this study.

Therefore, comparison with station data and wider-scale storm events has not been undertaken.

Winter storms or high wind speed events in the winter season could be strong and persistent, arriving and ceasing suddenly. During winter, katabatic winds were more frequent and of higher intensity than during the summer months (Doran *et al.* 2002a, Nylen *et al.* 2004), due to strong radiational cooling of the ice and snow surface (King *et al.* 1998, Knuth & Cassano 2011).

Due to the ferocity of some winter wind events, it could be assumed that they would be recorded at most, if not all stations, as was seen during the wind event on the 5th August 2011 (Figs. 6.12-6.15). However, for the example 15th - 21st August 2011 (Figs.6.16-6.19), this was not the case. The example in this chapter of a week long period surrounding a high speed wind event in August 2011 clearly showed that whilst some stations (Victoria Valley, Wright Valley & Mt Fleming) had a strong wind passing through around the same time, other sites such as Granite Harbour and Scott Base had no discernible high speed wind event for the same period. The example wind event observed during the 15th – 21st August 2011 was therefore determined to be a katabatic event or a small localised storm event as it was seen only at sites in the Dry Valleys. Doran *et al.* (2002a) did however report that the strong katabatic winds aren’t uniform across large areas, resulting in localised wind speed variations that may not be seen across all sites. The pattern of isolated storm events was not always the case over the recording period, with many examples of wind events affecting all sites within the network.

The example of the 15th – 21st August 2011 (section 6.7) showed that the clearest identification of the high speed wind event was at stations located in or at the head of the McMurdo Dry Valleys. The 15th – 21st August wind event could, therefore, have been an isolated storm event, or katabatic wind activity. However, discerning between katabatic winds, foehn winds and the more general downslope winds was not possible with single level wind speed and direction data alone (Parish & Cassano 2001).

The sudden increase in air temperature with wind onset is not a defining characteristic of any particular wind flow either, as the Dry Valley sites (Victoria Valley and Wright Valley) are situated in bowl-like depressions where cool air pools during winter. Therefore, any high speed wind event will rapidly increase air temperature relative to the pre-event cold pooled air, making the air temperature increases of foehn (Speirs *et al.* 2010) and katabatic (Nylen *et al.* 2004) winds unusable for characterisation. Conversely, Bromwich (1989b) reported that the fastest wind speeds occurred at the same time as the coldest air temperatures in Terra Nova Bay, which was not observed in my study.

The isolated nature of some wind events (e.g. 15th – 21st August 2011) highlights that whilst the winds are strong (some reaching 140 $kmhr^{-1}$, Minna Bluff, July 2011), the area of study is important and the high wind speeds may occur in locally confined areas. However, the high speed wind event on the 5th August 2011 is one example of a wind event that occurred at most sites, which are more common than smaller, isolated events.

6.8.5 What controls winter wind events?

As the sun descends below the horizon and the Ross Sea region of Antarctica changes to the polar winter of 24 hour darkness, there was an obvious transition in wind patterns on the 24th February 2011 in the Wright Valley and Victoria Valley (Fig. 6.3) as diurnal effects ceased to exert a control on the wind speeds. There was strong support in the literature (Bromwich 1989b, King *et al.* 1998, Parish & Cassano 2003, Nylen *et al.* 2004 and Knuth & Cassano 2011) for dominant katabatic wind flows during winter. However Speirs *et al.* (2010) suggested that wintertime winds are actually of foehn origin) when cooling of the ice/snow surface is strongest and winds become more unidirectional. However, little or no work has been done to differentiate winter cyclonic storm winds and katabatic winds due to the complexity of wind behaviour.

At some sites (Victoria Valley and Wright Valley) a marked decrease in general wind speed was observed in the 2011 example data in this chapter compared to 2000. The lower winds were frequently interspersed with sudden, relatively short-lived increases in wind speed which were likely to be storm events passing through. The consistent background winds that generally flowed at around

10 kmhr^{-1} (for the 2011 sample year) were possibly sea breezes, or driven by katabatic winds as the ice surface continued to radiationally cool, or foehn winds as air flow built up behind topographic barriers before breaking through and flowing past the sites (Speirs *et al.* 2010).

Other sites (including Mt Fleming, Scott Base and Minna Bluff) experienced an increase in wind speed and wind speed variability once the diurnal effect was removed in the dark winter months. The Victoria Valley and Wright Valley sites are located in a bowl-like depression within the valley floor, and cold air was able to settle in the depression forming a temperature inversion that only strong wind events could disrupt. Therefore the Victoria Valley and Wright Valley sites were effectively ‘sheltered’ from low to mid-scale storm or wind events, more than other sites, which may account for the more erratic wind pattern behaviour during the winter months at the Mt Fleming, Scott Base, Minna Bluff, Marble Point, Darwin Glacier, and to a lesser extent, Granite Harbour sites.

6.8.6 Seasonal changes in wind speed patterns

During the austral summer, the 24 hour sun acts to warm the continental surface, with maximum warming during midday when the sun is directly overhead. Therefore, Doran *et al.* (2002a) and Nylen *et al.* (2004) state that summertime katabatic winds exert less control on weather patterns than during winter. Depending on the surrounding topography, the ground surface may be shaded for part of the day, and so warming is reduced.

The ground and ice surface absorb short-wave radiation from the sun then re-emit it as long-wave radiation (Parish 1988). The emission of long-wave radiation is a loss of energy and therefore heat from the ground/ice surface.

The sun plays a strong controlling role on air temperature and wind patterns in the Ross Sea region of Antarctica. Katabatic winds are thermally-driven gravity winds that require a change in elevation and temperature difference between air masses to form (Parish & Cassano 2003). Solar effects on katabatic winds were seen in wind speed examples during summer months at Wright Valley and Victoria Valley (Fig. 6.29 b & c) as wind speeds reached a maximum in the mid-afternoon and a minimum in the early morning.

In the winter, no solar radiation is available, and the ground/ice surface continually loses radiational heat to the atmosphere, driving katabatic winds (Parish & Bromwich 1989, Renfrew & Anderson 2006). King *et al.* (1998) reported that increases in air temperature during the winter months is predominantly driven by storm and/or katabatic wind events, and that air temperatures took longer to return to pre storm- event air temperatures than wind speed decay. Katabatic and/or foehn winds are driven downslope, warming the air at the dry adiabatic lapse rate of 9.8 °C km^{-1}, thus, as the air mass reaches locations further downslope, the surrounding stationary air is relatively cooler than the katabatic flow (Nylen *et al.* 2004, Speirs *et al.* 2010). During summer the wind patterns were generally more cyclic and had a regular diurnal pattern (Fig. 6.29). During winter, low background winds were interspersed with high wind events at often apparently random intervals.

A representative week during each season (spring, summer, autumn and winter) was taken from the 2011 soil climate station wind speed data to view changing wind patterns throughout a typical year (Figs. 6.28 - 6.31). Seasonal weeks were selected based upon the week containing both calm and windy periods at most, if not all, sites. In addition, air temperatures and mean daily wind directions were graphed for each seasonal week to observe simultaneous changes in each variable (Figs. 6.28-6.31).

During spring (10^{th} – 16^{th} October 2011), the Mt Fleming and Darwin Glacier sites had a similar wind speed pattern which differed from the Wright Valley, Victoria Valley, Marble Point, Minna Bluff, Scott Base, and Granite Harbour sites. The Wright Valley site had similar patterns of high and low wind speeds and air temperatures to the Victoria Valley site (Fig. 6.28 B&C).

Wind directions were predominantly SW at the Mt Fleming, Wright Valley, Victoria Valley, Marble Point, and Darwin Glacier sites, whilst at the Minna Bluff, Scott Base, and Granite Harbour sites, wind directions were more variable (Fig. 6.28). Air temperatures during the spring week (10^{th} – 16^{th} October 2011) did not follow the same pattern as wind speeds.

When strong winds ceased at the Mt Fleming site, the dominant wind direction was from the SE, conversely, stronger winds flowed from the SW (Fig. 6.28 A). Stronger winds at Minna Bluff came from the NE, whilst calmer wind conditions were generated from the SE (Fig. 6.28 E). Stronger winds at the Scott Base site came from the NE, whilst the gentler winds originated from the SE (Fig. 6.28 F).

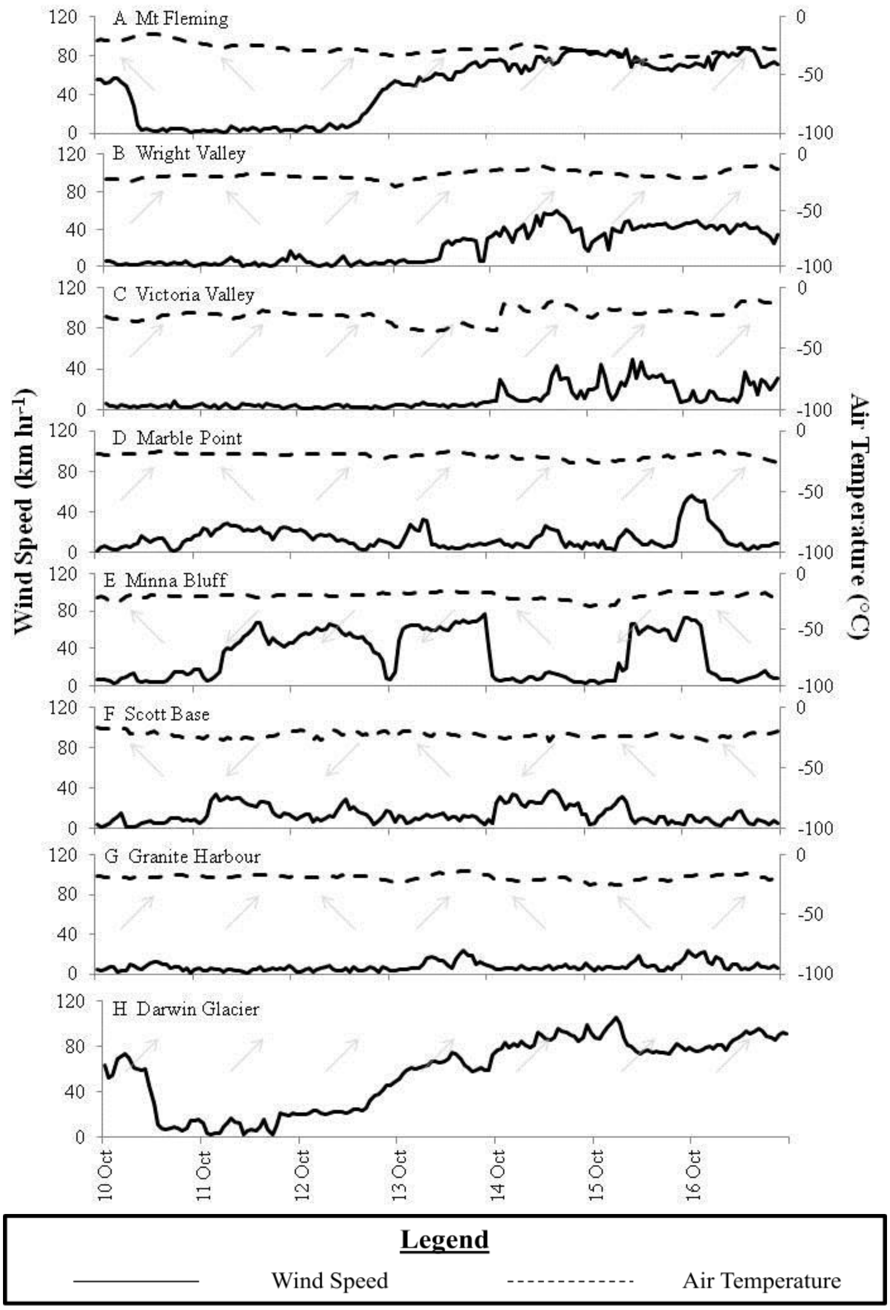

Fig. 6.28 Spring week in 2011. Wind speed vs. air temperature with grey arrows indicating mean daily wind direction. A: Mt Fleming, B: Wright Valley, C: Victoria Valley, D: Marble Point, E: Minna Bluff, F: Scott Base, G: Granite Harbour, H: Darwin Glacier (no air temperature data was available for the Darwin Glacier site).

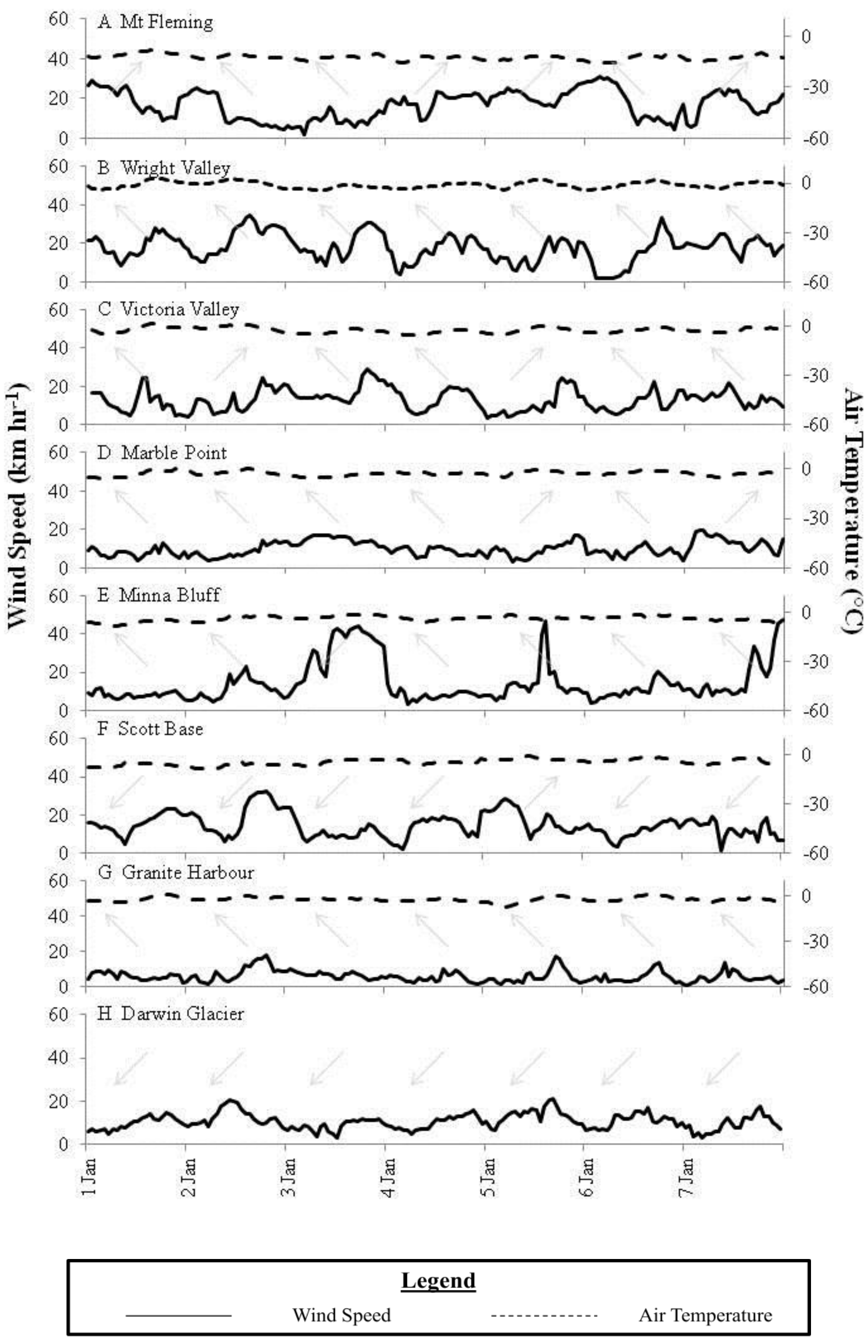

Fig. 6.29 Summer week in 2011. Wind speed vs. air temperature with grey arrows indicating mean daily wind direction. A: Mt Fleming, B: Wright Valley, C: Victoria Valley, D: Marble Point, E: Minna Bluff, F: Scott Base, G: Granite Harbour, H: Darwin Glacier (no air temperature data was available for the Darwin Glacier site).

During the summer week of 1st – 7th January 2011 (Fig. 6.29), distinct diurnal wind speed variations and corresponding gentle air temperature variations were observed at the Mt Fleming, Wright Valley, Victoria Valley, Scott Base, and Darwin Glacier (wind speed only) sites. Wind directions changed from a dominantly SW flow during the spring week, to more variable directions during the summer week. Winds from both the SW and SE dominate at the Mt Fleming, Victoria Valley, and Marble Point sites, whilst SE winds prevailed at the Wright Valley, Minna Bluff, and Granite Harbour sites (Fig. 6.29). At both the Scott Base and Darwin Glacier sites, the prevailing mean daily wind was from the NE.

Higher wind speeds were observed in an autumn (Fig. 6.30) week-long period (22^{nd} – 28^{th} April 2011) than in the spring or summer week periods (Figs. 6.28 - 6.29). The Mt Fleming and Darwin Glacier sites had near-constant high speed winds compared to the Wright Valley, Victoria Valley, Marble Point, Scott Base, and Granite Harbour sites. High winds with irregular calmer periods were observed at the Minna Bluff site. Long calm periods interspersed with faster winds were observed at the Wright Valley, Victoria Valley and Granite Harbour sites.

A high speed wind event was observed with a corresponding rise in air temperature, which could indicate the passage of a storm at the Wright Valley, Victoria Valley, Marble Point, Minna Bluff, Scott Base, and Granite Harbour sites. Identification of the wind event at Mt Fleming and Darwin Glacier was impeded by already high wind speeds (Fig. 6.30).

Air temperatures fluctuated with wind speeds most noticeably at the Wright Valley, Victoria Valley and Granite Harbour sites during the autumn week (Fig. 6.30).

Autumn mean daily wind directions were dominantly SW at the Mt Fleming, Victoria Valley, Marble Point, and Darwin Glacier sites (Fig. 6.30). At the Wright Valley and Minna Bluff sites, prevailing winds for the autumn week 22^{nd} – 28^{th} April 2011) were from the SE.

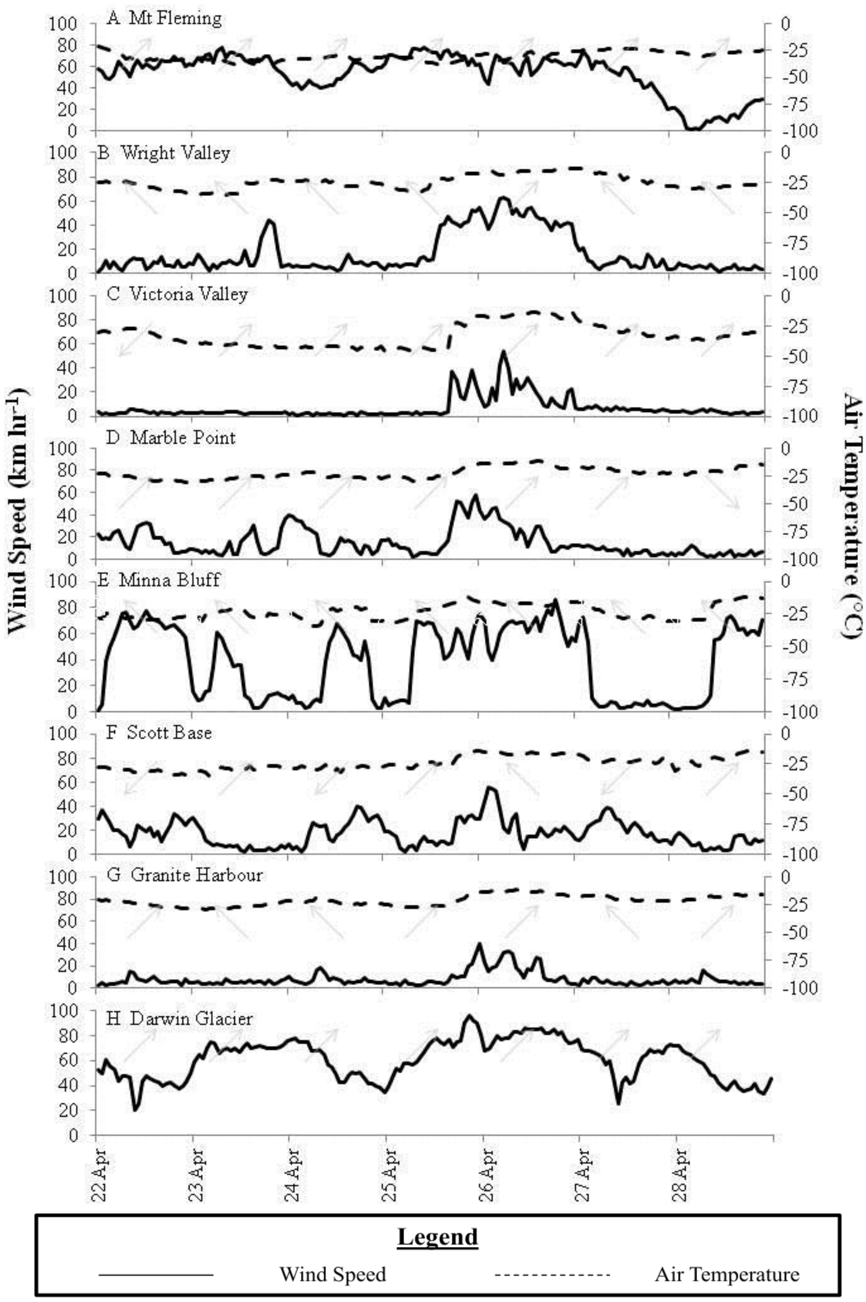

Fig. 6.30 Autumn week in 2011. Wind speed vs. air temperature with grey arrows indicating mean daily wind direction. A: Mt Fleming, B: Wright Valley, C: Victoria Valley, D: Marble Point, E: Minna Bluff, F: Scott Base, G: Granite Harbour, H: Darwin Glacier (no air temperature data was available for the Darwin Glacier site).

Wind speeds and directions, and air temperatures during a week in the winter (Fig. 6.31) of 2011 (15^{th} – 21^{st} July) were observed to have the highest wind speeds and lowest air temperatures of all the sampled 2011 seasons (Figs. 6.28 - 6.31).

Winds at Mt Fleming were from the SW and near constant, with little air temperature variation. The Wright Valley, Victoria Valley, Scott Base, and Granite Harbour sites had periods of calm interspersed with slightly windier episodes, however, winds at the Wright Valley, Victoria Valley, Scott Base, and Granite Harbour sites did not exceed 60 km hr^{-1} during the week of the 15^{th} – 21^{st} July 2011.

Two possible storm events were observed at the Mt Fleming, Wright Valley, Victoria Valley, Minna Bluff, and Darwin Glacier sites, identified by increased wind speeds around the 16^{th} and 21^{st} July 2011, and relatively warmer air temperatures at the Wright and Victoria Valley sites (Fig. 6.31).

Winds during the winter week of the 16^{th} – 21^{st} July 2011 were dominantly from the SW at the Mt Fleming, Victoria Valley, Marble Point, Granite Harbour, and Darwin Glacier sites (Fig. 6.31). Minna Bluff and Scott Base were the only sites to have mean daily wind directions from the NE. Wind directions were not observed to change with the onset of higher wind speed events.

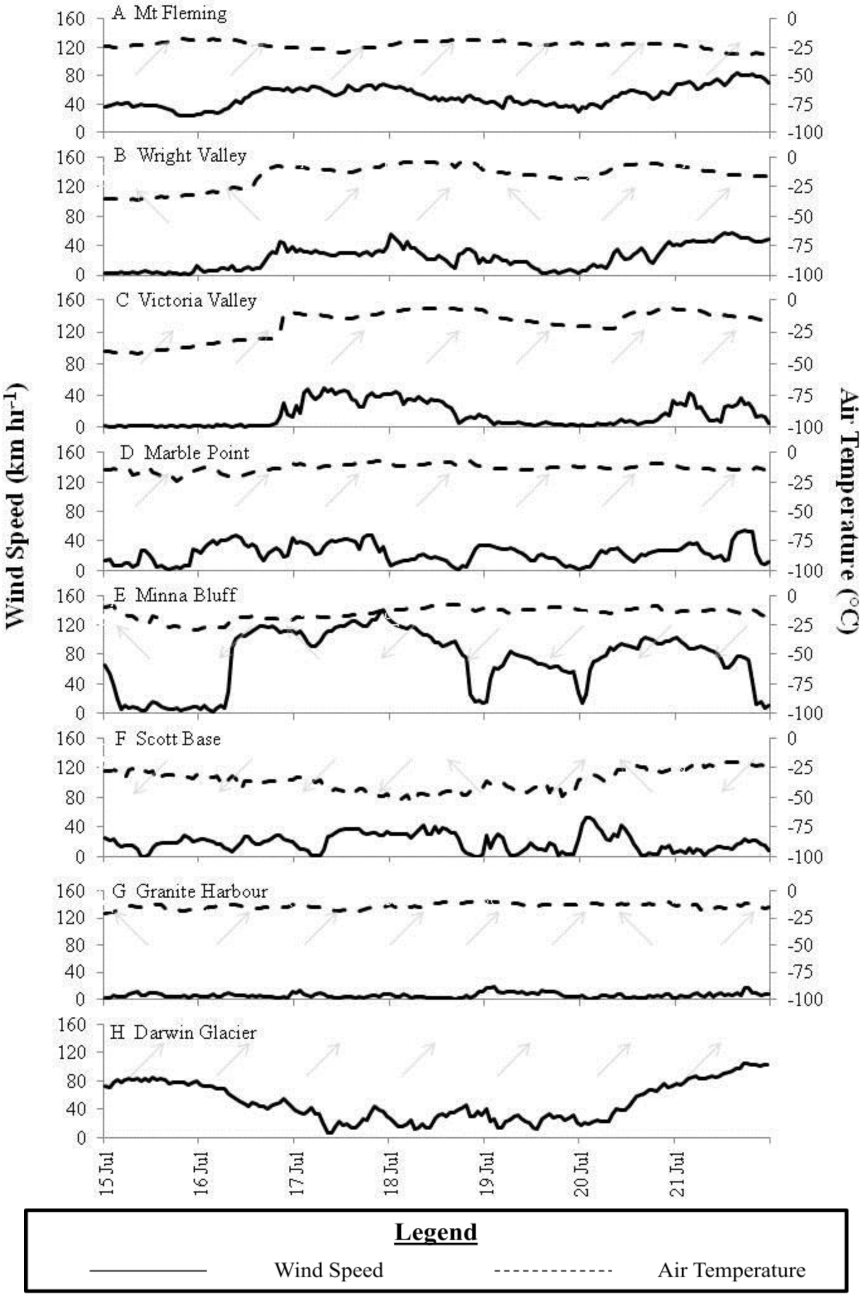

Fig. 6.31 Winter week in 2011. Wind speed vs. air temperature with grey arrows indicating mean daily wind direction. A: Mt Fleming, B: Wright Valley, C: Victoria Valley, D: Marble Point, E: Minna Bluff, F: Scott Base, G: Granite Harbour, H: Darwin Glacier (no air temperature data was available for the Darwin Glacier site).

The Mt Fleming site had similar wind patterns and directions to the Darwin Glacier site across the year (Figs. 6.28-6.31), as both sites were adjacent to the Polar Plateau, and so subjected to the strong and persistent SW winds. The wind speed and direction, and air temperature regime at Mt Fleming differed from the Wright Valley and Victoria Valley sites which are adjacent (Fig. 3.1). It is possible that the strong katabatic winds powering across the Polar Plateau, passed the Mt Fleming site and began to flow into the Wright and Victoria Valleys, however, cold air ponding in the floors of the Wright and Victoria Valleys may have created a temperature inversion preventing the adiabatically warmed air from reaching the valley bottoms. Instead, the relatively warmer air may have moved over the cooler, ponded air, and flowed away from the Wright and Victoria Valleys. Only a strong, high speed storm event would have disrupted the cold air temperature inversion in the valley floors and mixed the air masses. Support for this hypothesis was observed in the extended calm periods at the Victoria and Wright Valley sites during autumn and winter (Figs. 6.30 – 6.31), interrupted by an increase in both wind speed and air temperature.

Storm wind events were determined to be those that had a corresponding increase in air temperature with wind onset. Katabatic winds were determined to be those which were near consistent and unidirectional.

6.8.7 Is summer or winter windiest across the stations?

The summer months often had regular, predictable wind events that included high speed winds. The winter months however, were more erratic and had more high speed wind events interspersed with calm periods. Therefore, it is suggested that in general (except at the Victoria Valley and Wright Valley sites), winter months were windier than summer months.

6.9 Summary and conclusions

Wind speed and direction data were analysed for eight soil climate stations from Granite Harbour (77°S) to Darwin Glacier (79.5°S) with data records from 2000-2011. Mean hourly measurements were averaged to calculate mean annual wind speeds.

The Darwin Glacier site had the highest mean annual wind speed (47 kmhr^{-}1, 2007), whilst Granite Harbour had the lowest mean annual wind speed (6 kmhr^{-1}, 2004-2007). The highest recorded mean hourly wind speed was 169 kmhr^{-1} at Minna Bluff in 2009.

There was a moderate relationship of increasing wind speed with increased latitude (R^2=0.59), but no relationship between wind speed and altitude (R^2=0.17).

There was no significant change in mean wind directions over the recording period.

The Darwin Glacier site had the strongest wind speeds and most unidirectional wind direction, with winds consistently coming from the SW.

Weaker wind speeds were more variable in direction than strong winds at all sites.

The Dry Valleys sites (Victoria Valley and Wright Valley) had low winds from the end of February to mid October interspersed with sudden, short-term high-speed wind events. The low wind speed pattern was likely due to the bowl-like depressions that the soil climate stations are in within the valley floors creating a temperature inversion disrupted only by strong wind events.

All sites except the Victoria Valley and Wright Valley sites generally had higher wind speeds in winter than summer.

The windiest season at all sites was July-September (late winter).

Strong wind events recorded at Victoria Valley, were generally also recorded at the Wright Valley and Marble Point sites.

Large-scale storm events were recorded by most, if not all soil climate stations at all sites.

In summer the Granite Harbour, Darwin Glacier, Victoria Valley, Wright Valley and Minna Bluff sites showed diurnal wind speed variability. The Mt Fleming, Marble Point and Scott Base sites did not have strong summer diurnal wind speed variation.

The Victoria Valley, Wright Valley, and Granite Harbour sites had a correlation between summer diurnal air temperature fluctuations and diurnal wind speed with warmest temperatures and strongest winds generally mid-afternoon.

A high speed wind event was identified at Victoria Valley on the 17th August 2011. The Granite Harbour, Marble Point, and Scott Base sites did not record a strong wind event during this time.

An air temperature increase with wind onset in the 17th August 2011 was attributed to air temperature inversions over the low-lying Victoria and Wright Valley sites being disrupted by strong winds and the cooler denser stratified air being mixed and replaced with relatively warmer winds.

Summer and winter prevailing wind directions were calculated for all sites for the winter (June-August) of 2009 and the summer (December-February) of 2009/2010. No single wind direction dominated across all sites. Prevailing wind directions changed from winter to summer for Granite Harbour, Marble Point and Wright Valley.

Maximum wind speeds during winter 2009 were faster than wind speeds during the 2009/2010 summer at all sites except Victoria Valley and Wright Valley.

There was no single variable controlling wind speed and direction. Controls were likely to be a combination of altitude, latitude, local topography, and cyclonic storms.

Whilst it was possible to identify katabatic and storm wind events, it was not possible to distinguish foehn wind events.

Chapter 7: Summary and conclusions

7.1 Introduction

Air and soil temperatures and wind speeds were analysed at up to 10 soil climate stations in the Ross Sea region of Antarctica between 2000 and 2011. The soil climate station network extended from Cape Hallett in the north at 72.19°S to Darwin Glacier in the south at 79.5°S, and from sea level to 1689.5 m asl.

The aim of this thesis was to utilise climate data from the soil climate station network in the Ross Sea region of Antarctica to examine and characterise the temperatures and wind profiles and to investigate short-term climate variations over the twelve year period from 2000-2011. The three research objectives of this thesis were addressed in three results chapters (Chapters 4-6). The main findings of each results chapter are summarised below.

7.2 Summary

7.2.1 Air and soil temperature trends across latitudinal and altitudinal gradients

The research objective addressed in Chapter 4 was to: identify any increasing or decreasing air and soil temperature trends, over time or with altitude or latitude. The relationship between air and soil temperatures and inland and coastal locations were also investigated. The key outcomes of Chapter 4 are given below.

The warmest air temperature recorded was +11.9°C at Wright Valley in January 2002. The coldest air temperature recorded was -54.2°C at Victoria Valley in July 2011 (the only year for which we had minimum air temperatures for the Victoria Valley site).

The warmest shallow soil temperature (+18.3°C) was recorded at Granite Harbour (8 cm depth) in December 2008. The coldest shallow soil temperature (-55.3°C) was recorded in July 2004 at the Victoria Valley site (8 cm depth).

For deep soil (75-120 cm depth) temperature measurements, the warmest temperature recorded was +2.7°C, at 88 cm soil depth at the Granite Harbour site in December 2010. The coldest recorded deep soil temperature was -36.5°C at 120 cm depth at the Victoria Valley site in August and September 2008.

Mean annual air and soil temperatures from the Cape Hallett, Mt Fleming, Victoria Valley, Wright Valley, Scott Base, Minna Bluff and Darwin Glacier sites had no statistically significant trend of warming or cooling over the measurement period. A statistically significant ($P<0.05$) warming was observed at the Marble Point soil climate station for air and soil temperatures.

The Granite Harbour site had a statistically significant warming trend ($P=0.02$) in shallow soil (6 cm depth) temperatures. The trend at the Granite Harbour site was not evident in air temperatures or deeper soil temperatures (88 cm depth) and, due to the impact of melt-water flow across the site; the trend needs to be interpreted with caution.

There was marked inter-annual variability in temperature with relatively "warmer" (2003 and 2011) and "colder" (2002, 2006 and 2010) years identified.

7.2.2 Cumulative days at or above freezing for soil climate stations in the Ross Sea region

Chapter 5 examined the cumulative number of days at or above freezing per year for each site. The numbers of days at or above freezing were calculated for air, and for ~5, ~20, and ~75 cm soil depths. A summary of findings are outlined below.

Cumulative days with air T≥0°C ranged from: Mt Fleming (0.0), Scott Base (4.2), Darwin Glacier (7.3), Minna Bluff (7.6), Marble Point (9.7), Granite Harbour (10.4), Victoria Valley (22.3), to Wright Valley (33.3).

For the shallow soil (~5 cm depth), the cumulative number of days when soil T≥0°C ranged from: Mt Fleming (0.0), Cape Hallett (32.2), Scott Base (34.6), Victoria Valley (50.2), Minna Bluff (52.8), Marble Point (55.5), Granite Harbour (69.6), to Wright Valley (69.8).

At moderate soil depth (~20 cm), the cumulative number of days when soil T≥0°C ranged from: Mt Fleming (0.0), Scott Base (13.9), Cape Hallett (22.5), Minna Bluff (31.6), Marble Point (44.7), Wright Valley (52.0), to Granite Harbour (65.5).

For deep soil (~75 cm depth), Granite harbour was the only site (28.9 days) that had any cumulative number of days when soil T≥0°C.

There was no statistically significant increasing or decreasing trend in the number of days at or above freezing for any site within the network over the recording period 2000-2011.

Mid-depth (~20 cm depth) soil measurements had the greatest between-site variability in the cumulative number of days at or above freezing (ranging from 0.0 days at Mt Fleming to 65.5 days at Granite Harbour).

Shallow soil temperature measurements (~5 cm depth) had the greatest number (69.6 at Granite Harbour) of cumulative days at or above freezing, presumably due to direct solar radiational warming of the soil surface.

The cumulative number of days for air and soil measurements had similar increases and decreases in the number of days at or above freezing, indicating that air and soil measurements were correlated, at least down to the ~75 cm depth.

7.2.3 Wind patterns in the Ross Sea region of Antarctica

The aim of Chapter 6 was to characterise the wind patterns at each site. High speed wind events at each soil climate station were investigated to try to gain an understanding of storm events. Contrasts in wind speeds and directions between seasons were also identified.

Mean annual wind speeds from lowest to highest were: Granite Harbour (7 $kmhr^{-1}$), Victoria Valley (8 $kmhr^{-1}$), Marble Point (12 $kmhr^{-1}$), Wright Valley (14 $kmhr^{-1}$), Scott Base (17 $kmhr^{-1}$), Mt Fleming (29 $kmhr^{-1}$), Minna Bluff (42 $kmhr^{-1}$), TO Darwin Glacier (45 $kmhr^{-1}$).

Darwin Glacier was the overall windiest site, although the site at Minna Bluff had the fastest maximum wind speed on record of 169 $kmhr^{-1}$ in 2009. Granite Harbour was the least windy site within the network.

There was little inter-annual variation in mean wind speeds over the network.

There were no statistically significant increases or decreases in mean wind speeds over the recording period 2000-2011.

Winter wind patterns in the Dry Valleys sites (Victoria Valley and Wright Valley) were different to other sites, with long periods of low wind speeds and very cool air temperatures interspersed with short-term high speed wind events and rapid air temperature increases. The low wind, cool temperature periods were interpreted as cold air ponding in the bowl-shaped valley floors.

July to September was the windiest season at all sites.

Whilst some high speed wind events were recorded at only a few sites, most storm wind events were evident across all soil climate stations.

The Victoria Valley, Wright Valley, Granite Harbour, Darwin Glacier and Minna Bluff sites showed summertime diurnal variability in wind speeds.

It was evident that a combination of topography, altitude, latitude, and large-scale weather patterns all impacted on wind speeds and directions.

7.3 Discussion

It is important to highlight the uniqueness of this soil climate station dataset, as it provides a continuous record of air and soil temperatures into the permafrost in a network over a remote area, providing more information on soil temperatures than has ever before been available in the Ross Sea region of Antarctica.

Over the 12 year record from January 2000 to December 2011, two out of nine soil climate stations were observed to have an increasing trend in air and/or soil temperatures (Marble Point and Granite Harbour). There was no significant trend of increasing or decreasing air and/or soil temperatures at the Cape Hallett, Victoria Valley, Wright Valley, Mt Fleming, Scott Base, Minna Bluff, or Darwin

Glacier sites. Due to the sheltered location, presence of melt-water runoff, and atypical microclimate of the Granite Harbour site, data from the Granite Harbour site cannot be considered representative of the wider area.

Autumn (March – May) and winter (June – August) were found to be the windiest seasons with a higher frequency of katabatic and storm wind events at most sites. Summertime diurnal wind patterns were observed in the McMurdo Dry Valleys (Wright Valley and Victoria Valley), but not at other sites. The Dry Valley sites were also the coldest sites during winter as cold air ponded in the valley floors, only being disturbed by strong storm events, causing an increase in air temperature with wind onset. Wintertime katabatic flows were observed to flow from the Polar Plateau at the Mt Fleming site, but fail to reach the valley floors at the Wright or Victoria Valley sites.

Air and soil measurements at the Marble Point site showed that the site had significant warming over the recording period. However, there was no significant increase in the cumulative number of days when summer (November to February) air and soil temperatures were ≥0°C over the recording period. The lack of a significant increasing trend in the cumulative number of days when air and soil temperatures were ≥0°C indicated that whilst an increasing temperature trend was identified at Marble Point, temperatures remained below freezing. There was no change in wind patterns identified over the recording period at Marble Point, suggesting that wind patterns were not a controlling factor on air temperatures.

There was no link between relatively warmer years identified from mean air temperatures (2003, 2005, 2007 and 2011) and mean annual or maximum annual wind speeds, with winds neither being anomalously high or low during warmer years. Relatively warmer summers (November to February), identified at all sites by an increase in the cumulative number of days when air temperatures were ≥0°C, as the summers of 2001/2002, 2004/2005 and 2010/2011. The difference between mean air temperatures and cumulative days when air temperature was ≥0°C may have been due to the arbitrary year definition which intersects the polar summer. Thus, mean annual air temperatures actually captured only half of each summer period, so each annual air temperature may be controlled more by a cold or warm winter than summer.

Inter-annual variability at seven soil climate stations could be viewed as part of longer-term cyclic variability, and at present, are not indicative of short-term climatic change in the Ross Sea region of Antarctica.

7.4 Recommendations for further research

Further investigation of subsequent years of soil and air climate data is needed to improve our ability to identify any trends that may occur. Long-term monitoring sites are vital to further understanding to climatic changes, but monitoring sites need to be undisturbed and unchanged with time. Hence, soil climate monitoring sites in the Ross Sea region of Antarctica are unique due to their remote location and lack of anthropogenic change relative to more populated continents. Observational climatic data becomes more viable with time, as Comiso (2000) reported, a minimum of 10 years data is needed for reliable interpretation, with a 20 year record period classed as being more stable, and therefore reliable (Comiso 2000).

With more data, from both existing soil climate stations and recently constructed sites such as Don Juan Pond and Bull Pass East, a denser network can be constructed and a more detailed and longer term record of recent climate variables can be investigated.

Soil climate data could be used from a wide range soil landscape positions to model and predict soil climate with respect to regional topography.

7.5 Conclusions

The mean annual air temperatures for each sites entire recording period ordered from warmest to coolest were: Cape Hallett (-15.3°C), Granite Harbour (-16.6°C), Marble Point (-17.6°C), Darwin Glacier (-18.2°C), Minna Bluff (-18.3°C), Scott Base (-19.1°C), Wright Valley (-19.6°C), and Victoria Valley (-22.4°C).

The mean annual shallow soil (5-10 cm soil depth) temperatures for each site over the entire recording period ranged from highest to lowest: Granite Harbour (-14.4°C), Cape Hallett (-16.1°C), Minna Bluff (-16.3°C), Scott Base (-18.0°C), Marble Point (-18.2°C), Wright Valley (-19.8°C), Victoria Valley (-22.9°C), and Mt Fleming (-23.3°C).

The mean annual deep soil (75-120 cm soil depth) temperatures ordered from warmest to coolest, were: Granite Harbour (-13.2°C), Cape Hallett (-15.4°C), Minna Bluff (-16.4°C), Scott Base (-17.9°C), Marble Point (-18.2°C), Wright Valley (-19.5°C), Victoria Valley (-22.7°C), and Mt Fleming (-23.4°C).

Two (Marble Point and Granite Harbour) out of the ten sites measured showed evidence for warming over the measurement period. Air and soil temperature measurements showed that there was an increase ($P<0.05$) in mean annual air temperatures for Marble Point between 2004 and 2011 (R^2=0.59); mean annual shallow soil (7.5 cm) temperatures from 1999 to 2011 (R^2=0.61); and mean annual deep soil (120 cm) temperatures from 1999 to 2011 (R^2=0.40). A trend of temperature increase was also recognised at Granite Harbour for shallow soil temperatures from 2005 to 2011 (P=0.02). No statistically significant warming or cooling trend was identified at any other site over the recording period of 1999 to 2011. Both Marble Point and Granite Harbour were on the coast of the Antarctic mainland in relatively close proximity.

"Warmer" years (2003 and 2011), and "cooler" years (2002, 2006 and 2010), were observed and are considered to be part of natural variability and not necessarily indicative of climate change, and a longer dataset is needed to identify the presence or absence of long-term temperature trends in the Ross Sea region of Antarctica.

The cumulative number of days where $T \geq 0$°C were calculated for each soil climate station over summer months (November to February) for air, shallow soil (~5 cm depth), mid-depth soil (~20 cm depth), and deep soil (~75 cm depth). The overall mean number of cumulative days per summer with $T \geq 0$°C for air ranged from highest to lowest: Wright Valley (33.3), Victoria Valley (22.3), Granite Harbour (10.4), Marble Point (9.7), Minna Bluff (7.6), Darwin Glacier (7.3), Scott Base (4.2) to Mt Fleming (0.0).

For the shallow soil interval (~5 cm depth), the mean cumulative number of days per summer with T≥0°C ranged (from highest to lowest): Wright Valley (69.8), Granite Harbour (69.6), Marble Point (55.5), Minna Bluff (52.8), Victoria Valley (50.2), Scott Base (34.6), Cape Hallett (32.2) to Mt Fleming (0.0).

At the mid-depth soil (~20 cm depth) interval, the overall mean cumulative number of days where T≥0°C ranged (from highest to lowest): Granite Harbour (65.5), Wright Valley (52.0), Marble Point (44.7), Minna Bluff (31.6), Cape Hallett (22.5), Scott Base (13.9), Victoria Valley (1.8) to Mt Fleming (0.0).

Granite Harbour was the only site to have any cumulative days per summer with deep soil (~75 cm depth) T≥0°C, with an overall mean of 28.9 days.

There was marked between-summer variability in the cumulative days T≥0°C for air and all depths over the recording period from 1999/2000 to the 2010/2011 summer, but there was no overall increasing or decreasing trends in the number of days where T≥0°C over the time period recorded.

Soil surface temperatures (~5 cm) had more days with T≥0°C than air, and the cumulative number of days where T≥0°C decreased and became less variable with depth.

The Granite Harbour site had the highest mean number of days per summer at or above freezing for mid and deep soil summer temperature measurements, probably due to melt-water flow in the subsurface at the Granite Harbour site at the base of a steep north-facing slope. Mt Fleming was the only site to record zero days at or above freezing for air, ~20 and ~75 cm soil depth summer temperature measurements. At ~5 cm soil depth Mt Fleming only attained T≥0°C for a few hours in the 2010/2011 summer with 0.3 days recorded.

The number of days when soil T≥0°C can impact on the duration of time that liquid water is available within the soil profile, which, in turn, can act as a control on the presence and size of microbial populations within the soil.

Wind speed and direction data were analysed for eight soil climate stations from Granite Harbour (77°S) to Darwin Glacier (79.5°S) with data records from 2000-

2011. Mean hourly measurements were averaged to calculate mean annual wind speeds.

The Darwin Glacier site had the highest mean annual wind speed (47 $kmhr^{-1}$, 2007), whilst Granite Harbour had the lowest mean annual wind speed (6 $kmhr^{-1}$, 2004-2007). The highest recorded mean hourly wind speed was 169 $kmhr^{-1}$ at Minna Bluff in 2009. The Darwin Glacier site had the strongest wind speeds and most unidirectional wind direction, with winds consistently coming from the SW.

There was a moderate relationship of increasing wind speed with increased latitude (R^2=0.59), but no relationship between wind speed and altitude (R^2=0.17).

There was little variation in mean annual wind speeds between years, and no significant change in mean wind directions over the recording period.

All sites except Victoria Valley and Wright Valley generally had higher wind speeds in winter than summer.

Weaker wind speeds were more variable in direction than strong winds at all sites.

The Dry Valleys sites (Victoria Valley and Wright Valley) had low winds from the end of February to mid October interspersed with sudden, short-term high-speed wind events. The low wind speed pattern was likely due to the bowl-like depressions that the soil climate stations are in within the valley floors creating a temperature inversion disrupted only by strong wind events.

Summer and winter prevailing wind directions were identified for all sites for the winter (June-August) of 2009 and the summer (December-February) of 2009/2010. Prevailing wind directions were different in winter and summer for Granite Harbour, Marble Point, Wright Valley, and Scott Base, but not for Victoria Valley, Mt Fleming, and Minna Bluff.

In summer the Granite Harbour, Darwin Glacier, Victoria Valley, Wright Valley and Minna Bluff sites showed diurnal wind speed variability. The Mt Fleming, Marble Point and Scott Base sites did not have strong summer diurnal wind speed variation.

The Victoria Valley, Wright Valley, and Granite Harbour sites had a correlation between summer diurnal air temperature fluctuations and diurnal wind speed with warmest temperatures and strongest winds generally mid-afternoon.

There was no single variable controlling wind speed and direction. Controls were likely to be a combination of altitude, latitude, local topography, and cyclonic storms.

Whilst it was possible to identify katabatic and storm wind events, it was not possible to distinguish foehn wind events.

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Appendix 1: Cumulative days at or above freezing for air, ~5, ~20, and ~75 cm soil depth

1 Introduction

This appendix provides the complete cumulative number of days when air, ~5, ~20, and ~75 cm soil depth temperatures were ≥0°C over the summer periods (November – February) 1999-2011.

2 Cumulative days when air and soil temperatures were ≥0°C

Table 1: Cumulative total days with temperatures ≥0°C calculated from mean hourly air temperature over summer seasons November-February.

	Summers													
Station	**99/00**	**00/01**	**01/02**	**02/03**	**03/04**	**04/05**	**05/06**	**06/07**	**07/08**	**08/09**	**09/10**	**10/11**	**Mean**	**S.D**
Victoria Valley	6.7	10.7	32.7	19.3	26.3	27.6	27.8	22.4	19.7	23.8	23.6	26.5	22.3	7.4
Wright Valley	27.1	21.7	41.8	28.8	29.5	41.0	37.0	36.7	31.0	33.3	39.0	33.1	33.3	6.0
Mt Fleming								0.0	0.0	0.0	0.0	0.0	0.0	0.0
Granite Harbour						15	8.1	11.7	12.3	5.8	6.8	13.2	10.4	3.5
Marble Point					6.0	11.8	8.6	13.5	12.3	6.3	5.1	13.8	9.7	3.6
Scott Base	0.4	0.0	8.6	2.4	4.5	4.2	3.4	7.0	6.8	3.6	3.5	5.5	4.2	2.6
Minna Bluff										7.9	5.9	9.0	7.6	1.6
Cape Hallett						17.0							n/a	n/a
Darwin Glacier							7.1	7.5					7.3	0.3

Table 2: Cumulative total days with temperatures ≥0°C calculated from mean hourly ~5 cm soil depth temperature over summer seasons November-February.

	Summers												
Station	**99/00**	**00/01**	**01/02**	**02/03**	**03/04**	**04/05**	**05/06**	**06/07**	**07/08**	**08/09**	**09/10**	**10/11**	**Mean**
Victoria Valley 8 cm	18.3	20.3	44.3	46.8	57.8	65.6	62.5	54.9	51.4	57.4	66.8	56.0	50.2
Wright Valley 8 cm	70.0	66.0	73.1	59.6	64.9	77.5	73.2	72.0	67.3	66.9	79.1	67.4	69.8
Mt Fleming 8 cm				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
Granite Harbour 6 cm						79.3	76.6	57.0	58.7	72.5	66.4	76.4	69.6
Marble Point 8 cm	58.6	38.8	63.2	38.8	52.0	74.4	66.5	58.8	44.6	60.3	50.9	59.3	55.5
Scott Base 9 cm	37.7	14.6	36.3	22.6	31.9	44.7	37.5	44.0	36.8	43.3	31.3	35.0	34.6
Minna Bluff 5 cm								51.5		59.3	50.2	50.2	52.8
Cape Hallett 7 cm											32.1	32.3	32.2
Darwin Glacier 5 cm												43.5	n/a

Table 3: Cumulative total days with temperatures ≥0°C calculated from mean hourly ~20 cm soil temperature over summer seasons November-February.

	Summers													
Station	**99/00**	**00/01**	**01/02**	**02/03**	**03/04**	**04/05**	**05/06**	**06/07**	**07/08**	**08/09**	**09/10**	**10/11**	**Mean**	**S.D**
Victoria Valley 23 cm	0.0	0.0	1.1	0.0	0.6	0.0	12.1	1.3	1.6	4.2	0.0	0.3	1.8	3.5
Wright Valley 23 cm	49.6	35.3	56.4	38.9	55.0	58.5	59.6	48.2	51.9	58.3	62.5	49.8	52.0	8.3
Mt Fleming 23 cm				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Granite Harbour 22 cm						73.3	65.4	52.5	56.9	69.6	72.9	67.8	65.5	8.0
Marble Point 23 cm	54.2	17.7	51.4	22.4	42.7	62.1	58.0	43.7	40.8	52.3	47.0	44.3	44.7	13.2
Scott Base 24 cm	7.4	0.0	22.9	5.7	12.1	12.9	13.3	23.9	24.2	27.9	4.5	11.9	13.9	9.0
Minna Bluff 20 cm								55.6		34.8	20.2	15.7	31.6	18.0
Cape Hallett 22 cm											22.0	23.0	22.5	0.7
Darwin Glacier 20 cm												19.1	n/a	n/a

Table 4: Cumulative total days with temperatures ≥0°C calculated from mean hourly ~75 cm soil temperature over summer seasons November-February.

	Summers												
Station	**99/00**	**00/01**	**01/02**	**02/03**	**03/04**	**04/05**	**05/06**	**06/07**	**07/08**	**08/09**	**09/10**	**10/11**	**Mean**
Victoria Valley 75 cm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wright Valley 75 cm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mt Fleming 75 cm				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Granite Harbour 77 cm									12.7	27.5	18.3	57.2	28.9
Marble Point 75 cm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Scott Base 85 cm	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Minna Bluff 81 cm								0.0		0.0	0.0	0.0	0.0
Cape Hallett 68 cm											0.0		n/a

Appendix 2: Wind rose plots for each station over the recording period

1 Introduction

This appendix presents mean hourly wind roses over annual timescales (January – December) for each year over the recording period 1999 – 2011. Wind roses for the years 2009 and 2010 are in chapter 6 and so not included here.

2 Wind rose diagrams

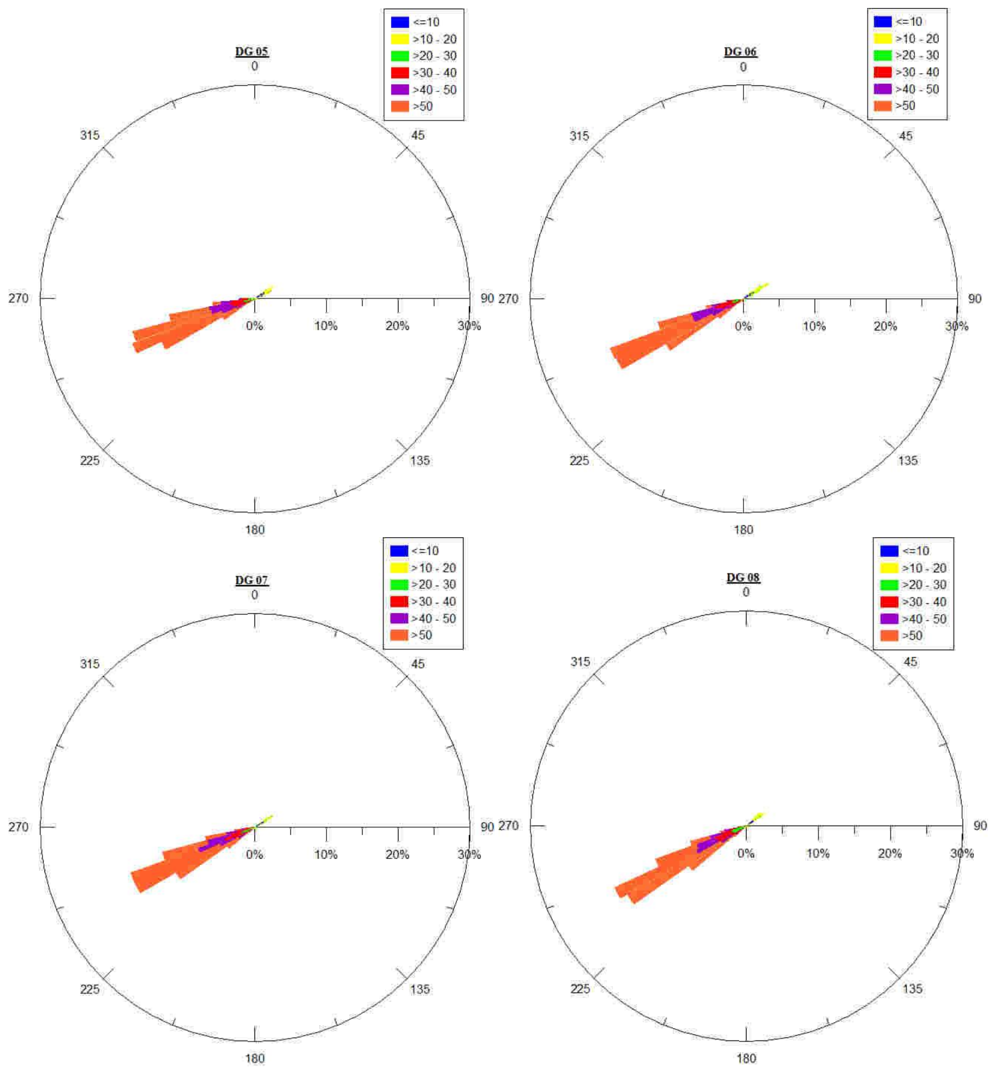
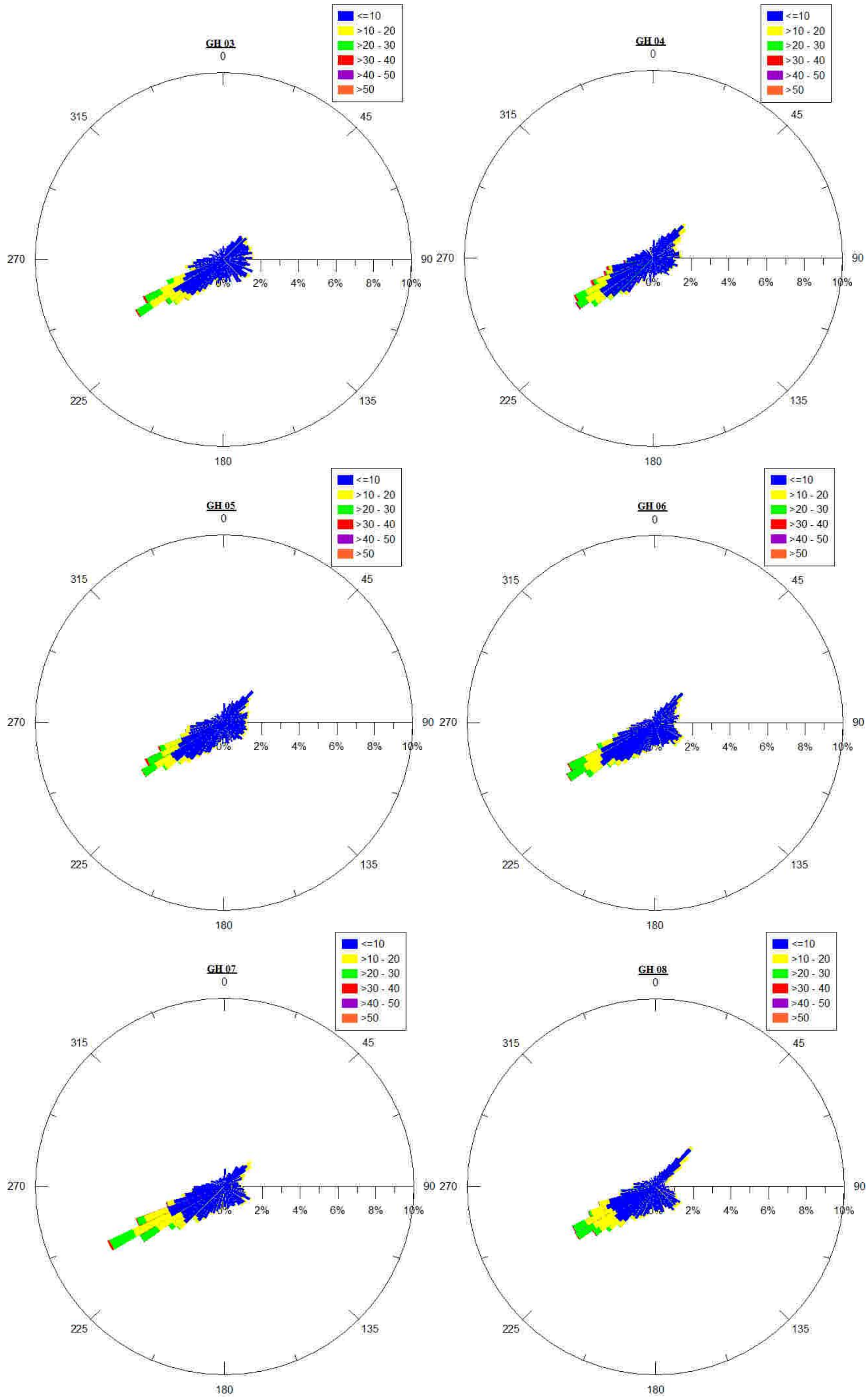


Figure 1: Wind rose plots for the Darwin Glacier site. Wind speed is measured on the radius axis. Wind direction is measured on the circumference of the wind rose.



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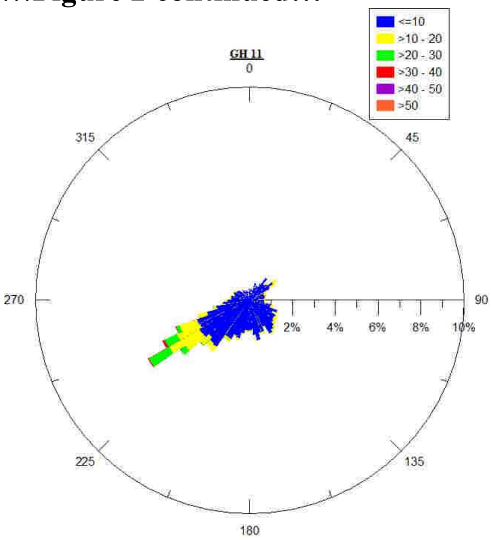


Figure 2: Wind rose plots for the Granite Harbour site. Wind speed is measured on the radius axis. Wind direction is measured on the circumference of the wind rose.

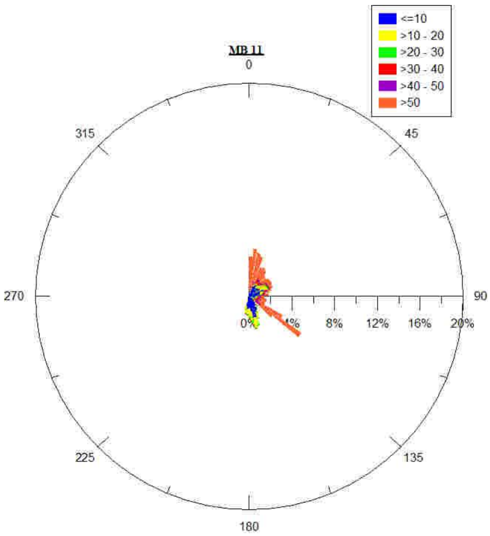
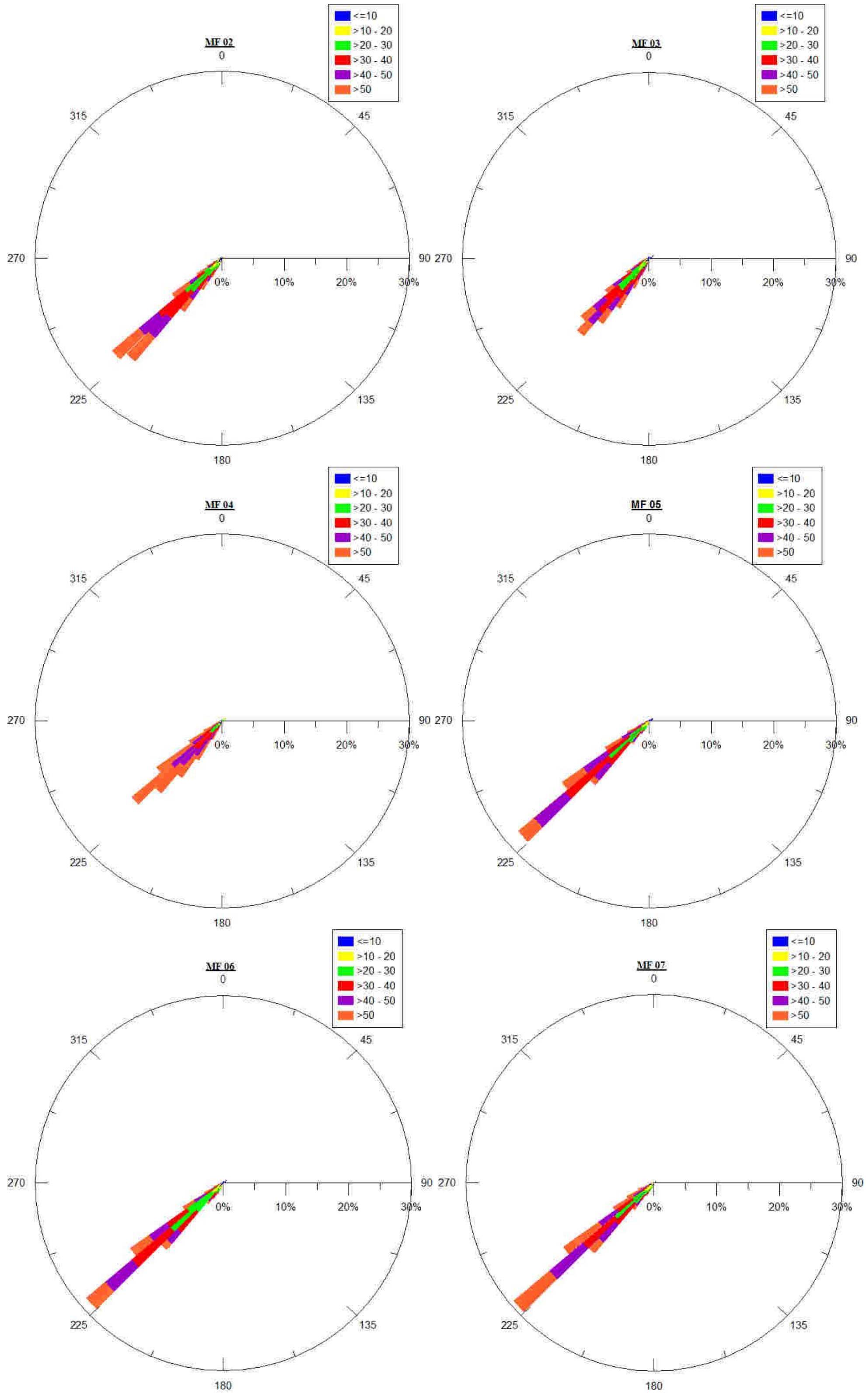


Figure 3: Wind rose plot for the Minna Bluff site. Wind speed is measured on the radius axis. Wind direction is measured on the circumference of the wind rose.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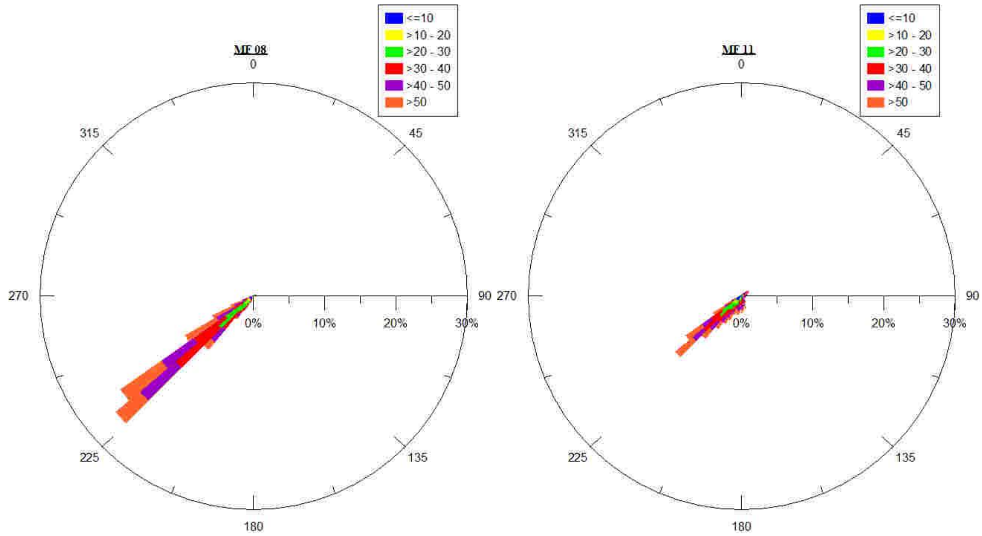
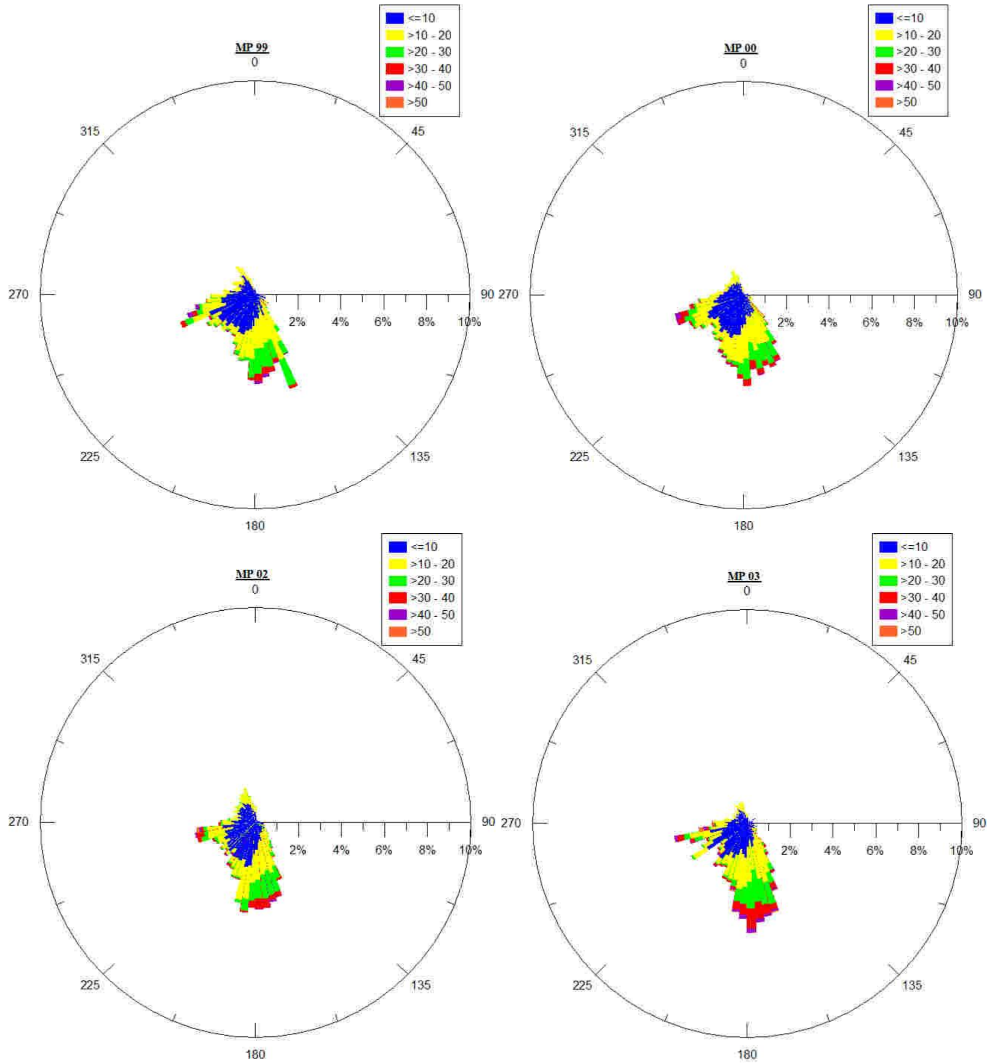


Figure 4: Wind rose plots for the Mt Fleming site. Wind speed is measured on the radius axis. Wind direction is measured on the circumference of the wind rose.



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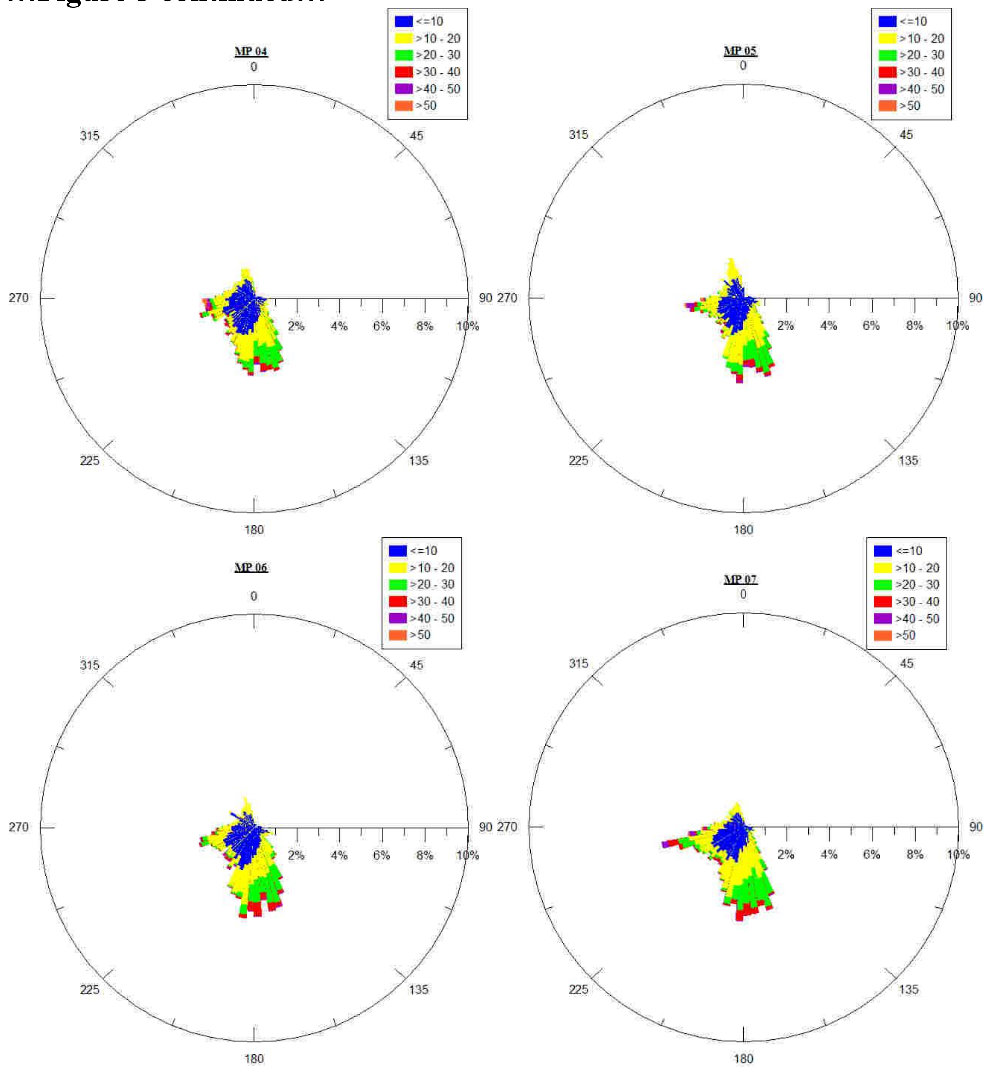
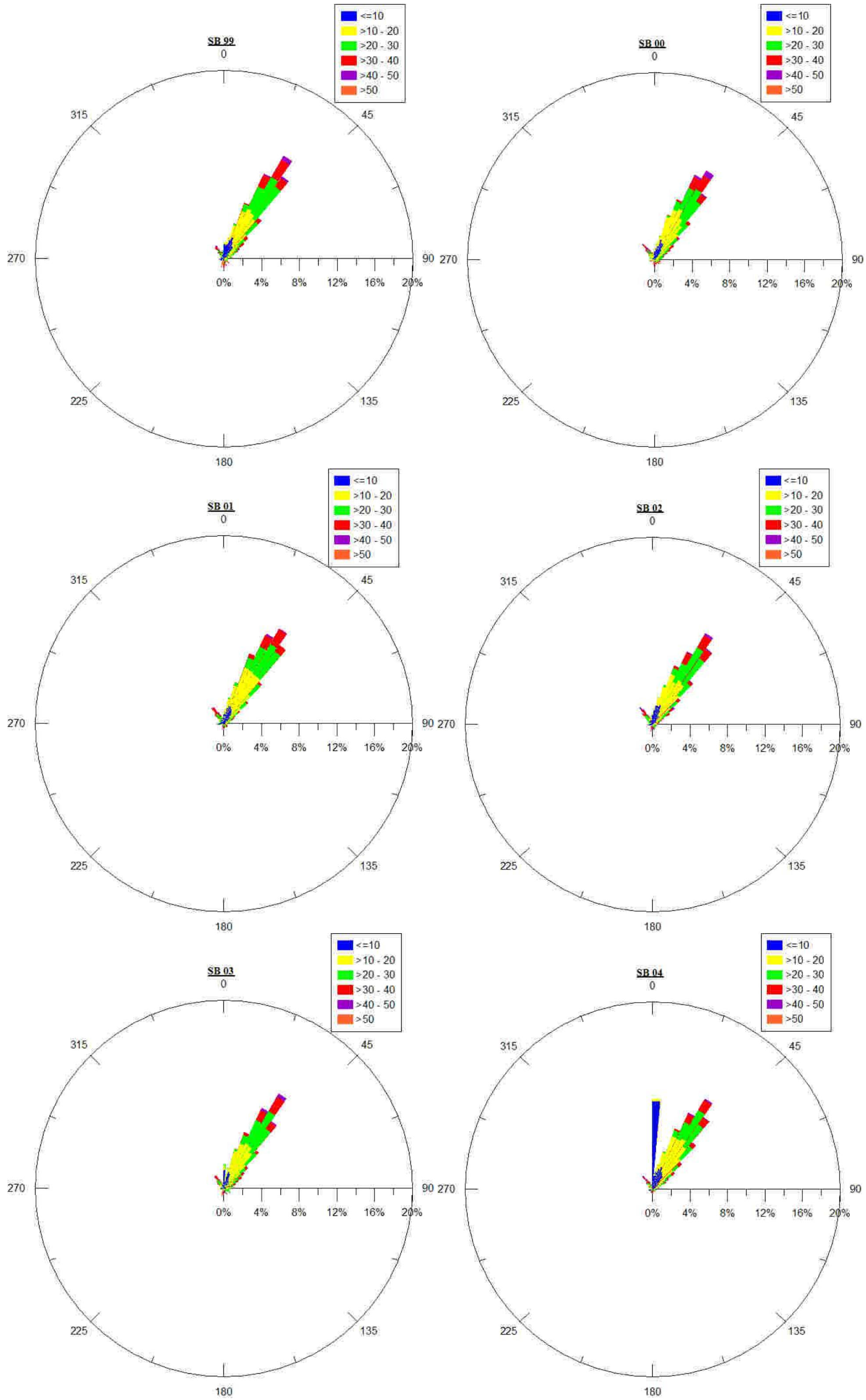


Figure 5: Wind rose plots for the Marble Point site. Wind speed is measured on the radius axis. Wind direction is measured on the circumference of the wind rose.



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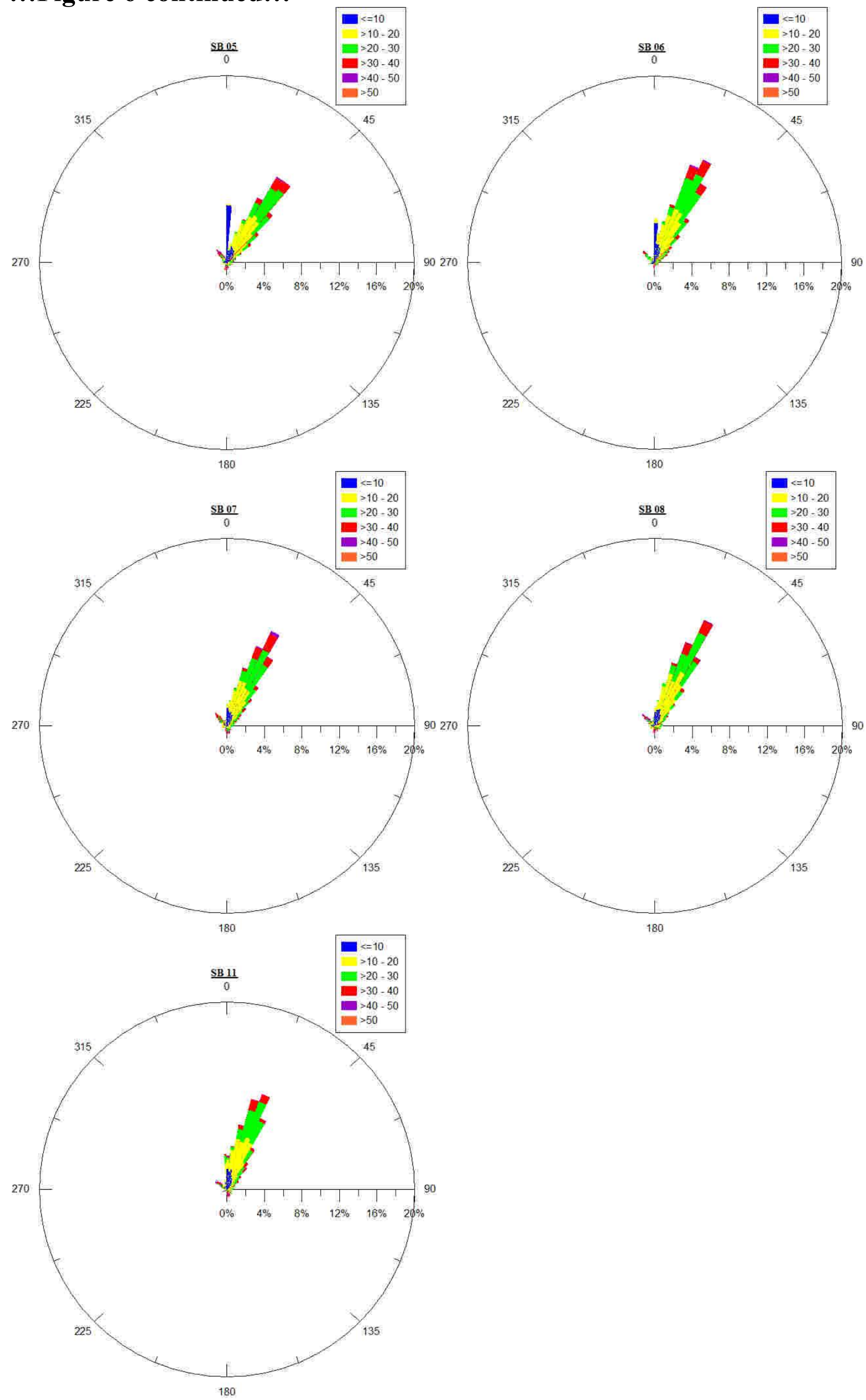
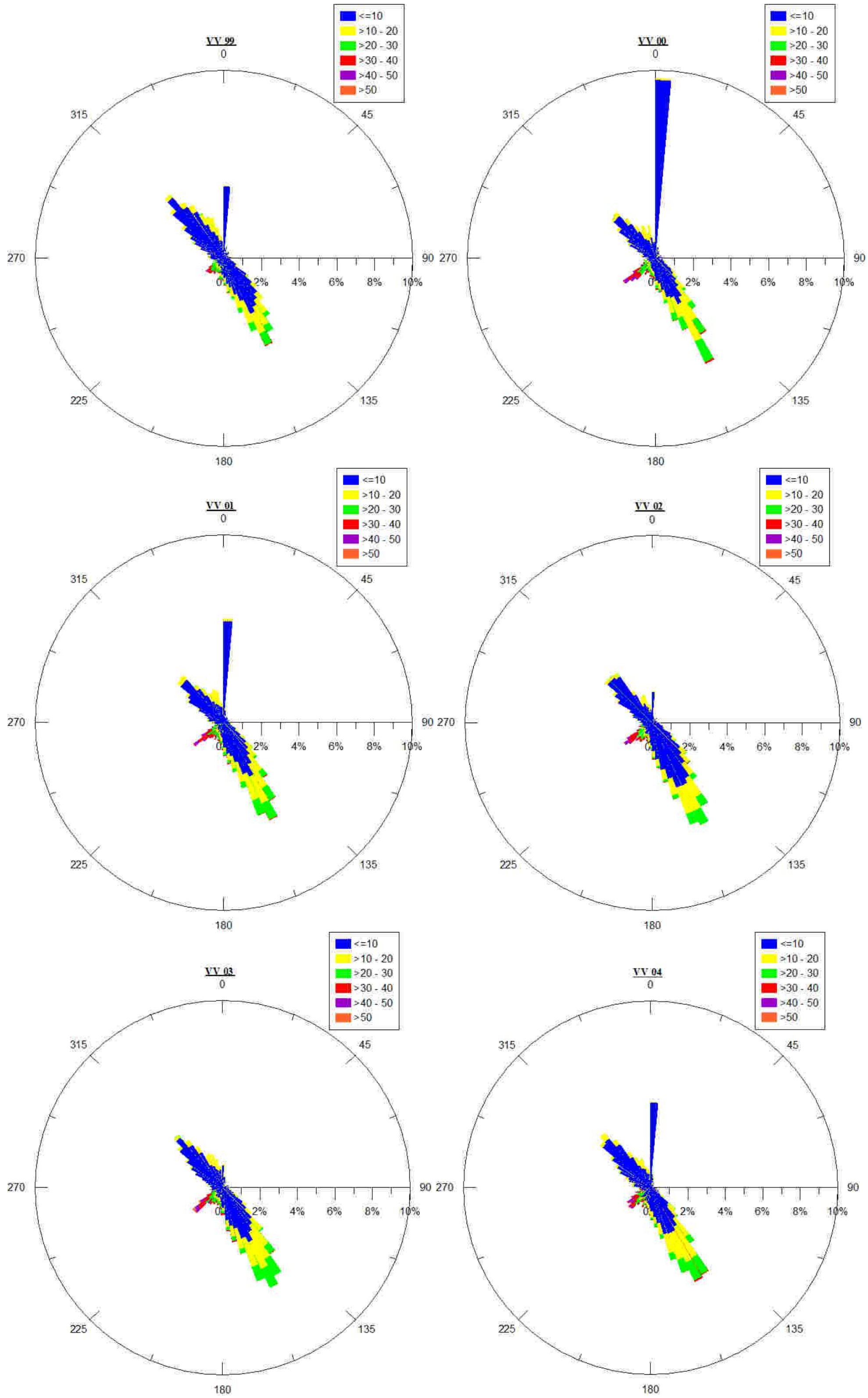


Figure 6: Wind rose plots for the Scott Base site. Wind speed is measured on the radius axis. Wind direction is measured on the circumference of the wind rose.



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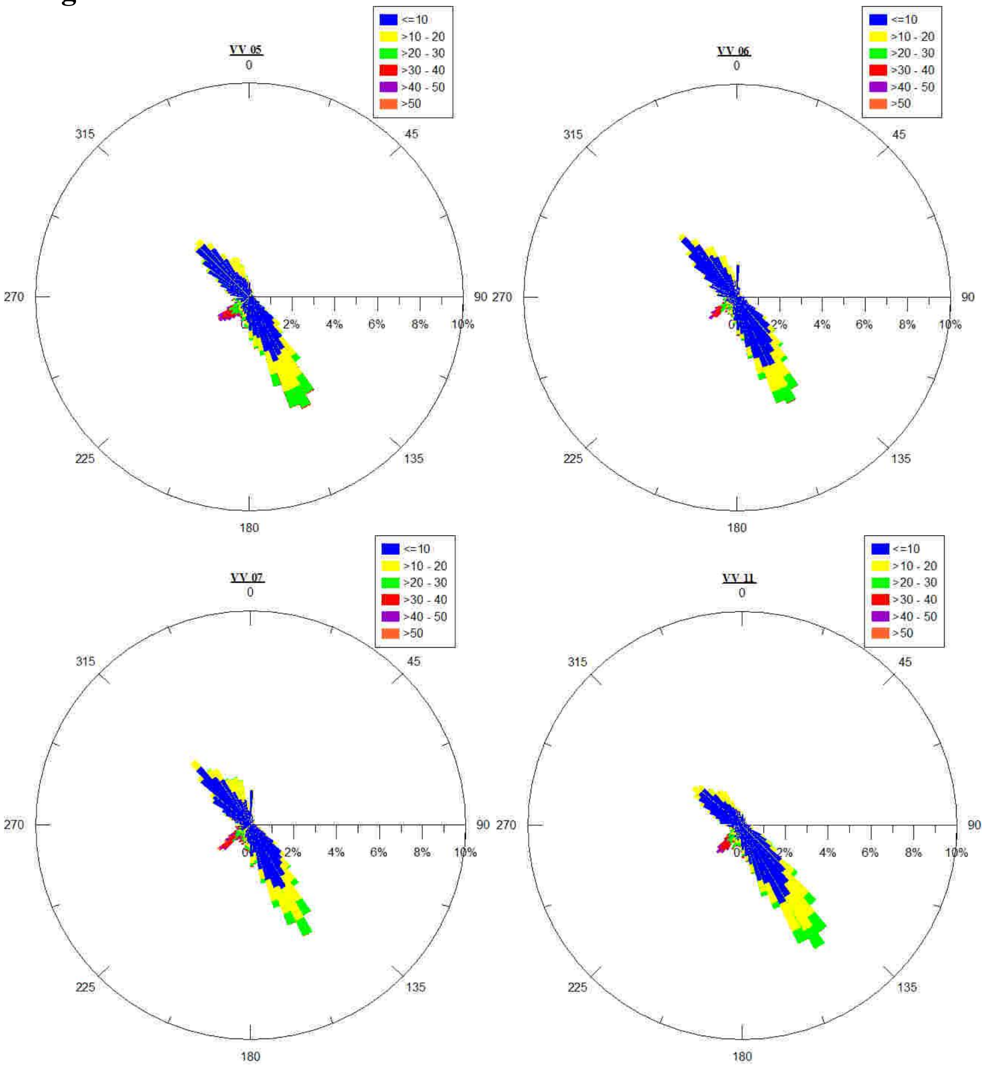
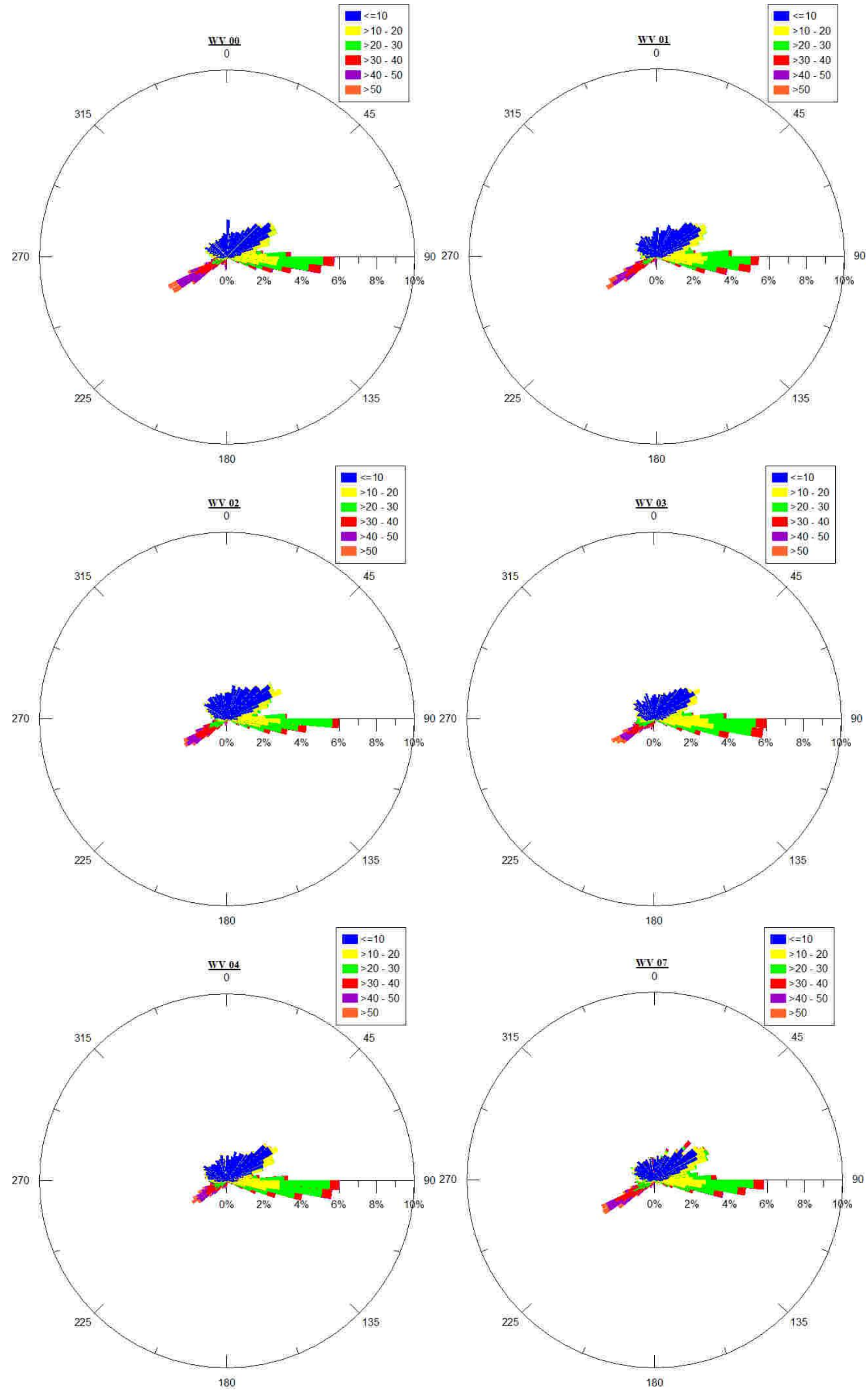


Figure 7: Wind rose plots for the Victoria Valley site. Wind speed is measured on the radius axis. Wind direction is measured on the circumference of the wind rose.



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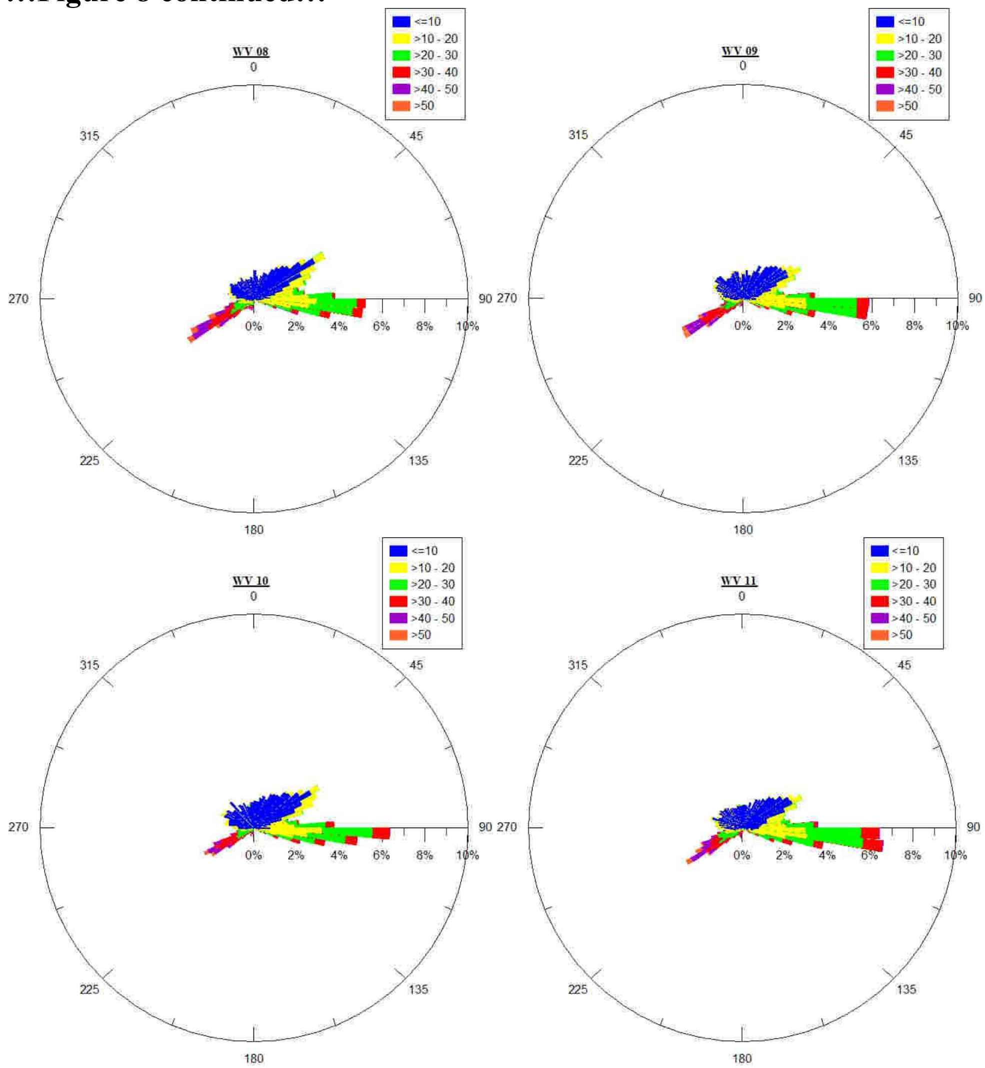

Figure 8: Wind rose plots for the Wright Valley site. Wind speed is measured on the radius axis. Wind direction is measured on the circumference of the wind rose.