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Soil climate and permafrost temperature monitoring in the McMurdo Sound region, Antarctica

A thesis
submitted in partial fulfilment
of the requirements for the Degree
of

Master of Science in Earth and Ocean Sciences

at the
University of Waikato
by

Leah Seree Adlam

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ABSTRACT

A soil climate monitoring network, consisting of seven automated weather stations, was established between 1999 and 2003 in the McMurdo Sound region of Antarctica. Soil temperature, soil water content, air temperature, relative humidity, solar radiation, and wind speed and direction are recorded hourly and downloaded annually. Two 30 m deep permafrost temperature monitoring boreholes were established adjacent to the soil climate stations in the Wright Valley and at Marble Point in January 2007. Sixteen thermistors (accurate to ±0.1°C) were installed in each borehole measuring temperature once every hour and recording the mean every six hours. One year of permafrost temperatures were available (January 2007 to January 2008). The overall aim of this thesis was to make use of the soil climate monitoring database from 1999 to 2007 to investigate Antarctic soil climate.

Active layer depth (depth of thawing) varied inter-annually, with no significant trend between 1999 and 2007. The active layer increased with decreasing latitude ($R^2 = 0.94$), and decreased with increasing altitude ($R^2 = 0.95$). A multiple regression model was produced whereby active layer depth was predicted as a function of mean summer air temperature, mean winter air temperature, total summer solar radiation and mean summer wind speed ($R^2 = 0.73$).

Annual temperature cycles were observed at all depths in the boreholes. At Marble Point, an annual temperature range of ≤1°C occurred at 15.2 m, ≤0.5°C at 18.4 m and ≤0.1°C at 26.4 m and at Wright Valley, an annual temperature range of ≤1°C occurred at 14.0 m, ≤0.5°C at 17.2 m and ≤0.1°C at 25.2 m. Given that the depth of “Zero Annual Amplitude” determined depends on the sensitivity of the measurement method, it is suggested that instead of referring to a depth of “Zero Annual Amplitude”, the depth at which the annual temperature range is less than a given value is a more useful concept.

Mean annual and mean seasonal air and soil temperatures varied inter-annually and there was no significant trend of warming or cooling over the 1999 – 2007 period. Mean annual air temperatures were primarily influenced by winter air temperatures. Mean annual and mean summer soil temperatures were warmer than air temperatures due to heating by solar radiation. Mean summer air temperatures correlated well with the Southern Annular Mode Index (SAMI) at all sites ($0.61 \leq R^2 \leq 0.73$) except Victoria Valley; however there was no correlation between mean annual or mean winter temperatures and the SAMI.

Air temperature was linearly correlated with near-surface soil temperature (1.3 – 7.5 cm) ($R^2 \geq 0.79$). Near-surface soil temperature was strongly correlated with incoming solar radiation at Victoria Valley ($0.14 \leq R^2 \leq 0.76$) and Granite Harbour ($0.49 \leq R^2 \leq 0.82$), but was not significantly correlated at other sites ($0 \leq R^2 \leq 0.57$). There was no significant correlation between air temperature and wind speed, air temperature and solar radiation and near-surface soil temperature and wind speed, despite occasions of strong correlation on the diurnal time scale. Diurnal summer cycles in air and soil temperatures were driven by solar radiation. Multiple regressions combining the effects of air temperature, solar radiation and wind speed approximated near-surface soil temperatures well at every site during both summer and winter ($0.88 \leq R^2 \leq 0.98$).

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Mum and Dad, Alaina, Kiel and Keenan; my family, you have always believed in me and pushed me to be all I can. I hope to always make you proud.

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CHAPTER 1: INTRODUCTION

1.1 Background

International interest in the concept of "global warming" has escalated in recent years due to increased media coverage and public concerns. There has been a lot of research regarding the natural causes for climate variation (Gerhard 2004). The polar regions have been predicted to have an amplified response to warming compared to more tropical regions (Kane *et al.* 1991). Warming trends have been reported in Antarctica (e.g. Doran *et al.* 2002b, Kwok & Comiso 2002), but not without challenge (e.g. Turner *et al.* 2002b). Gerhard (2004) suggested that observational data would be more helpful to test the hypothesis of global warming than continued modelling of climate scenarios.

Antarctica provides a unique perspective to the global warming debate because sites can respond to changes rapidly. Site characteristics like air and soil temperatures vary across small scales, such as within a few metres (e.g. Guglielmin 2004) and also at larger, regional scales, such as between sites at the coast to those in the McMurdo Dry Valleys (e.g. Campbell *et al.* 1997a, Campbell *et al.* 1998a).

Surface climate variables, such as air temperature and solar radiation, influence the subsurface thermal regime (MacCulloch 1996, Campbell *et al.* 1997a). Predicted warming of global air temperatures could potentially have an adverse effect on the active layer (annual thawing depth) and permafrost (material at or below 0°C for more than two years (Muller 1947)). Degradation of permafrost in the Arctic has led to forests where the trees are tilted due to the loss of their strong foundation (Walker 2007). Models of global warming have predicted that at least 60% of permafrost in the Northern Hemisphere will disappear by 2100 (Walker 2007). When it comes to the Antarctic climate and permafrost, it is important to understand how variables such as air and soil temperatures vary both temporally and spatially, before attempts are made to predict the response to warmer air temperatures.

In this thesis, approximately eight years of data from a soil climate monitoring network in the McMurdo Sound region of Antarctica, together with one year of permafrost temperatures to 30 m depth, was analysed to contribute to the discussion of Antarctic soil climate and variability. This chapter provides a description of the sites, methodology and the structure of the thesis.

1.2 Site descriptions

1.2.1 Soil climate monitoring network

There are seven long-term automated weather stations established in the McMurdo Sound region of Antarctica as part of a long term soil climate monitoring programme, which is a collaborative project between University of Waikato, Landcare Research (New Zealand) and USDA-NRCS (United States Department of Agriculture – National Resources Conservation Service). The stations have been established since January 1999 and are located at Marble Point (established 1999), Scott Base (1999), Victoria Valley (1999), Wright Valley (1999), Mt. Fleming (2002), Granite Harbour (2003), and Minna Bluff (2003) (Figure 1.1). Data collected includes: soil temperature at a range of depths, soil water content, air temperature, relative humidity, incoming solar radiation, and wind speed and direction. Atmospheric measurements were made at 10 second intervals and soil measurements were made at 20 minute intervals. All measurements were averaged hourly and recorded.

The location of the climate stations provided a latitudinal section, comprised of the stations at Minna Bluff (78.5°S), Scott Base (77.8°S), Marble Point (77.4°S) and Granite Harbour (77.0°S). Complementary to the latitudinal section was an altitudinal section from Marble Point (50 m) through Wright Valley (150 m), Victoria Valley (410 m) and Mt Fleming (1700 m). Full GPS locations, elevation, year of establishment and other important data about the automated weather stations are contained in Table 1.1.

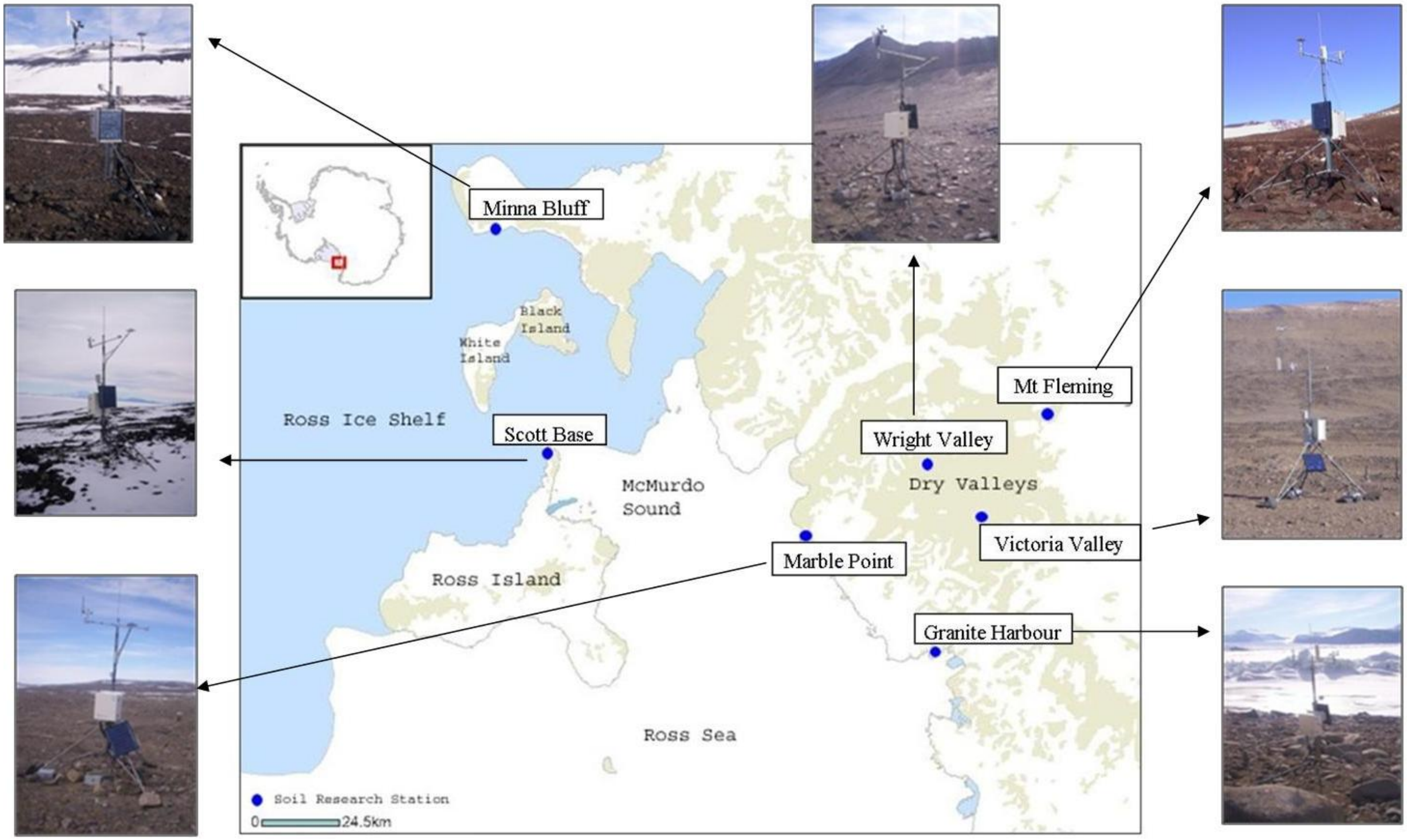

Figure 1.1: Site location and photographs of seven automated weather stations in the McMurdo Sound region of Antarctica (Adapted from http://soils.usda.gov/survey/scan/index.html).

Table 1.1: Site location and descriptions of seven automated weather stations established since 1999 in the McMurdo Sound region of Antarctica.

Site	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
GPS Location	78°30’41.6”S 166°45’58”E	77°50’53.6”S 166°45’44”E	77°25’10.6”S 163°40’55”E	77°00’23.7”S 162° 31’32.4”E	77°31’06.1”S 161°51’57”E	77°19’51.3”S 161°36’02.2”E	77°32’42.7”S 166°17’24.6”E
Year site established	2003	1999	1999	2003	1999	1999	2002
Site description	Peninsula of continental Antarctica extending into the Ross Ice Shelf	100 m north of Scott Base buildings on a slope of about 6°, southerly aspect	400 m east of the Wilson-Piedmont Glacier	Narrow (5 m wide) stretch of boulder material at the base of a cliff, northerly aspect	On the floor of the Wright Valley near the base of Bull Pass. 180° aspect.	On the valley floor approximately 30 m from the edge of Lake Victoria	In a large cirque on the north side of Mt Fleming, near the edge of the polar plateau
Elevation (m above sea level)	37	38	50	4	150	410	1700
Mean Annual Air Temperature (°C) (time period)	–19 (2004-2006)	–19 (1999-2007)	–18 (1999-2007)	–18 (2004-2007)	–20 (1999-2007)	–20 (1999-2007)	–23* (2007)
Bedrock/Parent material	Basalt and granite dominated	Basaltic scoria	Marble, granite and gneiss dominated till	Granite dominated boulder colluviums	Granite and sandstone dominated till and alluvium	Granite, dolerite with marble and sandstone till	Dolerite, sandstone and granite till

** Mean annual air temperature could only be calculated for Mt Fleming in 2007, as this was the only year in which a full data set was available.*

1.2.2 Permafrost temperature monitoring boreholes

In January 2007, two 30 m deep permafrost temperature monitoring boreholes were established in the McMurdo Sound region, one at Marble Point and one in the Wright Valley, in collaboration with Dr Mauro Guglielmin of the University of Insubria, Italy. Temperatures were measured every hour and the average recorded every six hours.

The Wright Valley permafrost temperature monitoring borehole was drilled at the foot of Bull Pass in the Wright Valley, in the granite bedrock on the valley floor. The Marble Point temperature monitoring borehole was located on a small knob at the south end of the largest coastal ridge, approximately 1400 m east of the United States helicopter refuelling station on an outcrop of marble bedrock. Both permafrost temperature monitoring boreholes were near automated weather stations established as part of the soil climate monitoring network. Above-ground climatic variables measured by the automated weather stations could potentially be applied to the borehole data to determine the impact of the weather on the subsurface thermal regime. Further detail on the establishment of the permafrost temperature monitoring boreholes is contained in Chapter 4.

1.3 Methods

1.3.1 Soil climate database

A database of up to eight years of hourly data was available from the seven automated weather stations, and is also available online at http://soils.usda.gov/survey/scan/antarctica/index.html. Data from the automated weather stations were downloaded manually from the dataloggers every January, and processed into annual Microsoft Excel spreadsheets by Dr Seybold (and previously Dr Ron Paetzold) of USDA-NRCS. From the Excel spreadsheets, data were organised into a binary database for manipulation and analysis in MATLAB v. 2006b

(The Mathworks Inc., Natick MA, USA). The binary database was initialised from 1 January 1999 at all sites, including those established in 2002 and 2003.

1.3.2 Data quality and filtering

Once organised into the binary databases, some variables when loaded contained spikes. In those sites established in 2002 and 2003, ‘hard’ spikes occurred between the date that the database was initialised and when the site was established, and the database had values of –6999. ‘Hard’ spikes also occurred where values were well outside the realms of variation e.g. air temperature at Minna Bluff in the winter of 2007 jumped from –20°C to +40°C. Some ‘soft’ spikes also occurred in the data but were harder to identify using simple indexing. When plotted, the variable had a noticeable peak for a short period of time (e.g. Figure 1.2). Both hard and soft spikes were filtered using indices in the MATLAB software.

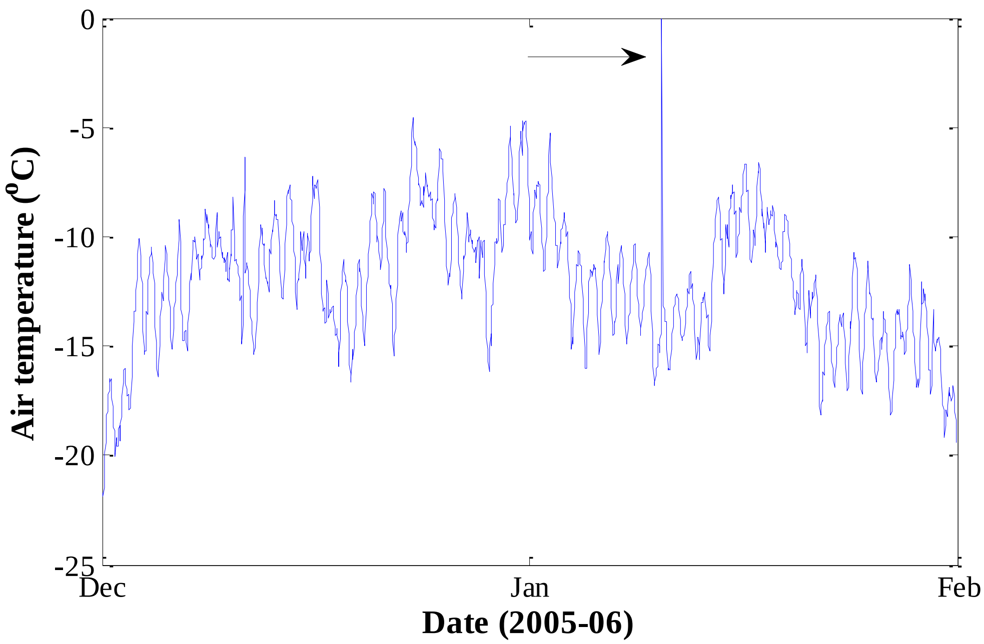

Figure 1.2: Air temperature at Mt Fleming from 1 Dec 2005 to 31 Jan 2006 with an arrow showing a ‘soft’ spike when the sensor had a value of zero.

1.3.3 Missing data

Marble Point, Wright Valley and Victoria Valley were established in early January 1999 and are therefore missing the first two weeks of the year. Excluding the first two weeks of 1999, Marble Point, Wright Valley and Victoria Valley are the only sites in the monitoring network which had a full dataset every year with no missing data. The other four sites (Granite Harbour, Minna Bluff, Scott Base and Mt Fleming) had missing data, due to either system failure or sensor problems.

At some sites in the monitoring network, the automated weather station would fail due to loss of power, which was registered in the binary database as consistent zeros. For example, the Granite Harbour site failed in July 2003, resulting in a flat line at zero when plotted (Figure 1.3), until the site was re-established on 8 January 2004. No mean annual temperature was able to be calculated for Granite Harbour in 2003. After 2003, no further system failure occurred at Granite Harbour.

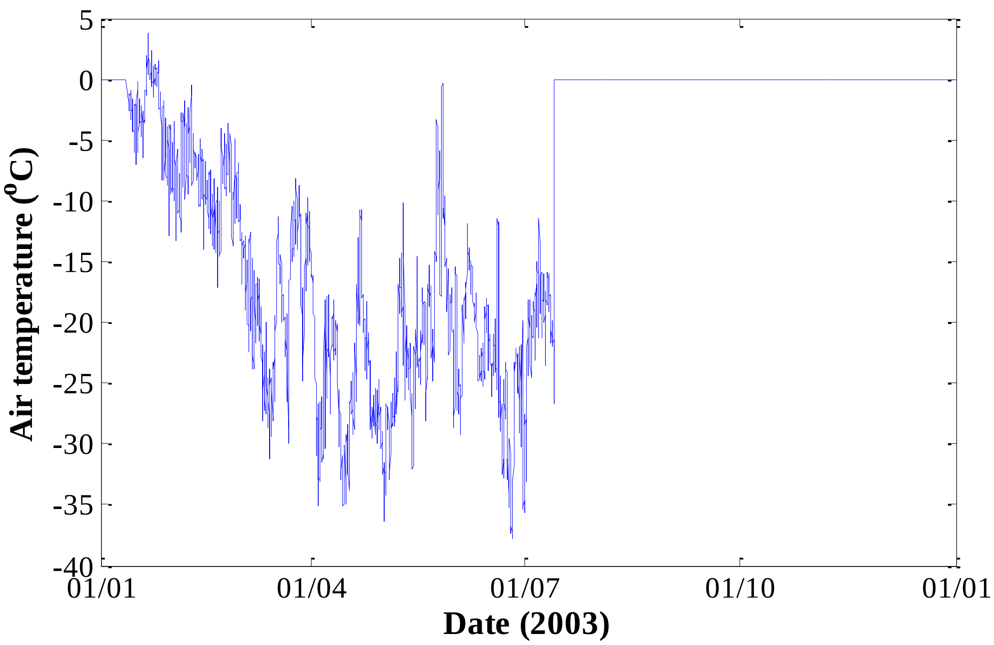

Figure 1.3: Air temperature at Granite Harbour from 1 January 2003 to 31 December 2003, showing system failure in mid-July and the subsequent zeroing out. The flat line at 0°C indicates system failure.

Minna Bluff had system failure from July 2007 onwards, after the solar panel was removed from the station by high winds, preventing the recharge of batteries when the sun rose above the horizon. Mt Fleming had consistent system failure in all winters since the site was established, except for 2007 which was the first full year of data. No mean annual data could be calculated for Minna Bluff in 2007 or for Mt Fleming in any year except 2007.

At some sites, some sensors were problematic for short periods of time. For example, at Scott Base the air temperature sensor registered temperatures of –53°C during January and February in 2005, which was evidence of sensor failure (D. Campbell, *pers. comm.*), rather than site failure. At Minna Bluff, the first MRC probe (Measurement Research Corporation, Gig Harbor, Washington) installed when the site was established in 2003 failed after about six months of operation, and so could not be used until a new MRC probe was installed in January 2006. Soil temperature measurements using 107 temperature probes were used for active layer depth calculations at Minna Bluff.

1.3.4 Data analysis methods

Raw data was available in the binary database for manipulation at all sites. All linear regressions and statistics were produced using the hourly data from the binary database. Annual and monthly means were available in the Microsoft Excel spreadsheets provided by Dr Seybold, which were collated into spreadsheets for comparison across time, latitude and altitude (Appendix I).

1.4 Research aim and objectives

The aim of this thesis was to make use of the large existing database of information collected by the soil climate monitoring stations from 1999 to 2007 in order to contribute to the discussion concerning Antarctic soil climate and variability. The aim was achieved using data management software, particularly MATLAB v.2006b and

Microsoft Excel v.2007, to analyse the accumulated data addressing the following specific research objectives:

(1) Determine the depth of thawing (active layer) each summer at each automated weather station, and describe how the active layer depth varies between summers, and with changes in latitude and altitude. Determine which above-ground climatic factors influence the inter-annual variation in active layer depth (addressed in Chapter 3).

(2) Detail the borehole drilling, ice-cemented core sampling and installation and instrumentation of permafrost temperature monitoring equipment in the Wright Valley and at Marble Point and describe the annual temperature cycles to 30 m depth (addressed in Chapter 4).

(3) Describe the seasonal and annual temperature cycles, investigate the damping depth, quantify the phase lag in transmission of surface temperature signals to about 1 m and about 28 m depth, and investigate the depth of "Zero Annual Amplitude" (addressed in Chapter 5).

(4) Investigate the existence of any warming or cooling trend in mean annual air and soil temperatures from 1999 – 2007, determine how mean summer and mean winter air temperatures influence mean annual air temperature and describe how mean annual temperatures change across latitude and altitude (addressed in Chapter 6).

(5) Determine the correlations between above-ground and below-ground climatic variables at each automated weather station from 1999 to 2007, and determine if the correlation was significant (addressed in Chapter 7).

1.5 Thesis structure

This thesis has been split into five major results sections, one per research objective. The first is a paper which addresses the active layer depth at all sites in the McMurdo Sound region (Chapter 3). Summer data from 1999 to 2007 was used to determine the depth of the active layer and the changes with time, latitude and altitude were discussed. The paper was submitted to the peer-reviewed journal *Antarctic Science* for publication in December 2008. The sites were established by several people acknowledged in the paper. Data analysis for the paper was undertaken by me, under the supervision of Dr Megan Balks and Dr Cathy Seybold. The principal draft of the paper was written first by me, with input from Dr Megan Balks, Dr Cathy Seybold and Dr David Campbell.

Chapter 4 is a University of Waikato internal report written for the Antarctic Research Unit describing the establishment of four boreholes at Marble Point and Wright Valley for ice-cemented core sampling and permafrost temperature monitoring. Chapter 4 contains details of the instrumentation, calibration and datalogger programming, along with site descriptions and descriptions of the first year of data collected. My role in this project was to prepare the datalogger and temperature sensors for deployment at two sites in Antarctica. The boreholes were drilled in the 2005-06 summer. I assisted in the establishment of the permafrost temperature monitoring equipment in the two boreholes in the summer of 2006-07 and in site maintenance in the summer of 2007-08. The principal draft of the report for the Antarctic Research Unit was written by myself, with input from Dr Megan Balks, Dr Mauro Guglielmin (University of Insubria, Italy), Fabio Baio (Italy) and Dr David Campbell.

Data from two 30 m deep permafrost temperature monitoring boreholes was used in conjunction with the data from the automated weather stations to describe the seasonal and annual temperature cycles and calculate the phase lag of the temperature signal between the soil surface and the deepest sensor at 1 m and 28 m depth (Chapter 5).

Chapter 6 describes the inter-annual variation in mean annual and mean seasonal air and soil temperatures. Changes in the mean annual air and soil temperatures over a latitudinal and an altitudinal transect are discussed.

Chapter 7 describes the correlations between above-ground and subsurface climatic variables.

A summary and brief discussion of the major findings of all results chapters is in Chapter 8, followed by conclusions and recommendations for further research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction to Antarctic climate

Antarctica is one of the coldest and driest places in the world (Campbell & Claridge 1987, Hatherton 1990, Fountain *et al.* 1999). The extremely low mean annual temperatures of Antarctica are the result of several factors; the "net annual deficit" of solar radiation caused by the absence of sunlight for six months during the austral winter (Hatherton 1990); low incidence angle of sunlight during the austral summer (Campbell & Claridge 1987, Bargagli 2005); the permanent ice-cover and the high average elevation of the continent (Bargagli 2005). Water is present in the form of ice, resulting in a low relative humidity (Campbell & Claridge 1987). Weyant (1966) likened Antarctica to a stationary anticyclone due to the lack of low pressure systems that cross the continent directly and the "outflow of cold air around its periphery" (Weyant 1966).

Temperatures over the continent are seasonably variable due to the changing insolation (solar radiation received at the earth's surface) which is caused by the change in sunlight incidence angle as the earth rotates around the sun (Weyant 1966). Maximum temperatures are achieved in the austral summer, between mid-December and mid-January. The reduction in temperature during autumn is swift, and the winter exhibited sudden, rapid and short-lived increases in temperature (Weyant 1966) due to the passage of winter storms (e.g. Balks *et al.* 1995).

Only about 2% of the Antarctic continent is ice-free (Bargagli 2005). The low albedo of the ice and snow surfaces in Antarctica lead to a reflection of incoming solar radiation and only a low proportion of incoming solar radiation is absorbed (Bargagli 2005), particularly when compared to the amount of longwave, "terrestrial" radiation emitted (Weyant 1966). The difference in absorbed and emitted radiation is such that the Antarctic continent acts as a "heat sink" (Weyant 1966).

The largest of the ice-free regions in Antarctica is the McMurdo Dry Valley system, which has valley floors of sandy gravel with extensive exposed bedrock (Fountain *et al.* 1999). There is considerable climatic variation between the McMurdo Dry Valleys (Fountain *et al.* 1999, Doran *et al.* 2002a, Bertler *et al.* 2006); for example, there is a "south-north" gradient in air temperature from Taylor Valley, which is the warmest, followed by the Wright Valley and finally the Victoria Valley which is the coldest (Doran *et al.* 2002a, Bertler *et al.* 2006).

Interest in "global warming" and its effect on the environment has increased in the last five years. It has been predicted that the magnitude of warming will be at least two to three times greater in the polar regions than in tropical regions (Kane *et al.* 1991), making investigation into climate and variability in Antarctica significant to understanding how the continent may respond to future shifts in climate. Fountain *et al.* (1999) stated that the hydrology of the Dry Valleys can vary remarkably in response to "small climatic changes", potentially making the Dry Valley system a sensitive indicator for changes in the global climate in coming years.

2.2 Climatic and soil zones of the Antarctic

2.2.1 Introduction

The Antarctic continent can be divided into three major zones of climate: The Interior Antarctic Plateau, the Antarctic Slope and the Antarctic Coast (Figure 2.1) (Weyant 1966, Campbell & Claridge 1987). The cold transitional zone (Dalrymple 1966) and the Maritime climate of the Antarctic Peninsula (Campbell & Claridge 1987) are not described here.

Differences in climate leads to differing soil properties spatially (Campbell *et al.* 1998a). The Interior Antarctic Plateau is the zone greater than 1500 m in elevation in West Antarctica and more than 2000 m in East Antarctica (Dalrymple 1966). It typically has clear skies with little cloud, light winds, low annual precipitation and extremely low annual temperatures (Weyant 1966, Campbell & Claridge 1987). As sites within this zone are continuously covered with ice, there is no soil formation (Campbell & Claridge 1987).

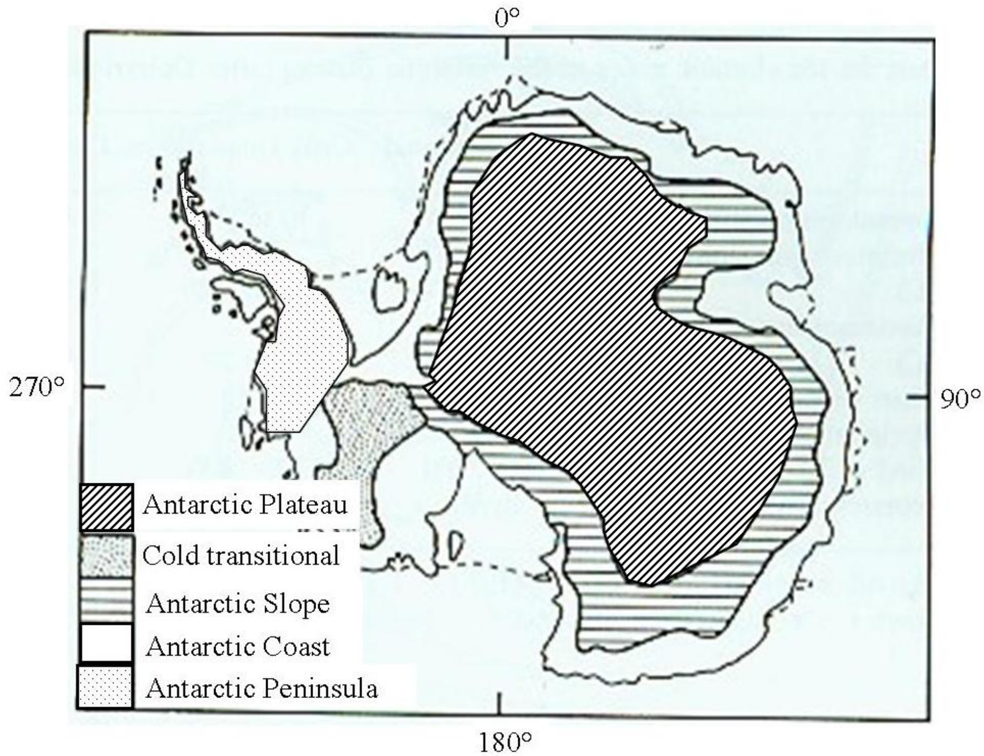

Figure 2.1: Map showing the major climatic regions of the Antarctic (Adapted from Dalrymple 1966 and Campbell & Claridge 1987).

2.2.2 Antarctic Slope

2.2.2.1 Broad definition of the Antarctic Slope

The Antarctic slope is a narrow zone of steep slopes around the outer edge of East Antarctica (Figure 2.1) (Campbell & Claridge 1987) and has a severe climate which varies with altitude and latitude (Weyant 1966). The Antarctic slope has strong katabatic winds, with the amount of cloud and the magnitude of annual temperature being in-between those of the Antarctic Plateau and the Antarctic coast (Weyant 1966, Campbell & Claridge 1987). The McMurdo Dry Valleys fall within the Antarctic slope and have strong katabatic winds, “very low precipitation, low mean annual temperatures and a large annual temperature amplitude” (Pringle *et al.* 2003).

The Antarctic Slope climate regime as defined by Weyant (1966) was further subdivided by Campbell and Claridge (1987) to include the TransAntarctic Mountains and was renamed the Mountain Zone, which is comprised of the Inland, Central Mountain and Coastal Mountain sub-zones (Campbell & Claridge 1987).

2.2.2.2 Inland Mountain sub-zone

The Inland Mountain sub-zone (>2000 m elevation) experiences extremely low precipitation and temperatures that are rarely sufficient to induce melting (Campbell & Claridge 1987). The soil climate at Inland Mountain sites is ultraxerous, meaning there is negligible moisture available (Campbell & Claridge 1987). Soil temperatures are cooler than those in the Dry Valleys or at the coastline (Campbell *et al.* 1998a) and have a moisture content of 1 – 4%, depending on the proximity to ice-cemented permafrost (Campbell *et al.* 1997b). The soil at Northwind in the Convoy Ranges at 1400 m altitude (close to the Inland Mountain sub-zone) examined by MacCulloch (1996) had a moisture content of only 3%.

2.2.2.3 Central Mountain sub-zone

The ice-free areas of the TransAntarctic Mountains comprise the Central Mountain sub-zone, where air temperatures rise close to freezing point during the summer but become very cold during the winter (Campbell & Claridge 1987). The xerous soil climate regime fits into the Central Mountain climatic subzone defined by Campbell & Claridge (1987), where air temperatures are intermediate and moisture is more readily available than the ultraxerous zone (Campbell & Claridge 1987). The moisture content of soils in the Dry Valleys, for example, was less than 1% (Campbell *et al.* 1997b). The moisture content is subject to change in response to water becoming available to the system, usually through the melting of snow (Wall 2004). For example, the low moisture content of soils in the Dry Valleys was found to increase to a maximum of 6% in the Wright Valley during “moistening events” (Wall 2004) which took about 7 days to dry out. Scott Base soil temperatures at a range of depths were found to be warmer during both cloudy and clear sky conditions compared to higher elevation sites inland, which were notably cooler (MacCulloch 1996).

2.2.2.5 Coastal Mountain sub-zone

The Coastal Mountain subzone exists where the TransAntarctic Mountains border the Ross Sea. McMurdo and Scott Bases are representative of the Coastal Mountain subzone climate regime (Campbell & Claridge 1987). Scott Base had a moisture content of about 6% (MacCulloch 1996), compared to less than 1% in the Dry Valleys (Campbell *et al.* 1997b). The mean summer soil moisture content at 2 cm depth at Scott Base was 5 – 6%. A maximum moisture content of 23% occurred in the summer of 2000-01 in response to a snow-melt event. It took about six days for the soil to dry out to the original moisture content of 5 – 6% (Wall 2004).

2.2.3 Antarctic Coast

The final broad climatic zone is the Antarctic coast, which is determined by latitude and local topography, including the proximity of the nearest slope (Weyant 1966, Campbell & Claridge 1987, Stearns *et al.* 1993). The coast is more frequently exposed to cyclonic storms than sites further inland (Weyant 1966). The circulation of cyclones around the coast becomes important in determining the local climate, though the katabatic effect may still have a strong influence (Campbell & Claridge 1987). The cyclonic storms and “lower level air masses” (Campbell & Claridge 1987) bring additional moisture to the Antarctic coast, making it generally warmer with greater precipitation and more cloud than the Antarctic slopes or the Interior Plateau (Weyant 1966, Campbell & Claridge 1987). The coastal zone is well-monitored, particularly when compared to the paucity of meteorological measurements from the interior of the continent (Stearns *et al.* 1993).

Coastal sites have been found to have warmer soil temperatures (Campbell *et al.* 1997a) and higher moisture content (Balks *et al.* 1995) than sites located further inland due to the differences in climatic conditions (Balks *et al.* 1995). The soils of the Antarctic coast climate zone are therefore classified as being subxerous. At Marble Point, the mean soil moisture content at 2 cm depth was about 5%. The maximum moisture content of 32% occurred during the summer, and the soil dried out again in about a week (Wall 2004).

As shown by the classifications of Campbell & Claridge (1987) and observations made at locations in each of the climatic zones (e.g. Balks *et al.* 1995, Campbell *et al.* 1997a), the climate and soil properties in Antarctica can vary significantly with distance. Distinct variation is not limited to the large scale and can be seen over relatively short distances between individual climate stations because of the influence of the surrounding environment (Bertler *et al.* 2004). Annual temperatures at individual sites may be influenced by the local winds (Doran *et al.* 2002b) and topography, such as the TransAntarctic Mountains which act as "a natural barrier for weather systems" (Bertler *et al.* 2004).

2.3 The effect of topography on air temperature

Local micro-climate and regional climate are strongly influenced by the local topography (Stearns *et al.* 1993, Doran *et al.* 2002a). For example, Marble Point on the Antarctic coast, and Lake Vanda in the Wright Valley (which has an East-West orientation), have a lower range of temperatures than Victoria Valley (Bull 1966). Victoria Valley has colder temperatures than other Dry Valley sites such as the Wright and Taylor Valleys (Doran *et al.* 2002a, Bertler *et al.* 2004). Doran *et al.* (2002a) suggest that the topography "shields" Victoria Valley from katabatic winds that could potentially warm the air column, and the winds instead drain through Bull Pass and other drainage valleys (Doran *et al.* 2002a).

Another possible explanation for the low range in temperature at Victoria Valley compared to Marble Point is the effect of altitude on the seasonal temperature. Marble Point, for example, is a low elevation coastal site (0 – 50 m) whereas the Victoria Valley is at a higher elevation (at least 350 – 400 m (Turnbull *et al.* 1994)). The climatic classifications of Weyant (1966) and Campbell & Claridge (1987) note the difference between temperatures at the Interior Antarctic Plateau compared to the Antarctic Coast. High elevation Polar Plateau sites (>2000 m) have extremely low temperatures, on the order of about –30 to –70°C, which is an effect of the topography (Stearns *et al.* 1993), while sites in the coastal zone have a temperature range of +12 to –12°C (Campbell & Claridge 1987).

2.4 Precipitation

Snow fall increases with increasing elevation (Campbell & Claridge 1987) and also with proximity to the coast (Fountain *et al.* 1999). The coastal zone has been shown to have greater precipitation than other climatic regions. The Dry Valleys have low precipitation; for example, the Wright Valley experiences about 45 mm water equivalent precipitation per year (Campbell & Claridge 1987), while Scott Base at a lower elevation receives snow fall the equivalent of approximately 200 mm water (Hatherton 1990). The precipitation may be the result of low pressure synoptic systems in the Ross Sea region (Fountain *et al.* 1999).

2.5 Katabatic winds

Winds in the McMurdo Dry Valleys can be high speed; for example, the mean August wind speed (1989 – 2001) in Taylor Valley was about 9 $m.s^{-1}$ (Nylen *et al.* 2004). Winds in the McMurdo Dry Valleys tend to run parallel to the valley orientation (Nylen *et al.* 2004), which is East to West for most of the Dry Valleys (Bull 1966). Dry Valley sites may be strongly influenced by katabatic wind events.

In Antarctica, katabatic winds play a dominant role in determining the local wind regime. Katabatic winds are the result of cold air that drains over a topographic slope (Weyant 1966, Hatherton 1990) and are associated with a sharp increase in wind speed and air temperature coupled with a decrease in relative humidity (Hatherton 1990, Doran *et al.* 2002a, Nylen *et al.* 2004). The sizeable "sloping surface" and uninterrupted surface cooling that occurs for a considerable portion of the year lead to strong katabatic circulation over Antarctica (King & Turner 1997).

The ground surface emits heat back to the atmosphere, which is termed "radiative cooling", and leads to a shallow layer of air about one kilometre thick that is cooler than the air above it (Hatherton 1990, King & Turner 1997). The cool air at the surface is heavier than the overlying air and it stays close to the ground surface. If there is a slope, the cool air will flow downslope (King & Turner 1997). The slope of the surface determines the speed of the katabatic wind (Weyant 1966, Parish & Bromwich 1991). A gentle slope will lead to relatively weak katabatic winds, while steeper terrain closer to the coast will result in stronger katabatic winds (Parish & Bromwich 1991). As the cool air descends, it warms adiabatically (Stearns *et al.* 1993, Fountain *et al.* 1999), and the air temperature is warmed by the katabatic wind (e.g. Nylen *et al.* 2004). For example, air temperature at Linnaeus Terrace (~1600 m elevation) varied by more than 20°C due to katabatic winds (McKay *et al.* 1998). Katabatic winds are usually persistent from a single direction (Weyant 1966), such as the westerly katabatic winds in the Wright Valley (Thompson *et al.* 1971).

Some authors state that katabatic winds occur most frequently during the winter months (Dalrymple 1966, Nylen *et al.* 2004). However, light winds were reported during the winter at Wright Valley (Thompson *et al.* 1971, Campbell & Claridge 1987). Strong westerly winds during winter, the usual direction for katabatic wind events, were attributed to higher atmospheric circulation (Thompson *et al.* 1971).

As katabatic winds occur near topographic slopes, they are stronger further inland from the coast (Weyant 1966, Campbell & Claridge 1987, Nylen *et al.* 2004), close to the slopes at the edge of the high interior of the continent (Weyant 1966). Comparatively, winds in the coastal zone are primarily influenced by cyclonic storms that circulate around the continent (Campbell & Claridge 1987). At some regions along the coast, such as at Terra Nova Bay in the Ross Sea region (King & Turner 1997, Carrasco *et al.* 2003), katabatic airflow can interact with warmer air and cause cyclogenesis (development and strengthening of depressions (King & Turner 1997, Carrasco *et al.* 2003)).

2.6 Reported trends in Antarctic air temperature

Warming trends in the Antarctic Peninsula and cooling in the interior of the continent have been reported recently (Doran *et al.* 2002b, Kwok & Comiso 2002). Annual temperature trends of warming or cooling in Antarctica can be quite small (Johanson & Fu 2007); for example Doran *et al.* (2002b) reported a cooling in surface air temperature of 0.7°C per decade over East Antarctica between 1986 – 1999.

Temperatures trends have been shown to be dependent on season. Cooling of summer (Dec – Feb) air temperature of about 1.2°C per decade (1986 – 1999) and autumn (Mar – May) air temperatures of 2.0°C per decade (1986 – 1999) was reported for the McMurdo Dry Valleys (Doran *et al.* 2002b). Winter (Jun – Aug) surface air temperatures have reportedly warmed by 0.6°C per decade (1986 – 1999) in the McMurdo Dry Valleys (Doran *et al.* 2002b) and the winter troposphere has warmed by 0.6°C around the Ross Sea region (1979 – 2005) (Johanson & Fu 2007).

The reported cooling trend in Antarctica has not been universally accepted. The brief communication by Turner *et al.* (2002b) disputes the methods used to calculate the regional cooling presented by Doran *et al.* (2002b), arguing that the high spatial variation between remote stations was not taken into account, producing an apparent cooling of temperature not supported by *in situ* measurements (Turner *et al.* 2002b).

2.6.1 The link between Antarctic temperatures and atmospheric circulation

2.6.1.1 The influence of the Southern Annular Mode

Low level atmospheric circulation has been found to be an important influence on the near-surface temperatures in Antarctica (e.g. Bertler *et al.* 2004, Marshall 2007). Important circulation patterns are the Southern Annular Mode (Kwok & Comiso 2002, Marshall 2007) and the El Niño Southern Oscillation (Bertler *et al.* 2004, Bertler *et al.* 2006), and particular scenarios in these circulation patterns have been found to lead to cooler or warmer near-surface temperatures.

The Southern Annular Mode is a symmetric ring-shaped circulation pattern (Kwok & Comiso 2002, Marshall 2007), where "atmospheric mass" oscillates between the Polar Regions (>60°S) and about 45°S (Kwok & Comiso 2002). The fluctuation of atmospheric mass between the mid- and polar latitudes leads to "synchronous pressure anomalies" (Marshall 2007), meaning that if the pressure is above average in the mid-latitudes, it will be below average at the same time in the polar regions. The Southern Annular Mode is said to be in a positive phase when the pressure is below average over Antarctica (Marshall 2007). When the Southern Annular Mode is in the positive phase, near-surface air temperatures measured by radiosonde and A Very High Resolution Radiometer (AVHRR) were shown to be generally cooler over the East Antarctic and warmer on the Antarctic Peninsula (Kwok & Comiso 2002, Johanson & Fu 2007, Marshall 2007).

The phase of the Southern Annular Mode has been linked to changes in near-surface temperatures (Kwok & Comiso 2002, Johanson & Fu 2007, Marshall 2007), where a positive phase of the Southern Annular Mode results in a cooling over the continent, excluding the Antarctic Peninsula which warms (Kwok & Comiso 2002, Johanson & Fu 2007, Marshall 2007). The cooling or warming of near-surface temperatures is seasonal, with cooling observed in the mean summer and autumn air temperatures, and warming observed in mean winter and spring air temperatures (Johanson & Fu 2007, Marshall 2007). Marshall (2007) examined Antarctic near-surface temperatures from the Reference Antarctic Data for Environmental Research (READER) project for 1957 – 2004 and the change in temperature related to changes in the Southern Annular Mode. Autumn temperatures were shown by Marshall (2007) to have cooled over 1957 – 2004 due to the Southern Annular Mode, and the summer air temperatures have also shown cooling in East Antarctica. The impact of the Southern Annular Mode on air temperatures varies from season to season (Marshall 2007). Marshall (2007) states that the READER data from 1957 – 2004 supports reports that part of the Antarctic continent is cooling.

2.6.1.2 The influence of the El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) is a variation on the Walker circulation pattern in the Pacific (King & Turner 1997, Sturman & Tapper 2005) with consequences on climate in regions beyond the bounds of the Pacific (King & Turner 1997). A "warm" ENSO event means that the sea temperature near South America, which under normal conditions is cold and cools the overlying atmosphere, is warmer than usual (King & Turner 1997, Sturman & Tapper 2005). As a result, the Walker circulation is weakened (King & Turner 1997, Sturman & Tapper 2005). "Normal" Walker circulation is known as La Niña.

The Southern Oscillation Index is used to determine the existence of warm or cold ENSO events (King & Turner 1997, Sturman & Tapper 2005). When the index is positive, Walker circulation is "normal" and La Niña conditions prevail, whereas a negative index indicates El Niño conditions (King & Turner 1997, Bertler *et al.* 2006).

During an ENSO warm event (El Niño), the position of a "semi-permanent low pressure system" in the Amundsen and Ross Sea regions (Bertler *et al.* 2006) is spatially shifted, and cool air is "imported" into the Ross sea region resulting in cooler conditions, particularly in the McMurdo Dry Valleys (Bertler *et al.* 2004, Bertler *et al.* 2006). Conversely, during ENSO cold events (La Niña) warmer air is available in the Ross Sea region, leading to warmer temperatures in the McMurdo Dry Valleys (Bertler *et al.* 2004, Bertler *et al.* 2006). Bertler *et al.* (2006) noted a seasonal difference in the strength of ENSO and its effect on Antarctic temperatures, where ENSO is stronger during the austral spring and summer (Bertler *et al.* 2006).

Bertler *et al.* (2004) found statistically significant cooling of summer temperatures at Scott Base of 0.83°C per decade (1986 – 2000), but has also stated that apparent cooling over the last few decades in the Ross Sea region is primarily due to the effect of El Niño and changing atmospheric circulation and thus does not support the regional cooling trend reported by Doran *et al.* (2002b).

2.7 Transfer of heat in soils

2.7.1 Heat transfer mechanisms

Heat is transferred within bodies by three main mechanisms; conduction, convection and radiation. Radiation is the transfer of heat via electromagnetic waves (Hillel 2004) and solar radiation is a strong driver of soil surface temperatures (MacCulloch 1996, Campbell *et al.* 1997a, Campbell *et al.* 1998a). Heat is propagated through the soil via conduction and convection (Koorevaar *et al.* 1983, Oke 1987, Hillel 2004).

2.7.2 Influences on soil temperatures

2.7.2.1 Influences on ground surface temperatures

Ground surface temperatures are of interest because they provide an integrated response to above-ground climate forces, such as air temperature, incoming radiation and snow cover (Guglielmin 2004, Guglielmin 2006). Soil temperatures in Antarctica are primarily influenced by the amount of solar radiation received at the soil surface (Balks *et al.* 1995, MacCulloch 1996, Campbell *et al.* 1997a), but are also affected by the surface air temperature, sun position and cloud cover and the extent of snow cover (Campbell & Claridge 1987, Kane *et al.* 1991, Guglielmin 2004, Smerdon *et al.* 2006).

2.7.2.2 The influence of solar radiation on soil temperatures

The 24 hour sunlight during the austral summer means that soil is able to be heated by the available energy (Campbell *et al.* 1997a). Cloudy days, when the solar radiation receipt at the soil surface is reduced, led to cooler maximum surface temperatures compared to those on clear sky days (MacCulloch 1996). Despite large differences in air temperatures at high elevation inland sites and low elevation coastal sites, the increased amount of solar radiation at the high elevation sites may lead to similar ground surface temperatures (Campbell & Claridge 1987).

The amount of solar radiation absorbed at the soil surface is influenced by the albedo (Campbell *et al.* 1997a). Snow cover increases the albedo and therefore the net radiation and thus the soil thermal regime; for example, when snow covered a Coombs hill site, the net radiation (Q*) was negligible leading to soil cooling (Campbell *et al.* 1997a).

2.7.2.3 The influence of albedo

Site characteristics such as the colour and rock type affect the albedo and thus the amount of energy available from solar radiation (Campbell & Claridge 1987, Campbell *et al.* 1998a). Albedo is influenced not only by colour, for example light coloured rock exhibits colder temperature than dark, but also surface roughness and snow cover (Campbell *et al.* 1998a). Snow has a high albedo and reflects a high proportion of incoming solar radiation and the snow body therefore has "low energy status" (Oke 1987), while darker surfaces absorb more energy from radiation and thus have warmer soil temperatures than those with light coloured surfaces (Bockheim & Hall 2002). Exposed soil has a lower albedo than snow-covered surfaces and thus the amount of solar radiation retained in Antarctic soils can be up to four times that of a snow surface (Weyant 1966). Heating of the surface can occur so that the ground surface is much warmer than the air temperature (MacCulloch 1996, McKay *et al.* 1998). Soil temperatures at Northwind Valley were cooler than at Coombs Hill despite the warmer air temperatures, which was attributed to the higher albedo of the light coloured material at Northwind (Campbell *et al.* 1997a).

2.7.2.3 The importance of snow cover

Snow cover is an important factor in determining subsurface temperatures because it alters the amount of energy available to the subsurface from solar radiation. Snow acts as an insulating layer, shielding the ground from temperature variations at the surface (Kane *et al.* 1991, Guglielmin 2004, Smerdon *et al.* 2006). For example, a thin snow cover (~3 cm) can shield the subsurface from sharp air temperature decreases, leading to subsurface temperatures that are warmer than the air temperature (Guglielmin 2004, Smerdon *et al.* 2006). The reflection of solar radiation by snow at the surface caused the diurnal soil temperature signal to be severely damped at Scott Base (Campbell *et al.* 1997a).

Where snow cover is ephemeral, the underlying soil temporarily gains moisture when the snowpack melts (Woo & Marsh 1990, Campbell *et al.* 1998a). Moisture content is spatially variable and can be dependent not only on the climatic zone the soil falls into, but also on the landscape position and associated differences in "albedo, soil temperature and evaporation potential" (Campbell *et al.* 1997b). Some Antarctic ground surface temperature measurements have the advantage over alpine locations in that snow cover does not complicate the relationship between air temperature and ground surface temperature for extended periods (Guglielmin 2004). Exposed bedrock sites, such as those at Marble Point and Wright Valley, will provide the most direct link between climate and the ground thermal regime (Smith & Riseborough 1996).

2.7.2.4 Ground surface and air temperature

For soils without snow cover, there is a strong correlation between soil surface temperature and air temperature. Direct correlations (R^2 of 0.84 – 0.97) were reported for the 1997 year between daily mean ground surface temperature and daily mean air temperature for several locations in the Victoria Land region in Antarctica (Guglielmin *et al.* 2003). At Boulder Clay, an Antarctic site near Terra Nova Bay, the average daily ground surface temperature had a strong relationship with air temperature for 1996-2002 ($R^2 = 0.93$) (Guglielmin 2006). The temperature at 2 cm depth was similar to air temperature in both magnitude and daily pattern of variation.

2.7.3 Heat conduction and factors affecting conduction

2.7.3.1 Heat conduction

In frozen soils, such as those of the Antarctic landscape, heat is primarily transferred by conduction (Kane *et al.* 1991). Conduction is the transfer of heat within a body by the transfer of kinetic energy of rapidly moving particles (Koorevaar *et al.* 1983, Oke 1987, Hillel 2004). If, for example, there is a temperature difference between the soil surface and a particular depth, the faster-moving warm particles will collide with slower, colder ones causing the transfer of kinetic energy from the warm region to the cold (Hillel 2004).

Heat conduction in a body is usually described using Fourier's first law of conduction (Campbell 1985, Hillel 2004), which states that in a uniform substance or body, heat will be transferred in the direction of the gradient, i.e. from hot to cold and will be dependent on the magnitude of the temperature difference (Hillel 2004). Fourier's law can be represented by:

$$q_h = -\kappa \, dT/dz \qquad \text{(Campbell 1985, Hillel 2004)}$$

Where q_h is the heat flux density (W.m^{-2}), κ is the thermal conductivity, T is temperature and z is the vertical distance (Campbell 1985, Hillel 2004). During the day, temperatures at the soil surface are generally warmer than at depth, leading to heat conduction from the surface into the soil, compared to heat transfer from warmer depths to the surface at night (Oke 1987).

The rate of heat transport is affected by soil properties that change in time, such as soil moisture content and those soil properties that change over space or distance, such as soil texture (Hillel 2004). Heat conduction in soils is influenced by three main soil properties; thermal conductivity, specific heat capacity and thermal diffusivity (Koorevaar *et al.* 1983, Oke 1987, Hillel 2004).

2.7.3.2 Thermal conductivity

Thermal conductivity is the quantity of heat transferred through a cross-sectional area if there is a temperature gradient present (Koorevaar *et al.* 1983, Oke 1987, Hillel 2004). Thermal conductivity is dependent on the soil mineral composition and bulk density (Campbell 1985, Hillel 2004) but is also strongly affected by the moisture content of the soil (Koorevaar *et al.* 1983, Oke 1987, Hillel 2004). Mineral soils have been found to have high thermal conductivities compared to organic soils (Kane *et al.* 1991). When moisture is added to a dry soil, the thermal conductivity increases as air, a poor heat conductor, is replaced by water, which conducts heat more readily (Koorevaar *et al.* 1983, Oke 1987, Hillel 2004). For example, an undisturbed soil site near Scott Base had a lower gravimetric moisture content (about 2%) than its disturbed counterpart (about 10%) in early January 1994 (Balks *et al.* 1995) resulting in lower thermal conductivity and diffusivity. Soil temperatures at several depths were warmer in the undisturbed soil and the diurnal temperature wave penetrated deeper in the undisturbed soil compared to the disturbed soil (Balks *et al.* 1995). As a result, the heat from radiation at the surface penetrated to greater depth in the disturbed soil, with less attenuation than in the undisturbed plot (Balks *et al.* 1995).

2.7.3.3 Specific heat capacity

Specific heat capacity is defined as the energy required to raise the temperature of a unit volume by 1°C (Oke 1987), or alternatively, the heat content per unit volume divided by the change in temperature (Koorevaar *et al.* 1983, Hillel 2004). Water, for example, requires more heat energy to raise its temperature by 1°C than air (Oke 1987, Hillel 2004). Therefore, if the moisture content of a soil is high, it will take more energy to cause a temperature change than if the soil moisture content was low.

2.7.3.4 Thermal diffusivity

Thermal diffusivity (D_h) is the rate at which the temperature signal in the soil is dissipated or diffused by conduction (Koorevaar *et al.* 1983, Oke 1987), and is determined by dividing the thermal conductivity (κ) by specific heat capacity (c_s) and density (ρ) (Hillel 2004):

$$D_h = \kappa / c_s \rho \qquad \text{(Hillel 2004)}$$

The thermal diffusivity determines how rapidly and how deep the surface temperature signal propagates to depth in the soil (Oke 1987). Campbell *et al.* (1997a) found that the thermal diffusivity of dry Antarctic desert soils was low (0.205 – 0.261 $W.m^{-1}K^{-1}$) and thus the variation in temperature was extreme and restricted to shallow surface layers.

2.7.4 Change in the temperature signal with depth

2.7.4.1 Influences on soil temperature

Soil temperatures are determined by changes in the air temperature at the surface (Koorevaar *et al.* 1983, Campbell & Claridge 1987, Guglielmin 2004), as well as solar radiation, albedo and snow cover (section 2.7.2). Temperature changes within the soil profile are the result of heat conduction from the surface to depth (Campbell *et al.* 1998a, Smerdon *et al.* 2006). The variation in temperature at a particular soil depth may be most simply described by the assumption that the variation follows a sinusoidal curve (Koorevaar *et al.* 1983, Hillel 2004). Such cyclical variations in temperature occur at the diurnal and annual scales.

2.7.4.2 Damping depth

The conduction of heat from the soil surface to depth is such that heat is absorbed on the pathway, and thus the temperature wave is 'damped' and the amplitude of the sine wave decreases (Figure 2.2) (Koorevaar *et al.* 1983, Oke 1987, Hillel 2004). The temperature signal decreases exponentially with increasing depth (Campbell 1985). The depth at which the temperature amplitude is approximately 0.37 times its surface value is known as the *damping depth* (Campbell 1985, Hillel 2004). The damping depth is a single variable that may be used as part of a larger equation to calculate the temperature at a given depth (Hillel 2004).

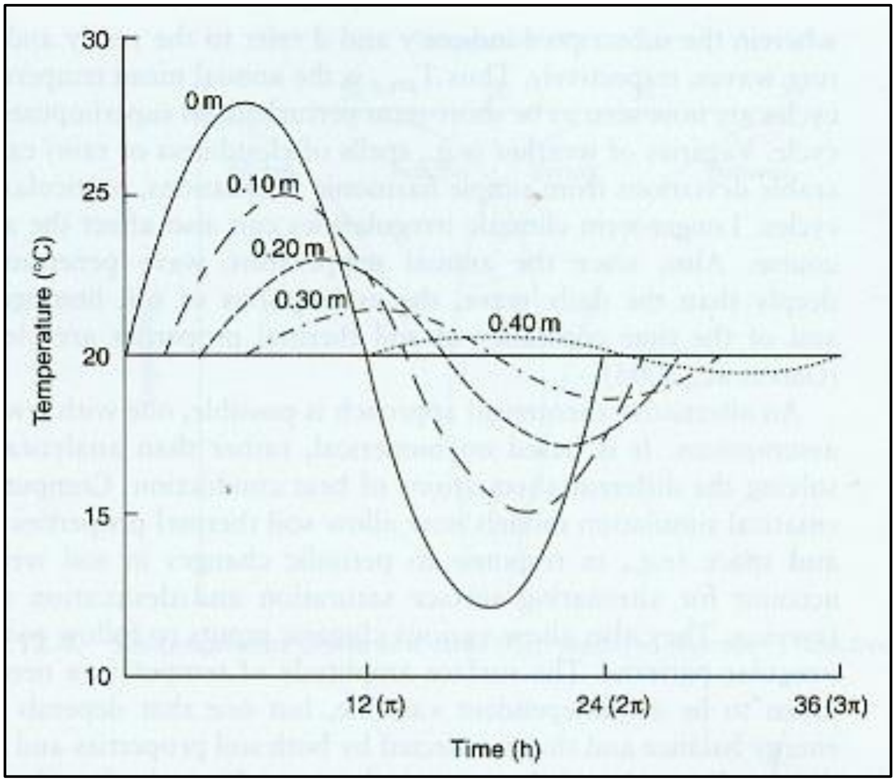

Figure 2.2: Schematic of soil temperature variation with time at different depths, demonstrating the phase lag and attenuation of the temperature signal as depth increases (Source: Hillel 2004).

The damping depth is dependent on both the soil thermal properties, which determine the extent to which temperature is attenuated, and the frequency of the surface temperature cycle (Koorevaar *et al.* 1983, Guglielmin 2004, Hillel 2004). Annual cycles have a deeper damping depth, whereas short period temperature fluctuations on the scale of days to weeks do not significantly penetrate below a couple of metres (Oke 1987, Hillel 2004, Smerdon *et al.* 2006). The annual damping depth is about 19 times greater than the diurnal damping depth (Buchan 1991, Hillel 2004). For example, diurnal damping depths in mineral soils may be on the order of 10 to 15 cm, compared to about 2 to 3 m for the annual cycle (Campbell 1985, Hillel 2004). The damping depth does not necessarily indicate that there is no temperature range below this depth (e.g. Figure 2.3), as the annual temperature cycle has been observed below 10 – 15 m depth (Bodri & Cermak 2007), which is greater than the annual damping depth of about 2 to 3 m suggested by Campbell (1985). Once determined, the damping depth may be used to estimate soil temperatures (Hillel 2004).

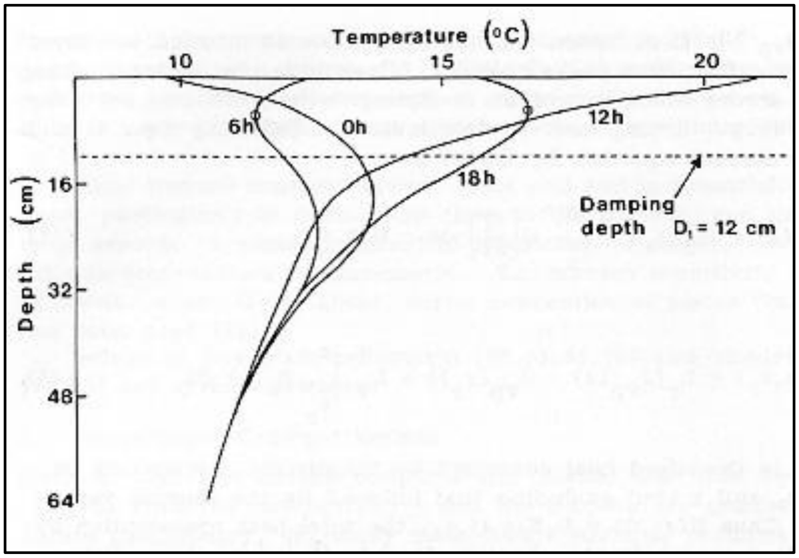

Figure 2.3: Depth profiles of soil temperature at six hour intervals over the space of a day, showing the diurnal damping depth of 12 cm (From Buchan 1991).

2.7.4.3 Phase lag of temperature signal

With increasing depth, the temperature signal is not only attenuated but there is also an associated phase lag in the peak temperature (Figure 2.2) which is typical to all soils (Oke 1987, Hillel 2004, Smerdon *et al.* 2006). For example, active layer monitoring in the Italian Central Alps demonstrated the smoothing and phase lag of daily temperature between 2 cm and 3 m depth (Guglielmin 2004). The thermal properties of the subsurface material, such as thermal conductivity, determine the speed with which temperature signals propagate from the surface to depth (Oke 1987, Smerdon *et al.* 2006). With increasing depth, the time delay in temperature changes increases so there are often maximum temperatures at depth that may occur days or months after the maximum at the surface (Smerdon *et al.* 2006).

2.7.4.4 Depth of Zero Annual Amplitude

The annual temperature cycle, like the diurnal cycle, follows a wave-like pattern (Oke 1987) but it penetrates to greater depth. The depth at which the variation in annual permafrost temperature becomes negligible is known as the depth of Zero Annual Amplitude (Muller 1947, Linell & Tedrow 1981, Oke 1987).

The annual temperature profile varies inter-annually (profiles I, II, III Figure 2.4), but there comes a depth at which the annual temperature profiles converge, which denotes the depth of Zero Annual Amplitude. The depth of Zero Annual Amplitude may be about 15 – 20 m depth (Linell & Tedrow 1981), which was at an Arctic site. Guglielmin (2006) found that the depth of Zero Annual Amplitude at Oasi in Antarctica was about 11 m.

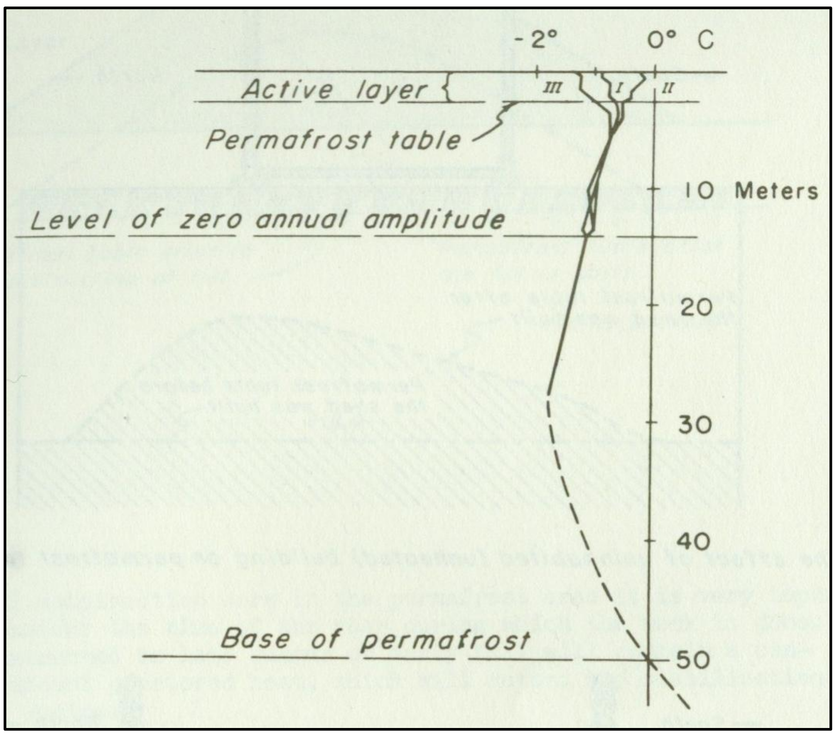

Figure 2.4: Schematic of subsurface temperature regime (Figure 7 from Muller 1947), showing the active layer, permafrost table, level of Zero Annual Amplitude and the base of the permafrost. Note the three different profiles above about 12 m depth, I= mean temperatures for 1928-1930, II= Temperatures for 1930 and III= Temperatures for 1929 (Muller 1947).

Determining the depth of Zero Annual Amplitude may be an objective of subsurface temperature monitoring. Guglielmin (2006) used thermal diffusivity to form an estimation of the Zero Annual Amplitude. The temperature at the depth of Zero Annual Amplitude may also be of interest as it may be used as a proxy for the mean annual air temperature at a site (Oke 1987), making it useful for assessing changes in response to changing air temperatures.

2.7.4.5 Effect of site location on attenuation and phase lag

Attenuation of the temperature wave and phase lag has been observed in soil profiles in various Antarctic locations examined by MacCulloch (1996), Campbell *et al.* (1997a), McKay *et al.* (1998) and Wall (2004). For example, the peak temperature measured at 12 cm depth lagged behind the surface by about six hours in Scott Base (Figure 2, Campbell *et al.* 1997a). The soil climatic zone has an effect on the depth to which the surface temperature signal propagates. Diurnal variation in soil temperatures was noted up to 55 cm depth at Marble Point (Balks *et al.* 1995) and to 46 cm depth at Vanda Station in the Wright Valley (Thompson *et al.* 1971).

The annual range in temperature decreases with depth as the temperature signal is attenuated. For example, at Vanda Station, at 8 cm depth, the range in annual temperature was 42°C compared to 15°C at 3 m depth (Thompson *et al.* 1971). At Linnaeus Terrace, at the soil surface, the range in annual temperatures was 57.5°C compared to 26.8°C at 40 cm depth (McKay *et al.* 1998).

2.8 The active layer and permafrost

2.8.1 The active layer

The sensitive and integrated response of ground and subsurface temperatures to above-ground forcing makes the active layer and permafrost good indicators of climate change (Guglielmin 2006). The active layer is important for sustaining biological activity in the polar regions (Burn 1998) and with global temperatures projected to increase, it is important to understand how active layer depth changes and the factors influencing active layer depth.

The active layer is defined as the layer of ground subject to annual thawing and freezing cycles in areas underlain by permafrost (Balks *et al.* 1995, Guglielmin 2006). The active layer can vary in thickness from year to year, but is usually shallowest close to the poles and increases with decreasing latitude (Muller 1947). The maximum annual depth of thawing coincides with the top of the permafrost table (Linell & Tedrow 1981). In the upper layers of the soil (about 2 – 20 cm depth), there can be several freeze-thaw cycles during the course of a single summer in response to diurnal temperature fluctuations (Wall 2004). The freeze-thaw processes lead to "intense physical disturbance" in the active layer (Campbell & Claridge 1987).

The active layer can be determined using field techniques, such as finding the depth to ice-cement, or by using thermistors at a range of depths and finding the graphical intercept of the maximum temperature profile with the 0°C (Burn 1998, Guglielmin *et al.* 2003). Burn (1998) suggested that the most reliable method of determining active layer depth is using thermistors, as it is replicable and not influenced by subjective investigators in the field (Burn 1998). Using this method also circumvents the problem of field investigation, whereby the seasonal maximum soil temperature may be missed due to sampling time.

The amount of time when the soil profile is completely thawed is only about two months in both the Antarctic and the Arctic (Linell & Tedrow 1981, Balks *et al.* 1995, Campbell *et al.* 1998a), which occurs in the hemisphere's summer. Therefore there is only a small window of time where soil biological activity may be promoted.

If there is snow present at the surface, there is a time lag between snowmelt caused by air temperature exceeding 0°C and when there is an observable change in ground surface temperature (Woo *et al.* 2007). The moisture in the active layer may be redistributed, and evaporation at the ground's surface may cause a reduction in moisture content (Woo & Marsh 1990). Moisture availability affects the transfer of heat within the soil profile by increasing thermal conductivity (Weyant 1966, Oke 1987), so the temperature signal will penetrate deeper in a moist soil, such as at the edges of streams and lakes (Conovitz *et al.* 2006) .

2.8.2 Factors affecting active layer depth

2.8.2.1 Surface air temperature

The depth of thawing is dependent upon surface air temperatures (Weyant 1966, Zhang *et al.* 1997, Woo *et al.* 2007) and has been shown to vary annually in response to warmer or cooler air temperatures. For example, Woo & Marsh (1990) showed that the active layer depth in the Northwest Territories of Canada increased by 10 cm depth due to warmer summer air temperatures. Active layer depth in the McMurdo Dry Valleys responded to surface air temperature over time scales as short as 24 hours (Conovitz *et al.* 2006). Examination of thermal regimes in soils at Scott Base, Marble Point and the Wright Valley revealed that during the cooler summer of 2000-01, soil temperatures at 2 cm depth had fewer cumulative hours above 0°C (e.g. 457 hours at Scott Base) than the warm summer of 2001-02 (e.g. 1011 hours at Scott Base) (Wall 2004).

The response of the active layer depth to changes in air temperature suggests that the active layer will be sensitive to minor changes if the projected increases in air temperature occur. A steady increase in air temperature will cause the active layer to get deeper which “may lead to subsidence and accelerated erosion” (Burn 1998).

2.8.2.2 Site location

At the regional scale, surface climate and thus the active layer depth varies according to the climatic zone (section 2.2) that the site falls into (Bockheim & Hall 2002, Bockheim *et al.* 2007). The local microclimate has a strong influence on the soil thermal regime. Sites in the Coastal Zone of Antarctica have typically warmer air temperatures than inland zones (Campbell & Claridge 1987), leading to an active layer from 30 – 80 cm deep (Bockheim & Hall 2002, Campbell & Claridge 2006). In contrast, at Mt Fleming, in the Mountain zone, the low air temperature leads to an active layer depth of only about 5 cm (Bockheim *et al.* 2007). Sites in the Dry Valleys, mid-way between the Coast and the Mountain Zones, have active layer depths of about 20 – 40 cm (Campbell *et al.* 1998a, Bockheim & Hall 2002). The change in active layer depth with increasing elevation was suggested to be linked to the adiabatic lapse rate and its effect on air temperature (Campbell & Claridge 2006). The active layer depth is therefore dependent on the climatic regime and elevation of the site (Table 2.1).

Table 2.1: Active layer depths from various climatic zones and elevations in the Ross Sea region.

Location	Elevation (m)	Active layer depth (cm)	Source
Cape Hallett	~2	80	Hofstee *et al.* (2006)
Minna Bluff	38	22	Bockheim *et al.* (2007)
Scott Base	38	30	Bockheim *et al.* (2007)
Granite Harbour	46	60	Bockheim *et al.* (2007)
Marble Point	75	43	Bockheim *et al.* (2007)
Bull Pass	175	50	Bockheim *et al.* (2007)
Victoria Valley	450	21	Bockheim *et al.* (2007)
Beacon Heights	600m above Taylor Glacier	5 to 10	Balks *et al.* (1995)
Linnaeus Terrace	1600	12.5	McKay *et al.* (1998)
Mt Fleming	2200	5	Bockheim *et al.* (2007)

The Mt Fleming, Linnaeus Terrace, Beacon Heights, Victoria Valley, Bull Pass and Marble Point climate stations form an altitudinal gradient, and Minna Bluff, Scott Base, Marble Point, Granite Harbour and Cape Hallett form a complementary latitudinal gradient. The sites comprise a range of different climatic zones. Mt Fleming, the highest location represents the Mountain zone and had the shallowest active layer with only 5 cm thickness. With decreasing elevation, the active layer progressively increased in thickness, reaching a maximum at Granite Harbour at the coast, where it is 60 cm thick (Bockheim *et al.* 2007). The active layer also increased with decreasing latitude. Minna Bluff, the southern-most site had an active layer depth of 22 cm (Bockheim *et al.* 2007), while further north at Cape Hallett in Northern Victoria Land the active layer thickness was estimated from groundwater observations to be ~80 cm in the summer of 2004-05 (Hofstee *et al.* 2006).

Air temperature, and by extension the climatic zone, alone is not able to fully explain the differences in active layer depth between coastal and inland sites (Zhang *et al.* 1997). The active layer depth was shown to be deeper in soils in the McMurdo Dry Valleys that had water running freely through the subsurface (Conovitz *et al.* 2006). Zhang *et al.* (1997) also noted the importance of the thaw season in determining the active layer depth, which is the period when the mean daily air temperature exceeds 0°C and there is no snow at the ground surface (Zhang *et al.* 1997).

2.8.3 Predicted change in the active layer in response to increasing surface temperature

The 2007 Assessment Report produced by the International Panel for Climate Change has predicted a global temperature rise of between 1.8 and 4.0°C between 2000 and 2099 (IPCC: www.ipcc.ch/index.htm), which will clearly have an impact on both the active layer thickness and permafrost in Antarctica if it occurs.

The studies by Campbell *et al.* (1998a) and Bockheim *et al.* (2007) demonstrated the variability in active layer thickness due to location and elevation. The active layer is dependent upon the local climate around any discrete climate stations. The ground surface temperature is strongly correlated to air temperature (Guglielmin *et al.* 2003, Guglielmin 2006), and air temperature has been used to predict temporal changes in active layer depth. Kane *et al.* (1991) used a model to predict the change in active layer depth in an Alaskan location in response to a 2°C, 4°C, 6°C and 8°C increase in surface temperature over a 50 year time period. Temperature profile models suggested that for a 2°C increase in temperature over a 50 year period the active layer would gradually increase in thickness by about 20 cm and a 4°C increase in air temperature would gradually increase active layer thickness by about 40 cm (Kane *et al.* 1991). With a greater increase in the surface temperature, the increase in active layer thickness was more pronounced.

Climate warming scenarios were also investigated by Woo *et al.* (2007) in Canada under high and low greenhouse gas emissions for the period 2021 – 2050, and 2071 – 2100. The high emissions scenario produced the greatest air temperature warming, though no specific values were given, and the median active layer depth at the tundra site was projected to increase by 40 cm by 2100 (Woo *et al.* 2007).

These two models suggest that in the Northern Hemisphere, the active layer depth will increase with increasing air temperatures, which may or may not be linked to increases in greenhouse gas emission. Kane *et al.* (1991) indicated that in Alaska "the permafrost will ultimately disappear" if the surface temperature warms by about 4.5^{o}C (Kane *et al.* 1991).

2.9 The transition zone

The active layer is the portion of the soil profile that freezes and thaws annually and the depth of the active layer changes annually (Muller 1947). Occasionally, the active layer depth in the summer does not thaw to the usual levels leaving a layer of frozen material which then thaws one or two summers later (Muller 1947, Shur *et al.* 2005). This layer has been classified using the Russian term *pereletok* (Muller 1947), but more recently has been ascribed the term *transition zone* , meaning the zone of the soil which occasionally thaws at time scales greater than one year (Bockheim & Hinkel 2005, Shur *et al.* 2005).

The transition zone is the upper part of the permafrost, but when it undergoes occasional thawing it becomes part of the active layer temporarily (Figure 2.5) (Shur *et al.* 2005). The transition layer is typically highly disturbed as the result of cryoturbation (Bockheim & Hinkel 2005). The ice and moisture content of the transition layer is greater than that of the underlying permafrost and the active layer above (Bockheim & Hinkel 2005, Shur *et al.* 2005). The mean volumetric moisture content in the transition layer at a site in Siberia was higher (55%) than in the overlying active layer (25%) (Davydov *et al.* 2008). There are a greater proportion of visible ice lenses and other ice-rich formations (such as "lens-wickers" (Davydov *et al.* 2008) in the transition layer (Bockheim & Hinkel 2005, Davydov *et al.* 2008). Due to the high water content of the transition layer, during warm years the energy required to melt the ice is greater than is available and so the permafrost underlying the transition layer is protected from thawing (Bockheim & Hinkel 2005). At Barrow, Alaska, the transition zone occurred at a range of depths between 20 and 55 cm.

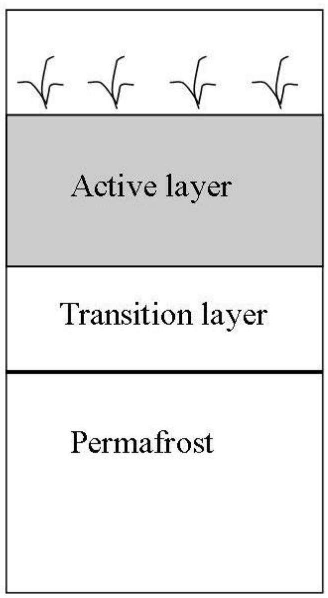

Figure 2.5: Schematic diagram of the active layer, transition zone and permafrost (simplified from Bockheim & Hinkel 2005, Shur *et al.* 2005).

2.10 Permafrost

2.10.1 Permafrost definition

Permafrost is defined as "the thermal condition in soil or rock of having temperatures below 0^{o}C persist over at least two consecutive winters and the intervening summer" (Linell & Tedrow 1981). More simply, permafrost is ground that remains continuously at or below 0^{o}C for more than two years (Linell & Tedrow 1981, Harris

1986, Balks *et al.* 1995, Shur *et al.* 2005). Permafrost is defined on the basis of temperature and therefore is not necessarily ice-cemented material, but rather a thermal condition of the subsurface material (Muller 1947, Campbell & Claridge 1987). The temperature of permafrost changes seasonally and may be relatively high at the surface of the permafrost with decreasing magnitude with depth (Linell & Tedrow 1981).

2.10.2 Spatial extent of permafrost

Permafrost exists below about 20% of the land surface of the world (Muller 1947, Linell & Tedrow 1981) occurring in places such as, but not limited to, the high mountains of the Tibetan Plateau (Linell & Tedrow 1981), the Arctic and Antarctica. Permafrost material underlies most of the soils in Antarctica (Campbell & Claridge 1987). Permafrost can range in thickness from metres to several hundreds of metres (Muller 1947, Linell & Tedrow 1981).

Permafrost is not limited to soil but may also include bedrock material (Linell & Tedrow 1981). Ice content in permafrost varies, sometimes filling the material matrix or sometimes virtually absent, which is the case in “dry permafrost” (Linell & Tedrow 1981). Three types of permafrost are recognised in the McMurdo Dry Valleys within 100cm of the surface; “ground ice, ice-cemented permafrost, and dry-frozen permafrost” (Bockheim *et al.* 2007). Well-drained deposits tend to lead to “dry permafrost” (Linell & Tedrow 1981).

2.10.3 Application of temperature monitoring with depth

With increasing depth, temperature is an integral of longer periods of time (Bodri & Cermak 2007). For example, at the depth of Zero Annual Amplitude, the measured temperature is an integral for the previous year’s temperature (Oke 1987, Bodri & Cermak 2007). Temperature monitoring in boreholes in permafrost locations has been used to reconstruct temperature histories (e.g. Guglielmin 2004, Majorowicz *et al.* 2006). The Permafrost and Climate in Europe (PACE) project was initialised in 1997 with one of the objectives being to use temperature measurements to predict changes in response to climate change and to verify past temperature reconstructions (Harris *et al.* 2001). The PACE boreholes are typically 100 m deep (Harris *et al.* 2001). Past temperature history reconstructions are based on the assumption that conduction is the only pathway for heat transfer within the borehole (Majorowicz *et al.* 2006). Due to the long term climate patterns that are usually observed using borehole temperatures, long datasets of more than ten years are required to draw any conclusions regarding trends in borehole temperatures (Bodri & Cermak 2007).

2.11 Concluding remarks

Further investigation using *in situ* climate stations is required to evaluate reported trends of cooling in the Antarctic (e.g. Doran *et al.* 2002b, Kwok & Comiso 2002). The link between air temperature and subsurface temperatures indicates that any warming trend in air temperatures will lead to a deepening of the active layer and degradation of the permafrost. The automated weather stations established since 1999 in the McMurdo Sound region by Landcare Research (New Zealand) and the United States Department of Agriculture – National Resource Conservation Services provides an eight year record of atmospheric and subsurface climate parameters. There are also two 30 m deep permafrost temperature monitoring boreholes in close proximity to the Marble Point and Wright Valley automated weather stations. The combination of automated weather station data and borehole temperature data will provide an opportunity to investigate both atmospheric conditions since 1999 and their impact on the subsurface temperature regime.

Temporal and spatial variation in active layer depth in the McMurdo Sound Region, Antarctica

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Abstract

A soil climate monitoring network, consisting of seven automated weather stations, was established between 1999 and 2003 in the McMurdo Sound region, ranging from Minna Bluff (78°30’-41.6”S) to Granite Harbour (77°00’-23.7”S) and from sea level to about 1700 m on the edge of the Polar Plateau. Active layer depth was calculated for each site by the graphical interception of the maximum soil temperature profile with the 0°C isotherm for eight successive Austral summers from 1999-2000 to 2006-2007. Active layer depth had a high degree of inter-annual variability. Active layer depth increased across the latitude range from Minna Bluff (78.5°S) to Granite Harbour (77°S), and decreased with increasing altitude from Marble Point (50 m) through to Mt Fleming (1700 m). The active layer was deepest in the warm summer of 2001-2002 at all recording sites. Active layer depth was strongly correlated with mean summer air temperature at most sites ($R^2 \geq 0.76$), and had only poor correlation with total summer solar radiation ($R^2 < 0.2$) and mean winter air temperature ($R^2 < 0.2$). A regression equation across all sites for active layer depth as a function of mean summer air temperature, mean winter air temperature, total summer solar radiation and mean summer wind speed ($R^2 = 0.73$) is presented.

Keywords: Latitudinal gradient, Altitudinal gradient, Cryosol, Gelisol, permafrost, soil temperature, active layer prediction.

Introduction

Global temperatures are predicted by the International Panel for Climate Change (IPCC) to increase by 1.8 – 4.0°C by 2099 (IPCC 2007 Assessment report www.ipcc.ch/index.htm). The polar regions are projected to have a magnified response to the projected increase in global temperatures compared to more temperate regions (Kane *et al.* 1991). Increased air temperature will have an impact on the active layer and permafrost. The active layer is defined as the layer of ground subject to annual freezing and thawing cycles in areas underlain by permafrost (Linell & Tedrow 1981, Guglielmin 2006), while permafrost is defined as the ground that remains continuously at or below 0°C for more than two years (Muller 1947, Linell & Tedrow 1981).

The active layer has been predicted to be significantly impacted by the projected increase in air temperature over the next several decades (Kane *et al.* 1991) particularly in Alaska where the mean annual air temperature is about 0°C. Kane *et al.* (1991) predicted that the active layer depth in Alaska will increase by 22 cm if mean annual air temperature warms by 2°C over the next 50 years, and an increase of 43 cm depth was predicted if air temperature was to warm by 4°C over a 50 year period.

Active layer depth in Antarctica is of interest as it provides a potentially sensitive indicator to climate change (Guglielmin 2004) due to its sensitivity to changes in air temperature (Kane *et al.* 1991, Conovitz *et al.* 2006) and the lack of vegetation which influences the relationship between active layer depth and surface climate parameters (Guglielmin 2006).

The active layer depth in Antarctica has been shown to be both spatially variable (Campbell *et al.* 1998, Bockheim & Hall 2002, Bockheim *et al.* 2007) and temporally variable (Guglielmin *et al.* 2003). Active layer depth is dependent on the climatic zone the site is located in, as defined by Weyant (1966) and Campbell & Claridge (1987). For example, Coastal Zone sites may have active layer depths of about 50 – 60 cm (Campbell *et al.* 1998, Bockheim *et al.* 2007) whereas sites that are in the

Inland Mountain subzone may have active layer depths on the order of about 5 – 10 cm (McKay *et al.* 1998, Bockheim *et al.* 2007).

With projected increases in global air temperature potentially impacting on the active layer and permafrost, it is important to understand how the active layer varies inter-annually, what drives the inter-annual variation and the trends in active layer depth across latitude and altitude, before attempting to predict the impacts of climate change on active layer depth. Measurements of the active layer from a single season in the McMurdo Sound region of Antarctica have been conducted previously (e.g. Guglielmin *et al.* 2003, Conovitz *et al.* 2006) but there is a paucity of work concerning the inter-annual variation in active layer depth.

Seven automated weather stations have been established in the McMurdo Sound Region since 1999 and are located at Wright Valley at the base of Bull Pass (established 1999), Marble Point (1999), Scott Base (1999), Victoria Valley (1999), Mt. Fleming (2002), Granite Harbour (2003), and Minna Bluff (2003) (Figure 1). Each station records micro-meteorological data every hour, including air temperature, solar radiation and soil temperature at a range of depths.

The objectives of this paper are to determine the active layer depth in each Austral summer at each of the seven automated weather stations and examine how the active layer depth varies between summers, with latitude, and with increasing altitude, and to determine the primary above-ground climatic influences.

Site descriptions, instrumentation and methods

Site descriptions

The location of the automated weather stations (Figure 1) presents a latitudinal transect, near sea level, from Minna Bluff through to Granite Harbour, including the Scott Base and Marble Point stations. Complementary to the latitudinal component, the stations established at Marble Point through Wright Valley, Victoria Valley and Mt. Fleming provide an altitudinal transect from 50 m above sea level to 1700 m above sea level (Table 1). All sites have no vegetation and are occasionally snow covered.

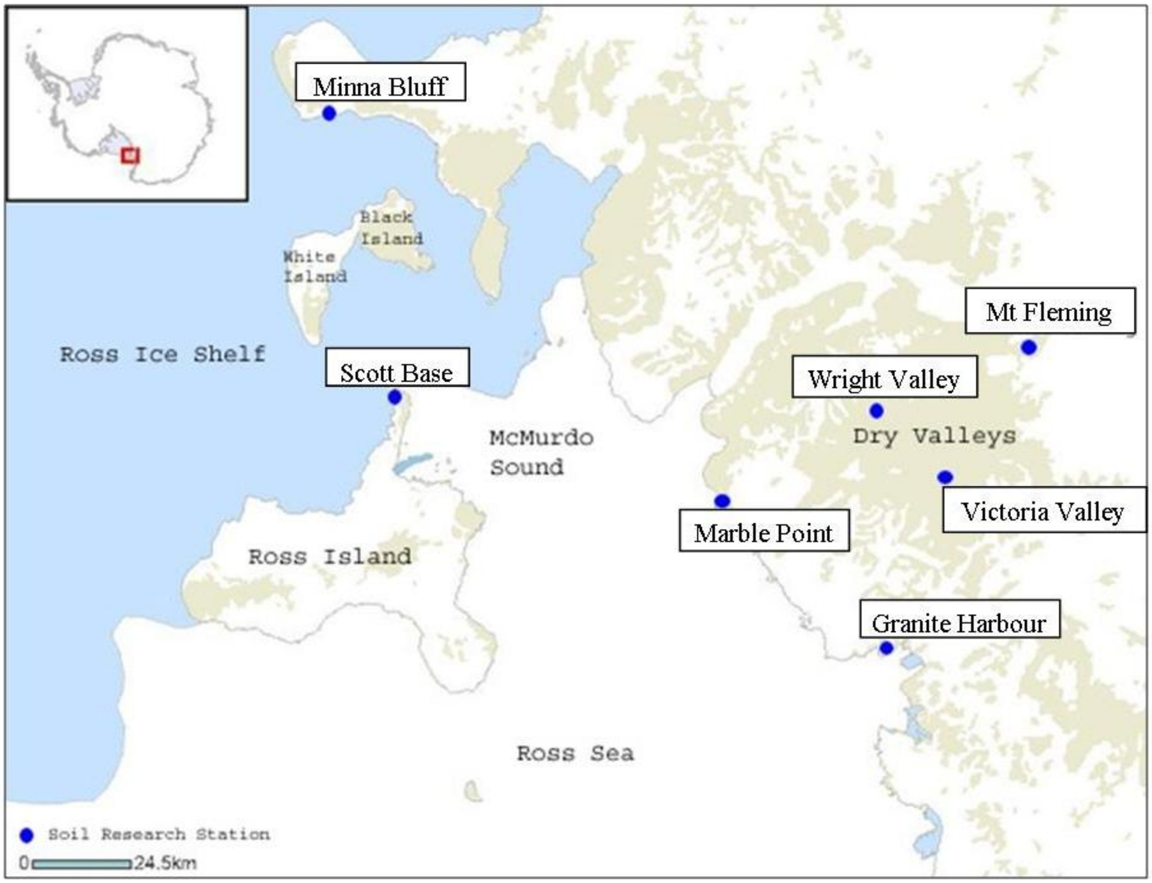

Figure 1: Locations of seven automated weather stations established in the McMurdo Sound region since 1999 (from http://soils.usda.gov/survey/scan/index.html).

Table 1: Site location and descriptions of seven automated weather stations established since 1999 in the McMurdo Sound region, Antarctica.

Site	**GPS Location**	**Site description**	**Elevation (m above sea level)**	**Mean Annual Air Temperature (°C) (time period)**
Minna Bluff	78°30'41.6"S 166°45'58"E	Peninsula of continental Antarctica extending into the Ross Ice Shelf	37	–19 (2004-2006)
Scott Base	77°50'53.6"S 166°45'44"E	100 m north of Scott Base buildings on a slope of about 6°, southerly aspect	38	–19 (1999-2007)
Marble Point	77°25'10.6"S 163°40'55"E	400 m east of the Wilson-Piedmont Glacier	50	–18 (1999-2007)
Granite Harbour	77°00'23.7"S 162° 31'32.4"E	Narrow (5 m wide) stretch of boulder material at the base of a cliff, northerly aspect	4	–18 (2004-2007)
Wright Valley	77°31'06.1"S 161°51'57"E	On the floor of the Wright Valley near the base of Bull Pass	150	–20 (1999-2007)
Victoria Valley	77°19'51.3"S 161°36'02.2"E	On the valley floor approximately 30 m from the edge of Lake Victoria	410	–20 (1999-2007)
Mt Fleming	77°32'42.7"S 166°17'24.6"E	In a large cirque on the north side of Mt Fleming, near the edge of the polar plateau	1700	–23* (2007)

**Mean annual air temperature could only be calculated for Mt Fleming in 2007, as this was the only year in which a full data set was available.*

Instrumentation

Soil pits were dug at each site and soil temperature probes were installed at a range of depths. Care was taken to ensure the soil was returned as closely as possible to the original site condition.

Soil temperature measurements used to calculate active layer depth in this study were taken using MRC (Measurement Research Corporation, Gig Harbor, Washington) temperature probes that were installed to 120 cm depth at Marble Point, Wright Valley and Victoria Valley, and to 115.6 cm depth at Scott Base. The MRC probes measure temperatures at 11 depths over the length of the probe. Temperature sensors (model 107; Campbell Scientific, Logan, Utah) were used at Mt Fleming (to 75 cm depth) and Minna Bluff (to 84 cm depth up until the 2006 summer). A combination of MRC and 107 temperature probe measurements were used at Granite Harbour (to 90 cm depth) and at Minna Bluff (to 112 cm depth) after 2006. The combination approach was used at Granite Harbour and Minna Bluff in order to get as many temperatures at as many depths as possible for the determination of the active layer depth.

Incoming solar radiation was measured 3 m above ground level using a pyranometer (LiCor model LI200X; Campbell Scientific, Logan, Utah) at Wright Valley, Scott Base, Marble Point, Minna Bluff, Granite Harbour and Mt Fleming, and 2 m above ground level at Victoria Valley.

Air temperature was measured using an RM Young RTD temperature probe (model 43347; Campbell Scientific, Logan, Utah) at Wright Valley (1.6 m above ground level). A Vaisala temperature and relative humidity probe was used at Scott Base (model HMP35C until January 2005, when it was replaced by HMP45C; Campbell Scientific, Logan, Utah) (1.6 m), Victoria Valley (HMP45C) (2 m), and at Marble Point (HMP45C) (1.6 m). Air temperature at Minna Bluff was measured using a Vaisala temperature and relative humidity probe (HMP35C) until January 2006, after which a Campbell Scientific 107 probe in a solar radiation shield was installed 2 m above ground level. A Campbell Scientific 107 temperature probe in a solar radiation shield was used at Mt Fleming (1.6 m) and at Granite Harbour (2 m).

All sensors were connected to dataloggers (CR10X-2M; Campbell Scientific, Logan, Utah). Atmospheric measurements were taken once every 10 seconds and soil measurements were taken once every 20 minutes. All measurements were averaged every hour and the hourly average was recorded. Data were manually downloaded each January.

Active layer determination

Active layer depth may be determined by the intercept of the annual maximum soil temperature profile with the 0°C isotherm (Burn 1998, Guglielmin *et al.* 2003). This method is reliable because it is replicable and not influenced by subjective observers (Burn 1998), and data at our sites are recorded all year round.

The use of annual maximum temperature at each depth allows for the determination of the maximum active layer depth for each site. As the Austral summer falls over two calendar years, it was deemed more appropriate in this study to limit the active layer determination to the period defined for the Austral summer, particularly as the soil profile is only completely thawed for about 2 months in both the Arctic and the Antarctic (Linell & Tedrow 1981, Balks *et al.* 1995, Campbell *et al.* 1998). In this study, we defined the Austral summer as the time from 1 December to 31 January. Active layer depth was calculated each summer by plotting the maximum temperature recorded at each depth and noting where the curve intercepted the 0°C isotherm (Burn 1998, Guglielmin *et al.* 2003).

Guglielmin *et al.* (2003) noted that the accuracy of the active layer depth calculation is dependent on the number of thermistors available, due to the strong changes in thermal diffusivity and thermal gradients in the upper 20 cm of the profile. All seven automated weather stations have at least four thermistors in the upper 25 cm of the soil profiles at each site.

Statistical analysis

All sites were subjected to a paired, two-tailed Student's T-test (using Microsoft Excel v.2007) to determine which sites were statistically different. Where two sites had different record lengths, the test was performed over the time scale of the shorter record.

Multiple regression was undertaken using Minitab (Minitab Inc. 2007) to assess the impact of four predictors on the active layer depth. The predictors were mean summer air temperature (1-Dec to 31-Jan), mean winter air temperature (1-Jun to 31-Aug in the previous winter), total summer solar radiation and mean summer wind speed All sites were pooled for multiple regression analysis, but Mt Fleming was excluded due to system failure during winter and thus the lack of mean winter air temperature.

Results and Discussion

Active layer depth

The active layer depth at the seven sites (Table 2) varied spatially and temporally. The active layer depths at sites in the coastal climatic zone (i.e. Scott Base, Marble Point, and Granite Harbour) were deeper than those further inland (i.e. Wright Valley, Victoria Valley and Mt Fleming). There was also variability in the active layer depth inter-annually at most sites. The shallowest mean active layer occurred at Mt Fleming. The high standard deviations about the means indicated that the active layer depth was variable from year to year.

Active layer depth at most sites within the study area were significantly different relative to each other. The Minna Bluff and Victoria Valley sites were not significantly different (Table 2). The Victoria Valley site showed greater variation in active layer depth than Minna Bluff. Marble Point and Wright Valley active layer depths were not significantly different. The hourly air temperatures over the summer period at Wright Valley were often equal to or warmer than the air temperatures at Marble Point in all summers, and only occasionally cooler than at Marble Point.

Table 2: Active layer depths (cm) at seven sites around the McMurdo Sound Region for eight successive summers, mean active layer depth and standard deviation. NE denotes that the site was not established in this summer.

Summer	Minna Bluff (cm)	Scott Base (cm)	Marble Point (cm)	Granite Harbour (cm)	Wright Valley (cm)	Victoria Valley (cm)	Mt Fleming (cm)
1999-00	NE	30.35	53.7	NE	38.4	15.6	NE
2000-01	NE	18.1	31.7	NE	36.6	15.5	NE
2001-02	NE	37.2	59.8	NE	58.8	26.15	NE
2002-03	NE	29.1	39.5	NE	44.7	19.35	7.2
2003-04	22.2	33.2	48.5	— *	46.4	23.4	8.5
2004-05	21.9	34.4	50.3	>90	45.4	21.5	5.4
2005-06	22.5	34.8	54.1	>90	48.4	23.7	6.7
2006-07	22.9	36	54.2	>90	51.2	23.5	3.25
Mean	22.4	31.6	49.0	>90	46.2	21.1	6.2
Std. Dev.	0.43	6.11	9.13	—	7.02	3.93	1.99
Notation#	a	b	c	d	c	a	e

* *No active layer depth was obtained for Granite Harbour in the summer of 2003-04 due to system failure from mid-July 2003. The site was reestablished in early January 2004 and it was likely that the summer maximum in soil temperatures was missed.*

The result of the paired T-test. Sites with the same letter notation were not significantly different and those with different letters were significantly different ($p<0.01$).

The date of maximum soil temperatures used to calculate the active layer depth varied inter-annually (Table 3). The time of maximum active layer depth ranged in occurrence from late December to late January. There was no trend in timing of active layer depth with either latitude or altitude.

Table 3: Date of occurrence of the maximum active layer depth at seven sites around the McMurdo Sound region. NE denotes that the site was not established in this summer. The date of occurrence is the date at which the soil temperature reaches its maximum at the two depths either side of the 0°C isotherm.

Summer	Minna Bluff	Scott Base	Marble Point	Granite Harbour*	Wright Valley	Victoria Valley	Mt Fleming
1999-00	*NE*	13/01/00	17/01/00	*NE*	18/01/00	17/01/00	*NE*
2000-01	*NE*	19/01/01	30/01/01	*NE*	26/01/01	24/01/01	*NE*
2001-02	*NE*	16/01/02	14/01/02	*NE*	18/01/02	8/01/02	*NE*
2002-03	*NE*	13/01/03	29/01/03	*NE*	15/01/03	5/01/03	24/01/03
2003-04	17/01/04	12/01/04	13/01/04	—	10/01/04	10/01/04	24/01/04
2004-05	23/01/05	14/01/05	22/01/05	12/01/05	20/01/05	18/01/05	19/12/04
2005-06	9/01/06	4/01/06	18/01/06	18/01/06	18/01/06	18/01/06	31/12/05
2006-07	13/01/07	31/01/07	30/01/07	29/01/07	14/01/07	26/01/07	9/12/06

**Date of occurrence at Granite Harbour was taken at the date of the maximum soil temperature at the deepest sensor (90 cm).*

Change in active layer depth with latitude

The active layer depth showed a clear latitudinal gradient (Figure 2) within the range from Minna Bluff (78°30’41.6”S) to Scott Base (77°50'53.6"), Marble Point (77°25'10.6") and Granite Harbour (77°00’23.7”S). All sites along the latitudinal transect were significantly ($p<0.01$) different (Table 2). Minna Bluff, the southernmost site, had the shallowest active layer depth each summer (mean = 22.4 cm) and Granite Harbour, 195 km north of Minna Bluff, had the deepest active layer in all available summers (>90 cm). The active layer depth at Scott Base (mean = 31.6 cm) was consistently shallower than that at Marble Point (mean = 49.0 cm). There were fewer freeze-thaw cycles per summer at Scott Base compared to Marble Point (Wall *et al.* 2004) and the mean summer air temperature was cooler at Scott Base compared to Marble Point (Adlam 2009).

Marble Point and Scott Base had the greatest inter-annual variability in active layer depth, particularly up to the summer of 2002-2003 (Table 2). Following the summer of 2002-2003, the inter-annual variability in active layer depth decreased. The low inter-annual variability in active layer depth at the Minna Bluff and Granite Harbour sites is partially due to the shortness of the available record and they may also be following the pattern of lower variability in the 2003-2007 period exhibited at Scott Base and Marble Point.

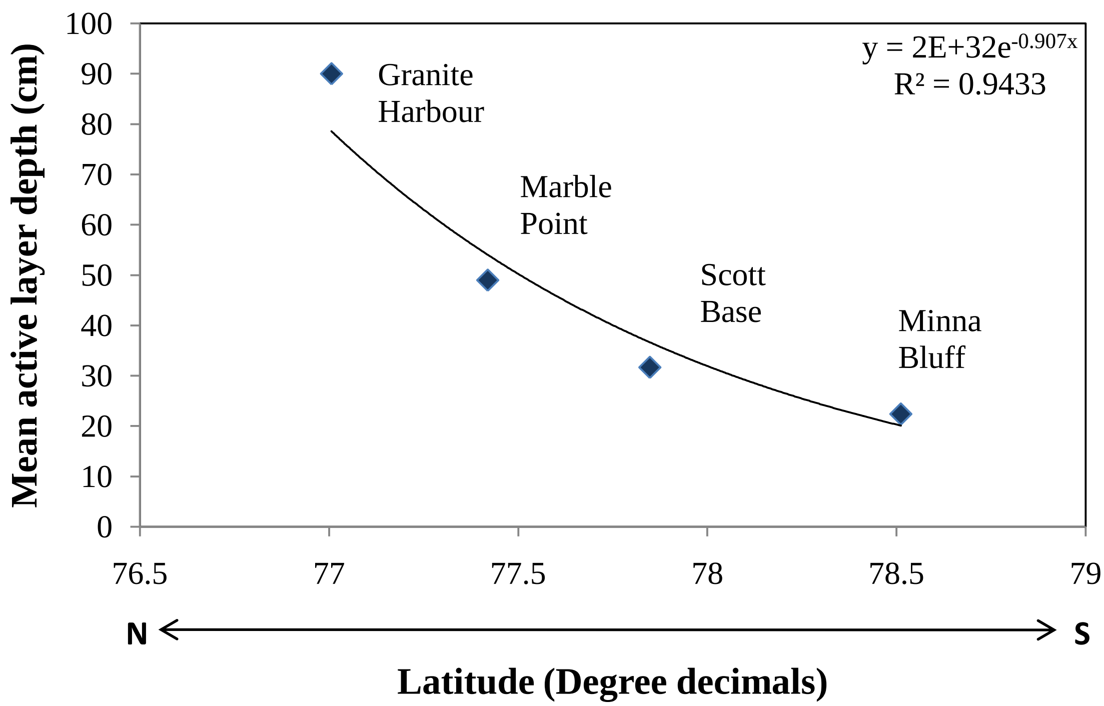

Figure 2: Mean active layer depth (cm) along a latitudinal transect from Minna Bluff (78.5°S) through Scott Base (77.8°S), Marble Point (77.4°S) and Granite Harbour (77.0°S) over the 1999-2007 period.

The gradient in active layer depth from Minna Bluff to Granite Harbour is not likely to be solely a factor of the latitude. Granite Harbour consistently had the deepest active layer depth of all our sites (>90 cm), which was higher than might be expected in the coastal climatic zone (e.g. Bockheim *et al.* 2007). The active layer depth at Granite Harbour is likely to be influenced by the local micro-topography, as the mean December and January air temperatures are not significantly warmer than those at any of the other three sites along the latitudinal transect (Adlam 2009). Local micro-topography and climate are important factors influencing active layer depth (Cannone *et al.* 2008).

It is hypothesised that the greater active layer depth at Granite Harbour is the result of meltwater percolating through the subsurface and thus accelerating the summer thaw process. A similar situation was shown by Conovitz *et al.* (2006) in their examination of active layer depths near Lake Fryxell in the Taylor Valley, where deeper active layers were found immediately below inflow streams due to the heat transfer via stream water to the subsurface. While local topography is clearly a key factor regulating the active layer depth, the importance of the latitudinal gradient should not be discounted.

Change in active layer depth with altitude

The active layer depth displayed an altitudinal gradient (Figure 3) within the range from Marble Point (50 m a.s.l.) to Mt Fleming (1700 m a.s.l.). All sites along the altitudinal transect were significantly different ($p<0.01$) to each other, except the Marble Point and Wright Valley sites (Table 2). Marble Point and Wright Valley had similar active layer depths which followed the same pattern of inter-annual variation. Victoria Valley had a shallower active layer and followed a similar pattern of variation to both Marble Point and Wright Valley. Mt Fleming had the shallowest active layer in every summer.

Marble Point, Wright Valley, and Victoria Valley all had the deepest active layer depth in the summer of 2001-2002 (Table 2). The maximum active layer depth at Mt Fleming occurred in the summer of 2003-2004 and showed only minimal inter-annual variation in active layer depth. The mean active layer depth at Mt Fleming (mean = 6.2 cm) was similar to that expected of sites in the Inland Mountain subzone, which have active layer depths of about 5 – 10 cm (McKay *et al.* 1998, Bockheim *et al.* 2007). The mean December and January air temperatures at Mt Fleming over the record were about 10°C cooler than the other sites along the altitudinal transect (Adlam 2009).

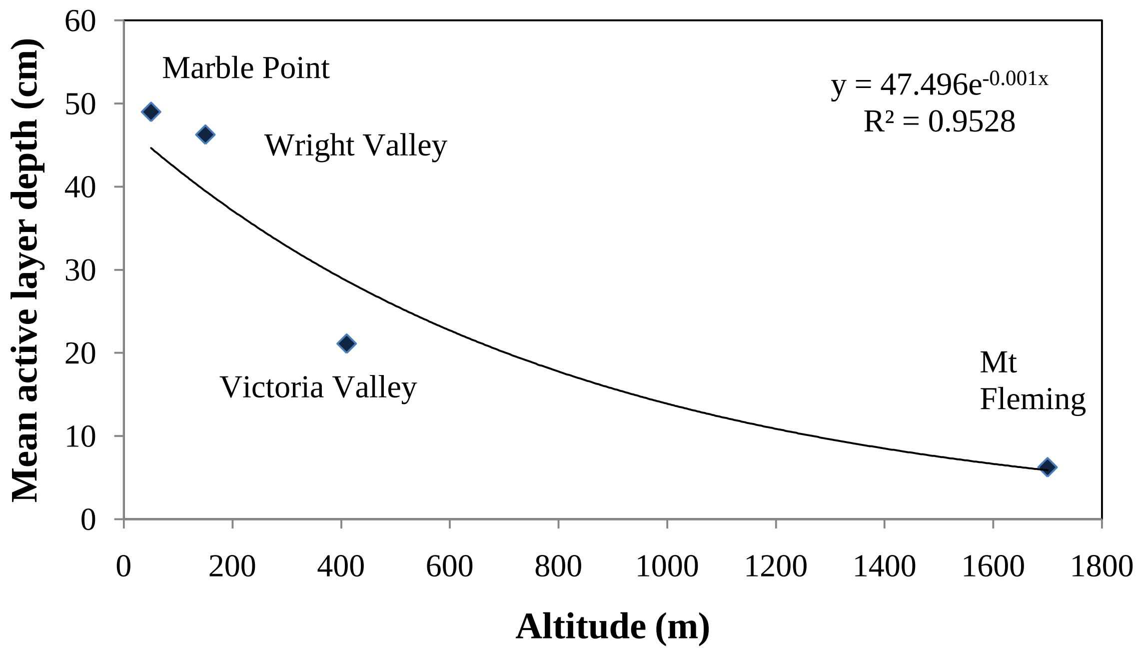

Figure 3: Mean active layer depth (cm) along an altitudinal gradient from Marble Point through to Wright Valley, Victoria Valley and Mt Fleming.

Campbell & Claridge (2006) attributed the decreasing active layer depth with increasing elevation to the adiabatic lapse rate. The dry adiabatic lapse rate is a maximum decrease of 0.98°C per 100 m increase in elevation (Sturman & Tapper 2005). Hatherton (1990) noted that air temperature decreased by about 1°C for every 100 m increase in elevation, suggesting that using the maximum dry adiabatic lapse rate was reasonable to estimate temperature differences with different elevation in Antarctica.

The observed mean summer air temperature was warmer than the mean summer air temperature (1-Dec to 31-Jan) predicted using the dry adiabatic lapse rate (Figure 4). The linear increase in temperature with the adiabatic lapse rate was not fully observed at our sites, as the Wright Valley site was warmer than Marble Point and so the observed temperature was initially warmer with the first elevation change, before decreasing with increasing elevation (Figure 4). Between the Wright Valley and Mt Fleming, the observed temperature increase had the same slope as that predicted by the dry adiabatic lapse rate, confirming the decrease in air temperature due to the adiabatic lapse rate. Site location is also an important factor, as seen by the observed difference in air temperature between Marble Point and Wright Valley. The data indicates that the coastal climate at the Marble Point site may be having a moderating effect on the mean summer air temperature, compared to the warmer inland climate observed at the Dry Valley sites.

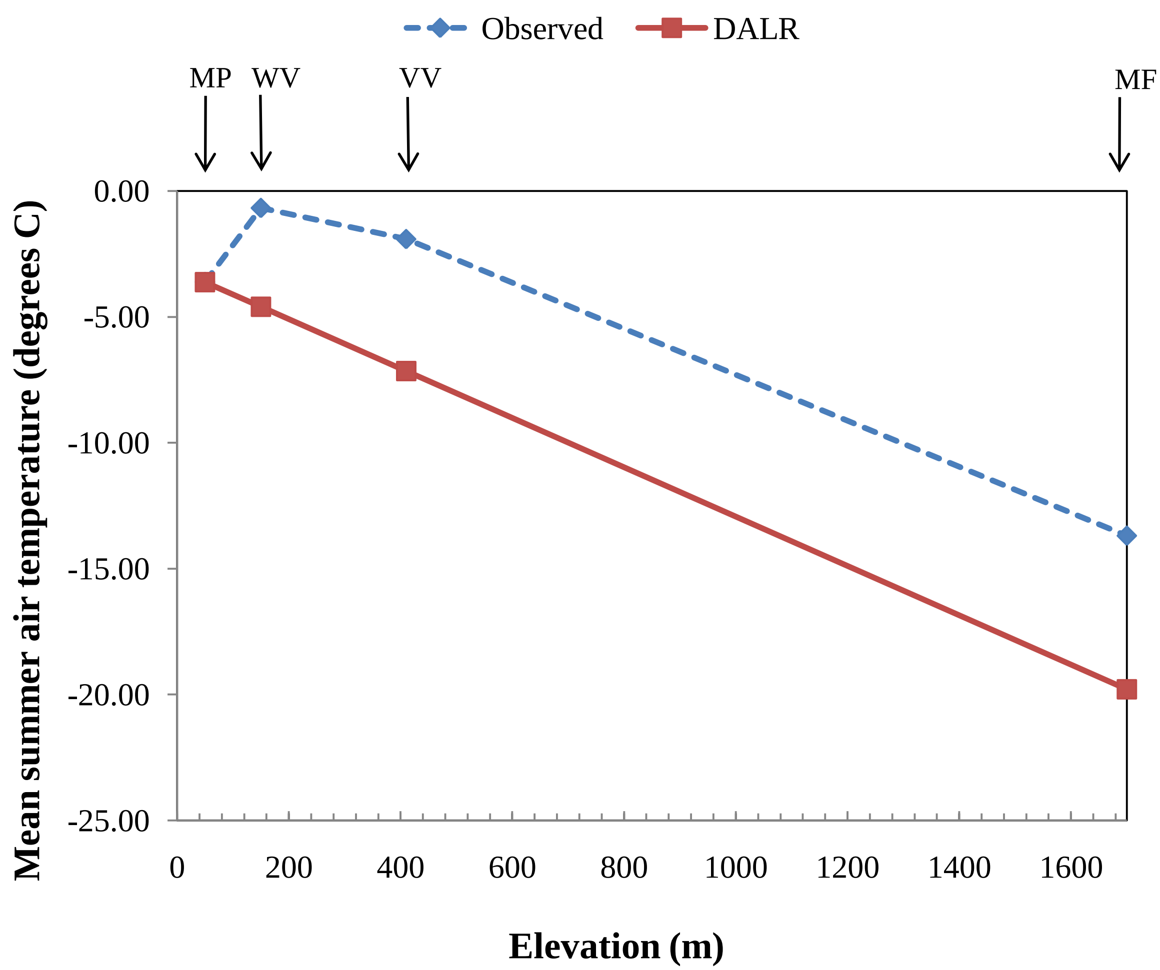

Figure 4: The predicted temperature at elevation as a result of the dry adiabatic lapse rate (DALR = 0.98°C decrease per 100 m increase in elevation) and the observed temperatures at each elevation for the 2002 – 2003 summer. MP = Marble Point, WV = Wright Valley, VV = Victoria Valley and MF = Mt Fleming.

The 2001-2002 warm summer

The active layer depths at all operational sites (Scott Base, Marble Point, Wright Valley and Victoria Valley) were deepest in the warm summer of 2001-2002. The difference in climatic zone, latitude and altitude between sites leads us to believe that the active layer, particularly in the 2001-2002 summer, must be, at least partially, driven by regional-scale atmospheric activity.

The summer of 2001-2002 was one of the warmest on record in the McMurdo Dry Valleys (Foreman *et al.* 2004, Barrett *et al.* 2008) and also in the Western Antarctic Peninsula and the Bellingshausen Sea (Massom *et al.* 2006). The warm summer of 2001-2002 was described as a "discrete warming event" in the McMurdo Dry Valleys that lasted from December 21 2001 to January 12 2002 (Barrett *et al.* 2008).

The warmer surface air temperatures resulted in increases in the annual lake level and stream flow in three lakes in Taylor Valley (Foreman *et al.* 2004, Barrett *et al.* 2008), and also an increase in soil temperature (Barrett *et al.* 2008). At Scott Base, Marble Point and Wright Valley, the cumulative hours where the soil temperature exceeded 0°C was much higher in the summer of 2001-2002 than in 1999-2000 or 2000-2001 (Wall 2004).

The summer of 2001-2002 was anomalous due to the atmospheric circulation surrounding the Antarctic continent. The warm temperatures experienced at several locations on the continent were caused by the presence of a "blocking high" (Turner *et al.* 2002, Massom *et al.* 2006), which is a large anticyclone in the Southern Atlantic that occasionally occurs. It was unusual in this instance because of its duration. The blocking high persisted from mid-September to February, which was linked, by the British Antarctic Survey, to the positive phase of the Southern Annular Mode (Masson *et al.* 2008). The blocking high caused a change in the normal air flow patterns, such as strengthened northerly flows in the Weddell Sea (Turner *et al.* 2002) and the Bellingshausen Sea (Massom *et al.* 2006), allowing the transport of warmer and moister air into the Weddell and Bellingshausen Seas (Turner *et al.* 2002, Massom *et al.* 2006).

The positive phase of the Southern Annular Mode leads to lower than average pressures over Antarctica, and has been shown to cause cooler air temperatures in East Antarctica and warmer air temperatures on the Antarctic Peninsula (Kwok & Comiso 2002, Johanson & Fu 2007, Marshall 2007). The McMurdo Sound region where our sites are located is not near the Antarctic Peninsula, but it is on the western side of the TransAntarctic Mountains. The warmer air temperatures in the summer of 2001-2002 at the seven sites in the McMurdo Sound region, and thus the deeper active layers, suggest that the McMurdo Sound region may respond to the Southern Annular Mode in a similar way to the Antarctic Peninsula.

Turner *et al.* (2002) noted that there was an anomalously low mean sea level pressure situation over the same period (2001-2002) in the Ross Ice Shelf region, which may be a contributing factor to the warmer surface air temperatures and thus deeper active layer depths recorded.

Relationship between active layer depth and climatic variables

Mean summer air temperature

Summer air temperature (Dec-Jan) has been documented to have a strong influence on the depth of the active layer (Zhang *et al.* 1997, Conovitz *et al.* 2006, Bockheim *et al.* 2007). Guglielmin (2004) noted the strong correlation between ground surface and air temperature (R^2>0.9) that occurred at all Antarctic sites investigated. Conovitz *et al.* (2006) found that the active layer depth could respond to changes in air temperature within a time period as short as 24 hours.

Active layer depth correlated to mean summer air temperature (1-Dec to 31-Jan) at Scott Base (R^2=0.76), Marble Point (R^2=0.83), Wright Valley (R^2=0.84) and Victoria Valley (R^2=0.88). Mt Fleming (R^2=0.06) and Minna Bluff (R^2<0.01) showed no relationship between mean summer air temperature and active layer depth. Granite Harbour was not included as all values for active layer depth were greater than 90 cm and no regression statistic was able to be calculated. All individual stations except Minna Bluff and Granite Harbour exhibited a positive correlation between active layer depth and mean summer air temperature, i.e. the active layer became deeper as mean summer air temperature increased.

The R^2 statistic for all sites indicated that mean summer air temperature was a strong influence on the active layer depth at most sites. Therefore, the warmer summer air temperatures at Wright Valley do contribute to a deeper active layer compared to Marble Point.

Mean winter air temperature

The correlation between active layer depth and mean winter air temperature (1-Jun to 31-Aug in the previous winter) was poor ($R^2 \leq 0.2$) at all sites except Minna Bluff ($R^2=0.61$). The poor relationship between mean winter air temperature and active layer depth suggested that the active layer depth responded more to the summer air temperature than to the winter air temperature. The relationship at Minna Bluff was positive, suggesting that as mean winter air temperature increased, so did active layer depth.

Solar radiation

The correlation between active layer depth and total summer solar radiation (1-Dec to 31-Jan) at all sites was poor ($R^2 \leq 0.2$), except at Mt Fleming which had a weak relationship ($R^2=0.28$). The low correlation found at our sites was similar to that found by Conovitz *et al.* (2006), who found no statistically significant relationship between active layer depth and total incoming solar radiation. The absorption or loss of solar radiation at the soil surface, and thus the amount of heating for the soil profile is determined by the surface albedo (Balks 1995, Campbell *et al.* 1997, Campbell *et al.* 1998). Lighter surfaces have a higher albedo and thus reflect more energy while darker surfaces absorb more energy (Oke 1987).

The poor correlation between active layer depth and total summer solar radiation indicated that the active layer depth was not primarily influenced by the incoming solar radiation at most sites. While the solar radiation does not directly impact the active layer depth, it may still be a mitigating factor in the inter-annual variability shown by all sites.

Prediction of active layer depth

Zhang *et al.* (1997) showed that there can be no single variable that explains the spatial differences in parameters such as the active layer depth. For example, the mean summer air temperature is not an independent variable as it is affected by other factors such as solar radiation and wind speed. Therefore, a single factor regression of active layer depth and any climatic variable, such as mean summer air temperature, cannot fully explain the inter-annual variation in active layer depth. A multiple linear regression analysis allows the impacts of other variables on active layer depth to be included.

A multiple regression analysis was undertaken with all sites pooled together and four predictors. The regression analysis produced the equation:

$$ALD = 222 + 5.69(MSAT) + 3.63(MWAT) - 10.6(TSSR) - 2.84(MSWS)$$

Where ALD = active layer depth, MSAT = mean summer air temperature, MWAT = mean winter air temperature, TSSR = total summer solar radiation and MSWS = mean summer wind speed.

Mean summer air temperature, mean winter air temperature, total summer solar radiation and mean summer wind speed explained 73% of the variation in the active layer depth. The regression had a residual standard deviation of 7.32, and was based on 34 observations across 6 sites. All four predictors made a significant contribution to the regression prediction of the active layer depth ($p<0.02$). A stepwise regression was undertaken with all sites pooled. Active layer depth was weakly correlated with mean summer air temperature ($R^2=0.15$) when all sites were combined. The combination of mean summer air temperature and mean winter air temperature improved the correlation to $R^2=0.65$. The R^2 was further improved to 0.68 by including total summer solar radiation, and the combined effect of mean summer air temperature, mean winter air temperature, total summer solar radiation and mean summer wind speed gave the best correlation of $R^2=0.73$. The regression equation may potentially be used as a predictor for active layer depth at sites in the McMurdo Sound region that have no subsurface monitoring regime.

Change in active layer over time

We also analyzed the slope of the active layer depth over time at all sites and we concluded that the mean slope (average increase in depth per year across all sites) is between –0.1 and +1.6 (95% confidence interval) and thus cannot rule out the possibility that the true mean is zero and that there is no trend in active layer depth. Due to the short time of the available record and large inter-annual variability in active layer depth, the weak trend does not provide conclusive evidence that the active layer depth is getting deeper. It is important to continue the monitoring for a much longer period to determine any long-term trends in active layer depth.

Conclusions

The maximum active layer depth was calculated for eight consecutive summers (starting 1999-2000 and ending 2006-2007) at seven sites located in the McMurdo Sound region. The active layer depth at most of our seven sites in the McMurdo Sound region demonstrated marked inter-annual variability.

Active layer depth showed a clear latitudinal gradient, with the southernmost site (Minna Bluff) having the shallowest active layer increasing through Scott Base and Marble Point, with the northernmost site (Granite Harbour) having the deepest active layer. Latitude is not the sole factor determining the active layer depth, as the local topography had a notable effect at Granite Harbour, where local meltwater probably transferred heat to the subsurface and accelerated the thawing process.

The altitudinal gradient in active layer depth was clear, though the Marble Point and Wright Valley sites had active layer depths that were similar in both magnitude and inter-annual variation. The variation in active layer depth at Victoria Valley was less than at Marble Point and the Wright Valley, which is most likely due to the increased elevation. Mt Fleming, the highest location, had the shallowest active layer depth, which is most likely due to its elevation.

Active layer depth at all sites correlated well ($R^2>0.7$) with mean summer air temperature, except for Minna Bluff and Mt Fleming which had only a weak relationship. Active layer depth did not correlate with mean winter air temperature ($R^2 \leq 0.2$) except at Minna Bluff ($R^2=0.61$), nor did active layer depth correlate with total summer incoming solar radiation ($R^2 \leq 0.2$) except at Mt Fleming which had only a weak relationship ($R^2=0.28$).

When all sites were included in multiple regression analysis, active layer depth is significantly influenced by mean summer air temperature, mean winter air temperature, total summer solar radiation and mean summer wind speed. When combined, the four predictors accounted for 73% of the variation in the active layer depth.

Acknowledgements

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BOREHOLE ESTABLISHMENT FOR ICE-CEMENTED CORE SAMPLING AND PERMAFROST TEMPERATURE MONITORING AT MARBLE POINT AND WRIGHT VALLEY, ANTARCTICA

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Abstract

With increasing concern about climate change, measurement of permafrost characteristics is important because permafrost is sensitive to changes in surface temperature. Borehole monitoring networks may be used to predict changes in permafrost temperature and distribution. This report details the installation of four permafrost boreholes in November 2005, two for permafrost temperature monitoring and two for ice-cemented core sampling.

Two boreholes were located in the Wright Valley at the foot of Bull Pass and two at Marble Point on the Ross Sea coastline. Boreholes were drilled in till material in the Wright Valley (to 7.5 m depth) and at Marble Point (to 2.7 m depth) to recover ice-cemented cores for microbial and geochemical analysis.

The second borehole at each site was into the bedrock (to about 30 m depth) for long-term permafrost temperature monitoring. The temperature monitoring borehole in the Wright Valley was drilled in the granite bedrock of the valley floor (Granite Harbour Intrusives Supergroup). The temperature monitoring borehole at Marble Point was drilled in marble (Ross Supergroup basement complex).

Permafrost temperature monitoring equipment was installed in the temperature monitoring boreholes in January 2007. Sixteen thermistors were installed at each site measuring temperature once every hour and recording an average every six hours using a datalogger. Daily maxima and minima were also recorded.

Both sites were recording successfully in 2007, and were revisited in January 2008. The first year of data was successfully downloaded, and the thermistors were reinstalled at depths of 0.3, 0.6, 1.0, 2.0, 3.0, 5.0, 7.0, 10.0, 12.0, 14.0, 15.0, 16.0, 18.0, 20.0, 25.0 and 29.5 m.

Initial temperature measurements undertaken in 2005 at the completion of drilling were compared to those on a similar date in 2007. The temperature profiles for 2005 and 2007 at Marble Point were similar in shape and magnitude.

The data collected from the permafrost temperature monitoring boreholes will be contributed to international databases including the Global Terrestrial Network for

Permafrost (GTN-P), Thermal State of Permafrost (TSP) and Antarctic Permafrost and Soils (ANTPAS).

It is intended that the temperature monitoring boreholes be utilised for developing a long term monitoring record. This report provides a detailed account of the temperature monitoring borehole establishment and equipment installation which will aid future workers in equipment maintenance and interpretation of the data.

Table of Contents

1. Introduction

1.1 Background to permafrost and active layer monitoring

With increasing concern about the effects of climate change, widespread monitoring networks have become important in order to try and understand the potential impacts of changing surface air temperature on permafrost temperature and distribution. Permafrost and active layer monitoring has been undertaken in the Arctic, Antarctica, the Tibetan Plateau, the Italian Alps and Western Canada among other locations (e.g. Harris *et al.* 2001, Guglielmin 2004, Guglielmin 2006, Majorowicz *et al.* 2006). Information from individual sites contribute to various permafrost and active layer monitoring networks, for example the Global Terrestrial Network for Permafrost (GTN-P), Thermal State of the Permafrost (TSP), Antarctic Permafrost and Soils (ANTPAS) and the Circumpolar Active Layer Monitoring (CALM) programme.

1.2 Site location

Four boreholes were drilled in November 2005, two in the Wright Valley at the foot of Bull Pass and two at Marble Point on the Ross Sea coastline (Figure 1). One borehole at each site was into moraine material and sampled to recover ice-cemented cores for microbial and geochemical analyses. The second borehole at each site was into the bedrock to enable long-term permafrost temperature monitoring.

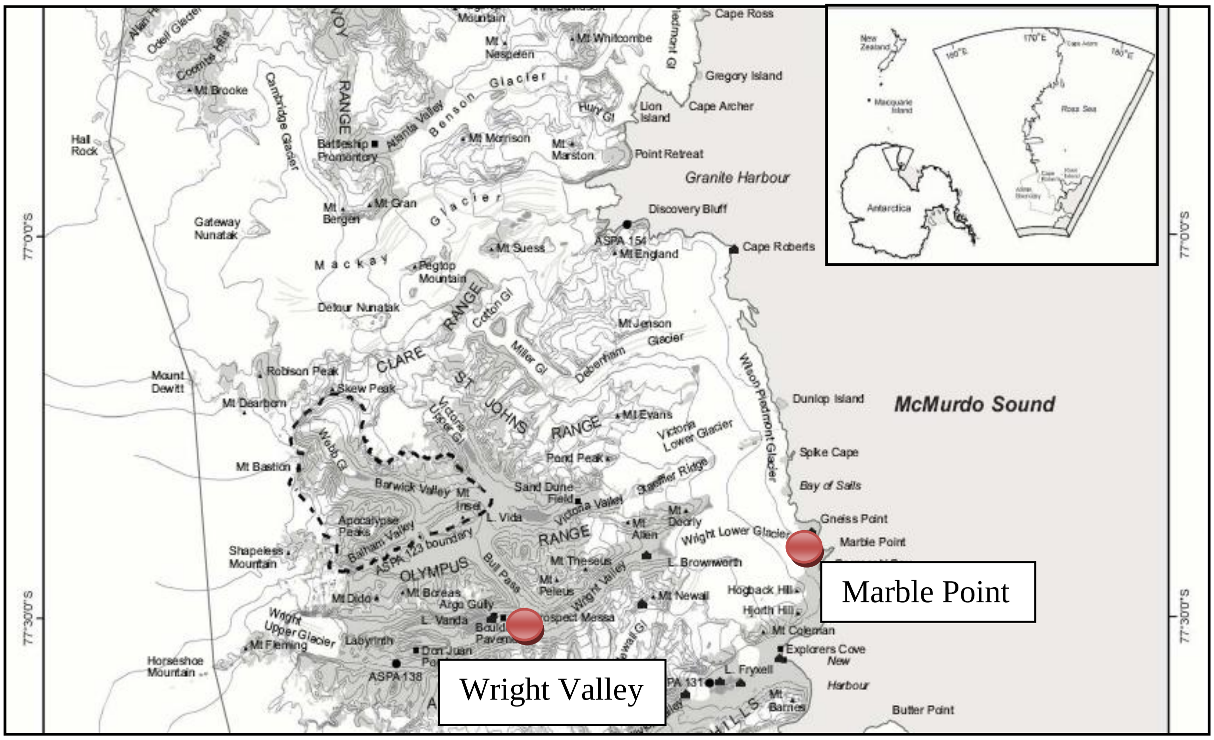

Figure 1: Location of two 30 m deep permafrost temperature monitoring boreholes and two ice-cemented core boreholes at Marble Point and Bull Pass in the Wright Valley in the Ross Sea Region where drilling was undertaken (Map adapted from Map A from http://www.mcmurdodryvalleys.aq/).

1.3 Report objective

The objective of this report is to detail the borehole drilling, ice-cemented core sampling and the installation and instrumentation of permafrost temperature monitoring equipment in the Wright Valley at the base of Bull Pass and at Marble Point. This report provides a comprehensive description of the installation of permafrost temperature monitoring equipment; because the boreholes are intended to be established for long term temperature monitoring, the background information about methods and site location must be readily accessible to any new personnel to the project.

2. Literature review

2.1 The active layer

The active layer can be defined as the upper layer of ground that is subject to annual freezing and thawing cycles, in areas that are underlain by permafrost (Balks *et al.* 1995, Shur *et al.* 2005, Guglielmin 2006). The depth of the active layer varies over distance and time, and has a sensitive response to changes in climate (Harris *et al.* 2001, Guglielmin *et al.* 2003). Site location and climatic zone are primary factors influencing the depth of the active layer. The active layer is deepest at the coastline due to warmer temperatures, and shallowest at the Polar Plateau, while sites in between, such as the Dry Valleys, have intermediate active layer depths (Campbell & Claridge 1987, Bockheim *et al.* 2007). For example, the depth of thawing reaches a maximum of approximately 80 cm in summer at Cape Hallett, a peninsula in Northern Victoria Land (Hofstee *et al.* 2006) compared to 22 cm in Victoria Valley in the McMurdo Dry Valleys (Bockheim *et al.* 2007). Data from the United States Department of Agriculture – National Resource Conservation Services (USDA–NRCS) showed that active layer depth in the McMurdo Sound region was primarily dependent on summer air temperature (Bockheim *et al.* 2007).

2.2 Permafrost

Permafrost is defined as ground that is continually frozen for two or more years (Linell & Tedrow 1981, Balks *et al.* 1995, Shur *et al.* 2005). Three types of permafrost are recognised in the McMurdo Dry Valley systems within 100 cm of the surface; “ground ice, ice-cemented permafrost, and dry-frozen permafrost” (Bockheim *et al.* 2007). Permafrost is spatially variable. Coastal regions tend to be predominantly ice-cemented permafrost (which makes up ~55% of the McMurdo Dry Valleys), while the Victoria and Wright Valleys have the largest areal extent of dry-frozen permafrost (comprising about 43% of the McMurdo Dry Valleys) (Bockheim *et al.* 2007). Ground ice covers about 2% of the McMurdo Dry Valleys (Bockheim *et al.* 2007).

2.3 Permafrost monitoring networks

Monitoring networks are established in order to obtain widespread data for investigative purposes. For example, the 'Permafrost and Climate in Europe' (PACE) project was initiated in 1997 to provide a latitudinal transect of boreholes across Europe (Harris *et al.* 2001). There are several monitoring networks that have been established, such as the Global Terrestrial Network for Permafrost (GTN-P), Thermal State of the Permafrost (TSP), Antarctic Permafrost and Soils (ANTPAS) and the Circumpolar Active Layer Monitoring (CALM) programme. These new boreholes were realised in the framework of the cooperation between Landcare Research (New Zealand), University of Waikato (New Zealand) and University of Insubria (Italy) with the logistic support of Antarctica New Zealand (Event K123) and Progetto Nazionale di Ricerca in Antartide (Project 5.3 Permafrost and Global Change in Antarctica).

Monitoring permafrost and subsurface temperatures over time in networks such as these are designed to lead to improved understanding of the processes occurring (Harris *et al.* 2001), such as the strong influence surface air temperature has on ground surface temperature (Guglielmin *et al.* 2003, Guglielmin 2006, Smerdon *et al.* 2006). Advancing understanding thus leads on to improved modelling capabilities such as the reconstruction of temperature histories from borehole temperature logs (Smerdon *et al.* 2006) or the change in active layer depth in response to warmer surface air temperatures (Kane *et al.* 1991). Borehole monitoring networks may also be used to create tools to predict the changes in permafrost temperatures and distribution which is one of the goals of the PACE monitoring network (Harris *et al.* 2001).

2.4 The importance of borehole temperature monitoring in Antarctica

The relationship between subsurface temperatures in boreholes, such as those established at Marble Point and Wright Valley in Antarctica, is of particular interest to the global warming debate. As permafrost has a sensitive response to surface forcing, continuous monitoring of subsurface temperatures will provide an Antarctic perspective to the global warming debate. In Antarctica the link between subsurface temperatures and above-ground parameters is potentially more direct than in places such as Canada, where vegetation can complicate the relationship between ground surface and subsurface temperatures.

3. Site location and descriptions, drilling operations and ice-core sampling

3.1 Site locations and descriptions of boreholes

3.1.1 Wright Valley temperature monitoring borehole

The Wright Valley permafrost temperature monitoring borehole was drilled at the foot of Bull Pass in the Wright Valley, in the granite bedrock on the valley floor. It was situated 90 m east of the seismic monitoring hut and about 150 m east of the United States shelter hut and 250 m east of the helicopter landing site (S 77^o 31.085, E 161^o 51.070) (Figure 2).

The borehole geology comprised granite for the entire depth. The underlying basement of the Wright Valley floor is comprised of plutonic and metamorphic rocks which are Pre-Cambrian and Ordovician in age (Turnbull *et al.* 1994). The rock is likely to be the Valhalla pluton of the Granite Harbour Intrusives supergroup (Turnbull *et al.* 1994).

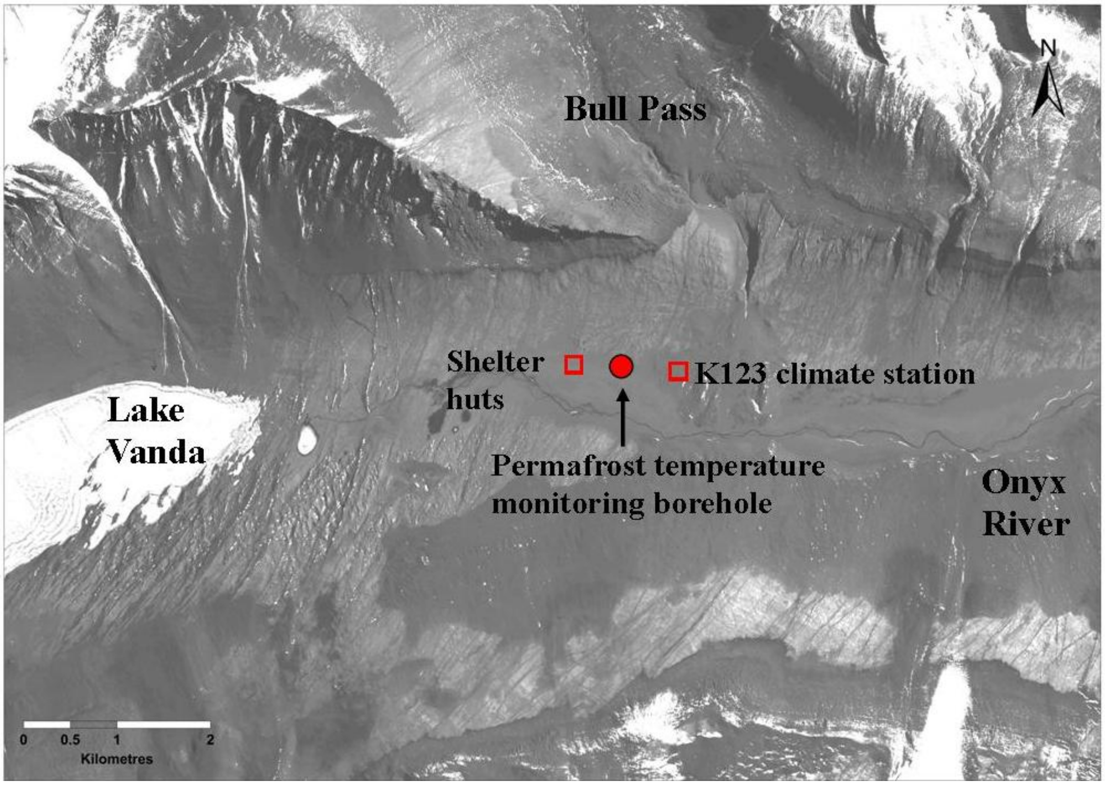

Figure 2: Location of the permafrost temperature monitoring borehole at Wright Valley.

3.1.2 Wright Valley ice-cemented core sampling borehole

The Wright Valley permafrost borehole for ice-cemented core samples was about 400 m south of the United States shelter hut and helicopter landing site (S 77° 31.085, E 161° 51.070) and about 150 m north of the Onyx River. The area selected was in the middle of a rectangular patterned ground polygon, about 4 m from the nearest patterned ground crack. The desert pavement comprised gravels and sand, with the surface being wind-sorted and with few larger stones or boulders (Figure 3).

Figure 3: Drilling site for ice-cemented core sampling in the Wright Valley.

3.1.3 Marble Point temperature monitoring borehole

The Marble Point temperature monitoring borehole was located on a small knob at the south end of the largest coastal ridge, approximately 1400 m east of the United States helicopter refuelling station on an outcrop of marble bedrock (S 77^{o} 24.439, E 163^{o} 43.748) (Figure 4).

The marble bedrock is part of the Ross Supergroup basement complex and is pre-Cambrian to early Palaeozoic in age (Claridge & Campbell 2007). The first 20 m of the borehole was predominantly marble with sections of gneiss 30 cm thick at 10 m and 11 m depth. Gneiss was more dominant between 20 m and 30 m depth, particularly with a 1.5 m thickness at 20 m. Bedrock close to the surface was fragmented, so a core was not obtained for thermal conductivity calculations. In place of a core sample, unweathered surface rock samples were obtained. The marble may be part of the Salmon Marble formation of the Koettlitz group: the Salmon Marble in the Bull Pass – St John's Range is described as "white, rusty-weathering, coarsely crystalline marble and quartzofeldspathic gneiss" (Turnbull *et al.* 1994). Bright brown FeO weathering was noticed at 20 – 30 cm depth in the permafrost core, which corresponds to the "rusty weathering" mentioned in the classification of the Salmon Marble formation by Turnbull *et al.* (1994).

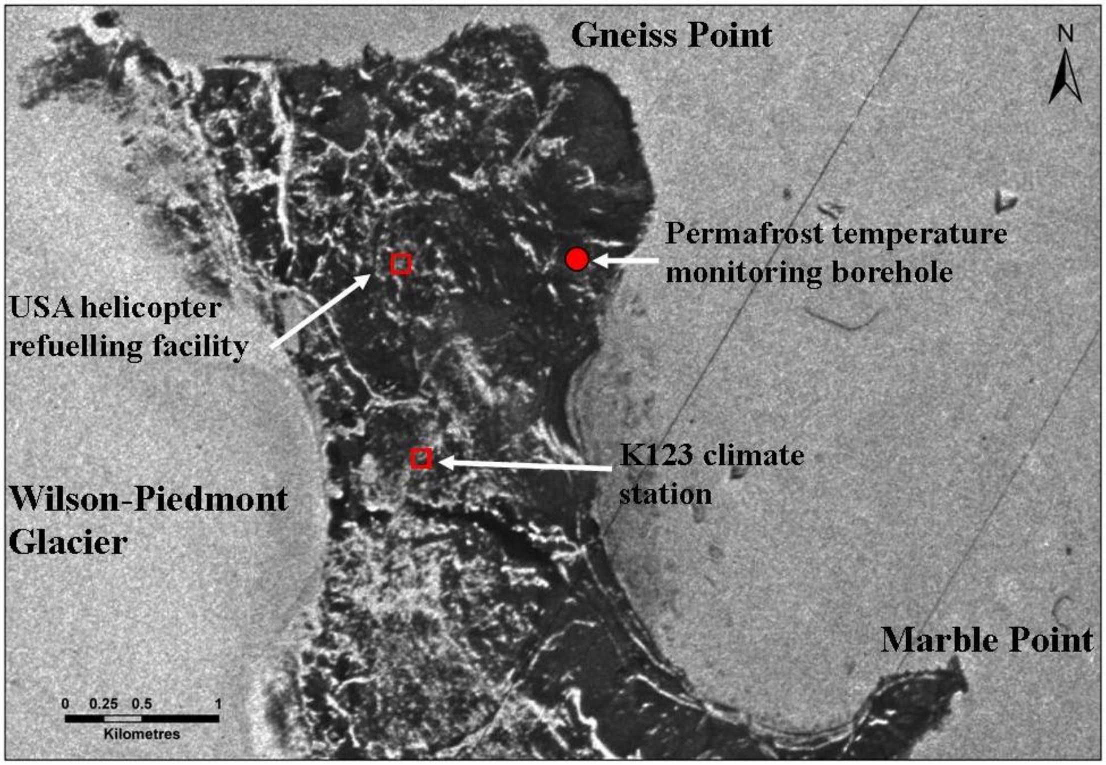

Figure 4: Location of the permafrost temperature monitoring borehole at Marble Point.

The Wright Valley and Marble Point permafrost monitoring boreholes were both established adjacent to automated weather stations managed by Antarctic Event K123 (Landcare Research, Natural Resource Conservation Services of the United States Department of Agriculture and the University of Waikato).

After drilling of the permafrost temperature monitoring boreholes was completed, some initial temperature measurements were taken by lowering a probe into the borehole and taking resistance measurements which were then converted to temperature (Appendix I).

3.1.4 Marble Point ice-cemented core sampling borehole

The permafrost borehole for ice-cemented core samples was located at grid reference S77°25.152’, E163°41.667’ which is about 300 m east of the K123 climate station and about 500 m south of the United States helicopter refuelling station. The borehole was drilled in the middle of a patterned ground polygon, in a relatively boulder-free area. The surface pavement was relatively undisturbed; the desert pavement was angular mixed till comprising sand, gravel and boulders with lithologies including granite, gneiss and marble (Figure 5).

Figure 5: Drilling site for ice-cemented core sampling at Marble Point.

3.2 Drilling operations

Drilling was undertaken using a compressed air-driven drill (Figure 6). A barrel corer was used where rock or ice-cement core sampling was required. A “rock-hammer” drill bit was used through most of the depth of the temperature monitoring boreholes to speed up the drilling process. Where the rock hammer was used, drill cuttings were sampled at 1.0 m intervals for mineralogical determination. Brief borehole logs were recorded (Tables 1 and 2).

In the temperature monitoring boreholes at both Wright Valley and Marble Point, the drill bit was changed at 19.5 m depth to a smaller diameter, resulting in a ledge within the borehole. The borehole was 101 mm in diameter at the top of the hole, and a steel cap with an external diameter of 88.9 mm was installed at the top of the borehole to prevent the build up of sediment or sand accumulation in the hole. Rock samples or core samples from near the top of the temperature monitoring borehole were taken for thermal conductivity analysis.

The final depth of the Wright Valley temperature monitoring borehole recorded in 2005 was 29.75 m and the Marble Point temperature monitoring borehole was 30.25 m deep. The depths of both boreholes were checked in January 2008 using a 35 m braided cord (with no apparent stretch) marked at one metre intervals with a 0.45 kg (16 oz) weight attached at the bottom. At both sites, the plumb line travelled easily down with no stopping. The measured depth was 29.4 m at the Wright Valley and 31.2 m at the Marble Point site. The difference in depth between 2005 and 2008 is most likely due to the limitations of accuracy of the measurement techniques used. Though slightly different, the depths plumbed indicated that there was negligible accumulation of ice or sand in the bottom of either borehole.

Because the bedrock at both temperature monitoring boreholes was coherent, no linings were installed. A steel cap which extended about 15 cm below the ground surface was installed in each temperature monitoring borehole to protect the top of the borehole and to prevent snow or sand from entering the borehole.

The final depth of the ice-cemented core sampling borehole in the Wright Valley was 7.5 m and the ice-cemented core sampling borehole at Marble Point was 2.7 m deep. Following completion of the ice-cemented core sampling boreholes, a rock was placed over the top of each one, primarily to restore the visual appearance of the sites.

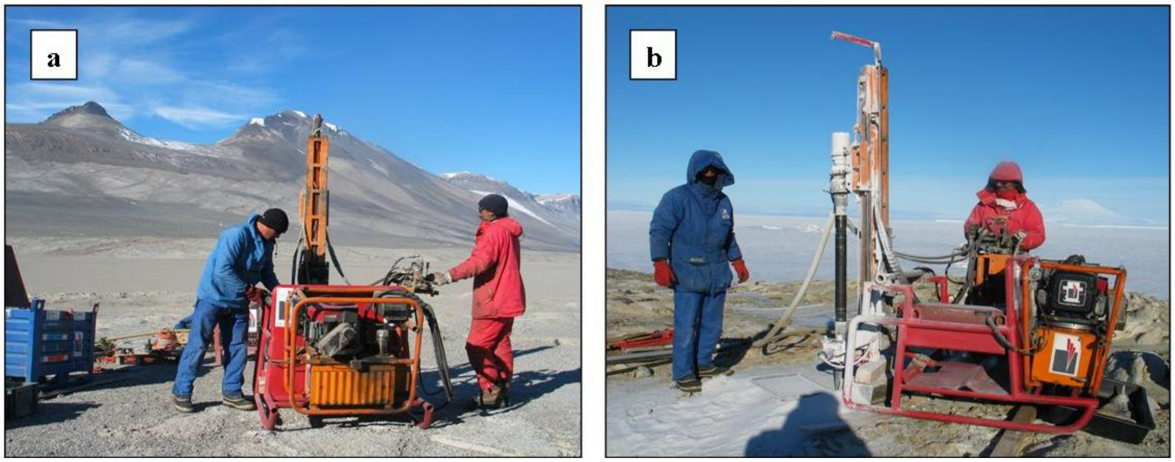

Figure 6: Operation of the drilling machinery (a) in the Wright Valley at the foot of the Bull Pass and (b) at Marble Point.

3.3 Ice-cemented core sampling in the Wright Valley and Marble Point

The ice-cemented cores were sent to Professor M. Guglielmin, University of Insubria, Italy for archiving and sampling (Figure 7). The drill logs for Wright Valley (Table 1) and Marble Point (Table 2) show composition of the cores and the changes with depth.

Table 1: Drill log for the ice-cemented core sampling borehole in the Wright Valley, November 2005.

Depth (cm)	Description
0 – 45	Loose dry gravely sand, ice cement at about 40 cm.
45 – 240	Ice-cemented gravely sand - good core.
240 – 340	Some good core was obtained from this depth range. Some was not ice-cemented. Material comprised sand dominated with rounded pebbles.
340 – 410	The core was moist but not ice-cemented (warmed by drilling). Samples were kept.
410 – 435	Ice-cemented core.
435 – 530	The core was soft (semi-thawed) but mainly intact. Some of the material in this depth range was no longer intact and was bagged as loose samples. Where the core was soft but intact we retained it. There should be no biological contamination in the centre of the core from this depth range but the user needs to be aware that the core was thawed by the drilling process and was refrozen within approximately one hour.
545 – 575	The core came up hot. Some material was soft but intact and some was loose. Samples from this depth range were bagged in order, bottom to top, and only the coherent bits will be sterile in centre.
575	Put on larger drill bit to prevent melting in centre of core
575 – 640	Excellent solid ice cemented core, some ice saturated
640 – 750	There was about 30 cm of non-coherent material and about 80 cm of solid ice cemented core

Table 2: Drill log for the ice-cemented core sampling borehole at Marble Point, November 2005.

Depth (cm)	Description
0 – 10	Loose, single grained dry gravely sand.
10 – 20	Weakly ice-cemented greyish brown loamy sand.
20 – 30	Moist gravely loamy sand, bright brown colour (FeO weathering).
30 – 35	Moist gravely loamy sand, some ghost mafic rocks dark dull brown colour.
35 – 60	Gravely sandy loam that was moist. Presumably some thawing due to drill heat. The core came up soft but intact and the centre is probably still sterile. Dull grey-brown colour.
60 – 70	Ice core – thin end at top.
60 – 70	Thawed material that was clay-brown colour came up in association with the ice-core listed above (hence two samples with same depth labelling). Sandy clay loam.
70 – 85	Ice core.
70 – 85	Thawed material (Grey, clay-brown colour) came up with ice core of same depth range. Sandy clay loam.
85 – 100	Ice cemented core – one section is black and looks like shattered rock.
100 – 115	Ice-cemented sandy core.
115 – 135	Ice-cemented core – sandy with some weathered rock material.
135 – 195	One long core, though a few cuttings and rock pieces from each end not saved. Core kept in plastic sleeve.
195 – 215	Frozen core in three pieces.
215 – 255	The core was partially shattered and some was lost and some saved. The ice-cemented segment was saved. Fragments showed ice-saturation. Included strongly weathered mafic rocks that could be crumbled by hand and some areas with Fe_2O_3. Finer cuttings were dominantly grey coloured.
255 – 270	Some fine material then cutting rock – rockpowder and stone fragments, some strongly oxidised – may be weathered paleosurface – interpreted as top of bedrock.

Figure 7: Ice-cemented core taken from Marble Point for archiving and analysis at University of Insubria, Italy.

4. Temperature monitoring equipment preparation

4.1 Inventory

The temperature monitoring equipment (Table 3) was checked, assembled, and calibrated at the University of Waikato prior to transport to Antarctica in December 2006.

Table 3: Summary of permafrost temperature monitoring equipment

Instrument	Quantity supplied
Campbell Scientific CR1000 measurement and control system datalogger	2
Weather-resistant 16”x18” enclosure	2
PS100 12V power supply with charging regulator	2
20W Solar panel, 10’ cable	2
Campbell Scientific CFM100 Compact Flash Module	2
64MB Silicon drive CF memory card	4
Campbell Scientific Model 109 Temperature sensors	32
12V lead-acid battery 24 amp-hours	4

4.2 Measurement and labelling of cables

Various target depths for temperature monitoring were identified (Table 4) and the Campbell Scientific Model 109 temperature sensors of various lengths were measured accordingly. The target ground level depth was marked on each thermistor cable using red insulation tape (Figure 8). Each cable was measured from the top of the sensor, with the bottom edge of the red tape marking the target ground level. Each sensor was 6 cm long. The temperature sensors were then wired into a CR1000 datalogger.

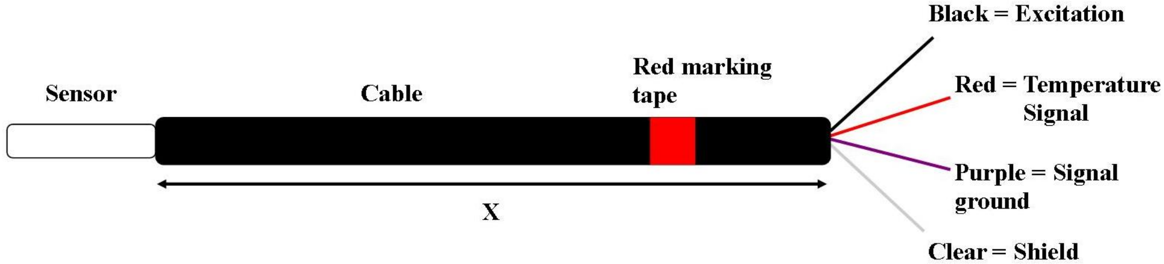

Figure 8: Marking of thermistor cables for depth from ground to sensor for each target depth (x).

Table 4: Lengths of 109 temperature sensor cables and associated target depth to monitor in borehole.

Sensor number	Cable length (feet)	Cable length (m)	Target depth to sensor (m)
1	10	3.05	0.3
2	11	3.35	0.6
3	13	3.96	1.0
4	16	4.88	2.0
5	19	5.79	3.0
6	26	7.92	5.0
7	32	9.75	7.0
8	42	12.80	10.0
9	49	14.94	12.0
10	55	16.76	14.0
11	61	18.59	15.0
12	68	20.73	16.0
13	75	22.86	18.0
14	85	25.91	20.0
15	91	27.74	25.0
16	108	32.92	29.5

4.3 Calibration test of 109 temperature sensors

The 109 temperature probes used in Wright Valley and Marble Point have a 'worst case' error of ± 0.6°C over the range of –50°C to +70°C when the thermistors are not tested before installation. The accuracy of the 109 thermistors used in the permafrost temperature monitoring boreholes was improved due to a calibration test undertaken in December 2006.

The Campbell Scientific 109 thermistors were calibrated at the University of Waikato in December 2006 using an ice and water bath. The temperature sensor used in the ice and water bath along with the thermistors was an Amarell Electronic ama-digit, ad 170 th model thermometer. The thermometer was calibrated on May 5th 2006 and has a calibration that is traceable to the Australian national standards of measurement, which are recognised internationally. The resolution of the thermometer is ± 0.1°C at the 95% confidence level. The thermistors were all reading in close agreement to the thermometer therefore the maximum error that can be expected of the 109 sensors installed in the borehole is ± 0.1°C.

4.4 Wiring the datalogger

Both CR1000 dataloggers were wired according to specifications in the CR1000 operations manual. Each probe had four wires to connect to the datalogger: black (excitation), red (temperature signal), purple (signal ground) and clear (shield). The excitation wires (black) of all sixteen thermistors were wired to an external connection, which was connected to one excitation channel (EX1). The temperature probes require a single-ended channel, so each red wire was connected sequentially into single ended channels 1 – 16 i.e. red wire for cable 1 was connected to single ended channel 1, red wire for cable 2 was connected to single ended channel 2 and so forth for all 16 cables. The purple signal ground wires were connected to the signal ground port (⏚) in pairs i.e. the purple wires for cables 1 and 2 were connected together in the signal ground channel associated with the single ended channels for the red wires (Figure 9). The clear shield wires were connected to the grounding port (G). The full wiring diagram is located in Appendix II.

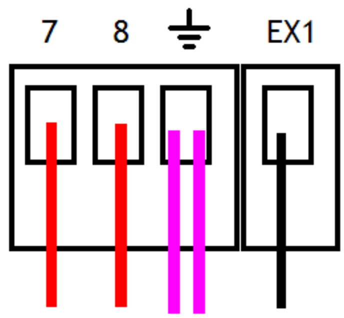

Figure 9: Schematic of one section of CR1000 datalogger wiring panel, showing the red temperature signal wires for sensors 7 and 8 being wired into the single ended channels 7 and 8. The purple signal ground wires for sensors 7 and 8 are wired into the signal ground port, and the black excitation wire is located in excitation channel one (Not to scale).

4.5 Solar panel stands

A simple A-frame stand was designed to support the solar panels (Figure 10). The front of the stand holds the panel at approximately 15° and directed to the North when mounted in order to catch maximum sunlight for charging the batteries at first sunlight in the spring. Stands were constructed of aluminium and were ‘L-sections’ in profile. The approximate dimensions are shown in Figure 11. The solar panel stands are about 0.77 m tall.

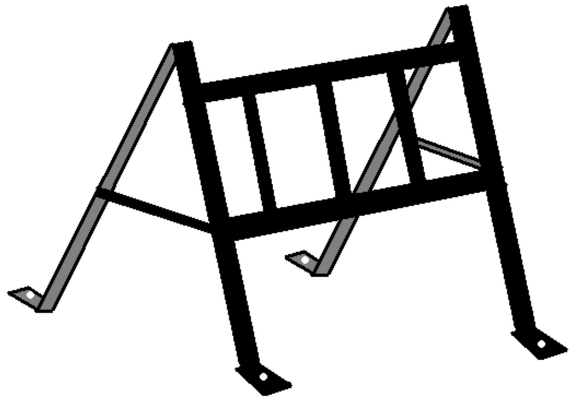

Figure 10: Schematic of solar panel arrangement used at both borehole locations. The solar panel was mounted on the three vertical bars between the A-frame legs. The feet are wide and flat for rocks to be piled on for stabilisation, and the holes are for pegs if required (Not to scale).

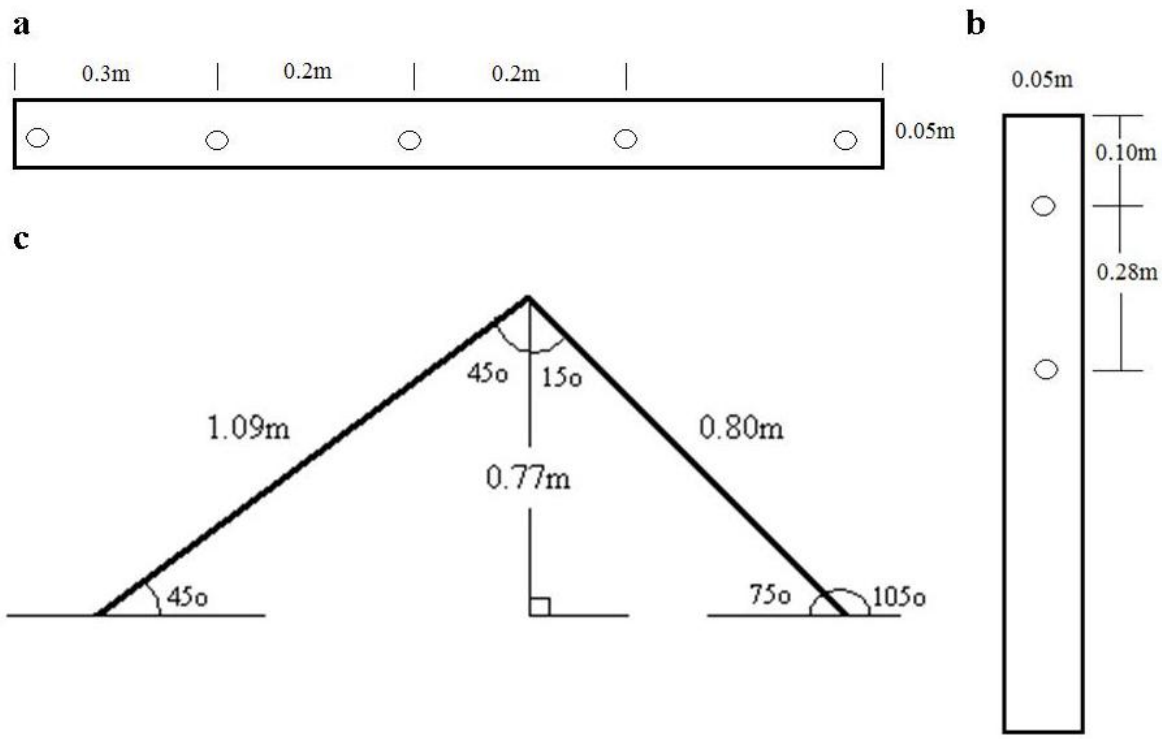

Figure 11: Schematic view of solar panel stand with dimensions. (a) Front view of mounting rail (b) front view of one side component of A-frame (c) side-on view (Not to scale).

The dismantled solar panel stand components (Table 5) were sent to Scott Base in December 2006 and reassembled prior to transport to the field sites in January 2007.

Table 5: Components of one solar panel stand when disassembled, as sent to Scott Base in December 2006.

Constituents	Quantity
A-frame sides	2
Brace between sides at back	1
Side braces	2
Brace between sides at front	2
Mounting rails	3

5. Temperature monitoring equipment installation – January 2007

The temperature monitoring equipment was installed in the temperature monitoring boreholes at Wright Valley and Marble Point on 16 January 2007. Temperatures were measured hourly with the mean recorded to the memory card in the Compact Flash Module every six hours. Daily minima and maxima are also recorded. Instructions for removing the memory cards correctly are contained in Appendix III.

5.1 Wright Valley

The temperature monitoring borehole at Wright Valley was visited on 16 January 2007 from 9:00 am to 12 noon. Initial seals on the hole around the cap from drilling in 2005 were in good condition. Additional rubber 0.5 cm thick was cut to shape and placed under the collar of the borehole cap to ensure a good seal between the cap and the ground. Cables were threaded through a U-bend plumber's fitting to prevent additional sediment entering the borehole after installation was completed. The U-bend was secured to the borehole cap with a rubber step-down connector, which was connected to both the cap and the U-bend using metal hose clips that were tightened with a screwdriver. A step-down rubber sleeve and hose clip was used at the outer end of the U-bend to secure the cables. When the metal clip was tightened to its limit, the cables were not securely held by the rubber sleeve, so duct-tape was used to further seal the cables (Figure 12) to prevent sediment and/or snow from entering the borehole.

Figure 12: Thermistor cables leading into the borehole at Wright Valley.

A small lead sinker was attached to the bottom of the cable bundle to give it weight to ensure maximum depth into the borehole was achieved. There was some initial difficulty getting the bundle of cables to reach the desired depth. The sensors were not secured tightly to the bundle of cables and one of the sensors became lodged between the walls of the hole. Upon exerting pressure, sensor number 11 bent. The bundle of cables was subsequently removed and the remaining sensors were taped securely with insulation tape to prevent them from catching on the edges of the hole and the cable was lowered once more into the borehole. Sensor 11 was not removed at this time.

The bundle of sensors did not make it to the target depths within the borehole. As the cable bundle was being lowered, the bundle appeared to be supporting its whole weight. When the bundle was lowered further into the hole, it seemed that the weight of the cable bundle was no longer supported and was resting on something. Possible explanations included:

- The borehole may have partially filled with sediment or ice over the last year. (Proven false by checking depths in 2008).
- Sensors got trapped on the ledge within the hole at 19.5 m as a result of changing the drill bit during the drilling operation of 2005.

- Sensors may have jammed at an indeterminate depth between the walls of the borehole.

After attempting to get the bundle of cables further into the borehole, it was decided to leave cables at the depth where the sensors were apparently hanging freely. The target depth-to-sensors (Table 4) was not achieved in 2007 and some sensors were not within the borehole. The length of cable from theoretical ground surface (as denoted by red tape on cables) to the actual ground level was measured as 2.8 m and 2.8 m was subtracted from the target depths to give the depths to sensors as installed in 2007 (Table 6), assuming that the sensors stretched to the full length when inserted into the hole. Four sensors did not reach within the borehole (Table 6). The exposed sensors were subsequently buried lightly with surface gravel to approximately 0.1m depth.

Before we left, a program (Appendix IV) was installed onto the datalogger that measured temperature every hour and averaged every six hours, resulting in four mean temperatures per day being recorded to the memory card in the Compact Flash Module. The daily maximum and minimum temperatures are also recorded.

Table 6: Sensor depths as installed at the Wright Valley monitoring station for 16 January 2007 to 17 January 2008.

Sensor number	Cable length (feet)	Depth to sensor January 2007 – January 2008 (m)	Depth to sensor 17 January 2008 onwards (m)
1	10	0.1[a]	0.3
2	11	0.1[a]	0.6
3	13	0.1[a]	1.0
4	16	0.1[a]	2.0
5	19	0.2	3.0
6	26	2.2	5.0
7	32	4.2	7.0
8	42	7.2	10.0
9	49	9.2	12.0
10	55	11.2	14.0
11	61	12.2	15.0
12	68	13.2	16.0
13	75	15.2	18.0
14	85	17.2	20.0
15	91	22.2	25.0
16	108	26.7	29.5

[a] *Sensor buried in shallow gravel*

The solar panel stand was set up to the south of the enclosure and faced approximately north to maximise the early sunlight in spring. Local rocks were used to anchor the feet solidly. The datalogger enclosure was also secured using rocks (Figure 13).

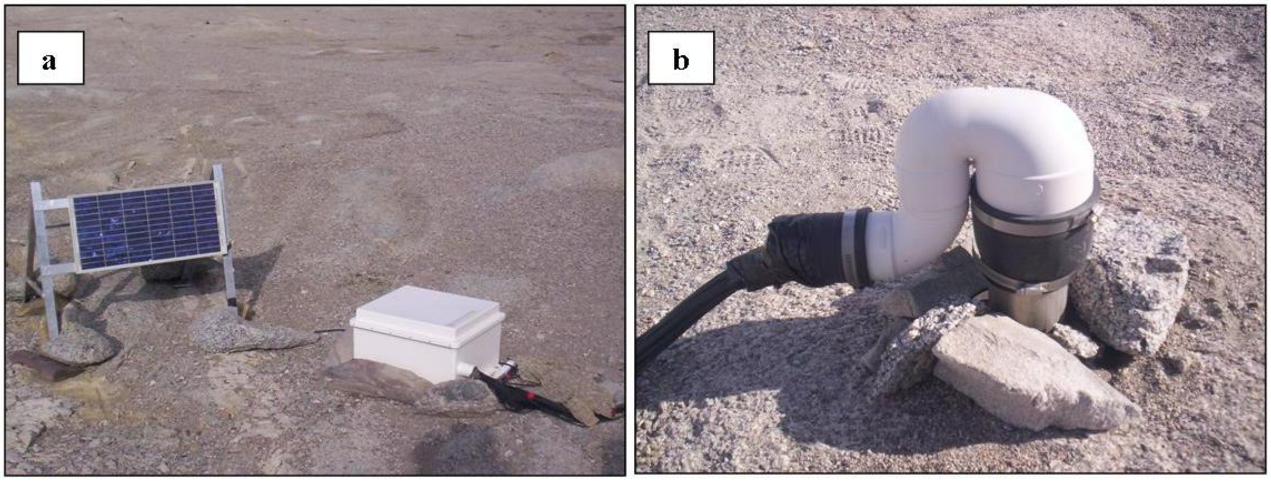

Figure 13: Arrangement of Wright Valley (a) monitoring enclosure and solar panel (b) U-bend fitting with bundle of cables (left) leading towards the enclosure.

5.2 Marble Point

The Marble Point location was visited on 16 January 2007. Following the difficulties experienced at the Wright Valley site, all sensors were secured closely before attempting to lower the bundle of cables down the borehole. The temperature sensor cables were secured using a plumbers U-bend fitting (Figure 14).

Figure 14: Thermistor cable leading into the U-bend plumbers fitting at Marble Point.

The bundle of sensors behaved similarly to those at the Wright Valley (Section 5.1) and did not make it to the target depths. The sensors were installed to a depth where the bundle of cables was hanging freely. The measured length of cable from the ground surface to the desired zero-point was 2.0 m, which was subtracted from the length of the sensor cable to give the adjusted depth to the sensor (Table 7). Three sensors were left exposed outside the secured U-bend. Sensors 1 and 3 were left exposed on the ground's surface and sensor 2 was covered by a marble rock approximately 5 cm thick. Sensor 4 was within the U-bend.

Table 7: Sensor depths as installed at the Marble Point monitoring station for 16 January 2007 to 17 January 2008

Sensor number	Cable length (feet)	Depth to sensor January 2007 – January 2008 (m)	Depth to sensor 17 January 2008 onwards (m)
1	10	0[a]	0.3
2	11	0[b]	0.6
3	13	0[a]	1
4	16	0[c]	2
5	19	1.0	3
6	26	3.0	5
7	32	5.0	7
8	42	8.0	10
9	49	10.0	12
10	55	12.0	14
11	61	13.0	15
12	68	14.0	16
13	75	16.0	18
14	85	18.0	20
15	91	23.0	25
16	108	27.5	29.5

[a] *Sensor on ground surface*
[b] *Sensor covered by rock approximately 5cm thick*
[c] *Sensor inside U-bend device*

The solar panel was assembled facing approximately north and local rocks were used to secure the enclosure, solar panel and cable (Figure 15).

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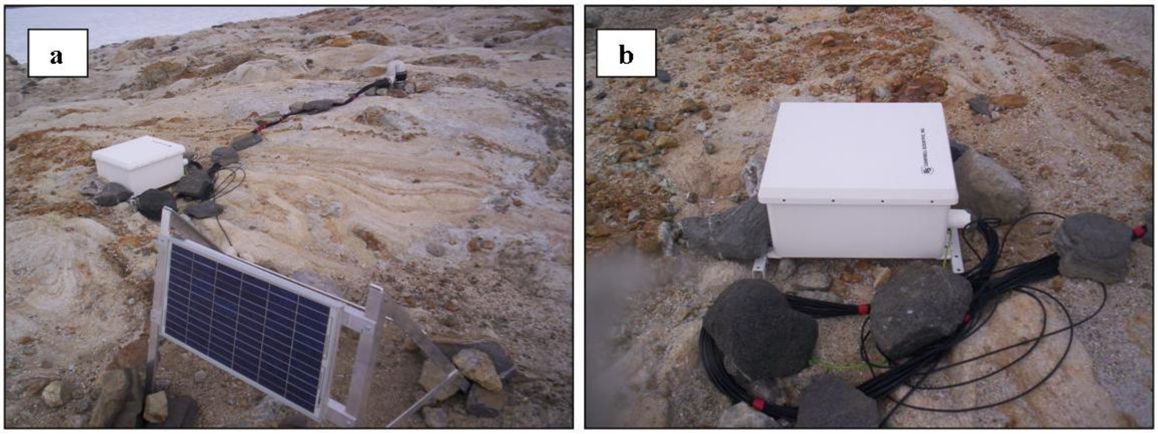

Figure 15: Arrangement of Marble Point monitoring station (a) solar panel set up and (b) enclosure.

A short-term temperature monitoring program was not initiated at Marble Point during the site visit due to lap-top battery failure. The datalogger was pre-programmed at Scott Base so that when the battery was turned on, the Marble Point station started monitoring temperature as per the long-term monitoring program (Appendix IV). The Marble Point borehole station was revisited on 18 January 2007 and the memory card in the datalogger was swapped, providing 36 hours of initial data.

6. January 2008 site visits

6.1 Wright Valley

The borehole at Wright Valley was visited on 17 January 2008 from approximately 2 pm to 5 pm. The configuration of equipment from January 2007 appeared to be in good condition, with no obvious wear and tear to either the solar panel or stand, enclosure or U-bend rubber coupling attached to the borehole cap. The thermistors buried in shallow gravel in 2007 were still covered to approximately 0.1 m.

The data for 2007 was saved to the memory card which was removed from the Compact Flash Module and a clean card was inserted. A laptop was used to connect to the datalogger for a manual download of the 2007 data to serve as a back up copy. The baud rate was changed from 115200 to 9600, allowing successful downloading.

The cable of thermistors was removed from the borehole and the insulation tape removed so each cable was lying flat individually. The sensor damaged in 2007 (number 11 installed at 12.2 m depth) was replaced with a new 109 probe. There was no obvious stretching of the cables due to the weight, and no bends in the cable to indicate the bundle had been caught up within the hole.

Separate lead sinkers (16 oz) were attached to each of the 16 temperature sensors using string (Figure 16), tying to both the thermistor and the cable. All sensors were then lowered back into the borehole, with the longest temperature sensor lowered first and the next longest sensor second and so on, to ensure there was minimal obstruction by sensors already within the borehole. All 16 sensors travelled down easily, with no obvious catching.

The enclosure was moved approximately 0.5 m closer to the borehole to allow the thermistor cables to reach the desired ground level. There was no strain evident on the cable connecting the datalogger to the solar panel. The U-bend coupling device was reattached and we were confident that the thermistors were now within ±5 cm of the original target depth (Table 4).

The hole where the wires were threaded into the enclosure was sealed with new sealing putty following the wiring of a new thermistor into the datalogger to replace the bent number 11 probe.

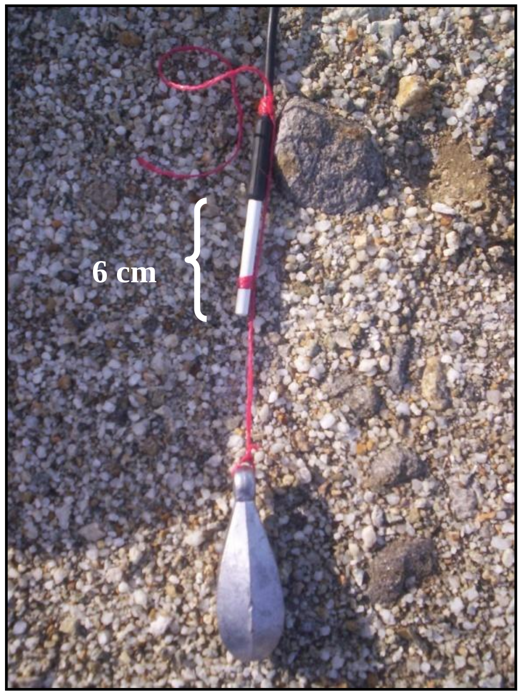

Figure 16: Sinker attached to a thermistor ready to be lowered back into the borehole. Note the length of the white sensor is 6 cm.

6.2 Marble Point

On 17 January 2008 the Marble Point borehole site was revisited from 9:30 am to 12 noon. The solar panel and stand, enclosure and U-bend rubber coupling were all in good condition.

The memory card from the Compact Flash Module was swapped and a clear memory card was inserted. There was a problem trying to connect the laptop computer to the datalogger for a manual download, as the error message "Datalogger connection failed" continually appeared. Several attempts were made to connect; using different ports on the datalogger, a different connection cable, and altering the baud rate from 115200 to 9600 but attempts were unsuccessful. On 18 January, at approximately 6:30 pm, we stopped briefly at Marble Point and managed to connect the laptop to the datalogger. The data for 2007 and January 2008, including one day with the thermistors at new depths, were downloaded to the laptop. It is unclear why the laptop connected the second time, as nothing was changed further after the previous attempt to connect. The data for 2007 was recorded on the memory card that was removed on 17 January 2008, which would have been used had the manual download of data not been successful.

The cable of thermistors was removed from the borehole and the insulation tape removed so each cable was lying flat individually. Thermistors had individual sinkers attached to them (Figure 16). Thermistors were lowered individually in the borehole and travelled down easily with no obvious blockages. The U-bend coupling was reattached and we were confident that the thermistors were now within ±5 cm of the target depths (Table 4).

7. Initial results – January 2007

7.1 Wright Valley

A short term monitoring program (Appendix IV) collected one minute temperature measurements during the installation process. Approximately 25 minutes after installation, the variation in temperature smoothed out (Figure 17) as the thermistors adjusted to temperatures in the borehole. Following installation, the sensors from 7.2 m to 26.7 m all showed a constant temperature at ~ –20°C. At 49 minutes following installation, four sensors showed a sudden decrease from ~ –19.0°C to ~ –23.0°C, before returning to ~ –19.0°C. The sensors were at 7.2 m, 12.2 m, 17.2 m and 22.2 m depth. The most likely explanation for this is an accidental short circuit during the installation process as we were still working around the datalogger at the time and there is no evidence of sudden dips in the data again over the year-long record.

The four sensors buried in shallow gravel showed more variation in temperature, most likely because they were closer to the ground's surface and only lightly buried, as well as due to continued disturbance caused during adjustment. Below the ground surface, the temperature decreased with depth.

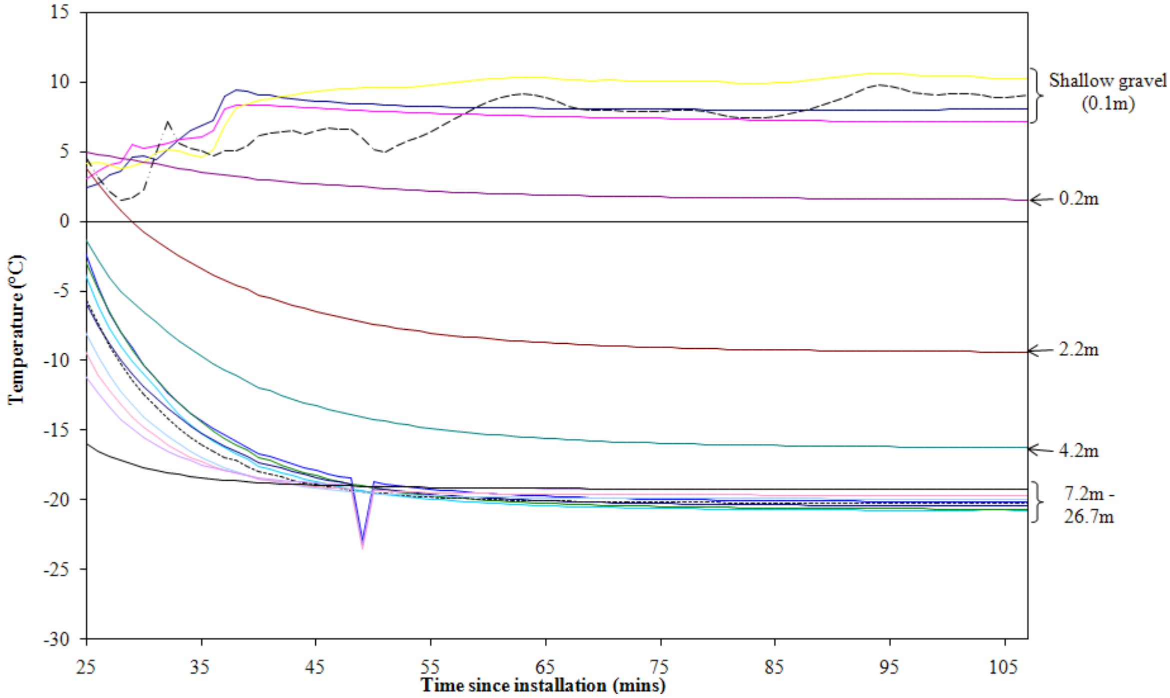

Figure 17: Initial temperature data recorded between 25 and 107 minutes after installation at Wright Valley on 16 January 2007

In January 2007, sensors from 7.2 m to 26.7 m depth exhibited an increase in temperature with depth (Figure 18).

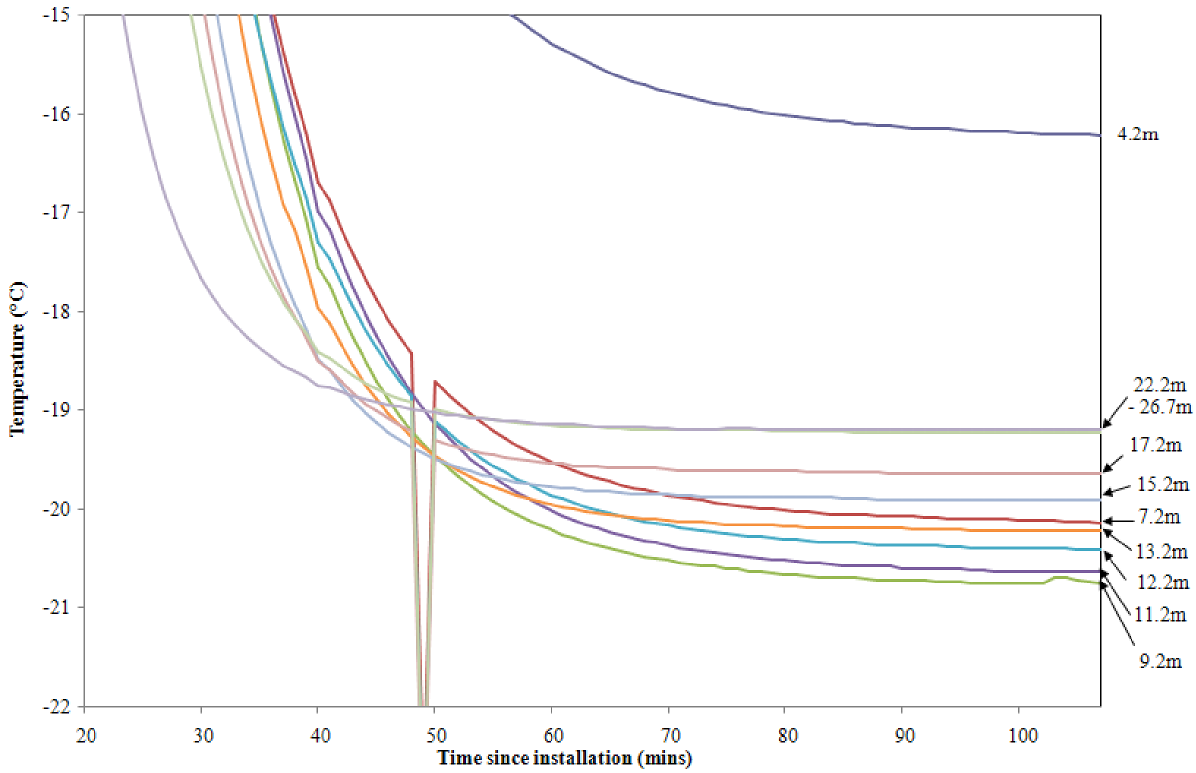

Figure 18: Temperatures measured by sensors from 9.2 m to 26.7 m depth, monitoring between 20 and 107 minutes after installation at Wright Valley (Enlarged view from Figure 17). Temperatures were measured once per second with the mean being recorded once per minute. Temperature curves are labelled with the depth of the temperature sensor.

7.2 Marble Point

Unlike the Wright Valley borehole, the Marble Point borehole did not have a high frequency short term monitoring program running. Thirty-six hours of initial data were obtained by revisiting the site on 18 January 2007. The first six hours show the adjustment of the sensors following installation and after this period the temperature recorded between 8.0 m and 27.5 m depth had stabilised at about –18°C (Figure 19).

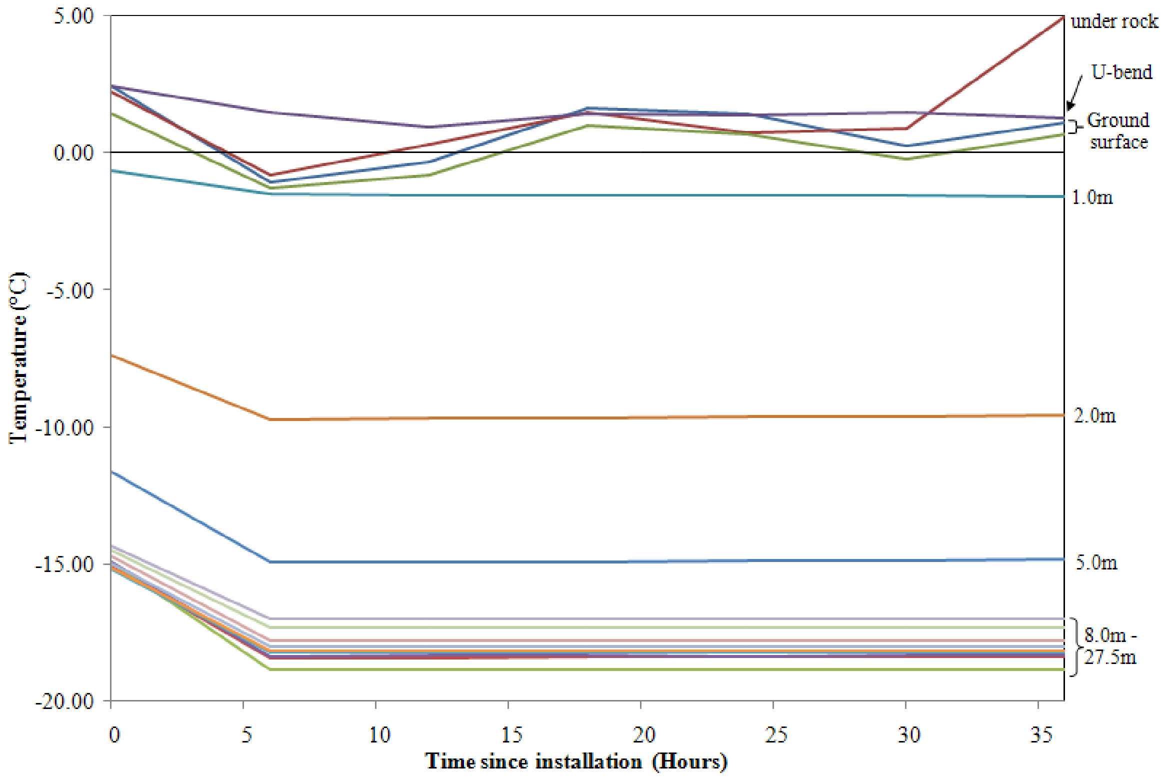

Figure 19: Initial temperature data recorded by the monitoring station at Marble Point between 6:00pm (0 hours following installation) 16 January 2007 and 6:00am 18 January 2007 (36 hours following installation).

Sensor 2 was covered by a rock (about 5 cm thick) and showed an increasing temperature around 36 hours after installation (6:00am 18 January 2007). The variability in the temperature measured by the upper three sensors was most likely caused by diurnal variation in the surface environment. Sensor 4 was placed within the U-bend device. The temperature recorded in the U-bend was similar in magnitude to those recorded by the sensors near the ground's surface but with less diurnal variation.

For the 36 hours of initial data in January 2007, the temperature between 10.0 m and 27.5 m was observed to increase with increasing depth (Figure 20).

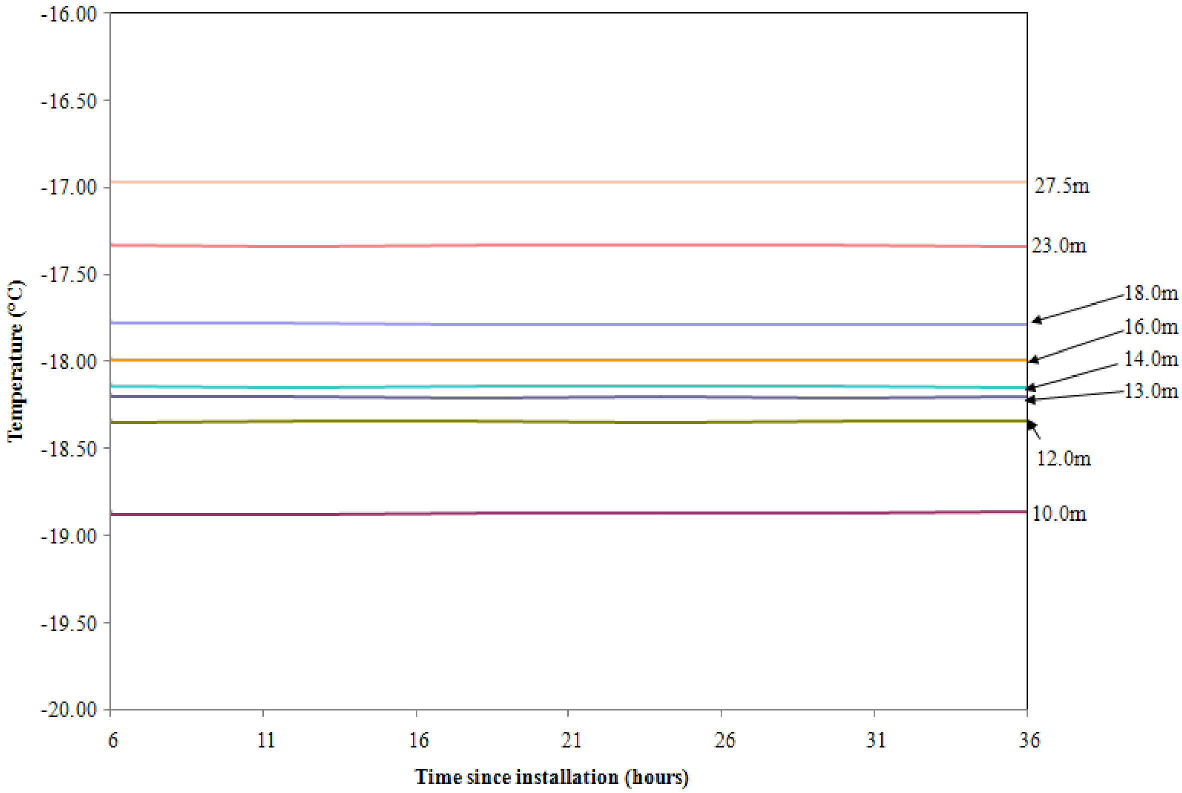

Figure 20: Temperatures measured by sensors from 10.0 m to 27.5 m depth, monitored between 6 and 36 hours after installation at Marble Point (Enlarged view from Figure 19). Temperatures were measured once per hour with mean recorded once every six hours. Temperature curves are labelled with the depth of the temperature sensor.

8. Data collected 17 January 2008 – full year

8.1 Wright Valley and Marble Point depth profiles

8.1.1 Initial 2005 temperature profiles at Wright Valley and Marble Point

Initial measurements of temperatures within the temperature monitoring borehole at Marble Point were first undertaken about 16 hours after completion of drilling in November 2005, and after at least 24 hours at the Wright Valley temperature monitoring borehole (Appendix I). Measurements were taken on two days at both Wright Valley and Marble Point sites. The Wright Valley temperature measurements were taken on 28 and 29 November and the Marble Point temperature measurements were taken on 22 and 24 November. An initial borehole temperature profile for each site was constructed using the measurements on 29 November for Wright Valley and 24 November for Marble Point.

Initial temperatures measured in the boreholes after drilling in 2005 showed that Marble Point and Wright Valley had similar temperatures in the upper 5 m of the borehole (Figure 21). At Wright Valley and Marble Point, temperatures decrease rapidly with depth to about 6 m, after which the temperature increases by about 3°C to 21 m, below which temperature was reasonably steady. Wright Valley borehole temperatures below about 9 m are about 2°C cooler than those at Marble Point, but the shape of the profile is similar.

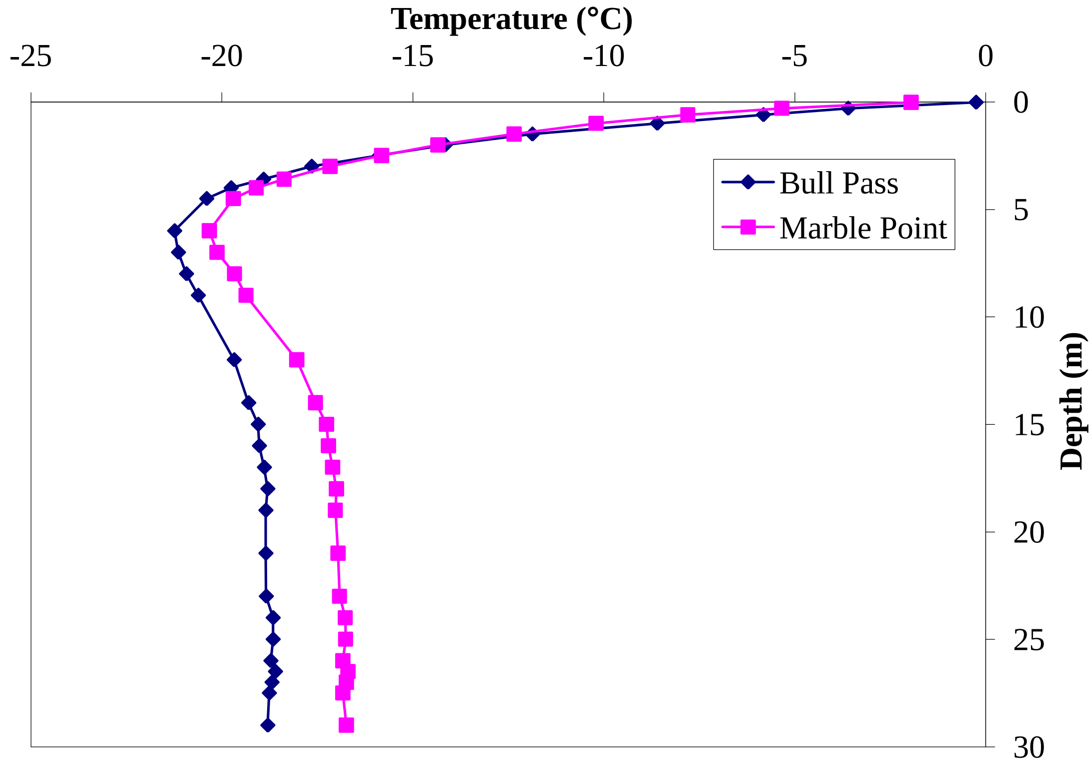

Figure 21: Initial temperature profile in the boreholes at Wright Valley and Marble Point in November 2005. The profiles were constructed using initial temperature measurements (Appendix I) from 29 November 2005 at Wright Valley and 24 November 2005 at Marble Point.

8.1.2 Temperatures measured by dataloggers in 2007

The temperatures measured by the dataloggers at a date in 2007 similar to the day of the 2005 measurements were collated (Appendix I) to compare to the initial measurements conducted in 2005. Temperatures for Wright Valley were reported as at 12:00pm (midday) on 29 November 2007. Marble Point temperatures were at 12:00pm on 24 November 2007 and were used to construct temperature-depth profiles.

8.1.3 Comparison of 2005 and 2007 temperature profiles at Wright Valley and Marble Point

A plot of the temperature measurements for 2005 and 2007 at Wright Valley showed that the depth profiles were similar in magnitude and pattern (Figure 22). The 2007 temperature profile is about 1.8 – 2.5°C cooler in the upper portion of the borehole, but below 7.2 m depth the difference between 2005 and 2007 measurements decreases to about 0.3°C.

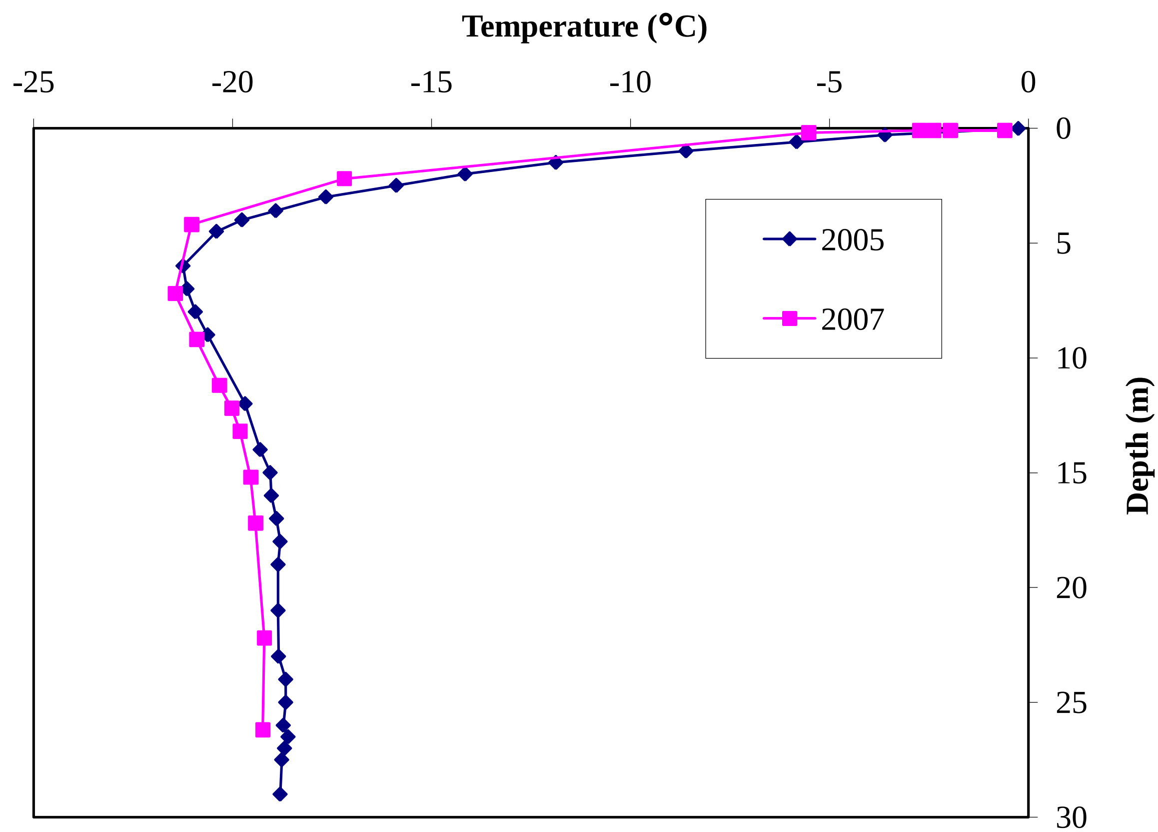

Figure 22: Comparison of initial temperature profile (29 November 2005) and temperature profile measured by 109 temperature probes 12:00pm 29 November 2007 for the Wright Valley temperature monitoring borehole.

A plot of 2005 and 2007 temperature measurements for Marble Point showed similarity in magnitude and pattern (Figure 23). The match between the 2005 and 2007 profiles was not as close as seen at Wright Valley. In approximately the upper

4.5 m of the borehole, the 2007 temperatures are up to 4.5°C cooler than those measured in 2005. The 2007 profile is between 0.3 and 1.2°C warmer than the 2005 profile between about 5 m and 14 m depth, below which it becomes about 0.5°C cooler than the 2005 profile.

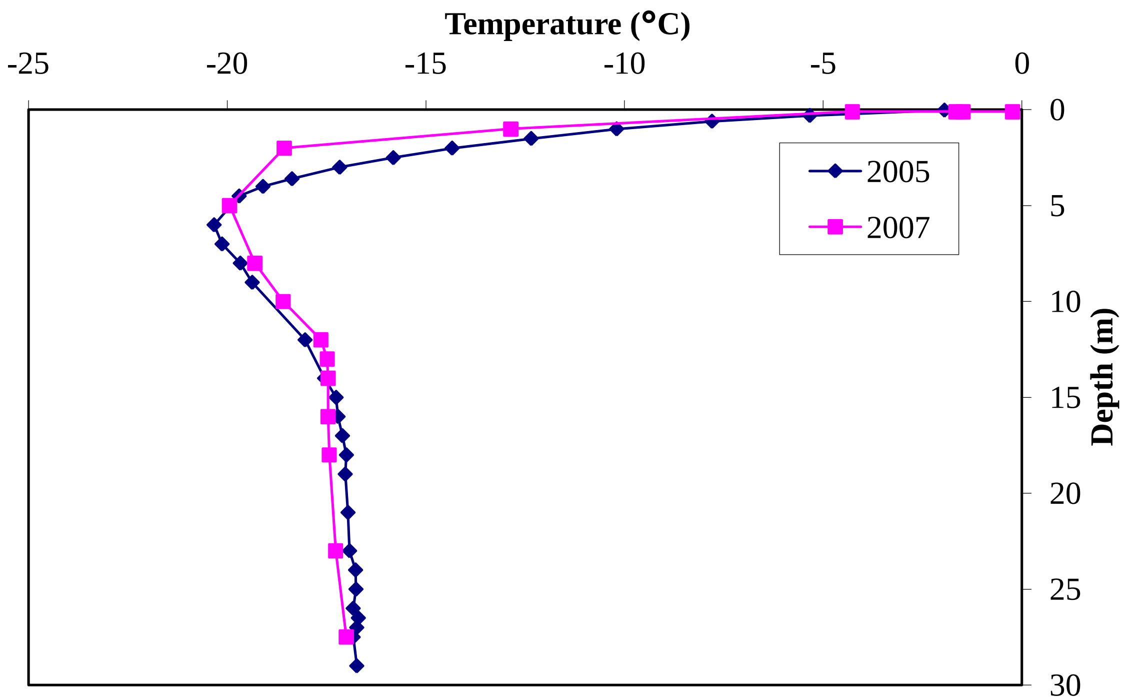

Figure 23: Comparison of initial temperature profile (24 November 2005) and temperature profile measured by 109 temperature probes 12:00pm 24 November 2007 for the Marble Point temperature monitoring borehole.

The 2005 temperatures were measured immediately after the borehole was drilled. The 2005 profile at both sites is usually warmer than the 2007 profile, which indicated that the borehole may have had some residual heat in the base of the borehole due to the drilling process. The close agreement between the temperatures measured in 2005 and 2007 suggests that the data are reliable.

The temperature profiles constructed for each location using initial 2005 and 2007 data are similar to those presented by Guglielmin (2004). A temperature profile from Stelvio, Italy was not linear and temperatures initially decreased to a depth of about 5

– 10 m, after which they warmed slightly (Guglielmin 2004). The profiles were taken during the Northern Hemisphere summer. Two depth profiles from Oasi, close to the Italian Antarctic Research station, in 1999 and 2004 demonstrated a similar pattern of initially decreasing temperature to approximately 11 m, followed by a slight increase. The two profiles from Oasi converged at 11 m, potentially indicating a region of Zero Annual Amplitude. The temperature profiles presented by Guglielmin (2004, 2006) were both constructed using temperatures recorded by a fixed datalogger string, such as those installed at Marble Point and Wright Valley.

8.2 Annual data for 2007

In January 2008, the data recorded for 2007 were downloaded from the Wright Valley and Marble Point boreholes. The record so far exists from installation on 16 January 2007 through to the day of download on 17 January 2008. Detailed analysis of the temperature data for 2007 is forthcoming in Guglielmin *et al.* (in preparation).

8.3 Wright Valley annual temperatures

The annual plot of borehole temperatures (Figure 24) showed the seasonal changes in temperature, with the minimum temperatures occuring near the ground surface in the winter months. The three thermistors buried in shallow gravel (0.1 m) exhibit the greatest variability in temperature at diurnal time scales. There was an annual cyclic pattern of decreasing magnitude in temperature with depth (Figure 24). The maximum temperatures recorded near the ground surface occurred in January, with minimum ground surface temperatures occurring in mid-July. The variation in temperature measured by the thermistor at 0.2 m is similar to the surface temperatures in pattern and timing, although the temperature range is slightly reduced. As depth increases, the daily variation in temperature is attenuated, and there is a visible delay between surface and subsurface maximum temperatures.

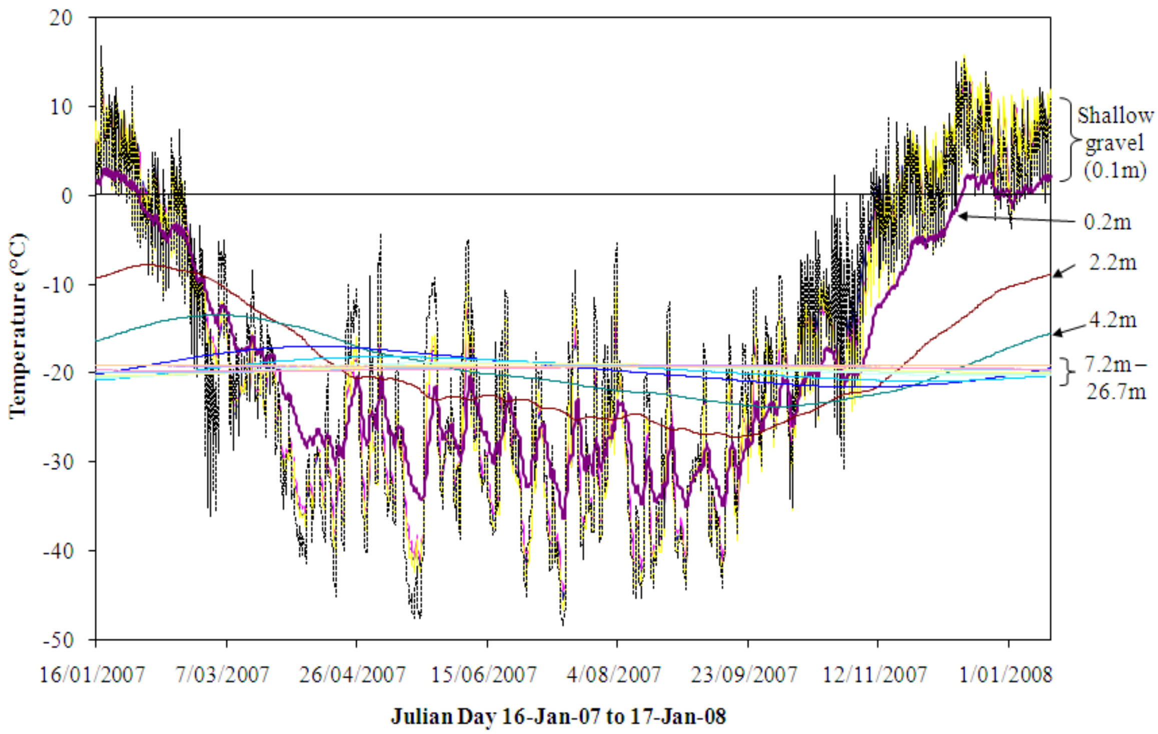

Figure 24: Subsurface six-hourly mean temperatures from the ground surface to 26.7 m depth at Wright Valley from 16 January 2007 to 17 January 2008.

The enlargement of the annual chart (Figure 25) shows the variation in temperature decreases with depth, resulting in a virtually flat line at 22.2 m and 26.7 m depth. The timing of occurrence of the maximum annual temperature peak is visibly delayed with increasing depth.

The bent sensor at 12.2 m did not appear to be malfunctioning in a significant manner, with the temperatures measured fitting between those measured at 11.2 m and 13.2 m.

The maximum temperature decreased rapidly from about +15°C at the ground surface (from sensors buried in shallow gravel) to –17.1°C at 7.2 m depth. Below 7.2 m, the difference in temperature between successive sensors levels off, demonstrating the attenuation of the temperature signal with depth (Figure 25).

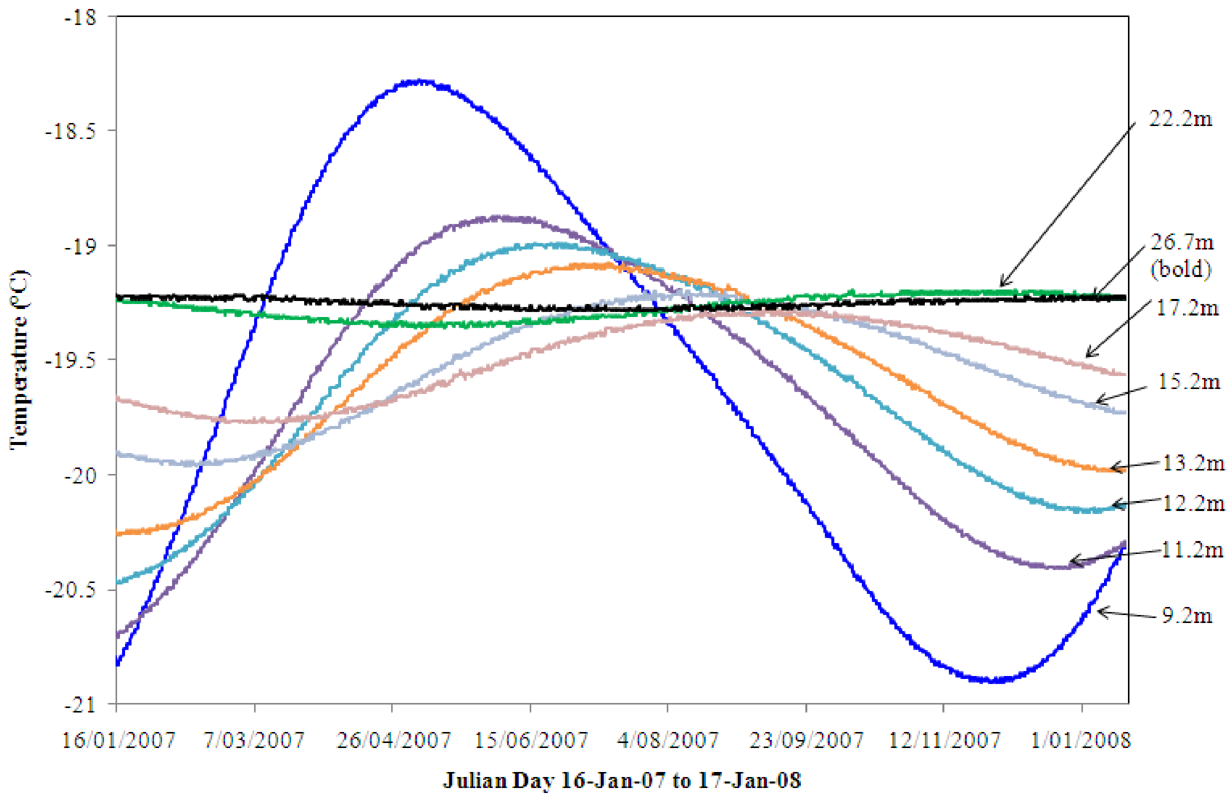

Figure 25: Subsurface temperatures from 9.2 m to 26.7 m depth at Wright Valley from 17 January 2007 to 17 January 2008 (Enlarged from Figure 24).

8.4 Marble Point annual temperatures

The temperature recorded by thermistors at all depths show an annual cyclic pattern (Figure 26), though Marble Point borehole temperatures are slightly warmer than those measured at Wright Valley. The maximum temperature recorded near the ground's surface occurred in mid December, with minimum ground surface temperatures occurring around mid-July to mid-August. As with the Wright Valley borehole, the magnitude of the temperature signal decreased with depth below 11.0 m. The tempearture records from the two deepest thermistors (23.0 m and 27.5 m) are effectively flat lines and the annual range is approximately the same as the limits of accuracy of the 109 temperature probes (Figure 27).

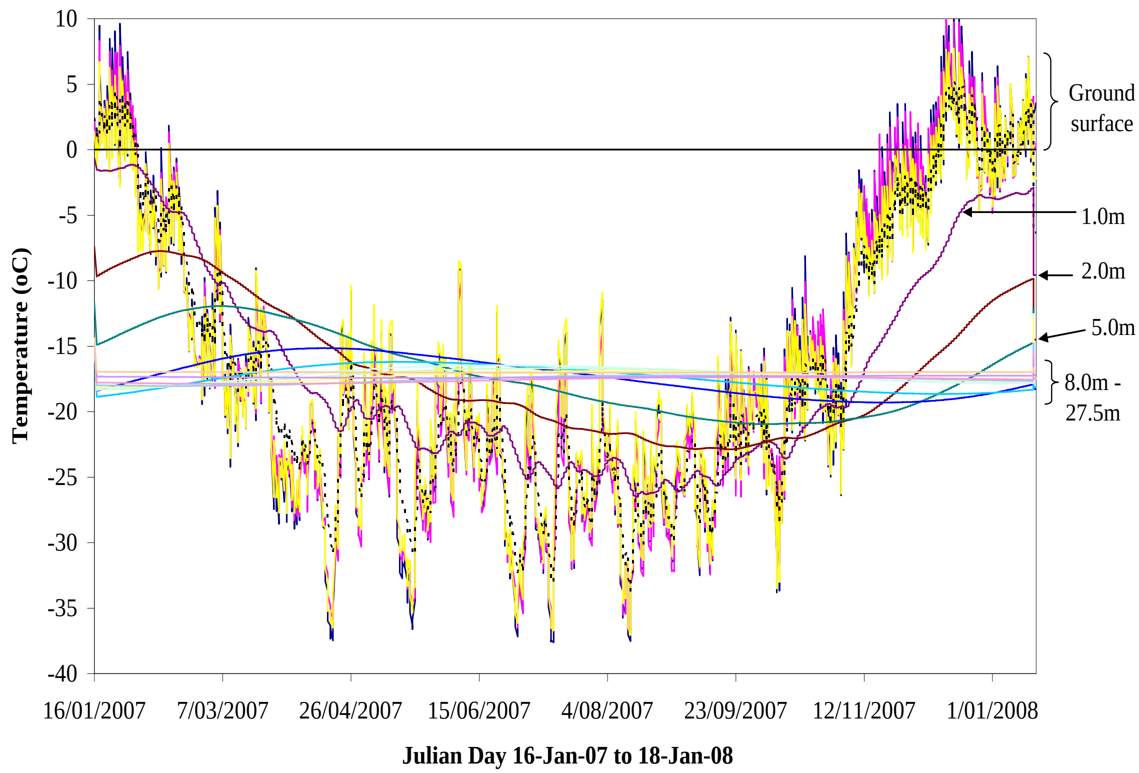

Figure 26: Subsurface six-hourly mean temperatures from the ground surface to 27.5 m depth at Marble Point from 16 January 2007 to 18 January 2008

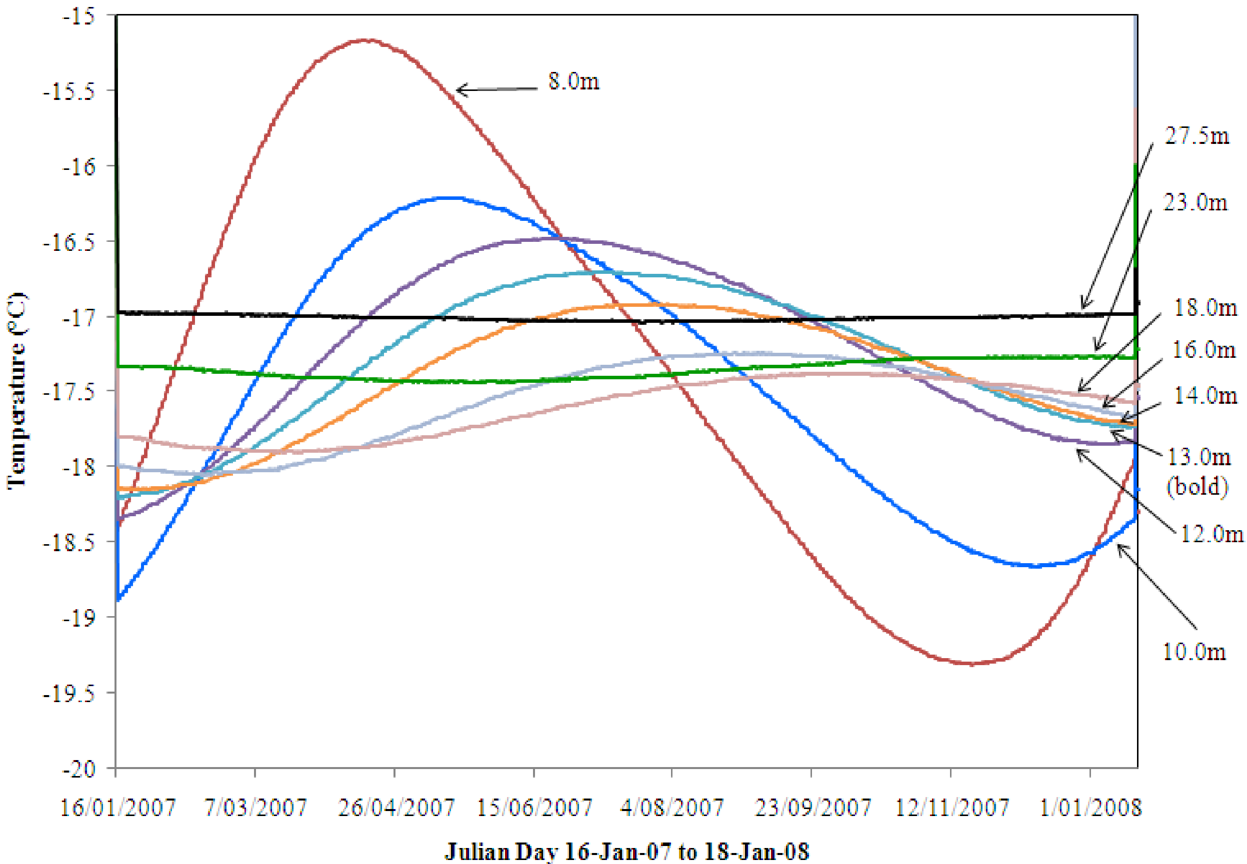

Figure 27: Subsurface temperatures from 13.0 m to 27.5 m depth at Marble Point from 17 January 2007 to 18 January 2008 (Enlarged from Figure 26).

9. Conclusions

Four boreholes were drilled in November 2005, two at Wright Valley and two at Marble Point. One borehole at each site was sampled for ice-cemented core, which was sent to Professor M. Guglielmin at the University of Insubria, Italy for archiving and analyses. The other borehole was drilled to 30 m depth for permafrost temperature monitoring.

Sixteen Campbell Scientific 109 temperature probes were installed in the boreholes in January 2007. While some difficulties were encountered during the installation process, we were confident that the depths where temperature was being measured were sufficient to provide one year of satisfactory data. In January 2008, the data for 2007 was successfully downloaded. The thermistors were reinstalled in the borehole, ensuring that temperature will be measured within a few centimetres of the target depths from January 18^{th} 2008 onwards.

Initial results showed an annual temperature cycle throughout the borehole to about 25 m depth.

There needs to be a longer record before any definite conclusions can be drawn from depth profiles or from annual charts of temperature. At the start and end of the current record are installation days, where the thermistors were on the ground's surface while the site was set up in 2007 and the thermistors were adjusted in 2008. Therefore, the temperatures recorded at the start and end of the record will not be fully representative of those in the borehole, so there is not a truly representative annual cycle as yet. A longer record will allow monthly and annual mean temperatures to be calculated at each depth, which will give a record of how temperatures change over time. This will be of particular interest over at least the next decade due to concerns about the changing global climate.

The proximity of climate stations established by Antarctic event K123B will allow the subsurface temperature regime to be further investigated, along with it's relationship to above-ground parameters. When the above-ground climate data becomes available, it will be useful to investigate the local climate factors influencing the subsurface thermal regime.

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Appendix I: Initial measurements from the temperature monitoring boreholes after drilling in 2005

A.I.1 Wright Valley initial resistance measurements

The first sets of resistance measurements were conducted on 28 November 2005, when the air temperature was estimated to be approximately 0 to +3°C. The second sets of resistance measurements were conducted on 29 November 2005, when the air temperature was estimated to be approximately 0 to +3°C. Resistance was measured in the upper 9 m of the borehole by a short cable (Table 1) and from 4.0 m to 29.0 m by a longer cable (Table 2).

Table 1: Resistance measurements conducted within the upper 9 m of the Wright Valley borehole using the short cable on 28 November 2005 and 29 November 2005.

Depth (m)	Resistance measured 28 November 2005 (ohm)	Resistance measured 29 November 2005 (ohm)
0.05	9.300	8.905
0.30	10.421	10.595
0.60	11.883	11.893
1.00	13.780	13.801
1.50	16.391	16.481
2.00	18.593	18.716
2.50	20.427	20.612
3.00	22.516	22.775
3.60	24.237	24.531
4.50	26.317	26.727
6.00	27.644	28.054
7.00	27.472	27.890
8.00	27.310	27.531
9.00	26.637	27.058

Table 2: Resistance measurements conducted between 4.0 m and 29.0 m in the Wright Valley borehole using the long cable on 28 November 2005 and 29 November 2005.

Depth (m)	Resistance measured 28 November 2005 (ohm)	Resistance measured 29 November 2005 (ohm)
4.0	25.410	25.744
9.0	26.544	26.966
12.0	25.307	25.624
14.0	24.787	25.052
15.0	24.454	24.692
16.0	24.424	24.659
17.0	24.235	24.460
18.0	24.125	24.350
19.0	24.191	24.407
21.0	24.275	24.408
23.0	24.274	24.385
24.0	24.059	24.157
25.0	24.068	24.165
26.0	24.461	24.550
27.0	24.488	24.570
27.5	24.383	24.460
28.30	24.226	24.290
28.65	n.r.	n.r.
28.75	n.r.	n.r.
29.0	24.285 (?)	24.810 (?)

A.I.2 Marble Point initial resistance measurements

The first sets of resistance measurements were conducted on 22 November 2005, when the air temperature was estimated to be approximately 0 to +3°C. The second sets of resistance measurements were conducted on 24 November 2005, when the air temperature was estimated to be approximately –5°C. Resistance was measured in the upper 9 m of the borehole by a short cable (Table 3) and from 4.0 m to 29.0 m by a longer cable (Table 4).

Table 3: Resistance measurements conducted up to 9.0 m in the Marble Point borehole using the short cable on 22 November 2005 and 24 November 2005.

Depth (m)	**Resistance measured 22nd November 2005 (ohm)**	**Resistance measured 24th November 2005 (ohm)**
0.05	11.750	9.724
0.30	12.402	11.598
0.60	13.210	13.232
1.00	14.490	15.040
1.50	16.382	16.937
2.00	18.378	18.894
2.50	19.990	20.554
3.00	21.483	22.183
3.60	22.945	23.768
4.50	24.670	25.653
6.00	25.513	26.612
7.00	25.210	26.292
8.00	24.690	25.600
9.00	24.271	25.160

Table 4: Resistance measurements conducted between 4.0 m and 29.0 m in the Marble Point borehole using the long cable on 22 November 2005 and 24 November 2005.

Depth (m)	**Resistance measured 22 November 2005 (ohm)**	**Resistance measured 24 November 2005 (ohm)**
4.0	23.893	24.780
9.0	24.193	25.081
12.0	22.721	23.312
14.0	22.222	22.660
15.0	n.r.	22.310
16.0	21.865	22.245
17.0	21.790	22.073
18.0	21.630	21.957
19.0	21.673	21.981
21.0	21.663	21.910
23.0	21.675	21.870
24.0	21.480	21.662
25.0	21.470	21.650
26.0	21.822	21.988
27.0	21.841	22.008
27.5	21.740	21.892
28.30	21.607	21.750
28.65	n.r.	n.r.
28.75	n.r.	n.r.
29.0	21.498 (?)	22.932 (?)

A.I.3 Temperatures at Wright Valley and Marble Point in November 2005

The resistance measurements undertaken in November 2005 were converted to temperature in order to construct temperature profiles (Table 5).

Table 6: Initial temperatures in the temperature monitoring boreholes at Wright Valley and Marble Point in November 2005. Measurements were made on 28 and 29 November 2005 at Wright Valley and 22 and 24 November 2005 at Marble Point. Temperatures reported are from 29 November for Wright Valley and 24 November for Marble Point.

Depth (m)	Wright Valley temperature 2005 (°C)	Marble Point temperature 2005 (°C)
0.02	-0.25	-1.95
0.3	-3.6	-5.34
0.6	-5.82	-7.8
1	-8.6	-10.2
1.5	-11.87	-12.35
2	-14.15	-14.34
2.5	-15.88	-15.82
3	-17.65	-17.17
3.6	-18.91	-18.37
4.0	-19.76	-19.1
4.5	-20.4	-19.7
6	-21.24	-20.33
7	-21.14	-20.13
8	-20.93	-19.67
9	-20.62	-19.37
12.0	-19.68	-18.04
14.0	-19.3	-17.55
15.0	-19.05	-17.26
16.0	-19.02	-17.21
17.0	-18.89	-17.1
18.0	-18.8	-17
19.0	-18.85	-17.03
21.0	-18.85	-16.96
23.0	-18.84	-16.92
24.0	-18.66	-16.77
25.0	-18.66	-16.76
26.0	-18.72	-16.83
26.5	-18.6	-16.7
27.0	-18.69	-16.74
27.5	-18.76	-16.83
29.0	-18.8	-16.74

A.I.3 Temperatures at Wright Valley and Marble Point in November 2007

The temperatures measured at the Wright Valley and Marble Point boreholes on a similar date to the 2005 measurements were collated for construction of depth profiles (Table 6).

Table 6: Temperatures in the boreholes at Wright Valley and Marble Point in November 2007 as measured by the 109 temperature probes installed in January 2007. Temperatures are reported for Wright Valley at 12:00pm (midday) on 29 November 2007. Depths recorded as 0.1 m denote those sensors buried in shallow gravel in the Wright Valley. Temperatures are reported for Marble Point at 12:00pm (midday) on 24 November 2007. Depths recorded as 0.0m denote those sensors at the ground surface, covered by a rock approximately 5cm thick, at the ground surface and inside the U-bend device at Marble Point.

Depth (Wright Valley) (m)	Midday temperature at Wright Valley 2007 (°C)	Depth (Marble Point) (m)	Midday temperature at Marble Point 2007 (°C)
0.1	-1.96	0.1	-0.24
0.1	-2.37	0.1	-1.48
0.1	-0.59	0.1	-1.66
0.1	-2.73	0.1	-4.27
0.2	-5.52	1.0	-12.86
2.2	-17.19	2.0	-18.56
4.2	-21.03	5.0	-19.94
7.2	-21.44	8.0	-19.30
9.2	-20.90	10.0	-18.59
11.2	-20.33	12.0	-17.64
12.2	-20.02	13.0	-17.48
13.2	-19.81	14.0	-17.46
15.2	-19.54	16.0	-17.46
17.2	-19.42	18.0	-17.43
22.2	-19.20	23.0	-17.27
26.2	-19.24	27.5	-17.00

Appendix II: Wiring of CR1000 datalogger

Table 1 shows the wiring of sixteen 109 temperature sensors into one CR1000 datalogger, making up one permafrost temperature monitoring station. Note that the black excitation wires for all 16 sensors are wired into an external wiring block, which was then wired into EX1 channel (visible in Figure 1).

Table 1: Wiring diagram for CR1000 dataloggers installed at Marble Point and Wright Valley

Instrument	CR1000 input	Colour of the wire
Temperature_1	SE1	Red
(109 thermistor)	Signal Ground_1	Purple
	EX1	Black
	G1	Clear
Temperature_2	SE2	Red
(109 thermistor)	Signal Ground_1	Purple
	EX1	Black
	G2	Clear
Temperature_3	SE3	Red
(109 thermistor)	Signal Ground_2	Purple
	EX1	Black
	G3	Clear
Temperature_4	SE4	Red
(109 thermistor)	Signal Ground_2	Purple
	EX1	Black
	G4	Clear
Temperature_5	SE5	Red
(109 thermistor)	Signal Ground_3	Purple
	EX1	Black
	G5	Clear
Temperature_6	SE6	Red

(109 thermistor)	Signal Ground_3	Purple
	EX1	Black
	G6	Clear
Temperature_7	SE7	Red
(109 thermistor)	Signal Ground_4	Purple
	EX1	Black
	G1	Clear
Temperature_8	SE8	Red
(109 thermistor)	Signal Ground_4	Purple
	EX1	Black
	G2	Clear
Temperature_9	SE9	Red
(109 thermistor)	Signal Ground_5	Purple
	EX1	Black
	G3	Clear
Temperature_10	SE10	Red
(109 thermistor)	Signal Ground_5	Purple
	EX1	Black
	G4	Clear
Temperature_11	SE11	Red
(109 thermistor)	Signal Ground_6	Purple
	EX1	Black
	G5	Clear
Temperature_12	SE12	Red
(109 thermistor)	Signal Ground_6	Purple
	EX1	Black
	G6	Clear
Temperature_13	SE13	Red
(109 thermistor)	Signal Ground_7	Purple
	EX1	Black
	G1	Clear

Temperature_14	SE14	Red
(109 thermistor)	Signal Ground_7	Purple
	EX1	Black
	G2	Clear
Temperature_15	SE15	Red
(109 thermistor)	Signal Ground_8	Purple
	EX1	Black
	G3	Clear
Temperature_16	SE16	Red
(109 thermistor)	Signal Ground_8	Purple
	EX1	Black
	G4	Clear

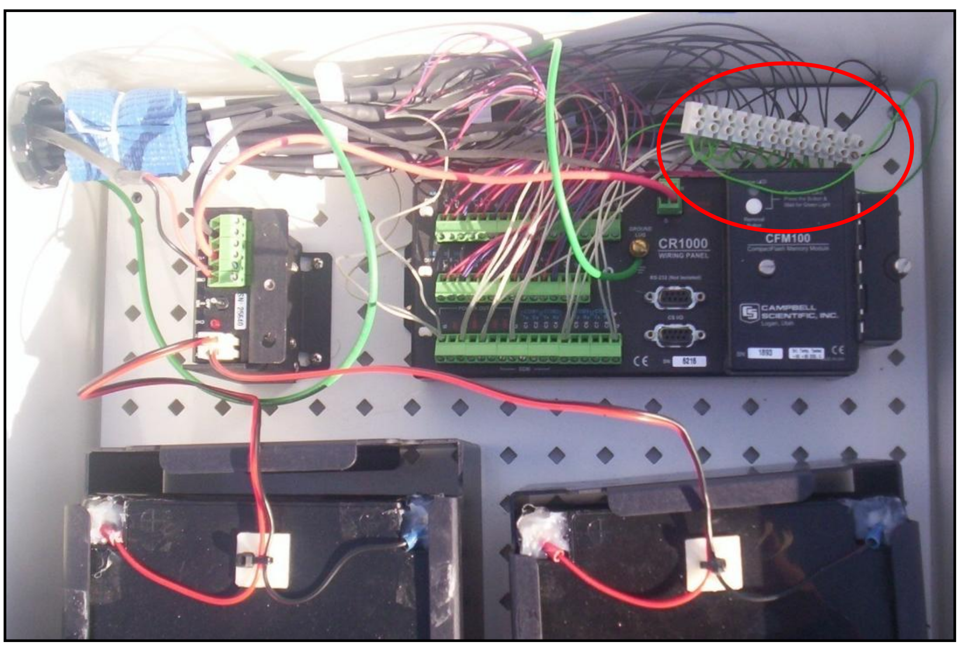

Figure 1: Wiring of CR1000 datalogger deployed in Wright Valley and Marble Point. External wiring block visible in red circle.

Appendix III: Removal of memory card from Campbell Scientific CFM100 Compact Flash Module

A.III.1 Requirements for removal of memory card from module

When removing the memory card from the Compact Flash Module (CFM), it must be replaced with a blank memory card (Figure 1), otherwise new data will not be able to be recorded on the card. Upon insertion, the datalogger will format the card for the data to be recorded, and it will not be able to be removed and inserted to a new CFM. To ensure the memory card is blank, it can be inserted into a simple USB memory card reader and assessed using the "Explorer" function on any computer. If the memory card is clear, it is free to be inserted into a CFM.

Figure 1: Memory card similar to those used at Marble Point and Wright Valley.

A.III.2 Memory card removal – procedure

Removing the memory card from the flash storage module is simple. The card is stored on the right hand side of the module (Figure 2).

1. Unscrew the right hand bolt to reveal the memory card.
2. When the "door" has been unscrewed and the operational memory card revealed, press the white button as shown in Figure 2.
3. When the card is ready to be removed, the LED above the white button will show green.
4. Eject the formatted card from the CFM100 module by pushing the black lever inside the door (next to the memory card slot).

5. Insert the blank memory card.
6. The LED will flash an orange light as the blank memory card is being formatted. After about 10 seconds, the light will stop flashing and data will now be recorded to the newly inserted card. If the LED stays a solid orange colour after 30 seconds, the card inserted was not able to be formatted and will not be able to record data.

If no clean card is inserted, data will be logged to the datalogger internal memory. Data files on the formatted card need to be converted from TOA5 binary format to ASCII format for manipulation. The utility for doing the conversion is called "CardConvert". The CardConvert program is additional to the Loggernet program, and is available from Campbell Scientific, Inc. and may be ordered through the website (http://www.campbellsci.com). To access the conversion software, take the following path from your PC start menu:

Start → Programs → Loggernet → Utilities → CardConvert.

Figure 2: CFM100 module used at both monitoring locations for data storage. (Adapted from http://www.campbellsci.com/cfm100)

Appendix IV: Datalogger programs

A.IV.1 Wright Valley temporary monitoring program

```
'CR1000
'Bp_Initial_reading.CR1
'Wright Valley initial temperature program, to run 16 Model 109 probes in a 30m borehole
'Program to be sent upon arrival at location, measuring temperature rapidly for approx. 2 hours
'to provide initial data sets

'written by Leah Adlam and Dr. David Campbell
'Department of Earth and Ocean Sciences
'University of Waikato
'December 2006

'Declare Variables and Units
Public Batt_Volt
Public Temp(16),PTemp
Dim RTherm(16),V_Vx(16),lnRt(16),i


Units Batt_Volt=Volts
Units Temp=Deg C
Units PTemp=Deg C

'Define Data Tables
DataTable(AvgTemp,True,-1)
        cardout (0 ,-1)
        DataInterval(0,1,Min,0)
        average(16,Temp,IEEE4,False)
        Average(1,PTemp,IEEE4,False)
        Minimum(1,Batt_Volt,IEEE4,False,False)
```

```
EndTable



'Main Program
BeginProg
	Scan(1,Sec,1,0)
		'Default Datalogger Battery Voltage measurement Batt_Volt:
		Battery(Batt_Volt)
		'109 Temperature Probe measurement T109_C:
		BrHalf(V_Vx,16,mV2500,1,Vx1,16,2500,True,0,_50Hz,1,0)
		for i=1 to 16
		RTherm(i)=24900*(1/V_Vx(i)-1)

		lnRt(i)=Log(RTherm(i))

		'Apply Steinhart and Hart equation
		Temp(i)=1/(1.129241e-3+2.341077e-4*lnRt(i)+8.775468e-8*(lnRt(i)^3))-
273.15
		next

		'Wiring panel temperature measurement
		PanelTemp(PTemp,_50Hz)

		'Call Data Tables and Store Data
		CallTable(AvgTemp)

	NextScan
EndProg
```

A.IV.2 Wright Valley long-term monitoring program

```
'CR1000
'BP_SH_CFCARD.CR1
```

```
'Wright Valley long-term temperature program, to run 16 Model 109 probes in a 30m borehole

'written by Leah Adlam and Dr. David Campbell
'Department of Earth and Ocean Sciences
'University of Waikato
'December 2006

'Declare Variables and Units
Public Batt_Volt
Public Temp(16),PTemp
Dim RTherm(16),V_Vx(16),lnRt(16),i



Units Batt_Volt=Volts
Units Temp=Deg C
Units PTemp=Deg C

'Define Data Tables
DataTable(Sixhour,True,-1)
        cardout (0 ,-1)
        DataInterval(0,360,Min,0)
        average(16,Temp,FP2,False)
        Average(1,PTemp,FP2,False)
        Minimum(1,Batt_Volt,FP2,False,False)

EndTable

DataTable(Daily,True,-1)
        cardout (0 ,-1)
        DataInterval(0,1440,Min,0)
        minimum (16,Temp,FP2,False,False)
        maximum (16,Temp,FP2,False,False)
EndTable
```

```
'Main Program
BeginProg
	Scan(30,Min,1,0)
		'Default Datalogger Battery Voltage measurement Batt_Volt:
		Battery(Batt_Volt)
		'109 Temperature Probe measurement T109_C:
		BrHalf(V_Vx,16,mV2500,1,Vx1,16,2500,True,0,_50Hz,1,0)
		for i=1 to 16
		RTherm(i)=24900*(1/V_Vx(i)-1)

		lnRt(i)=Log(RTherm(i))

		'Apply Steinhart and Hart
		Temp(i)=1/(1.129241e-3+2.341077e-4*lnRt(i)+8.775468e-
8*(lnRt(i)^3))-273.15
		next

		'Wiring panel temperature measurement
		PanelTemp(PTemp,_50Hz)

		'Call Data Tables and Store Data
		CallTable(Sixhour)
		CallTable(Daily)

	NextScan
EndProg
```

A.IV.3 Marble Point temporary monitoring program

```
'CR1000
'MP_INITIAL_READING.CR1
'Marble Point initial temperature program, to run 16 Model 109 probes in a 30m borehole
```

```
'Program to be sent upon arrival at location, measuring temperature rapidly for approx. 2 hours
'to provide initial data sets

'Declare Variables and Units
Public Batt_Volt
Public Temp(16),PTemp
Dim RTherm(16),V_Vx(16),lnRt(16),i



Units Batt_Volt=Volts
Units Temp=Deg C
Units PTemp=Deg C

'Define Data Tables
DataTable(AvgTemp,True,-1)
	cardout (0 ,-1)
	DataInterval(0,1,Min,0)
	Average(16,Temp,IEEE4,False)
	Average(1,PTemp,IEEE4,False)
	Minimum(1,Batt_Volt,IEEE4,False,False)

EndTable



'Main Program
BeginProg
	Scan(1,Sec,1,0)
		'Default Datalogger Battery Voltage measurement Batt_Volt:
		Battery(Batt_Volt)
		'109 Temperature Probe measurement T109_C:
		BrHalf(V_Vx,16,mV2500,1,Vx1,16,2500,True,0,_50Hz,1,0)
		for i=1 to 16
		RTherm(i)=24900*(1/V_Vx(i)-1)
```

```
            lnRt(i)=Log(RTherm(i))

            'Apply Steinhart and Hart
            Temp(i)=1/(1.129241e-3+2.341077e-4*lnRt(i)+8.775468e-8*(lnRt(i)^3))-
273.15
            next

            'Wiring panel temperature measurement
            PanelTemp(PTemp,_50Hz)

            'Call Data Tables and Store Data
            CallTable(AvgTemp)

    NextScan
EndProg
```

A.IV.4. Marble Point long-term monitoring program

```
'CR1000
'MP_SH_CF.CR1
'Marble Point long-term temperature program, to run 16 Model 109 probes in a 30m borehole

'written by Leah Adlam and Dr. David Campbell
'Department of Earth and Ocean Sciences
'University of Waikato
'December 2006

'Declare Variables and Units
Public Batt_Volt
Public Temp(16),V_Vx(16),PTemp
Dim RTherm(16),lnRt(16),i
```

```
Units Batt_Volt=Volts
Units Temp=Deg C
Units PTemp=Deg C

'Define Data Tables
DataTable(AvgTemp,True,-1)
        cardout (0 ,-1)
        DataInterval(0,360,Min,0)
        Average(16,Temp,IEEE4,False)
        Average(1,PTemp,IEEE4,False)
        Minimum(1,Batt_Volt,IEEE4,False,False)

EndTable



'Main Program
BeginProg
        Scan(30,Min,1,0)
                'Default Datalogger Battery Voltage measurement Batt_Volt:
                Battery(Batt_Volt)
                '109 Temperature Probe measurement T109_C:
                BrHalf(V_Vx,16,mV2500,1,Vx1,16,2500,True,0,_50Hz,1,0)
                for i=1 to 16
                RTherm(i)=24900*(1/V_Vx(i)-1)

                lnRt(i)=Log(RTherm(i))

                'Apply Steinhart and Hart
                Temp(i)=1/(1.129241e-3+2.341077e-4*lnRt(i)+8.775468e-8*(lnRt(i)^3))-
273.15
                next

                'Wiring panel temperature measurement
                PanelTemp(PTemp,_50Hz)
```

```
        'Call Data Tables and Store Data
        CallTable(AvgTemp)

    NextScan
EndProg
```

CHAPTER 5: PHASE LAG AND ATTENUATION OF TEMPERATURE SIGNAL WITH DEPTH

5.1 Introduction

Over varying time scales, changing environmental conditions lead to diurnal, seasonal and annual variations in air and soil temperatures. Surface temperature changes are attenuated with increasing depth and there is an associated time delay, or phase lag, due to the time it takes to conduct heat to depth (Chapter 2, Section 2.7.4). The objective of this chapter is to describe the seasonal and annual temperature cycles, investigate the damping depth, quantify the phase lag in transmission of surface temperature signals to about 1 m and about 28 m depth, and investigate the depth of “Zero Annual Amplitude”.

5.2 Seasonal air and soil temperature cycles

5.2.1 Summer cycles of air and soil temperatures

During the austral summer, Antarctica is subject to continuous, 24-hour, solar radiation which provides a source of radiative energy to the soil surface. During summer sunny periods, peaks in daily air and near-surface soil temperatures are delayed behind daily maxima in solar radiation (e.g. Scott Base, Figure 5.1). The air and soil temperatures at all seven sites in the McMurdo Sound region exhibited diurnal cycles over the summer period (1 Dec 06 to 31 Jan 07) (Figure 5.2).

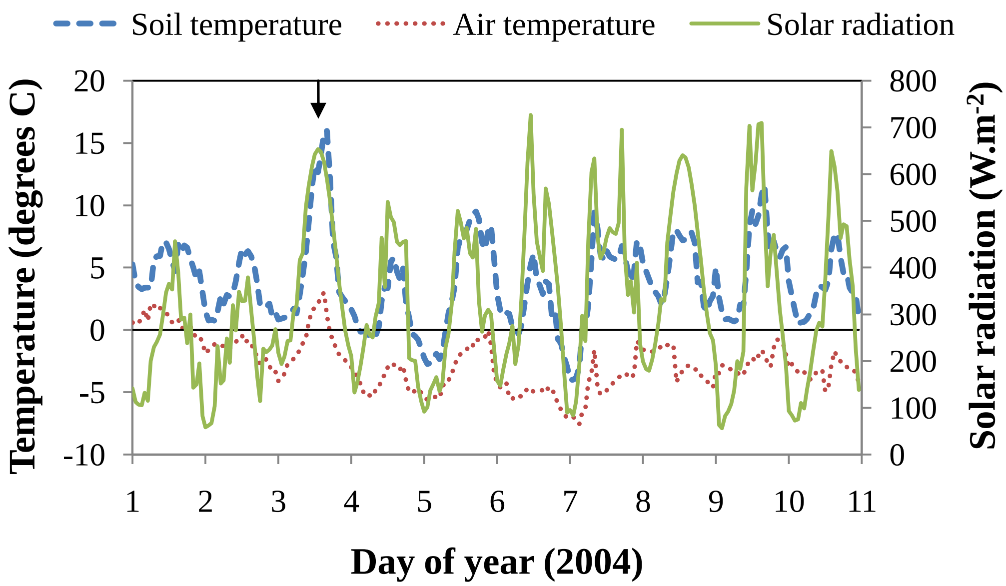

Figure 5.1: Air temperature, soil temperature at 1.3 cm depth and solar radiation at Scott Base from 1 – 10 January 2004 illustrating diurnal air and soil temperature and solar radiation cycles. Arrow illustrates an example of peak air and soil temperatures slightly delayed behind peak solar radiation.

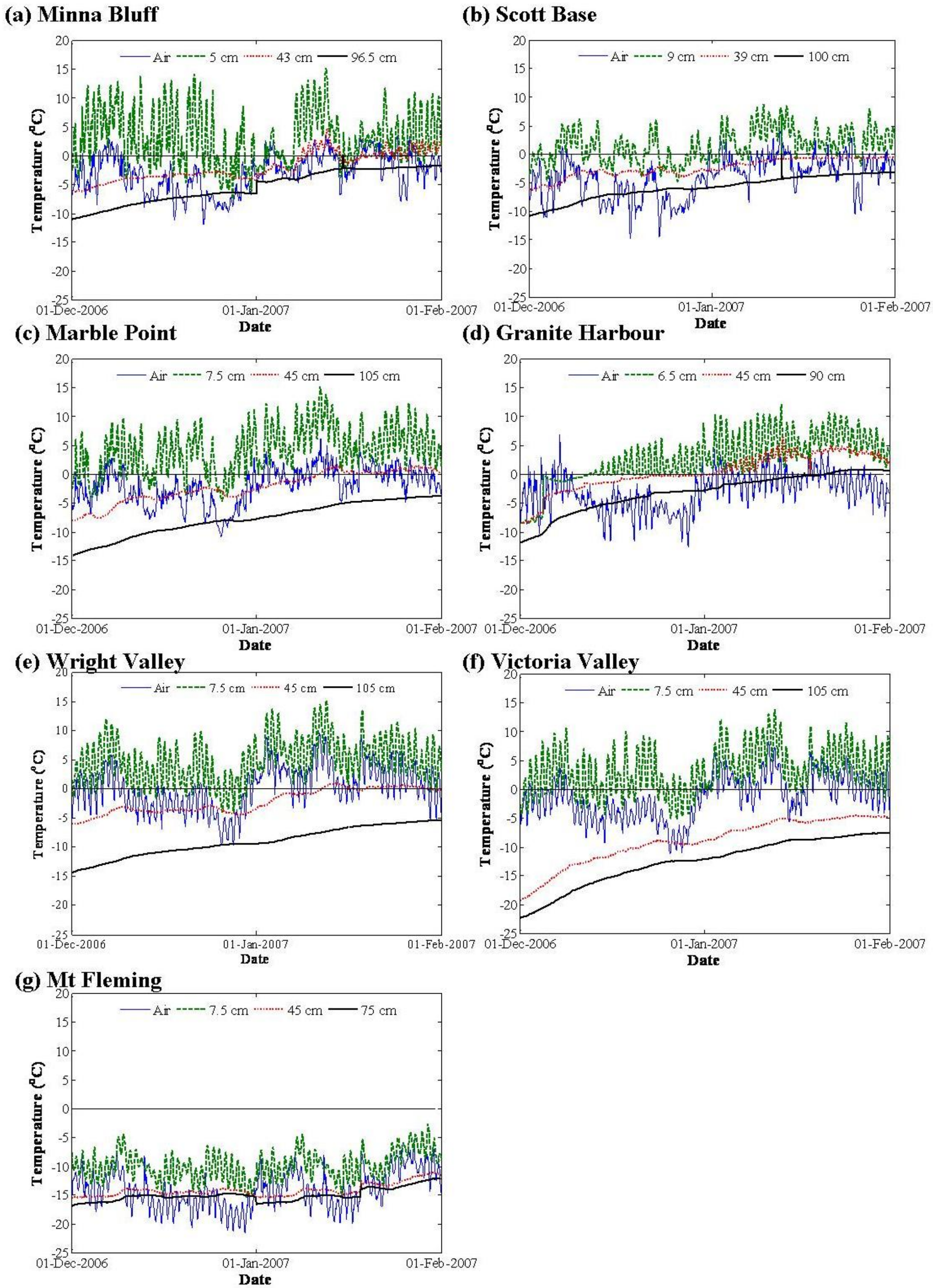

Figure 5.2: Air temperature, shallow soil temperature (5 – 9 cm), mid-depth soil temperature (39 – 45 cm) and deep soil temperatures (75 – 105 cm) at (a) Minna Bluff, (b) Scott Base, (c) Marble Point, (d) Granite Harbour, (e) Wright Valley, (f) Victoria Valley and (g) Mt Fleming during a single summer (1 December 2006 to 31 January 2007).

At all sites in the McMurdo Sound region, the near-surface (5 – 9 cm) soil temperatures exceeded the air temperatures by up to 10°C, which was indicative of the heating of the soil surface, presumably due to solar radiation (Figure 5.2). The diurnal temperature signal was damped with increasing depth, and no diurnal cycle was observed below about 45 cm depth at any site. The low diurnal variability of temperatures in the 0.5 – 1 m depth ranges led to instances where the summer air temperature was cooler than all soil temperatures, due to the time required for changes at the surface to translate to the subsurface and the attenuation of the temperature signal with depth. The continuous solar radiation during the summer period and the subsequent heating of the soil led to the consistent increase in all air and soil temperatures observed over the summer period. Near-surface soil temperatures exceeded 0°C at all sites during the summer period, except for Mt Fleming, the highest elevation site. The near-surface soil temperatures were reasonably similar at all sites, despite differences in daily air temperature ranges.

5.2.2 Winter cycles of air and soil temperatures

During the winter (June to August), the air temperatures could be up to 40°C cooler than during the summer period. In the winter, near-surface soil temperatures were sometimes cooler than the air temperature during periods when the air temperature rose sharply (Figure 5.3). There was no diurnal cycle in air or soil temperatures due to the absence of solar radiation acting as a heat source. The damping of the temperature signal was evident below about 7.5 cm depth at all sites, and the soil temperature range over the winter, at all depths, was less than the winter range in air temperature.

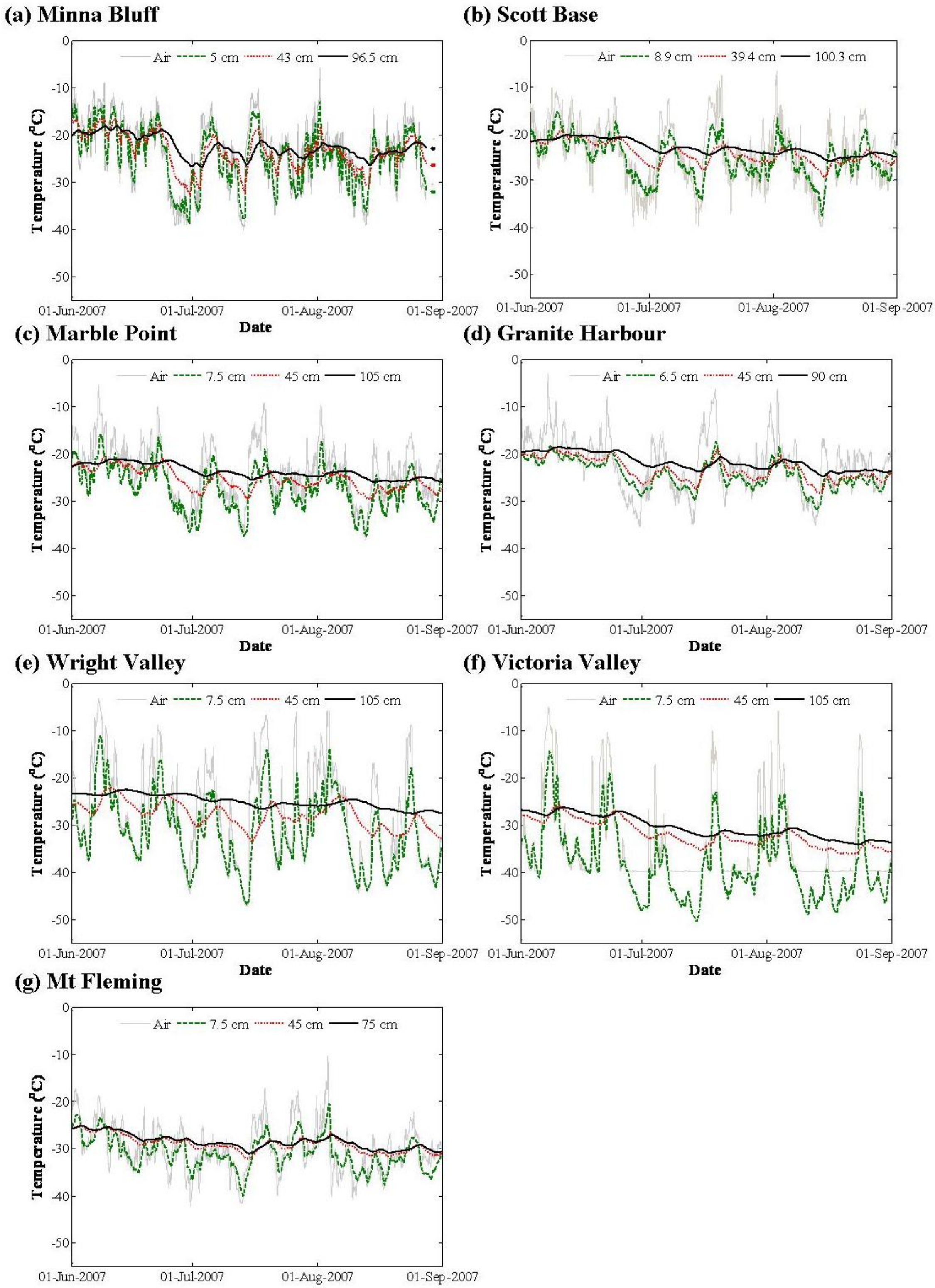

Figure 5.3: Air temperature, shallow soil temperature (5 – 9 cm), mid-depth soil temperature (39 – 45 cm) and deep soil temperatures (75 – 105 cm) at (a) Minna Bluff, (b) Scott Base, (c) Marble Point, (d) Granite Harbour, (e) Wright Valley, (f) Victoria Valley and (g) Mt Fleming during a single winter (1 June 2007 to 31 August 2007).

The air temperature range (maximum – minimum) at our sites during the winter period was up to 46°C, compared to a range of about 20°C in the summer, indicating greater extremes in the air temperature during winter. The large temperature range was evident at all sites, but was particularly striking at Victoria Valley (Figure 5.3f), where the air temperatures could rise from –40°C to –10°C rapidly and for a short duration. Such perturbations were interpreted as winter storm events and are described further in Chapter 7. A peak in near-surface soil temperatures was evident with a slight delay behind the air temperature. Soil temperatures at 75 – 105 cm depths were influenced by the large (up to 30°C) surface temperature perturbations during the winter whereas diurnal cycles of up to 15°C during the summer did not penetrate below about 45 cm depth. The maximum winter air temperatures were sometimes delayed from registering at the ground surface by up to three hours, indicating that there may have been snow cover at all sites for part of the winter period.

5.3 Deeper permafrost temperature cycles (down to 30 m depth)

At Marble Point and Wright Valley, permafrost temperature monitoring boreholes were installed down to about 30 m depth in January 2007 (Chapter 4). Temperatures measured inside the borehole cover and by sensors exposed at the ground surface at Marble Point (Figure 5.4a) were less extreme than those buried in shallow gravel (0.1 m) at Wright Valley (Figure 5.4b). The temperatures at Marble Point may have been shielded from extremes by the borehole cover. Upon enlargement of Figure 5.4, annual temperature cycles were still evident at about 18 m depth (Figure 5.5). The annual temperature signal penetrated deeper into the subsurface compared to the relatively shallow damping depth observed in the diurnal cycles during summer. Temperatures at the surface and relatively shallow depths in the boreholes exhibited more extreme temperature regimes compared to the deeper sensors. Deeper permafrost temperatures at Wright Valley were cooler than those at Marble Point (Figure 5.5). Temperatures measured by the deeper sensors did not have as great an annual temperature range as the shallower sensors, which was indicative of the attenuation of the surface temperature signal with depth. The temperatures below about 7 m depth at Marble Point (Figure 5.4a) and below about 8 m depth at Wright Valley (Figure 5.4b) were warmer than the shallower depths (0 – 7 m) during the winter.

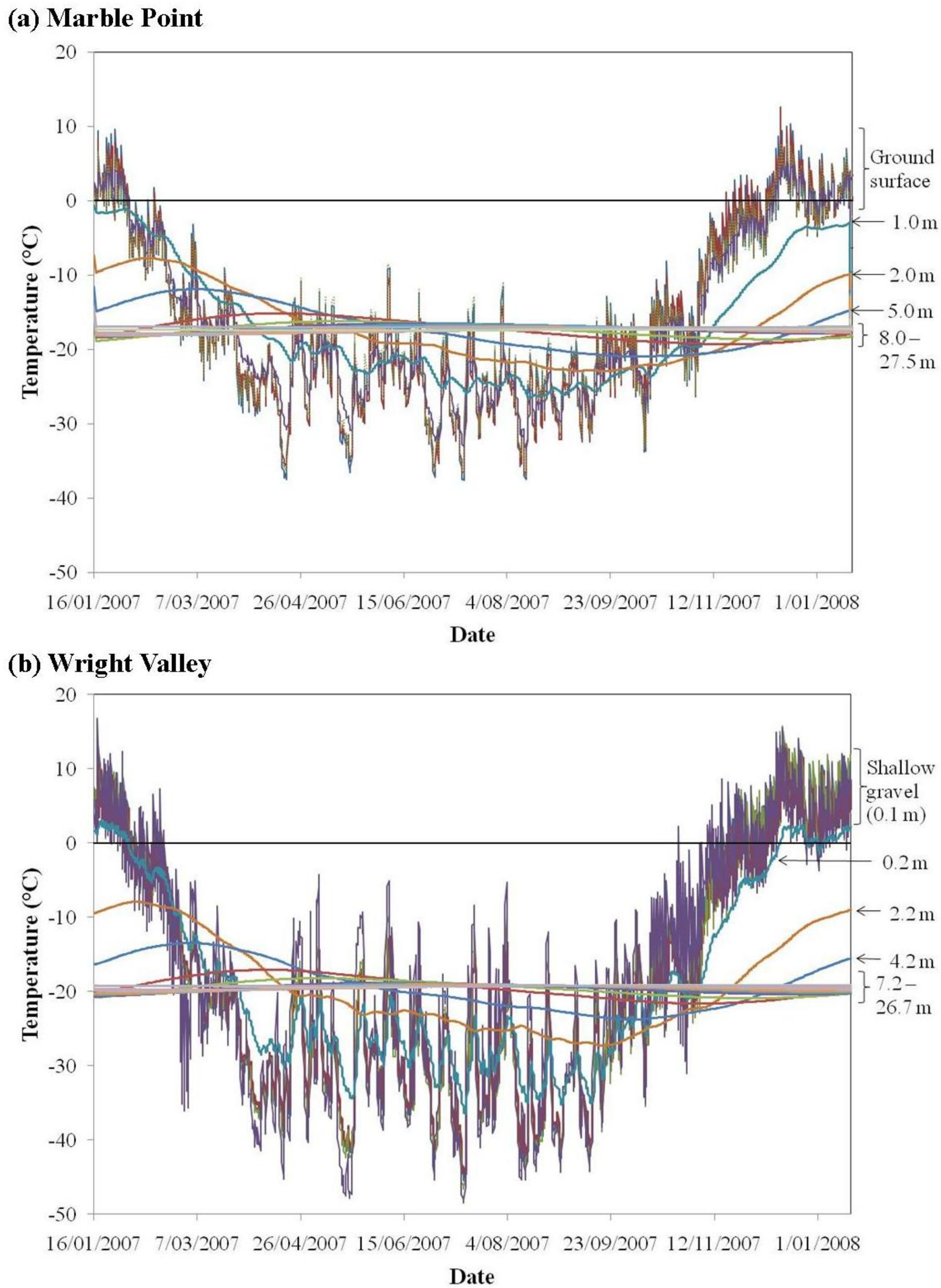

Figure 5.4: Subsurface six-hourly mean temperatures (a) from the ground surface to 27.5 m depth at Marble Point from 16 January 2007 to 18 January 2008 and (b) from the ground's surface to 26.7 m depth at Wright Valley from 16 January 2007 to 17 January 2008.

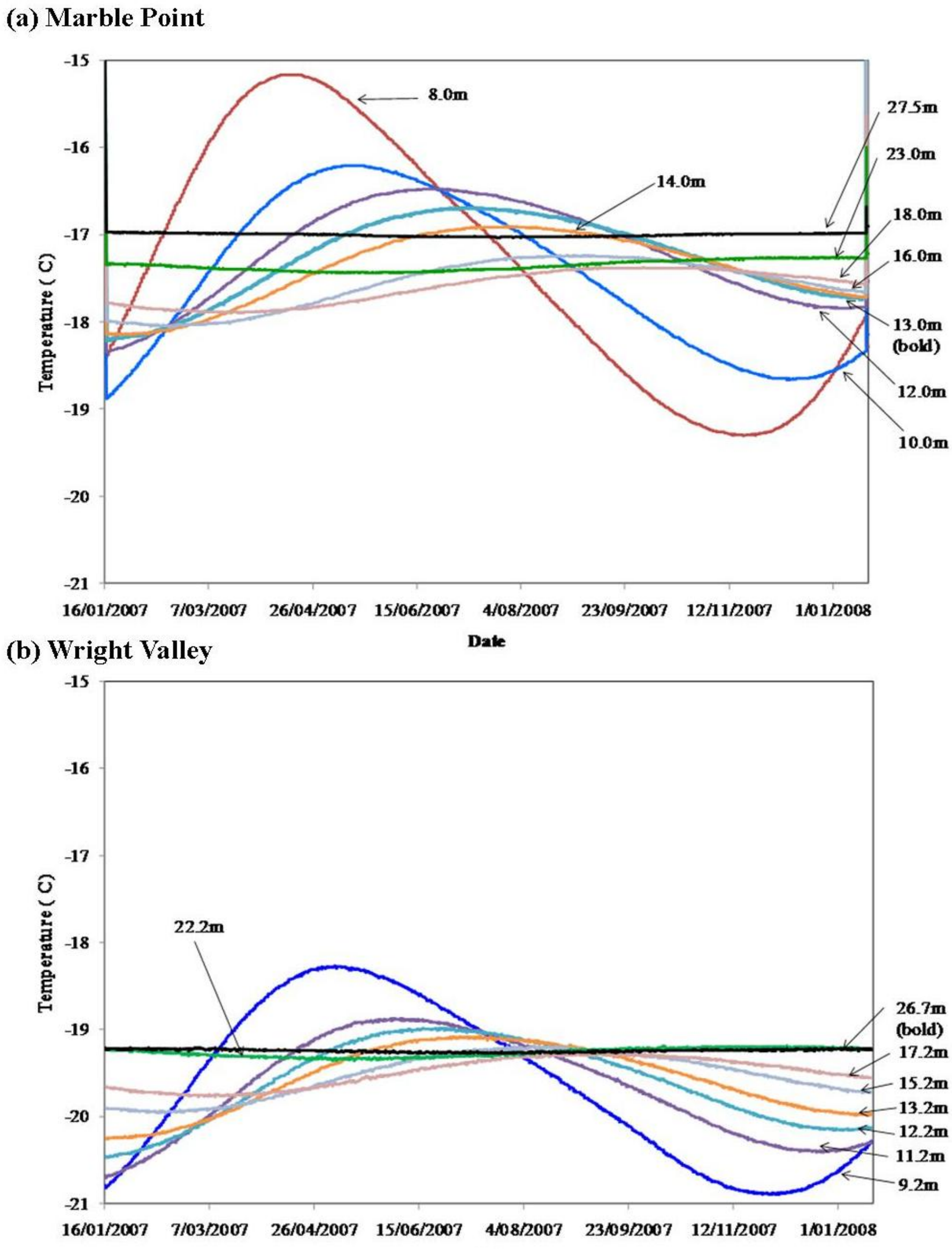

Figure 5.5: Subsurface six-hourly mean temperatures (a) from 8.0 m to 27.5 m depth at Marble Point from 16 January 2007 to 18 January 2008 and (b) from 9.2 to 26.7 m depth at Wright Valley from 16 January 2007 to 17 January 2008 (Enlargement of Figure 5.4).

5.4 Damping depth

The damping depth is the depth at which the temperature amplitude is 0.37 times the surface amplitude (Campbell 1985, Hillel 2004). The damping depth was calculated for both the diurnal summer variations and for a single surface perturbation during a winter storm event. During the summer, the diurnal temperature variations had a damping depth of 17 – 64 cm while the damping depth in the winter was about 30 cm at all sites (Table 5.1). The annual damping depth was about 250 cm at Marble Point and 190 cm at Wright Valley. The damping depth during the summer at each site was similar to the damping depth during the winter storm, except at Granite Harbour, Victoria Valley and Mt Fleming.

Table 5.1: Diurnal damping depth during summer (1 Dec 06 to 28 Feb 07), damping depth during a winter storm (7 – 15 Jun 07) at each automated weather station and annual damping depth at Marble Point and Wright Valley permafrost temperature monitoring boreholes (16 Jan 07 to 18 Jan 08).

Site	Diurnal damping depth during summer (cm)	Damping depth in response to winter storm (cm)	Annual damping depth (cm)
Minna Bluff	32	31	
Scott Base	32	32	
Marble Point	35	33	250
Granite Harbour	64	30	
Wright Valley	27	30	190
Victoria Valley	17	28	
Mt Fleming	19	26	

Diurnal temperature variations were not detected below about 45 cm depth (Figure 5.2), which corresponded to the damping depth at most sites (Table 5.1). However, the continued heating of the soil during the summer period led to the constant increase of the deep soil temperatures below the damping depth (Figure 5.2). Therefore the seasonal maximum temperature in the deep soil is responding not to a single surface maximum event, but is probably responding to the extended period of heating over the summer.

5.5 Phase lag of the temperature signal

Phase lag was determined to provide an insight into the length of time taken for a surface perturbation, such as the summer maximum surface temperature, to penetrate to depth. The phase lag was determined through the soil profile to about 90 cm depth and in deeper permafrost to about 28 m depth. The phase lag was calculated using the maximum near-surface soil temperatures to avoid issues with snow insulation complicating the transmission of air temperature maxima to the ground surface.

5.5.1 Phase lag in soil profile (down to 90 cm depth)

An extended summer period (1 Dec 06 to 28 Feb 07) was used to determine the phase lag of the temperature signal at depths down to about 90 cm. The summer period was used due to the diurnal cycles in soil temperatures and the relatively clear progression of daily maxima through the subsurface. Maximum temperatures at each depth in the soil at each site were used to calculate the phase lag between near-surface soil (5 – 11 cm) and about 90 cm depth (75 – 90 cm) (Appendix III). The phase lag between near-surface soil surface maximum temperatures and the maximum soil temperature at about 90 cm depth was 15 - 22 days (Table 5.2).

As the temperature signal was attenuated with depth, the phase lag was harder to determine below about 45 cm depth. The temperatures below about 45 cm steadily increased during the summer, probably due to the gradual summer heating of the soil in response to warmer air temperatures and continuous solar radiation. For those depths below about 45 cm, the summer maximum temperature was used to determine the phase lag between the surface and about 90 cm depth for the summer period (Appendix III). It is important to note that while the maximum near-surface temperature was used, soil deeper than about 45 cm depth would not be responding to a single surface maximum event but rather to extended ‘noise’ of diurnal cycles at the longer-term summer scale.

Table 5.2: Summer maximum near-surface (5 – 11 cm) and "deep" (75 – 90 cm) soil temperatures, date of maximum and time lag between surface and depth at each automated weather station (1 Dec 06 to 28 Feb 07).

Site (Depth range)	**Maximum near-surface temperature (°C)**	**Date of near-surface maximum**	**Maximum temperature at ~90 cm depth (°C)**	**Date of maximum at ~90 cm depth**	**Time lag from surface (days)**
Minna Bluff (5 – 81 cm)	14.54	12/01/2007	-3.53	4/02/2007	22.4
Scott Base (9 – 85 cm)	8.68	9/01/2007	-2.26	3/02/2007	21.1
Marble Point (7.5 – 90 cm)	15.24	11/01/2007	-3.00	2/02/2007	21.5
Granite Harbour (11 – 90 cm)	12.85	13/01/2007	0.86	29/01/2007	15.6
Wright Valley (7.5 – 90 cm)	15.22	12/01/2007	-4.43	31/01/2007	20.5
Victoria Valley (7.5 – 90 cm)	13.78	12/01/2007	-6.79	2/02/2007	21.8
Mt Fleming (7.5 – 75 cm)	-4.52	9/12/2006	-14.70	27/12/2006	17.8

For comparison, maximum soil temperatures, which occurred over short time periods during winter storm events (1 Jun – 31 Aug 2007), were used to calculate how quickly the temperature signal propagated from the surface to depth, in the absence of continued solar heating during the summer. In response to a single surface perturbation, the maximum soil surface temperature (5 – 11 cm) progressed to depth (75 – 90 cm) in 1 – 6 days (Table 5.2).

Table 5.3: Maximum near-surface (5 – 11 cm) and “deep” (75 – 90 cm) soil temperatures during a prominent winter storm, date of maximum and time lag between surface and depth at each automated weather station (1 Jun 07 to 31 Aug 07).

Site (Depth range)	Maximum surface temperature (°C)	Date of near-surface maximum	Maximum temperature at ~90 cm depth (°C)	Date of maximum at ~90 cm depth	Time lag from surface (days)
Minna Bluff (5 – 81 cm)	-13.25	8/06/2007	-18.69	12/06/2007	4.9
Scott Base (9 – 85 cm)	-15.34	7/06/2007	-20.10	10/06/2007	2.1
Marble Point (7.5 – 90 cm)	-15.97	8/06/2007	-21.28	12/06/2007	4.8
Granite Harbour (11 – 88 cm)	-16.61	19/07/2007	-20.47	20/07/2007	1.3
Wright Valley (7.5 – 90 cm)	-11.09	8/06/2007	-22.73	13/06/2007	5.7
Victoria Valley (7.5 – 90 cm)	-14.46	8/06/2007	-26.18	11/06/2007	2.2
Mt Fleming (7.5 – 75 cm)	-22.79	2/06/2007	-25.13	3/06/2007	1.3

5.5.2 Phase lag in permafrost (down to 28 m depth)

The phase lag calculation down to 28 m depth was undertaken using the annual maximum and minimum temperatures at a range of depths recorded in the 30 m permafrost temperature monitoring boreholes at Marble Point and Wright Valley (Chapter 4). The phase lag at both sites was calculated over the annual period from midnight 25 January 2007 to 6:00 pm 16 January 2008. The first 192 hours (8 days) of the record at both Marble Point and Wright Valley was removed to eliminate the effects of installation on recorded temperatures. As dataloggers were installed in the boreholes on 17 January 2007, no data from the start of the 2006-07 summer was available. Therefore the phase lag at each site was calculated relative to date of the the maximum near-surface soil temperature determined by the adjacent automated weather stations (Table 5.2).

Annual maximum and minimum temperatures at each depth were used to determine the phase lag between the near-surface and the deepest sensor at each site. There was some difficulty determining the date of occurrence for the minimum temperature, because with increasing depth, there were extended periods where the recorded temperature varied by about 0.01-0.02°C about the annual minimum. In order to get a representative date for the annual minima, the date in the middle of the extended period of temperatures within ±0.01°C of the annual minimum was defined as the date of the annual minimum.

The cumulative phase lag, to the nearest month, between the near-surface and the deepest sensor (27.5 m at Marble Point, 26.7 m at Wright Valley) was 12-13 months at Marble Point (Table 5.4) and 11-12 months at Wright Valley (Table 5.5). The phase lag calculated using the annual minimum temperatures was about the same as that for the maximum temperature. The difference between phase lags as calculated using annual maximum and minimum temperatures may be attributed to the difficulty encountered with defining the date of annual minima.

Table 5.4: Annual maximum and minimum temperature (25 Jan 07 to 16 Jan 08) and date of maximum and minimum temperature at each depth in the Marble Point borehole.

Depth (m)	Maximum temperature (°C)	Date of maximum	Time lag (months)	Minimum temperature (°C)	Date of minimum	Time lag (months)	Temperature Range (°C)
0.075[a]	15.24	11/01/2007	0	-37.53[b]	13/07/2007	0	52.77
1.0	-1.16	30/01/2007	0.5	-26.53	15/08/2007	1	25.37
2.0	-7.75	10/02/2007	1	-22.88	20/09/2007	2	15.13
5.0	-11.95	5/03/2007	2	-20.96	5/10/2007	3	9.01
8.0	-15.16	16/04/2007	3	-19.31	19/11/2007	4	4.15
10.0	-16.20	17/05/2007	4	-18.69	25/01/2007	6.5	2.49
12.0	-16.48	15/06/2007	5	-18.30	25/01/2007	6.5	1.82
13.0	-16.70	14/07/2007	6	-18.19	25/01/2007	6.5	1.49
14.0	-16.91	31/07/2007	6.5	-18.15	28/01/2007	6.5	1.24
16.0	-17.24	29/08/2007	7.5	-18.06	17/02/2007	7	0.82
18.0	-17.37	2/10/2007	8.5	-17.90	20/03/2007	8	0.53
23.0	-17.26	22/12/2007	11	-17.44	19/05/2007	10	0.18
27.5[c]	-16.97	10/02/2007	13	-17.04	31/07/2007	12	0.07

[a] *Summer maximum near-surface soil temperature from the automated weather station (1 Dec 06 – 28 Feb 07).*
[b] *Annual minimum near-surface soil temperature from the automated weather station (1 Jan 07 – 31 Dec 07).*
[c] *Based on the progression of phase lags at previous depths, the phase lag was assumed to continue increasing at 27.5 m depth.*

Table 5.5: Annual maximum and minimum temperature (25 Jan 07 to 16 Jan 08) and date of maximum and minimum temperature at each depth in the Wright Valley borehole.

Depth (m)	Maximum temperature (°C)	Date of maximum	Time lag (months)	Minimum temperature (°C)	Date of minimum	Time lag (months)	Temperature range (°C)
0.075[a]	15.22	12/01/2007	0	-46.65[b]	14/07/2007	0	61.87
0.23[c]	6.93	13/01/2007	0	-39.88	15/07/2007	0	46.81
2.2	-7.94	5/02/2007	0.5	-27.29	18/09/2007	2	19.35
4.2	-13.50	4/03/2007	1.5	-23.83	2/10/2007	3	10.33
7.2	-17.11	11/04/2007	3	-21.64	4/11/2007	4	4.53
9.2	-18.27	6/05/2007	4	-20.9	30/11/2007	5	2.63
11.2	-18.87	5/06/2007	5	-20.63	25/01/2007	6	1.76
12.2	-18.99	23/06/2007	5.5	-20.43	25/01/2007	6	1.44
13.2	-19.07	14/07/2007	6	-20.25	27/01/2007	6	1.18
15.2	-19.19	9/08/2007	7	-19.96	12/02/2007	7	0.77
17.2	-19.28	8/09/2007	8	-19.77	8/03/2007	8	0.49
22.2	-19.19	10/10/2007	9	-19.36	7/05/2007	10	0.17
26.7	-19.21	28/12/2007	11	-19.28	15/07/2007	12	0.07

[a] *Summer maximum near-surface soil temperature from the automated weather station (1 Dec 06 – 28 Feb 07).*
[b] *Annual minimum near-surface soil temperature from the automated weather station (1 Jan 07 – 31 Dec 07).*
[c] *Maximum and minimum soil temperature at about 0.23 m depth from the automated weather station.*

The maximum temperatures in the surface layer (e.g. down to about 2 m) occurred in the summer period at both Marble Point (Table 5.4) and Wright Valley (Table 5.5). The timing of occurrence of the maximum temperature was later with increasing depth; for example, the maximum temperature at 1.0 m depth at Marble Point occurred in late January while the maximum temperature at 16.0 m depth occurred in late August. Annual minimum temperatures in the deep sensors (e.g. deeper than about 14 m) occurred early in the calendar year, which coincided with the annual maximum temperatures recorded by the near-surface sensors (e.g. Figure 5.5).

The annual temperautre range (maximum – minimum) was plotted against depth for both Marble Point (Figure 5.6) and Wright Valley (Figure 5.7). The annual temperature range decreased exponentially with increasing depth at both sites (R^2=0.99 at Marble Point, R^2=0.98 at Wright Valley). The temperature ranges also decreased exponentially in the summer ($0.40 \leq R^2 \leq 0.81$) and the winter ($0.75 \leq R^2 \leq 0.95$) periods (Appendix III).

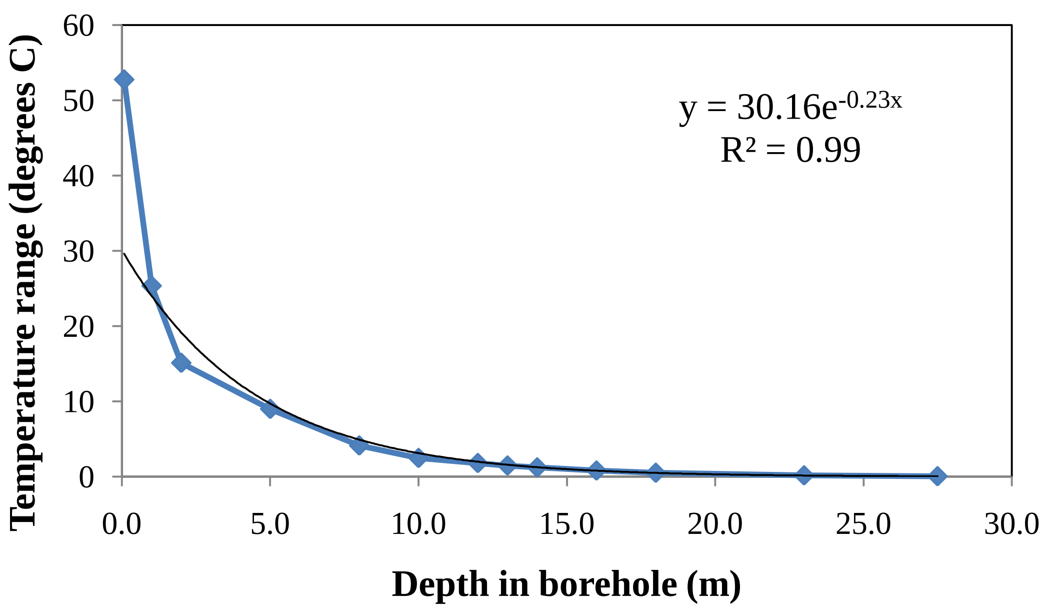

Figure 5.6: Temperature range (maximum – minimum) with depth in the borehole at Marble Point from 25 January 2007 to 16 January 2008.

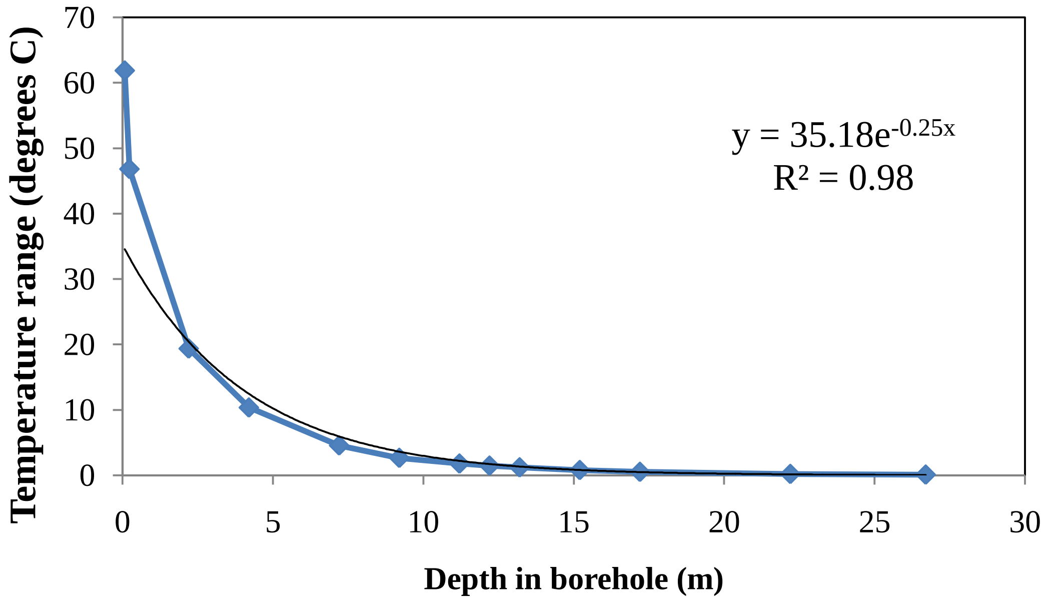

Figure 5.7: Temperature range (maximum – minimum) with depth in the borehole at Wright Valley from 25 January 2007 to 16 January 2008.

5.6 Depth of "Zero Annual Amplitude"

The depth of "Zero Annual Amplitude" is the depth at which the annual temperature range becomes "negligible" (Muller 1947, Linell & Tedrow 1981, Oke 1987). The temperature at depth of Zero Annual Amplitude can be used as a proxy for mean annual air temperature (Oke 1987), because it provides an integrated response to the air temperatures for the previous year (Bodri & Cermak 2007). The depth of Zero Annual Amplitude is here estimated on the basis of the annual temperature range (maximum – minimum).

The primary difficulty with the concept of the depth of "Zero Annual Amplitude" stems from the ambiguity of the definition. While defined as the depth at which the annual temperature range is "negligible", this does not provide practical boundaries for application to temperature observations. The accuracy of the sensors at Marble Point and Wright Valley was ±0.1°C which is more accurate than the temperature measurements which some previous workers have used.

As seen in the annual deeper permafrost temperature cycles (section 5.3), the amplitude of the temperature cycle decreased with increasing depth (Figures 5.4 and 5.5). In both boreholes, the annual temperature range at about 23 m depth was 0.2°C, and at about 27 m depth it was 0.1°C. When the temperature at 23.0 m and 27.5 m at Marble Point, and 22.2 m and 26.7 m depth at Wright Valley were plotted with an enlarged vertical scale, clear annual cycles were observed (Figure 5.8). Flickers in the temperature were evident, when the temperature changed by about ±0.02 – 0.03°C, which were attributed to sensor variability.

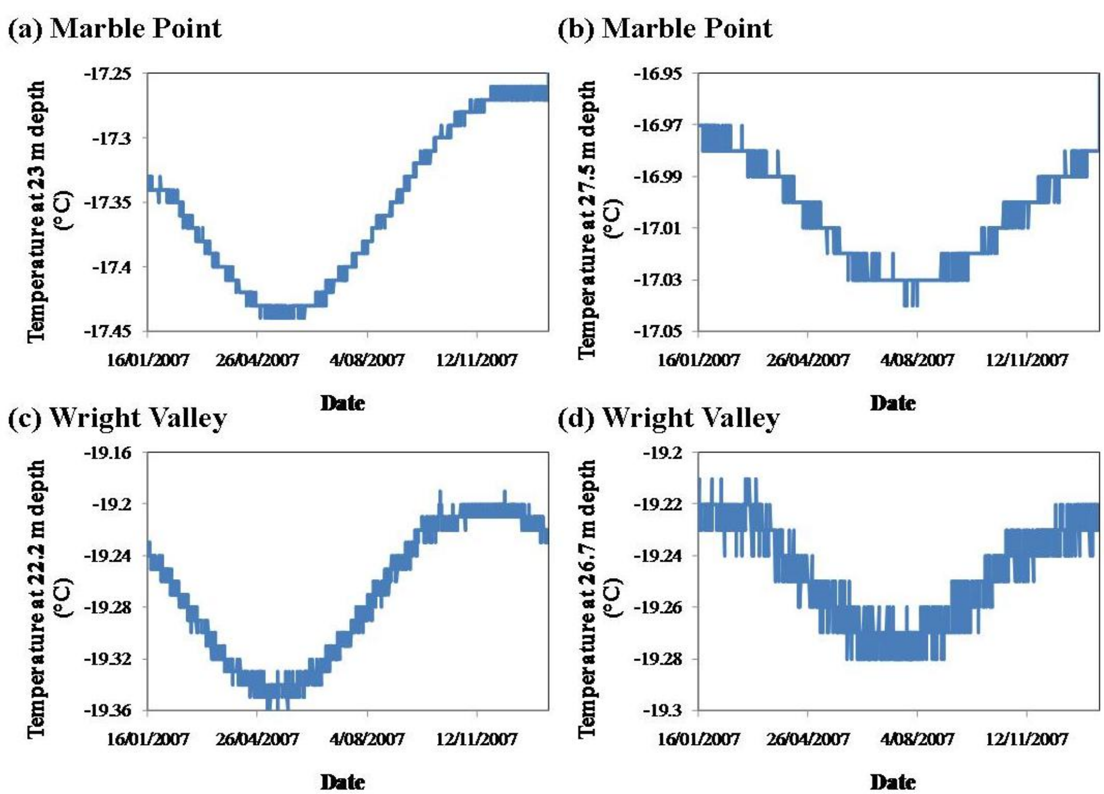

Figure 5.8: Annual temperatures at (a) 23 m depth at Marble Point, (b) 27.5 m depth at Marble Point, (c) 22.2 m depth at Wright Valley and (d) 26.7 m depth at Wright Valley.

Though the annual temperature range below about 22 m depth was low (≤0.2°C), it was clear that an annual temperature cycle existed. The calibration of the sensors to an accuracy of ±0.1°C prior to installation gave credence to the annual temperature cycles observed. In light of this, it was clear that the depth of Zero Annual Amplitude was likely to be at least as deep as the borehole (i.e. 30 m), if not deeper. The mean annual temperature was –17.0°C at 27.5 m at Marble Point and –19.2°C at 26.7 m at Wright Valley.

If the accuracy of the temperature measurements was reduced, for example to ±1°C or ±0.5°C, the depth to which the annual temperature cycle can be observed is less. Figures 5.6 and 5.7 were enlarged (Figures 5.9 and 5.10) to determine the depth the annual temperature cycle could be observed at various accuracies (Table 5.6). At Marble Point, the annual temperature range was ≤1°C at 15.2 m, ≤0.5°C at 18.4 m and ≤0.1°C at 26.4 m, while at Wright Valley, an annual temperature range of ≤1°C occurred at 14.0 m, ≤0.5°C at 17.2m and ≤0.1°C at 25.2 m.

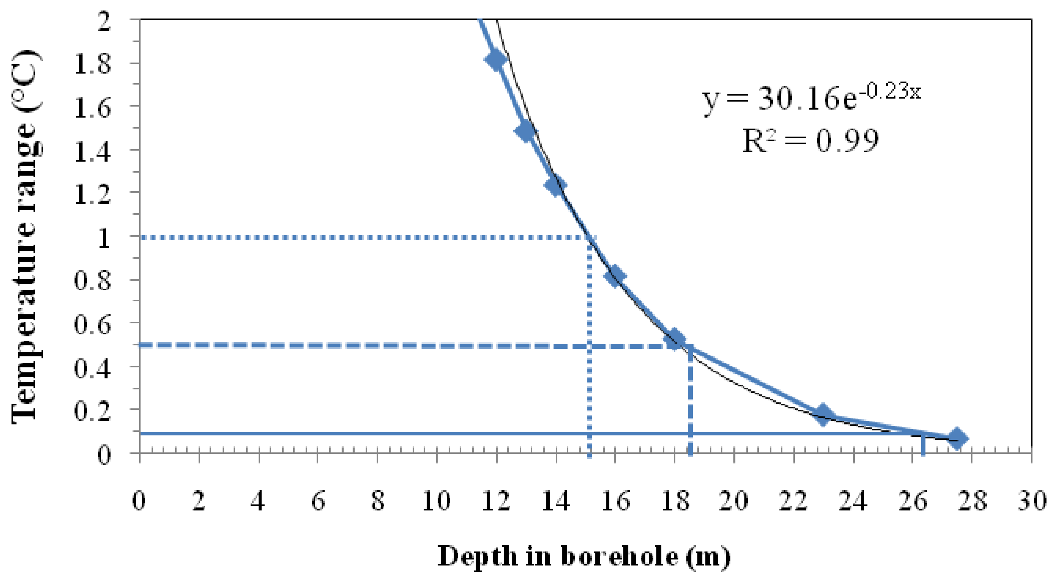

Figure 5.9: Annual temperature range with depth in the borehole at Marble Point from 25 January 2007 to 16 January 2008 (Enlargement of Figure 5.6). The lines indicate the depths where the annual temperature range is less than 1°C (dotted line), less than 0.5°C (dashed) and less than 0.1°C (solid).

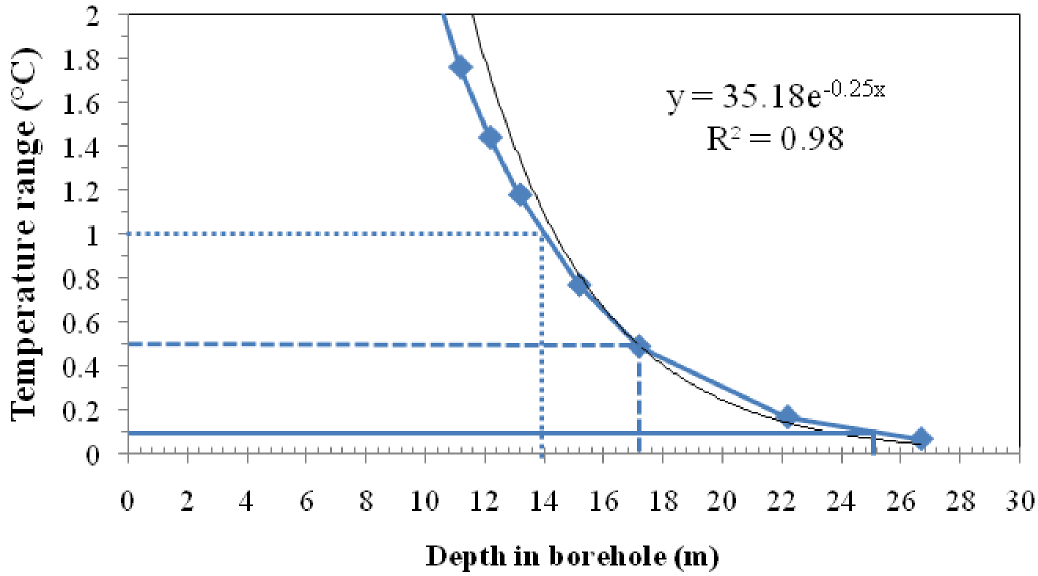

Figure 5.10: Annual temperature range with depth in the borehole at Wright Valley from 25 January 2007 to 16 January 2008 (Enlargement of Figure 5.7). The lines indicate the depths where the annual temperature range is less than 1°C (dotted line), less than 0.5°C (dashed) and less than 0.1°C (solid).

Table 5.6: Depth of "Zero Annual Amplitude" at Marble Point and Wright Valley at accuracies of 1°C, 0.5°C and 0.1°C, estimated using a graphical interpolation from Figures 5.9 and 5.10.

Sensor accuracy (°C)	Marble Point (m)	Wright Valley (m)
1.0	15.2	14.0
0.5	18.4	17.2
0.1	26.4	25.2

5.7 Discussion

5.7.1 Comparison of seasonal and annual temperature cycles

The annual temperature cycle displayed both a summer diurnal and an annual sinusoidal pattern at Marble Point and Wright Valley. The sinusoidal pattern has been noted as the simplest representation of soil temperature at most depths within the soil (Koorevaar *et al.* 1983, Hillel 2004). The sinusoidal pattern is usually observable at the diurnal time scale (Hillel 2004) and has been previously observed in Antarctica e.g. at Marble Point (Balks *et al.* 1995), Linnaeus Terrace (McKay *et al.* 1998), and Boulder Clay (Guglielmin 2006). In Antarctica, the diurnal pattern was evident only during the summer and only in the air temperature and near-surface (5 – 9 cm) soil temperatures (Figure 5.2).

The simple sinusoidal patterns at the daily and annual scales may be complicated by episodic disturbances, such as weather patterns, snow, or warm events (Buchan 1991, Hillel 2004). For example, there were several peaks in temperature measured at the ground surface during the winter at Marble Point (Figure 5.4a) and Wright Valley (Figure 5.4b). Episodic, rapid warming events were observed in the near-surface soil during the winter at all stations in the soil climate monitoring network, and in the surface sensors in the Marble Point and Wright Valley boreholes. Balks *et al.* (1995) attributed such disturbances to winter storms that cause intermittent warming of temperatures during the winter period, beginning in May or June, when the temperature would usually be expected to continue cooling, which is also known as the coreless winter (Wexler 1959, Thompson 1969). The air and soil temperature at all depths at all sites increased steadily from the start of the summer period through to the end of January, which was also observed at Marble Point by Balks *et al.* (1995) and Campbell *et al.* (1998b).

Temperatures during the winter at all sites in the soil climate monitoring network and those measured by the two 30 m deep boreholes showed that deeper sensors were often warmer than the sensors closest to the surface. The soil may have been a heat source during the winter as the surface air temperature and shallow soil temperatures were cooler than those at depth at all seven automated weather stations. A similar situation was observed at Pomquet Station, Canada by Beltrami (2001), who used soil temperature observations over the course of one year. Heat was transferred from 0.5 m and 1 m depth to the surface and thus acting as a heat source to the atmosphere during autumn and winter, compared to heat transfer from the surface to depth during the spring and summer seasons (Beltrami 2001).

5.7.2 Comparison of attenuation of the temperature signal and phase lag at seasonal and annual scales

5.7.2.1 Attenuation of the temperature signal and damping depth

Attenuation of the temperature signal was observed with increasing depth at all sites during the summer and winter periods and at the annual scale. Surface temperature maxima during the summer were attenuated by about 45 cm depth, which corresponded to the diurnal damping depth (Table 5.3). There were no short-term changes in the soil temperatures at 75 – 90 cm depth during the summer. The attenuation of the temperature cycle was also observed at 55 cm depth at Marble Point (Balks *et al.* 1995), 40 cm depth at Linnaeus Terrace (McKay *et al.* 1998) and 30 cm depth at Boulder Clay (Guglielmin 2006).

The damping depths calculated using both summer and winter data were usually similar at all sites. Differences between summer and winter damping depths may be due to changes in the water/ice content during freezing and thawing and thus changes in the thermal conductivity of the soil. For example, the soil at Granite Harbour has been observed to have meltwater percolating through the subsurface in summer (M. Balks, *pers. comm.*), which is hypothesised to enhance the transfer of heat through the soil profile (Chapter 3). Therefore the temperature cycle penetrated further into the soil with less damping, leading to the deeper damping depth compared to other sites in the McMurdo Sound region (Table 5.1). Damping depth is also partially a function of the temperature range at the surface, which presumably led to the range of damping depths observed in this study (Table 5.1). For example, the summer damping depths at Victoria Valley and Mt Fleming were shallower than in winter, probably due to the markedly greater soil surface temperature range during the winter (e.g. shallow soil, Figure 5.3f) compared to the summer (e.g. shallow soil, Figure 5.2f).

The annual temperature cycle was easily observed at depths greater than 10 m, because shorter period temperature fluctuations (e.g. diurnal) were attenuated more rapidly than the larger annual temperature fluctuations (Koorevaar *et al.* 1983, Hillel 2004, Bodri & Cermak 2007). Despite the fact that surface maxima penetrated to about 45 cm depth within about a day, the soil below about 45 cm depth during the summer responded to longer period temperature cycles than diurnal temperature cycles. Campbell (1985) and Buchan (1991) stated that diurnal temperature cycles tend to be damped within about 0.1 m of the surface. However the damping depth calculated for the seven sites in the McMurdo Sound region showed that the diurnal temperature penetrated below 0.1 m depth. The longer period seasonal scale temperature variation means that the temperature signal will penetrate further than the diurnal temperature wave.

The temperature amplitude decreased exponentially with depth (Campbell 1985, Bodri & Cermak 2007) at all sites during the summer ($0.4 \leq R^2 \leq 0.8$) and winter ($0.75 \leq R^2 \leq 0.95$) (Appendix III) and at Marble Point and Wright Valley at the annual scale ($R^2 > 0.9$). Soil temperatures at Linnaeus Terrace down to 40 cm depth, (McKay *et al.* 1998), showed an exponential decrease in annual temperature range.

5.7.2.2 Phase lag of the temperature signal

The summer maximum temperature at about 90 cm depth was delayed behind the surface maximum by 15 – 22 days (Table 5.2). The phase lag in the soil at Marble Point and Wright Valley (~20 days) was about the same as the phase lag of about half a month at 1.0 m depth at Marble Point (Table 5.4) and about 2.2 m depth at Wright Valley (Table 5.5). The similarity between the phase lags between soil profiles and permafrost temperature monitoring boreholes indicated that there were similarities in thermal conductivity of the rock materials.

At a monitoring station in Pomquet, Canada, Beltrami (2001) reported a phase lag of about 2 months to 1 m depth. The Canadian site differed from our Antarctic sites because it was vegetated and located near forest, and the vegetation may have initially attenuated the temperature signal. More importantly, however, would be the difference in the thermal properties of the subsurface. The temperature signal is delayed in time and decreased amplitude due to diffusive heat conduction (Bodri & Cermak 2007) and heat conduction is affected by the thermal conductivity, heat capacity and thermal diffusivity (Koorevaar *et al.* 1983, Oke 1987, Hillel 2004). Different rock and soil types and varying soil moisture contents will have different thermal properties, thus affecting the transmission of heat through the subsurface (Koorevaar *et al.* 1983, Oke 1987, Hillel 2004).

Despite differences in parent materials or bedrock (Chapter 1) the phase lag to about 1 m depth during the summer was similar at all sites (about 20 – 22 days). No thermal conductivity data was available for the seven sites, so no definitive conclusions can be drawn about the impact of differing material on the phase lag. However, other local factors were likely to affect the transmission of the surface temperature maxima to depth. As previously stated, the presence of soil moisture in the subsurface at Granite Harbour may be causing heat to transfer rapidly to depth, thus leading to the shortest phase lag of all sites in this study over the same approximate depth range. The short phase lag at Mt Fleming may be due to the relatively shallow depth (75 cm) compared to the other sites (90 cm). It is possible that at 90 cm depth at Mt Fleming, the phase lag may be similar to the other sites, but more sensors would be necessary to confirm this theory.

The phase lag of the annual cycle between the surface and the deepest sensors in the permafrost monitoring boreholes was 12-13 months at Marble Point and 11-12 months at Wright Valley. With increasing depth, the temperature was an integrated response to temperatures at longer time scales (MacLean & Eyres 1985, Bodri & Cermak 2007). The phase lag to about 30 m depth was only a best estimate because there was only one year of data available from the permafrost temperature monitoring boreholes. Bodri & Cermak (2007) suggested that temperatures below 20 – 30 m depth were not responding to annual temperature cycles and would more likely be responding to longer-term climatic fluctuations, which may be possible considering the phase lag of about one year that was calculated, though more data will be required to accurately assess the phase lag between the surface and the deepest sensor.

5.7.3 Depth of “Zero Annual Amplitude”

Annual temperature cycles have been said to penetrate to depths of 10 – 15 m (Oke 1987, Bodri & Cermak 2007), which is shallower than the depth at which annual temperature cycles were observed at Marble Point and Wright Valley. The accuracy of the calibrated sensors measuring temperature at Marble Point and Wright Valley (±0.1°C) led to the annual temperature cycle being observed at depths greater than might have been anticipated. The mean annual temperature at 27.5 m depth (–17.0°C) at Marble Point, and at 26.7 m (–19.2°C) at Wright Valley were similar to the mean annual air temperature recorded at the automated weather stations (–18°C at Marble Point, –20°C at Wright Valley).

Depth of “Zero Annual Amplitude” was determined at two sites in Northern Victoria Land near the Italian Antarctic Research station (both 74°S) by Guglielmin (2006). At Boulder Clay, thermal diffusivity values were used to estimate the depth of Zero Annual Amplitude as being between 12.9 and 14.3 m (Guglielmin 2006). Temperature-depth profiles were used at Oasi and the region where two profiles converged suggested that the depth of Zero Annual Amplitude was between 10 and 11 m (Guglielmin 2006). Boulder Clay and Oasi had a shallower depth of “Zero Annual Amplitude” than measured at Marble Point (77.4°S) and Wright Valley (77.5°S). The accuracy of thermistors used by Guglielmin (2006) was ±0.1°C, so the difference between the depths of “Zero Annual Amplitude” must be due primarily to the method of determination, but potentially also due to subsurface thermal properties, such as thermal conductivity, and local climate factors. At similar latitude to Marble Point and Wright Valley in the Northern Hemisphere was Janssonhaugen, Svalbard (78°N), where the depth of “Zero Annual Amplitude” was reported as 18 m (Isaksen 2000).

There was difficulty in comparing the depth of “Zero Annual Amplitude” between sites, due to differing methods of determining “Zero Annual Amplitude” between studies. For example, Guglielmin (2006) reported estimated depths of “Zero Annual Amplitude” using two different methods. The first was to use thermal properties to estimate the depth of “Zero Annual Amplitude”, which was deeper than sensors in the 3.6 m borehole at Boulder Clay were measuring. The second method used by Guglielmin (2006) was to present temperature-depth profiles and estimate the depth of “Zero Annual Amplitude” as where the two profiles intercepted each other. While the depth of “Zero Annual Amplitude” may be reported at various locations, differing definitions and methods used makes the comparison between studies ultimately meaningless until a normalised method is identified and applied.

As the accuracy of the sensor improves, the annual temperature cycle could be observed at increasing depth (Table 5.6). Using year round, permanently installed temperature measurements allows the sensors to equilibrate to being in the borehole, and thus removing some of the systematic error that can occur when using a thermistor string for a short period during the summer. With increasing sensor accuracy and the establishment of year-round temperature monitoring boreholes, the depth of “Zero Annual Amplitude” becomes an obsolete and misleading term, and should be redefined. From this data, the concept of “Zero Annual Amplitude” appears flawed, because with increasing sensor accuracy, the temperature cycle will be able to be observed at greater and greater depths, with a true annual temperature range of zero never being attainable. I would suggest a possible redefinition of the concept as the depth at which the annual temperature range is less than a specific value, such as ≤1°C, ≤0.5°C and ≤0.1°C, providing that the temperature sensors are calibrated accordingly prior to installation.

5.7 Conclusions

The annual temperature cycle displayed a sinusoidal pattern, which was disrupted during the winter by peaks in surface temperatures associated with winter storms. Plots of soil temperatures at all seven McMurdo Sound sites revealed a diurnal cycle during the summer in air and soil temperatures, which were not observed below about 45 cm depth. In winter, there was no diurnal soil temperature cycle due to the lack of sunlight to force it. Temperatures instead had episodic peaks in response to winter storm passage which registered in air and soil temperatures down to about 1 m depth.

There was probably snow cover at all sites at some times during the year, particularly in the winter. In winter, deeper permafrost temperature (below about 7 m) were warmer than those between about 1 and 5 m depth, and soil temperatures at about 1 m depth were warmer than near-surface soil temperatures (5 – 9 cm), indicating that during the winter, the subsurface can become a heat source.

The damping of the diurnal temperature cycle during the summer was observed to about 45 cm depth, while annual temperature cycles penetrated to below 15 m depth, due to the longer period of the annual temperature cycle. The phase lag between the near-surface (5 – 9 cm) and about 90 cm was 15 – 22 days at both Marble Point and Wright Valley. The phase lag between the surface and about 27 m depth was 12-13 months at Marble Point and 11-12 months at Wright Valley.

The seasonal and annual temperature range (maximum – minimum) decreased exponentially with depth. Annual temperature cycles were observed by the deepest sensors at both Marble Point and Wright Valley, indicating that the depth of "Zero Annual Amplitude" was a flawed concept as sensor accuracy is constantly improving. With no standard method of defining the depth of "Zero Annual Amplitude", comparison between sites is meaningless. The depth of "Zero Annual Amplitude" was clearly dependent on the accuracy of the sensors being used, with improved accuracy leading to the annual temperature cycle being observed at greater depths. A standard method of determination is required to make results of different studies comparable. Potentially, the term "Zero Annual Amplitude" needs to be redefined or renamed to avoid confusion. I propose that instead of the depth of "Zero Annual Amplitude", that one refers instead to the depth at which the annual temperature range is less than 1°C, less than 0.5°C and less than 0.1°C. At Marble Point, the annual temperature range was ≤1°C at 15.2 m, ≤0.5°C at 18.4 m and ≤0.1°C at 26.4 m, while at Wright Valley, an annual temperature range of ≤1°C occurred at 14.0 m, ≤0.5°C at 17.2m and ≤0.1°C at 25.2 m.

CHAPTER 6: MEAN ANNUAL AND SEASONAL AIR AND SOIL TEMPERATURES

6.1 Introduction

Mean annual air temperatures, shallow soil temperatures (6.5 – 9 cm depth) and deep soil temperatures (75 – 105 cm depth) are reported for seven sites in the McMurdo Sound region for 1999 – 2007. Mean annual air temperatures were examined for evidence to investigate reported trends of cooling (Doran *et al.* 2002b) in Antarctica. Mean summer air temperature (Dec – Jan), mean winter air temperatures (Jun – Aug) and mean monthly air temperatures are reported. Active layer depths are repeated from Chapter 3 for comparison with mean annual and mean summer air temperatures.

The objective of this chapter is to investigate the existence of any warming or cooling trend in mean annual air and soil temperatures from 1999 – 2007, determine how mean summer and mean winter air temperatures influence mean annual air temperature and describe how mean annual temperatures change across latitude and altitude.

6.2 Mean annual air and soil temperatures

6.2.1 Mean annual air temperature

Mean annual air temperature varied inter-annually (Figure 6.1). The maximum mean annual air temperature at all sites occurred in 2007, except at Victoria Valley where the maximum occurred in 2003. All recording sites except Victoria Valley had a minimum mean annual temperature in 2004, with a slight increase in 2005.

There was no trend ($0 \leq R^2 \leq 0.2$) in the mean annual air temperature at any site between 1999 and 2007, except at Granite Harbour ($R^2 = 0.8$). The high R^2 value at Granite Harbour was influenced by the shortness of the record (4 years). The mean annual air temperature at Granite Harbour was not significantly different ($p > 0.05$) to Marble Point and Scott Base (other sites along the latitudinal section). The mean annual air temperature at Granite Harbour may therefore have followed a similar pattern of inter-annual variation as exhibited at Marble Point and Scott Base, prior to site installation in 2003.

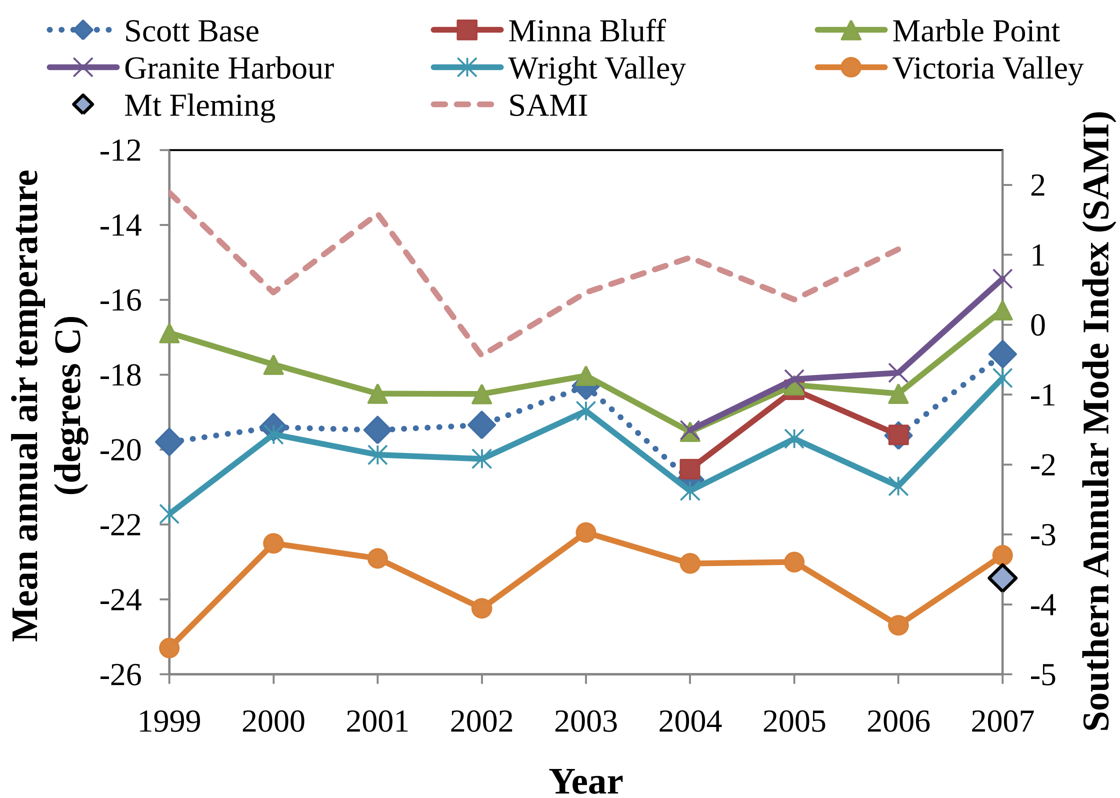

Figure 6.1: Mean annual air temperatures at seven sites in the McMurdo Sound region of Antarctica for 1999 – 2007. The Southern Annular Mode Index (SAMI) (dotted line) was provided by Willem deLange, after Nan & Li (2003).

The warmest mean annual air temperatures occurred at Marble Point and Granite Harbour, both sites being in the coastal climate zone (Chapter 2, Section 2.2). Victoria Valley had the lowest mean annual temperature every year except 2007, when Mt Fleming was colder than Victoria Valley by 0.6°C. The 107 air temperature sensor at Victoria Valley could not read below –40°C and often flat-lined at –40°C during the winter, so the mean presented in Figure 6.1 is the maximum possible mean annual air temperature for Victoria Valley, with the true mean potentially lower.

The Southern Annular Mode (SAM) has been linked to air temperature in Antarctica (Kwok & Comiso 2002, Marshall 2007). The positive phase of the SAM leads to below average pressure in Antarctica and thus warmer temperatures on the Antarctic Peninsula and colder temperatures in Eastern Antarctica. The Southern Annular Mode Index (SAMI) from 1948 to 2007 was provided by Willem deLange (pers. comm. 2008) (after Nan & Li (2003)), which was then plotted against the mean annual air temperature to determine if there was any correlation between the SAMI and the mean annual air temperature. The inter-annual change in the annual SAMI did not match any pattern in the mean annual air temperature at any of the seven sites in the McMurdo Sound region, which was contrary to what was expected based on the literature. The negative phase of the SAMI in 2002 would be expected to cause cooler temperatures in the McMurdo Sound region, based on the assumption that the McMurdo Sound region responds in a similar way to the Antarctic Peninsula (Chapter 3) due to its position on the western side of the TransAntarctic Mountains. However, no trend towards cooler mean annual air temperature could be observed at any of the seven sites in the McMurdo site region. There were cool mean annual air temperatures at Victoria Valley in 2002, but cool temperatures also occurred in 2006 when the SAMI was in the positive phase, so the 2002 mean annual air temperature cannot be reliably linked to the SAMI in this study.

6.2.2 Mean annual soil temperatures

6.2.2.1 Shallow soil depth range (6.5 – 9 cm)

The mean annual temperature in the shallow soil depth range was warmest at Granite Harbour (Figure 6.2). Victoria Valley always had the coolest mean annual shallow soil temperature. There were no significant differences between the mean annual shallow soil temperatures at Scott Base and Marble Point, but all other sites were significantly different from each other ($p < 0.05$). Minna Bluff and Mt Fleming were excluded from the significance testing as there was only one year at each site where the mean annual soil temperature could be calculated.

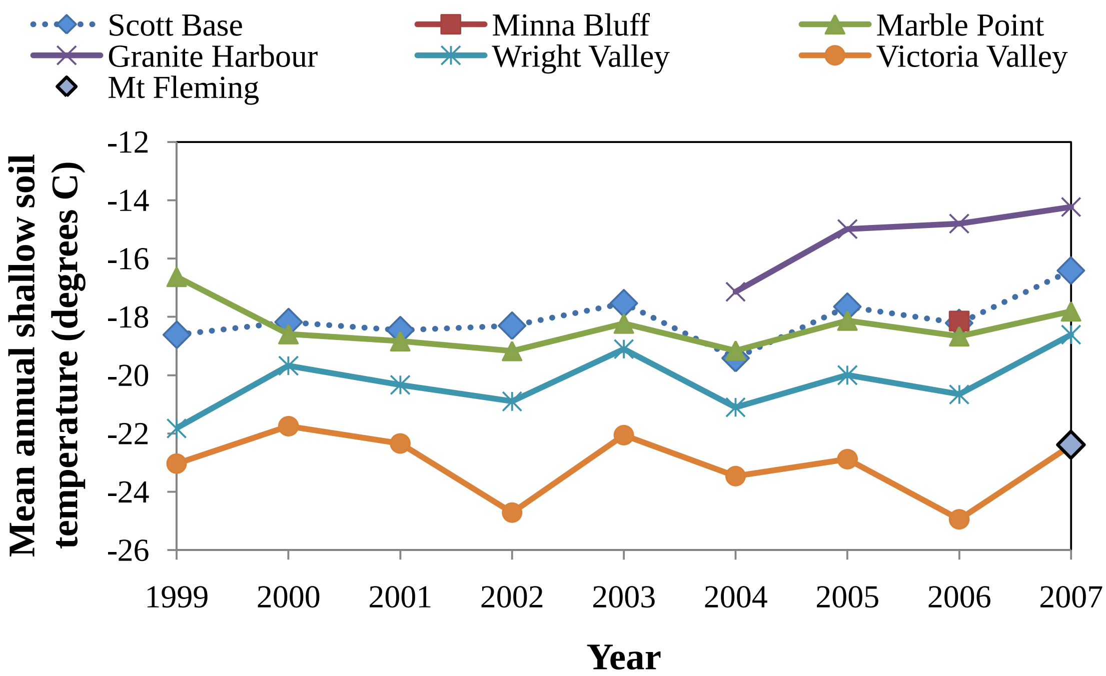

Figure 6.2: Mean annual temperature at the shallow soil depth (6.5 – 9 cm) at seven sites in the McMurdo Sound region of Antarctica for 1999 – 2007.

The mean annual temperature at the shallow soil depth range was within ±4°C of the mean annual air temperature. The mean annual temperature in the shallow soil depth range at all sites displayed the same general pattern as mean annual air temperature, though the inter-annual range (maximum – minimum) was less in shallow soil temperatures than the air temperatures. The mean annual shallow soil temperature was usually warmer than the mean annual air temperature.

The maximum mean annual temperature at the shallow soil depth range occurred in 2007 at all sites except Marble Point (maximum in 1999) and Victoria Valley (2000). There was no trend in the mean annual temperature between 1999 and 2007 ($0.04 \leq R^2 \leq 0.25$) at any site except Granite Harbour ($R^2 = 0.8$).

6.2.2.2 Deep soil depth range (75 – 105 cm)

The mean annual temperatures at the deep soil depth range (Figure 6.3) showed inter-annual variability similar to the shallow soil layer (Figure 6.2). The inter-annual variability in mean annual deep soil temperatures was less than that in the shallow soil depth range, presumably due to the damping effect of the temperature signal with depth. At the annual scale, the damping of the temperature signal was not marked between the shallow and deep soil layers because annual signals penetrate to depths greater than 10 m, while diurnal cycles are more visible within the depth range explored here.

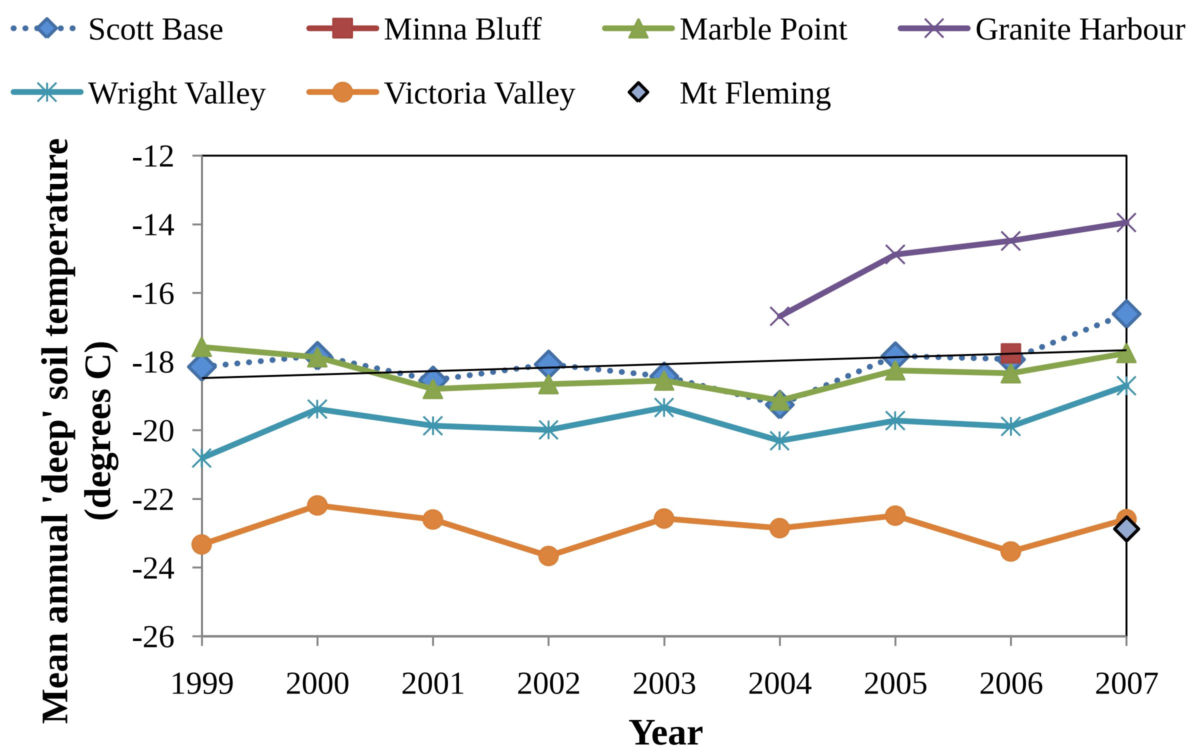

Figure 6.3: Mean annual temperature at the deep soil depth (75 – 105 cm) at seven sites in the McMurdo Sound region of Antarctica for 1999 – 2007.

There was no trend in the mean annual temperatures at any sites between 1999 and 2007 ($0 \leq R^2 \leq 0.27$), except Granite Harbour ($R^2 = 0.9$), which had a shorter record. Granite Harbour had the warmest temperatures in the deep soil depth range, while Victoria Valley was the coldest.

6.3 Mean seasonal air temperatures

6.3.1 Mean summer air temperature

The mean summer air temperature (1 Dec to 31 Jan) (Figure 6.4) followed a different pattern of inter-annual variability to the mean annual air temperature (Figure 6.1). The summer of 2000-01 was a cooler summer (Wall 2004, M. Balks *pers. comm.)* than usual, while 2001-02 was warmer (Wall 2004, Massom 2006, Barrett 2008). The inter-annual variation in mean summer air temperature differs in pattern from mean annual air temperature due to taking the summer across two calendar years, thus splitting the influence of the combined December-January warm summer temperatures. The warm summer of 2001-02 (Chapter 3) was not evident as a peak in the mean annual air temperature (Figure 6.1), which suggested that warm summer air temperatures may be balanced by the winter air temperatures. By splitting the summer season across two calendar years, the impact of warm summer air temperatures may be masked by the autumn, winter and spring air temperatures that comprise the remainder of the year, and thus have a greater influence on the mean annual air temperature.

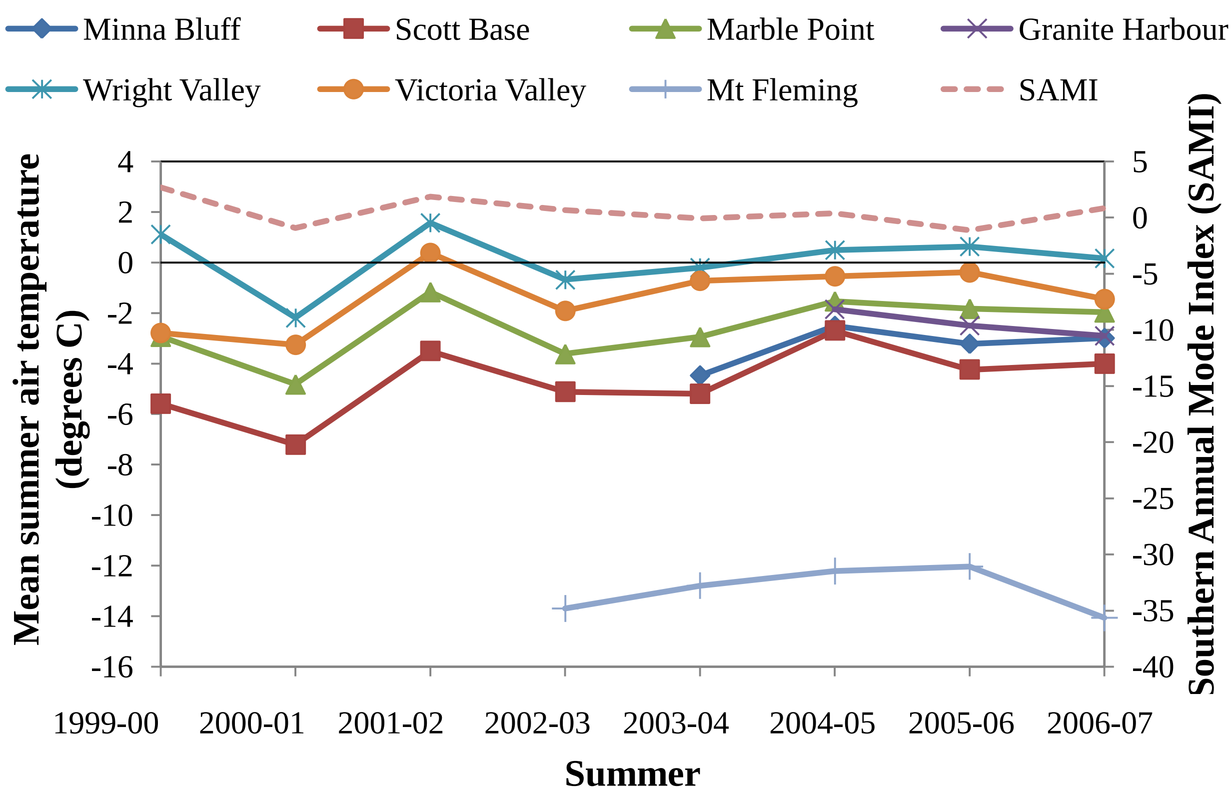

Figure 6.4: Mean summer (1-Dec to 31-Jan) air temperature at seven sites in the McMurdo Sound region of Antarctica for up to eight successive summers (1999-00 to 2006-07). The Southern Annular Mode Index (SAMI) for the summer periods (Dec-Feb) was provided by Willem deLange, after Nan & Li (2003).

The mean summer air temperature was warmest at Wright Valley and coolest at Mt Fleming. Wright Valley was the only site, except for one occasion at Victoria Valley, where the mean summer air temperature exceeded 0°C. Preliminary analysis by Aislabie *et al.* (2006) also showed that mean January air temperatures at Marble Point and Wright Valley exceeded 0°C, which was attributed to continuous summer solar radiation. Most sites followed a similar pattern of variation, where the minimum mean summer air temperature occurred in 2000-01, and the maximum occurred in 2001-02.

In chapter 3, the McMurdo Sound region was seen to respond to the Southern Annular Mode in a similar way to the Antarctic Peninsula; the positive phase of the Southern Annular Mode led to warmer summer air temperature in 2001-02, and therefore the negative phase could be expected to lead to cooler summer air temperatures. When the Southern Annual Mode Index (SAMI) for Dec – Feb was plotted along with the mean summer air temperatures (Dec – Jan) for the seven sites in the McMurdo Sound region, the peaks and troughs in the SAMI aligned with the major peaks and troughs in the mean summer air temperature. For example, the negative SAMI in the summer of 2000-01 corresponded to the cool summer air temperatures, while the maximum, positive SAMI corresponded to the warm summer of 2001-02. The negative SAMI value in the summer of 2005-06 led to cooler mean summer air temperature at Scott Base, Marble Point, Granite Harbour and Minna Bluff. There may be a degree of mismatch between the SAMI available and the mean summer air temperatures reported here, due to the mean summer air temperatures being taken across December and January only, while the SAMI includes February. However, the variations in the SAMI do not completely explain the variation in mean summer air temperature from year to year. It is interesting to note that while the mean summer air temperature and the Southern Annular Mode index varied concurrently, the mean annual temperature at all sites followed no such pattern. When Southern Annular Mode Index was plotted against mean summer air temperature for each site, there was no correlation at any site ($0 \leq R^2 \leq 0.39$).

6.3.2 Active layer depth

The active layer depth showed inter-annual variability (Figure 6.5), which did not correspond to the changes in mean annual air temperature (Figure 6.1). The shallow active layer in 2000-01 and the deep active layer in 2001-02 corresponded to the cool and warm summers evident in the mean summer air temperature (Figure 6.4). Like the mean summer air temperature, the active layer depth has two distinct peaks (shallow in the cool summer and deep in the warm summer) after which there was no significant trend in active layer depth. The active layer depth at Granite Harbour was greater than 90 cm in each summer because the temperature-depth profile did not intercept the 0°C isotherm within the 90 cm deep observation range (Chapter 3).

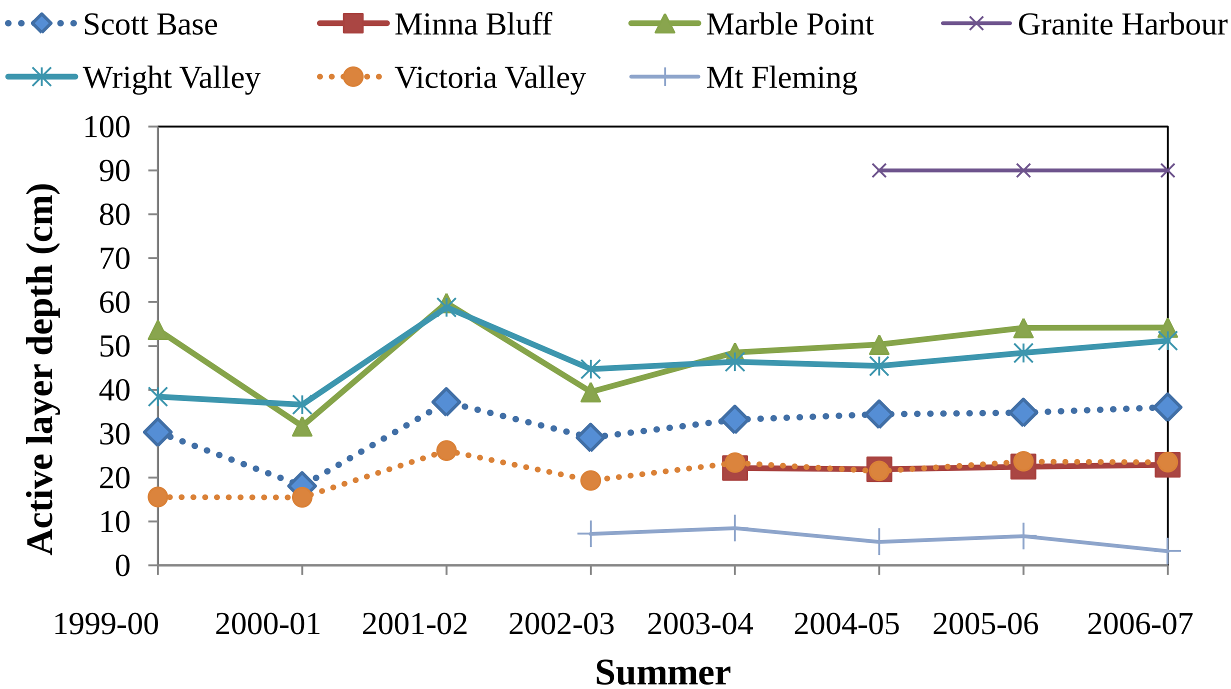

Figure 6.5: Active layer depth at seven sites in the McMurdo Sound region of Antarctica for up to eight successive summers (1999-00 to 2006-07). Note that the active layer depth at Granite Harbour was greater than 90 cm in all three summers.

6.3.3 Mean winter air temperature

At all sites except Victoria Valley, the warmest mean winter (June to August) air temperature occurred in 2007 (Figure 6.6). The mean annual air temperature at all sites except Victoria Valley was warmest in 2007, suggesting that the winter air temperatures may be more influential on the mean annual air temperature than the mean summer air temperature. Scott Base, Marble Point and Granite Harbour had the minimum mean winter air temperature in 2004. Mean winter air temperature was cooler at Wright Valley compared to Scott Base (Figure 6.6), as also shown by Thompson *et al.* (1971) using data from 1969 – 1970.

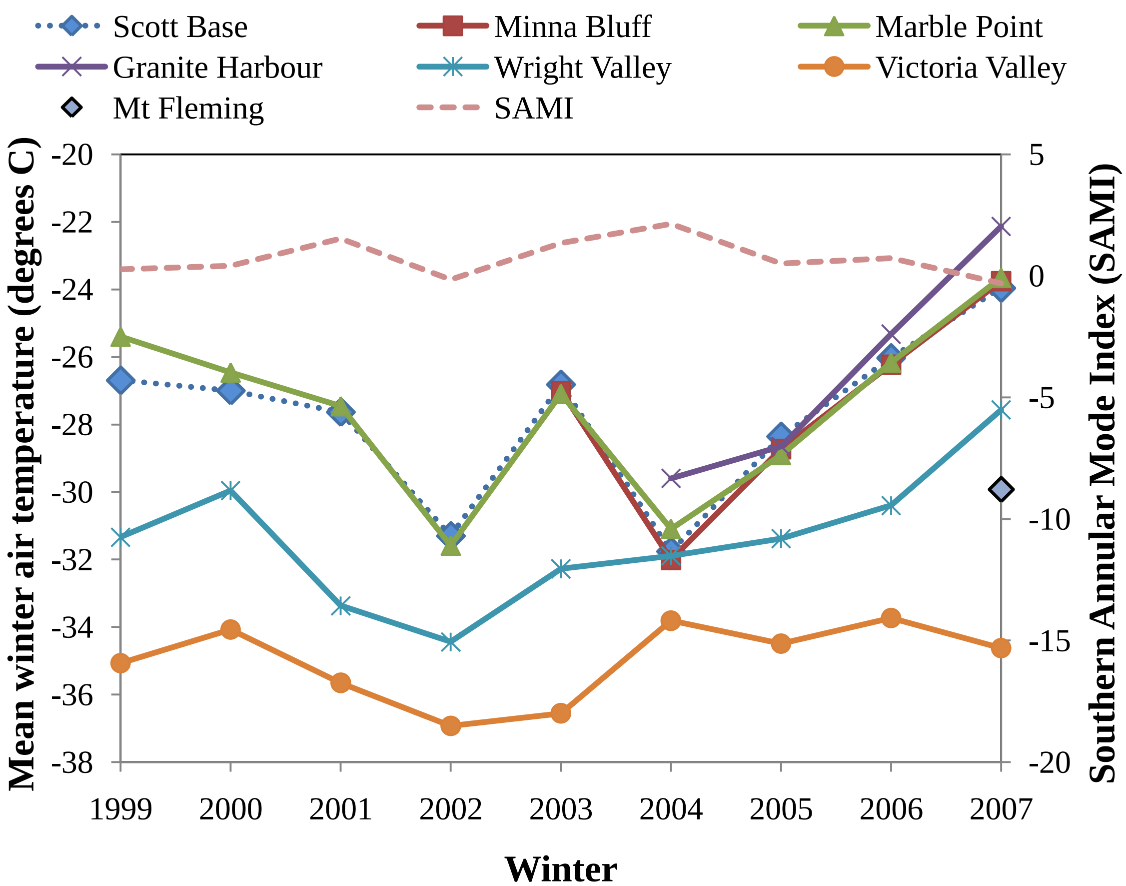

Figure 6.6: Mean winter (1 Jun to 31 Aug) air temperature at seven sites in the McMurdo Sound region of Antarctica for up to eight successive winters (1999 – 2007).

When plotted with the Southern Annular Mode Index (SAMI), there was no evident similarity in inter-annual variation of SAMI and the mean winter air temperature. The peak positive SAMI was aligned with the minimum mean winter air temperature, which was contrary to what would be expected. The peaks of SAMI in 2001 and 2004 would be expected to lead to warmer air temperatures. However, the positive SAMI in 2004 was aligned with the coldest mean winter air temperature at five out of seven sites. When plotted, SAMI was negatively correlated with mean winter air temperature at Minna Bluff ($R^2 = 0.73$) and Granite Harbour ($R^2 = 0.66$), but was not correlated with any of the other sites ($0.02 \leq R^2 \leq 0.16$). The SAMI for 2002 appeared to be an outlier on the scatterplot (not shown), and when removed, the correlation improved at Scott Base ($R^2 = 0.66$), Marble Point ($R^2 = 0.66$) and Wright Valley ($R^2 = 0.61$). Victoria Valley had no correlation with SAMI ($R^2 = 0.02$).

6.4 Mean monthly air temperatures

Mean monthly air temperatures were investigated to see how the mean temperatures changed from month to month. All mean monthly air temperatures from 1999 to 2007 are available in tabular format in Appendix I. The mean January and mean April air temperatures from 1999 to 2007 are described here, as they display the variability in mean monthly air temperatures between months.

6.4.1 January

The mean January air temperature at all sites showed inter-annual variability of up to 5°C (Figure 6.7). The mean January temperature was lowest in 2001, which was noted to be a cool summer (Wall 2004). The mean January air temperature was 4°C warmer in 2002 than in 2001; the summer of 2001-02 was a noted warm summer at various locations in Antarctica (Foreman *et al.* 2004, Wall 2004, Barrett *et al.* 2008). The maximum and minimum January air temperatures were reflected in the mean summer air temperatures (Figure 6.4). Despite the warmest mean January air temperatures occurring in 2007, the summer of 2006-07 was no warmer than the summer of 2001-02. The summer of 2006-07 was not a notably warm summer because the mean December air temperatures were coolest in 2006 (Appendix I), so the cool mean December temperatures balanced the warm mean January air temperatures.

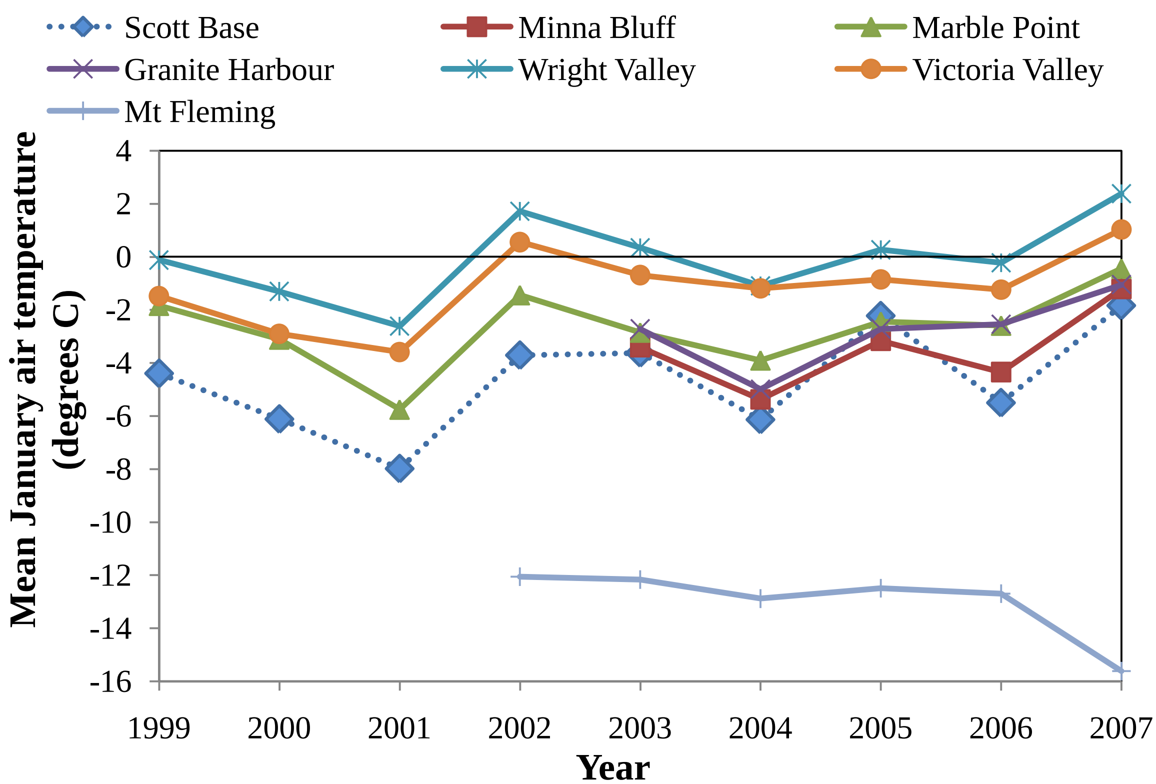

Figure 6.7: Mean January air temperature at seven sites in the McMurdo Sound region from 1999 – 2007.

The inter-annual variability in mean January air temperature did not match with the inter-annual variability in mean annual air temperature. For example, the minimum mean January air temperature of 2001 did not register as a minimum on the mean annual air temperature (Figure 6.1).

6.4.2 April

The mean April air temperatures were between 13°C and 37°C cooler than the mean January air temperatures. The coastal sites were warmer than inland sites in April and Victoria Valley was the coolest site (Figure 6.8). The mean April air temperatures at the coastal sites were not significantly different to each other. There was no trend in the mean April air temperature at any of the seven sites in the McMurdo Sound region between 1999 and 2007 ($0.02 \leq R^2 \leq 0.12$).

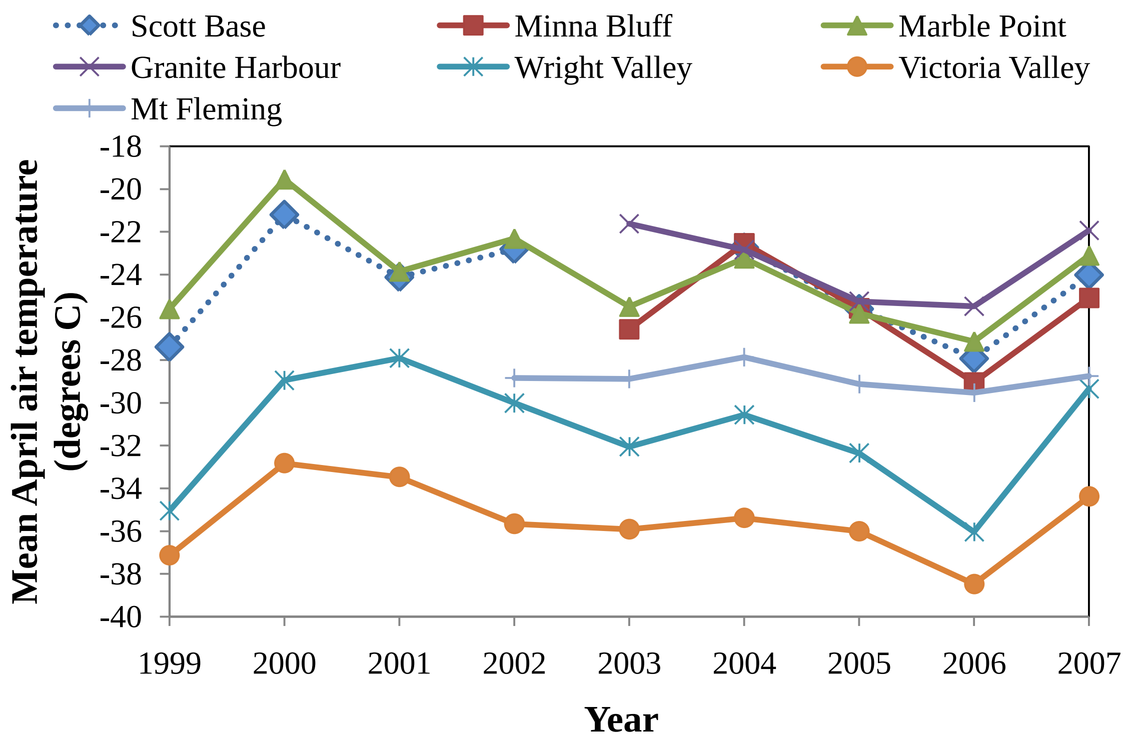

Figure 6.8: Mean April air temperature at seven sites in the McMurdo Sound region from 1999 – 2007.

The mean April air temperature did not steadily decrease with increasing altitude. Mt Fleming, the highest elevation site, did not have the coldest mean April air temperature. The mean April air temperature at Mt Fleming was warmer than both Victoria Valley and the Wright Valley. Mean monthly air temperatures at Mt Fleming were warmer than Victoria Valley from March through to September (Appendix II), after which mean air temperatures became colder at Mt Fleming. Winter air temperatures in the Victoria Valley have been noted to be the coldest in the McMurdo Sound region (Fountain *et al.* 1999, Doran *et al.* 2002a). The mean April air temperature at Mt Fleming was about 7°C warmer than at Victoria Valley.

Victoria Valley has a bowl shape, which may allow cold air to be trapped in the valley bottom (Doran *et al.* 2002). When conditions are calm, a strong temperature inversion can occur where the layer of air closest to the ground is much colder than the overlying layer due to the lack of solar heating (Doran *et al.* 2002a, Nylen *et al.* 2004). Nylen *et al.* (2004) presented radar imagery which showed a persistent temperature inversion in the Victoria Valley during winter. The temperature inversion may be disrupted by katabatic winds draining from the Polar Plateau (Doran *et al.* 2002a). Katabatic wind events, instead of disrupting the cold cell in the bottom of the Victoria Valley, may instead preferentially drain through drainage valleys connected to Victoria Valley (Doran *et al.* 2002a). If the katabatic wind is weak compared to a strong inversion, it will not be sufficient to overcome the temperature inversion and warm the air column (Nylen *et al.* 2004). This phenomenon is known as the "frost hollow effect", whereby air at a high elevation (e.g. Mt Fleming) cools radiatively and flows downslope as a katabatic wind to settle to the lower elevation site (e.g. Victoria Valley) (Oxford Dictionary of Earth Sciences 2003, Trewin 2005). Air and soil temperatures at Victoria Valley examined in Chapter 5 demonstrated that there were frequent perturbations during the winter period (Figure 5.3f), which were interpreted as winter storm events when a particular occurrence was detected at all climate stations. Such perturbations could raise the air temperature by up to 30°C at a time, implying that the inversion in Victoria Valley was frequently disrupted.

6.5 Changes in means across a latitudinal and altitudinal transect

6.5.1 Latitudinal section

The mean annual shallow soil (6.5 – 9 cm), mid-depth soil (39 – 45 cm depth) and deep soil (75 – 105 cm) temperatures did not have a clear latitudinal gradient (Figure 6.9), though the mean annual air and soil temperatures appeared to increase with decreasing latitude. There was no correlation of soil temperatures with latitude, but mean annual air temperature increased linearly with decreasing latitude (R^2 = 0.79). As seen in previous sections, the mean annual air and soil temperatures were reasonably similar and were not significantly different from each other (Appendix I).

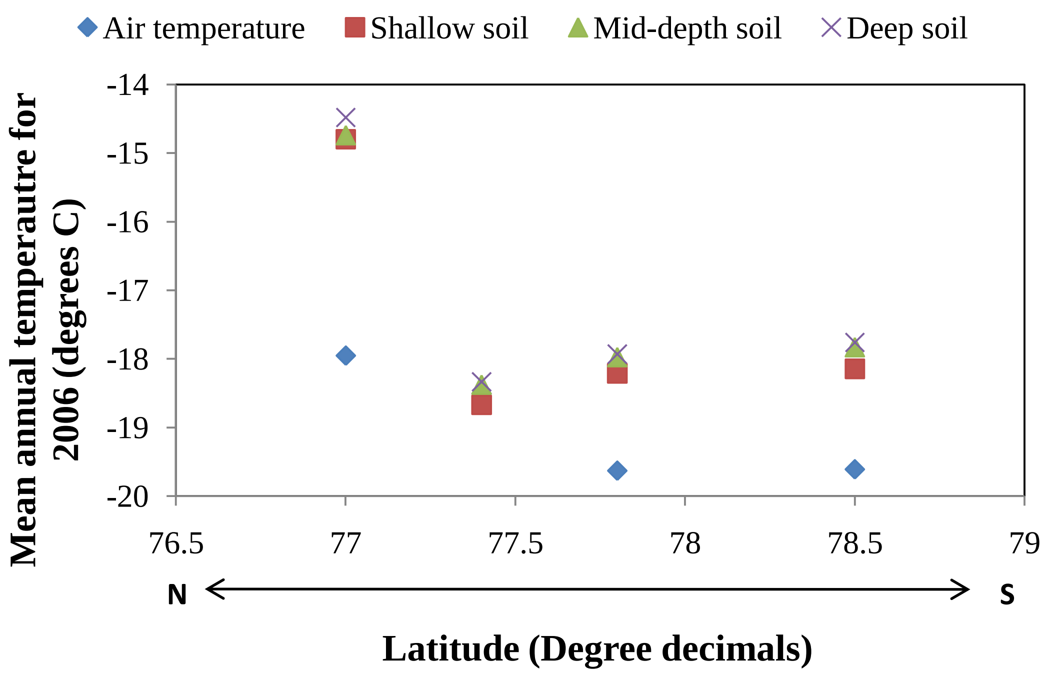

Figure 6.9: Mean annual air, shallow soil, mid-depth soil and deep soil temperatures along a latitudinal transect from Minna Bluff (78.5°S), Scott Base (77.8°S), Marble Point (77.4°S) and Granite Harbour (77.0°S). Mean values are reported for 2006, as this is the only year with data available for Minna Bluff.

The mean shallow soil, mean mid-depth soil and mean deep soil depth ranges were within ±3.5°C of the mean annual air temperature. The closeness between the mean annual air and mean annual soil temperatures is a function of the depth to which soil temperature was measured. Annual-scale temperature changes penetrate to a depth of about 15 – 20 m (Linell & Tedrow 1981, Hillel 2004), while the shallow depths reported here are sensitive to diurnal temperature variations.

6.5.2 Altitudinal section

The mean annual air and soil temperatures followed an altitudinal gradient (Figure 6.10), where the mean annual temperatures decreased with increasing elevation. The similarity in magnitude of mean annual temperatures at Mt Fleming and Victoria Valley was probably due to the frost hollow effect leading to warmer air temperatures at Mt Fleming than Victoria Valley.

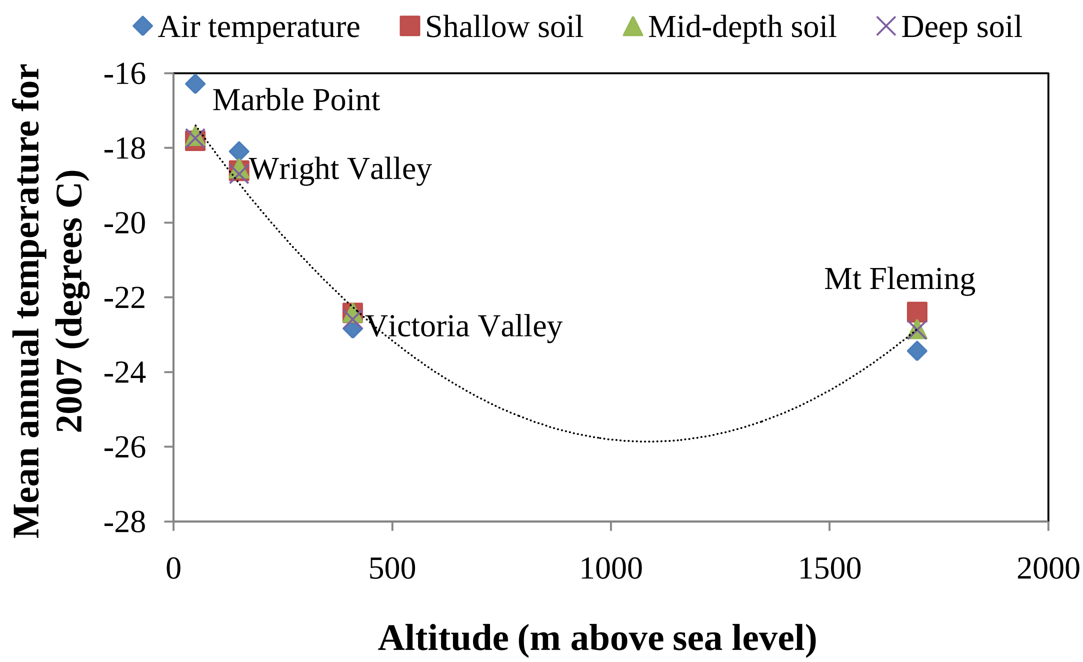

Figure 6.10: Mean annual air, shallow soil, mid-depth soil and deep soil temperatures along an altitudinal transect from Marble Point (50 m), Wright Valley (150 m), Victoria Valley (410 m) and Mt Fleming (1700 m). Mean values are reported for 2007, as this is the only year with data available for Mt Fleming.

It is important to note that the progression of mean annual temperatures at our sites is not necessarily attributable solely to the influence of altitude on the sites. Local physiography was likely to be influencing the mean annual temperatures. For example, the frost hollow effect during winter led to the coldest mean annual air temperature occurring at Victoria Valley. The difference in altitude between Victoria Valley (410 m) and Mt Fleming (1700 m) left almost 1300 m of elevation change unmonitored within our soil climate network. The change in mean annual air and soil temperature cannot therefore be attributed solely to changes in altitude.

Using the dry adiabatic lapse rate, air temperature decreases by 0.98°C per 100 m increase in elevation (Sturman & Tapper 2005). The difference in mean annual temperatures between Marble Point and Mt Fleming were predicted using the dry adiabatic lapse rate (–0.98°C/100 m), and calculating the temperature change over changing elevation, always relative to Marble Point (Figure 6.11). The observed mean annual air temperatures were cooler than the mean temperature predicted by the dry adiabatic lapse rate (Figure 6.11), except at Mt Fleming. The predicted mean annual air temperature was up to 3°C warmer than the observed and in some cases was within ±0.01°C of the observed mean annual air temperature. The mean annual temperature at Mt Fleming was 9°C warmer than predicted using the dry adiabatic lapse rate in 2007. The difference between the observed and the predicted mean annual air temperature varied inter-annually (not shown).

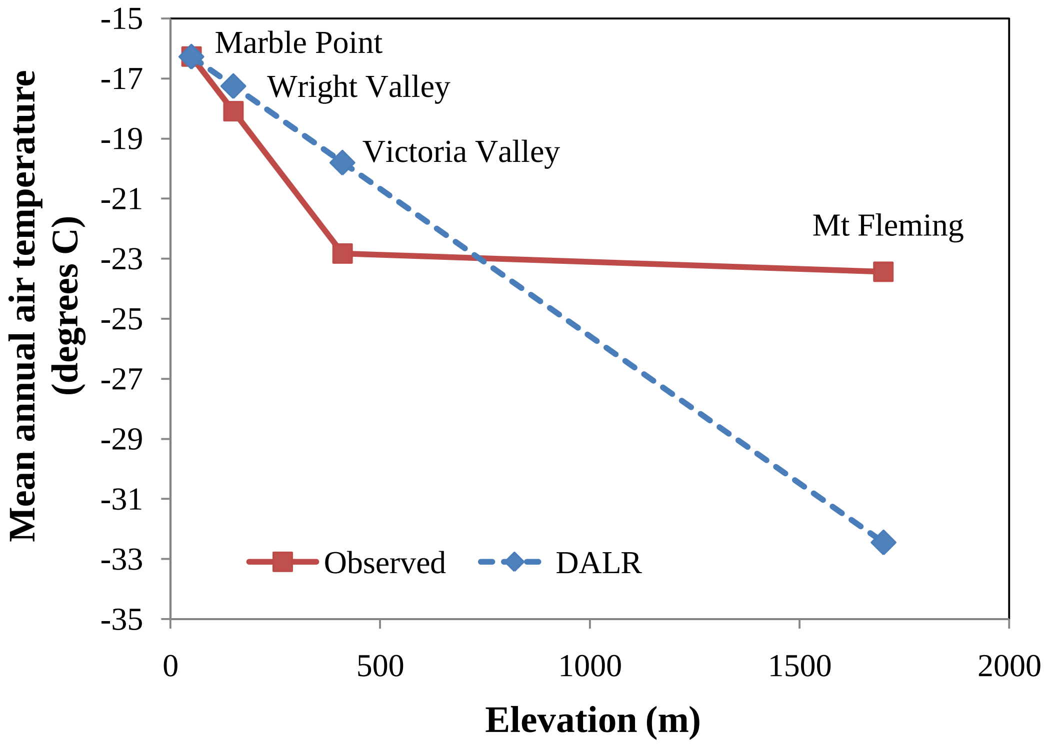

Figure 6.11: The predicted temperature at elevation (dotted line) from the dry adiabatic lapse rate (DALR = 0.98°C decrease per 100 m increase in elevation) (calculated relative to Marble Point) and the observed temperatures (solid line) at each site along the altitudinal transect for 2007.

6.6 Discussion

6.6.1 Mean annual and mean monthly air temperatures and mean annual soil temperatures

6.6.1.1 Mean annual air temperatures

The mean annual air and shallow and deep soil temperatures varied inter-annually and there was no significant trend ($0 \leq R^2 \leq 0.3$) of warming or cooling in the mean annual temperatures at any site between 1999 and 2007. Preliminary work on this dataset by Aislabie *et al.* (2006) reported mean annual air temperatures between 1999 and 2003 of –18°C at Marble Point, –20°C at Wright Valley and –24°C at Mt Fleming. With the extended database (1999 – 2007), the mean annual temperatures reported by Aislabie *et al.* (2006) were confirmed as being within ±1°C of the mean calculated from 1999 to 2007 (Appendix I).

The mean annual air temperature at Scott Base (–19.9°C), Marble Point (–18.0°C), Wright Valley (–20.1°C) and Victoria Valley (–23.4°C) between 1999 and 2007 were similar to those reported at Scott Base (–19.3°C from 1987 – 2000, Doran *et al.* 2002a), Wright Valley (–20°C from 1969 – 1970, Thompson *et al.* 1971) and at Lake Vida in Victoria Valley (–27.4°C from 1995 – 2000, Doran *et al.* 2002a). The close agreement in Wright Valley temperatures over the 1999 – 2007 dataset compared to the 1969 – 1970 data presented by Thompson *et al.* (1971) suggested that there has been no significant warming of mean annual air temperatures since 1969, contrary to the 0.7°C warming per decade reported by Doran *et al.* (2002a). However, further comparison will be needed in order to make conclusions regarding warming trends.

6.6.1.2 Mean monthly air temperatures

Mean monthly air temperatures varied inter-annually at all sites over the 1999 – 2007 period (Appendix I). Mean monthly air temperatures at Scott Base (1999 – 2007) were compared to those reported by Bromley (1994) for the 1952 – 1992 period. Mean monthly temperatures at Scott Base from 1999 to 2007 were within ±2.5°C to those reported by Bromley (1994) (Table 6.1). This would indicate that while monthly temperatures may be highly variable from year to year, when averaged over a longer time period, short-term variability is masked in the monthly mean temperature. The agreement between our dataset and the longer dataset presented by Bromley (1994) indicated that the data collected at Scott Base was consistent with what has already been published.

Table 6.1: Mean monthly air temperatures at Scott Base calculated from the USDA-NRCS automated weather station from 1999 – 2007 and reported by Bromley (1994) from 1952 – 1992.

Month	**Mean monthly air temperature (1999 – 2007)**	**Mean monthly air temperature (1952 – 1992)**
January	-4.6	-4.7
February	-11.1	-11.1
March	-21.6	-20.2
April	-24.5	-24.0
May	-25.0	-26.2
June	-25.9	-26.3
July	-27.6	-29.1
August	-29.5	-30.2
September	-25.5	-28.1
October	-20.2	-22.0
November	-10.7	-11.2
December	-4.6	-5.0

6.6.1.3 Mean annual soil temperatures

The mean annual soil temperatures at the shallow and deep depth ranges displayed inter-annual variability coincident with variations in the mean annual air temperature. The mean annual soil temperature was always warmest at Granite Harbour and coolest at Victoria Valley at both depth ranges. The mean annual shallow soil temperatures were warmer than the mean annual air temperatures at Granite Harbour, Marble Point, Scott Base and Minna Bluff, and were similar at the Wright and Victoria Valleys. The warmer mean annual soil temperatures compared to the mean annual air temperature was most likely due to the continuous solar radiation during the austral summer providing heat to the soil surface which is then transferred to depth through conduction (Chapter 2, section 2.7). Solar radiation has been recognised as a strong driver of soil surface temperatures (MacCulloch 1996, Campbell *et al.* 1997a, Campbell *et al.* 1998a, Balks *et al.* 2002); solar radiation is first available from early August when the sun rises for the first time following the winter. During the summer, the soil temperature can be more than 10°C warmer than the air temperature (Campbell *et al.* 1998b). For example, during the summer of 2006-07, the soil temperature at 9 cm depth at Scott Base was up to 13°C warmer than the air temperature (Figure 6.12).

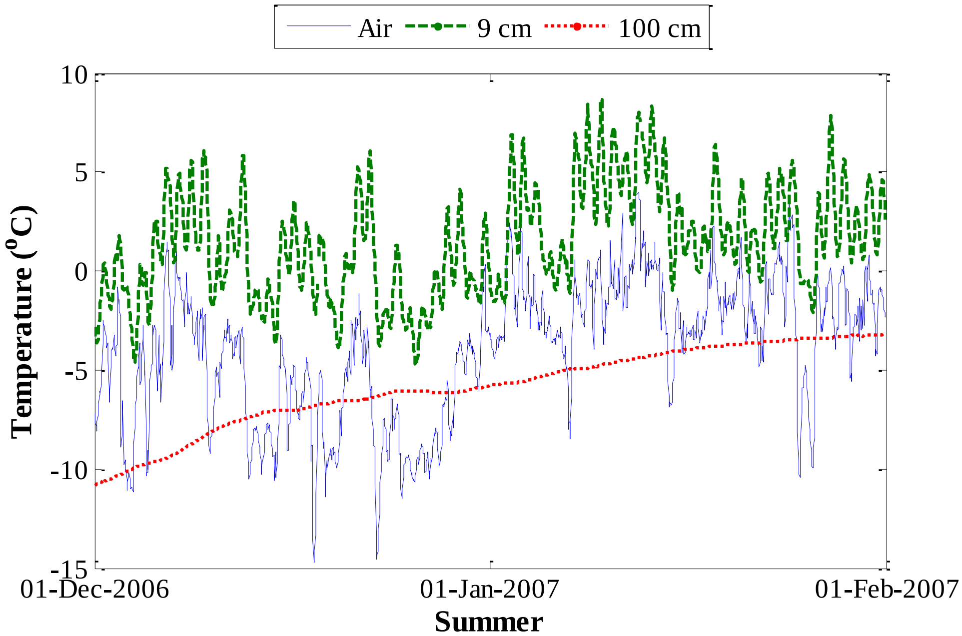

Figure 6.12: Air temperature and soil temperature at 9 cm depth and 100 cm depth at Scott Base from 1 December 2006 to 31 January 2007.

Mean annual shallow soil temperatures may also be warmer than the air temperature due to the effects of snow insulation during the winter period. When snow is present at the surface, it limits the transfer of heat between the air and the soil surface. Heat transfer through the snowpack is slowed, so when air temperatures are particularly cold, the soil beneath the snow remains at a relatively warm temperature. For example, at Granite Harbour during winter 2006, soil temperatures at all depths followed a different pattern of variation to the air temperature (Figure 6.13). There was no appreciable difference between soil temperatures at 7.5 cm, 30 cm and 60 cm depth. The soil at all depths did not display sharp peaks in temperature, as seen in the air temperature. The lack of a pattern in soil temperatures corresponding to changes in air temperature at Granite Harbour suggested that there was a thick snow cover during the winter of 2006.

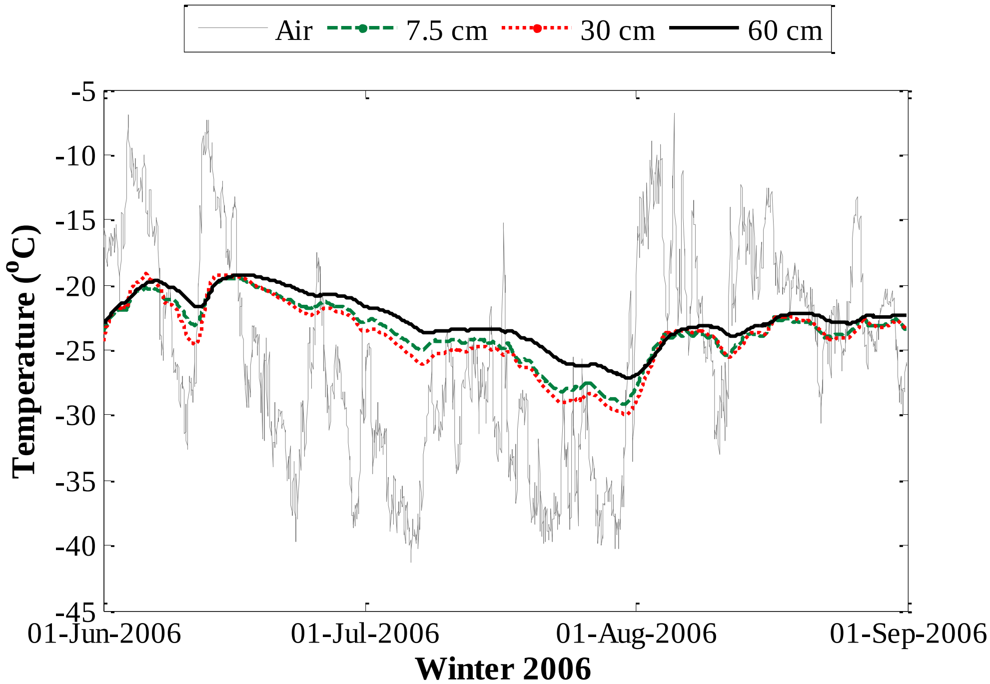

Figure 6.13: Air temperature and soil temperatures at 7.5 cm, 30 cm and 60 cm depth at Granite Harbour from 1 June 2006 to 31 August 2006.

The mean annual deep soil (75 – 105 cm) temperature was warmer than the mean annual air temperature at all sites. The deep soil depth range did not exhibit diurnal temperature cycles in response to daily changes in solar radiation and air temperature (Figure 6.12), but deep soil temperatures steadily increased during the summer period due to sustained heating of the soil surface and subsequent heat conduction to depth. The inter-annual variation in mean annual soil temperature at the 'deep' range is less than the inter-annual variation in the mean annual air temperature or mean annual shallow soil temperature. The lower inter-annual variability in the soil temperatures was indicative of the attenuation of the temperature signal with depth, as heat is conducted through the soil profile.

6.6.2 Influences on mean annual air temperature

6.6.2.1 Seasonal air temperatures

The mean annual temperature was not influenced by the mean summer (Dec – Jan) air temperature; the warm summer of 2001-02 did not register as a peak in the mean annual air temperature. Mean winter air temperature had a more notable effect on mean annual air temperature; warmer or cooler winters (Jun – Aug) were often aligned with warmer and cooler mean annual air temperatures. Doran *et al.* (2002a) noted that the variation in mean annual air temperature was primarily influenced by variations in winter temperatures, due to the warming of winter air temperatures due to the occurrence of katabatic winds. Winter perturbations have been observed where air and shallow soil temperatures warmed significantly (up to 30°C) at all sites in the monitoring network, interpreted as winter storm events (Figure 5.3).

6.6.2.2 Influence of Southern Annular Mode on mean annual air temperature

The Southern Annular Mode has been shown to influence the air temperatures in Antarctica (e.g. Kwok & Comiso 2002, Marshall 2007). The Southern Annular Mode Index (SAMI) was provided by Willem deLange from Nan & Li (2003) and plotted against mean annual, mean summer and mean winter air temperature. There was no correlation between the phase of the SAMI and mean annual air temperatures ($0.01 \leq R^2 \leq 0.7$) or mean winter air temperatures ($0.01 \leq R^2 \leq 0.7$). The high R^2 value (0.7) was from two short data sets, Minna Bluff and Granite Harbour, and should not be considered reliable. Excluding Minna Bluff and Granite Harbour, the highest R^2 value was 0.3, indicating no relationship between SAMI and mean annual or mean winter air temperatures.

The mean summer air temperature (Dec – Jan) followed a similar pattern of inter-annual variability to the summer SAMI (Dec – Feb), though the correlation was poor ($0.01 \leq R^2 \leq 0.3$). The cool summer of 2000-01 coincided with a negative phase and the warmest summer of 2001-02 corresponded to a positive phase of the Southern Annular Mode. The trend towards cooler mean summer temperatures between the summers of 2001-02 and 2003-04 coincided with the SAMI decreasing towards lower values with a negative phase in 2003-04. The lack of correlation between mean annual air temperature and SAMI suggested that SAMI was more influential on the mean summer air temperature than at the annual scale.

6.6.2.3 Influence of latitude on mean annual and seasonal air and soil temperatures

The mean annual air temperature at Marble Point was significantly different ($p < 0.05$) to mean annual air temperature at Minna Bluff, Scott Base and Granite Harbour. Mean annual air temperatures at Minna Bluff, Scott Base and Granite Harbour were not significantly different to each other. The mean annual air temperature was coldest at Scott Base and Minna Bluff (Figure 6.1) and warmer at Marble Point and Granite Harbour. Despite the similar mean annual air temperatures, the mean annual shallow and deep soil temperatures were always about 2°C warmer at Granite Harbour than at the other sites in the latitudinal section. The warmer mean annual soil temperatures at Granite Harbour were most likely due to the solar radiation on this north-facing site and the transfer of heat through the soil profile by percolating meltwater (Chapter 3). Similar mean monthly soil surface temperatures at Vanda (Wright Valley) and Cape Hallett stations due to heating by solar radiation has been suggested as an indication that latitude has no effect on temperature (Campbell & Claridge, 1987). Mean annual, mean January, mean April, mean November and mean winter air temperatures at Minna Bluff, Scott Base, Marble Point and Granite Harbour were not significantly different to each other, indicating the lack of a latitudinal effect on air temperature within our short latitudinal section (78.5°S to 77.0°S). Mean summer air temperatures at Minna Bluff were significantly different to those at Scott Base and Granite Harbour ($p < 0.05$), and Minna Bluff and Marble Point mean summer air temperatures were not significantly different to each other. As mean air temperatures at sites along the latitudinal section were only significantly different during the summer period, it is likely that mean summer air temperatures were also affected by site micro-climate factors, such as solar radiation and wind speed, rather than latitude alone. For example, the active layer depths at sites in the latitudinal section were significantly different ($p < 0.05$) and showed a clear latitudinal gradient but were also influenced by local micro-topography and climate (Chapter 3). Therefore, the effect of latitude on air temperature may not be clear across our short range of stations.

6.6.2.4 Influence of altitude on mean annual and seasonal air and soil temperatures

Mean annual, mean summer and mean winter air temperatures and the mean annual shallow soil and mean annual deep soil temperatures were significantly different at Marble Point, Wright Valley, Victoria Valley and Mt Fleming ($p < 0.05$). The coldest mean annual air, shallow soil and deep soil temperatures were at Victoria Valley, except in 2007 when Mt Fleming had a full year of data available.

The mean annual temperatures of air, shallow soil and deep soil all displayed an altitudinal gradient, where the mean annual temperatures decreased with increasing elevation (Figures 6.10 and 6.11). The exception to the clear altitudinal gradient was during the winter months, when the air temperatures at Mt Fleming were about 7°C warmer than at Victoria Valley, probably due to a frost hollow effect. The mean summer air temperature was coldest at Mt Fleming by about 10°C (Figure 6.4), which was also noted by Aislabie *et al.* (2006). The cold temperatures at Mt Fleming are due to the elevation of the site and the proximity to the Polar Plateau and the associated cold winds passing through the site.

As previously stated, the altitude difference between Victoria Valley and Mt Fleming is too great to conclude that the progression of mean annual temperatures at our sites can be attributed solely to altitude. To demonstrate, mean annual air temperatures at Marble Point, Wright Valley, Victoria Valley and Mt Fleming were plotted against altitude above sea level (Figure 6.14), along with mean annual air temperatures reported for Linnaeus Terrace (McKay *et al.* 1998), Lake Bonney and Lake Fryxell in the Taylor Valley (Fountain *et al.* 1999), and Lake Hoare in the Taylor Valley, Lake Brownworth in the Wright Valley and Lake Vida in the Victoria (Doran *et al.* 2002a). Figure 6.14 shows that there is no evident altitudinal gradient in mean annual air temperature, though there was still a large gap in the reported data between Victoria Valley and the higher elevation sites at Linnaeus Terrace and Mt Fleming. Fountain *et al.* (1999) observed a high degree of variability in the climate of the Taylor Valley between Lake Fryxell and Lake Bonney, which was due to the distance from the coast and the resulting interaction of different air masses (i.e. katabatic and coastal winds).

The statement by Doran *et al.* (2002a) that mean annual air temperature could not be estimated solely on elevation above sea level appears to be ratified by the comparison of observations from the soil climate monitoring network and published literature.

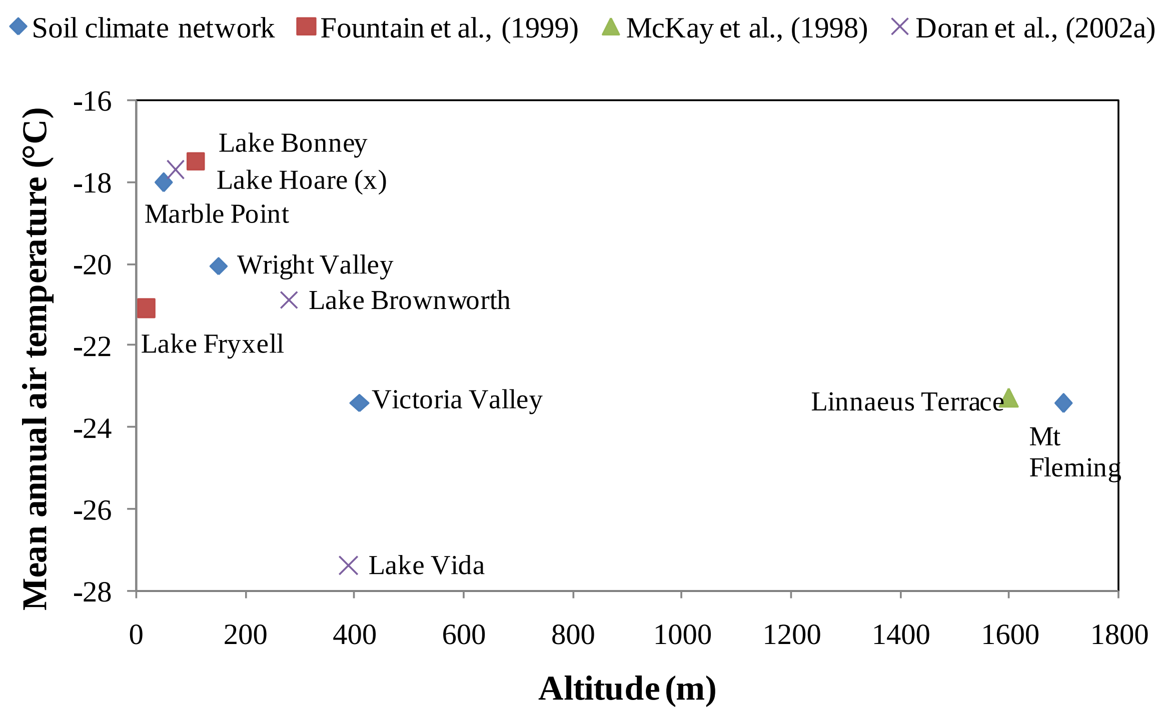

Figure 6.14: Mean annual air temperature at a range of elevations above sea level at Marble Point, Wright Valley, Victoria Valley and Mt Fleming (soil climate monitoring network), Linnaeus Terrace (McKay *et al.* 1998), Lake Bonney and Lake Fryxell in the Taylor Valley (Fountain *et al.* 1999) and at Lake Hoare (Taylor Valley), Lake Brownworth (Wright Valley) and Lake Vida (Victoria Valley) (Doran *et al.* 2002a).

6.7 Summary and Conclusions

This chapter explored the mean annual air temperatures, shallow soil and deep soil temperatures, mean seasonal and mean monthly air temperatures at seven sites in the McMurdo Sound region from 1999-2007. There was considerable inter-annual variability in the mean annual, mean seasonal and mean monthly air and soil temperatures over the available record. The mean annual and mean summer soil temperatures were warmer than the air temperatures due to warming of the soil by solar radiation during summer, and shielding of the soil from extreme cold air temperatures by snow insulation during winter. There was less inter-annual variation in the mean annual deep soil temperatures due to the attenuation of the temperature signal with depth.

Between 1999 and 2007, there was no trend of warming or cooling of the mean annual air and soil temperatures ($0 \leq R^2 \leq 0.3$). Mean annual air temperatures were influenced primarily by winter air temperatures rather than summer air temperatures, because summer only accounted for 1 – 2 months in the calendar year. There was no correlation between the mean annual or mean winter air temperature and the Southern Annular Mode Index (SAMI), but mean summer air temperature correlated reasonably well with the SAMI.

Mean annual air and soil temperatures decreased with increasing latitude, but the lack of significant difference between the sites suggested that latitude was not a strong driver of air and soil temperature over the range investigated. It is likely that micro-topography and micro-climate factors, such as solar radiation and wind speed, are more influential on temperatures.

Mean monthly air temperatures at Mt Fleming, the highest elevation site (1700 m) were warmer than those at Victoria Valley (410 m) for about six months of the year. The cold air temperatures at Victoria Valley were attributed to a probable frost hollow effect, where cold air pooled in the bowl-shaped valley during the winter months.

CHAPTER 7: CORRELATIONS BETWEEN ABOVE-GROUND AND SUBSURFACE VARIABLES

7.1 Introduction

Understanding the inter-relationships between different climatic variables is important to improve our ability to predict soil climate using more common measurements, such as air temperature and solar radiation. The objective of this chapter is to determine the correlations between above-ground and below-ground climatic variables at each automated weather station from 1999 to 2007, and determine if the correlation was significant. Linear correlations were explored (using hourly data from each automated weather station) between the following variables:

1. Air temperature and near-surface soil temperature (1.3 – 7.5 cm depth);
2. Air temperature and incoming solar radiation;
3. Air temperature and wind speed;
4. Near-surface soil temperature and wind speed;
5. Near-surface soil temperature and incoming solar radiation.

The correlations were produced for three separate time periods:

1. The entire site record from site establishment (Table 1.1) to January 2008;
2. Each summer (1 December to 31 January);
3. Each winter (1 June to 31 August).

All correlation figures can be found in Appendix IV.

7.2 Air temperature and soil surface temperature

There was a positive correlation ($R^2 \geq 0.79$) between air temperature and near-surface soil temperature for the full available record at each of the soil climate stations (Table 7.1). The strong correlation between air temperature and soil temperature at the ground surface showed that as air temperature increased, the soil temperature also increased (e.g. Marble Point, Figure 7.1).

During the summer (1 Dec to 31 Jan), air and soil temperatures were reasonably well correlated at most sites ($0.21 \leq R^2 \leq 0.76$). The highest summer correlation (R^2=0.76 at Mt Fleming) was less than the lowest correlation over the full record (R^2=0.79). The weaker correlation between air and soil temperatures during the summer period compared to the full record was indicative of other influences on soil temperature, such as heating of the ground surface by direct, incoming solar radiation. Soil temperatures just below the ground surface displayed diurnal temperature cycles that coincided with the diurnal cycles in air temperature and solar radiation (e.g. Granite Harbour, Figure 7.2). Soil temperatures during the summer were often warmer than air temperature which was further evidence of another influence on soil temperatures.

Table 7.1: Correlations between air temperature and near-surface soil temperature (1.3 – 7.5 cm depth) for all available data*, summer data (1 Dec – 31 Jan) and winter data (1 Jun – 31 Aug) at each automated weather station#.

Time period	**R^2 value (soil depth)**						
	Minna Bluff (5 cm)	**Scott Base (1.3 cm)**	**Marble Point (7.5 cm)**	**Granite Harbour (2 cm)**	**Wright Valley (7.5 cm)**	**Victoria Valley (3 cm)**	**Mt Fleming (2 cm)**
Full record	0.93	0.95	0.93	0.79	0.92	0.93	0.93
Summer							
1999-00	NE	0.53	0.43	NE	0.69	0.62	NE
2000-01	NE	0.62	0.21	NE	0.65	0.59	NE
2001-02	NE	0.66	0.65	NE	0.75	0.55	NE
2002-03	0.28	0.54	0.43	NE	0.64	0.64	0.74
2003-04	0.28	0.67	0.49	—	0.66	0.62	0.62
2004-05	0.23	0.42	0.47	0.41	0.66	0.64	0.64
2005-06	0.41	0.53	0.60	0.40	0.66	0.69	0.76
2006-07	0.23	0.55	0.60	0.29	0.73	0.43	0.64
Winter							
1999	NE	0.94	0.98	NE	0.87	0.84	NE
2000	NE	0.94	0.87	NE	0.87	0.91	NE
2001	NE	0.95	0.87	NE	0.90	0.87	NE
2002	NE	0.93	0.85	NE	0.78	0.86	0.86
2003	0.96	0.92	0.81	0.97	0.85	0.82	—
2004	0.94	0.91	0.84	0.85	0.86	0.90	—
2005	0.92	0.95	0.85	0.43	0.86	0.83	—
2006	0.91	0.96	0.86	0.24	0.88	0.77	—
2007	0.88	0.94	0.81	0.76	0.80	0.89	0.88

** Up to eight years (1999-2007) where available. Full details in Table 1.1.*
 # NE = Site not established and a dash (—) indicates system failure affecting the correlation calculation.

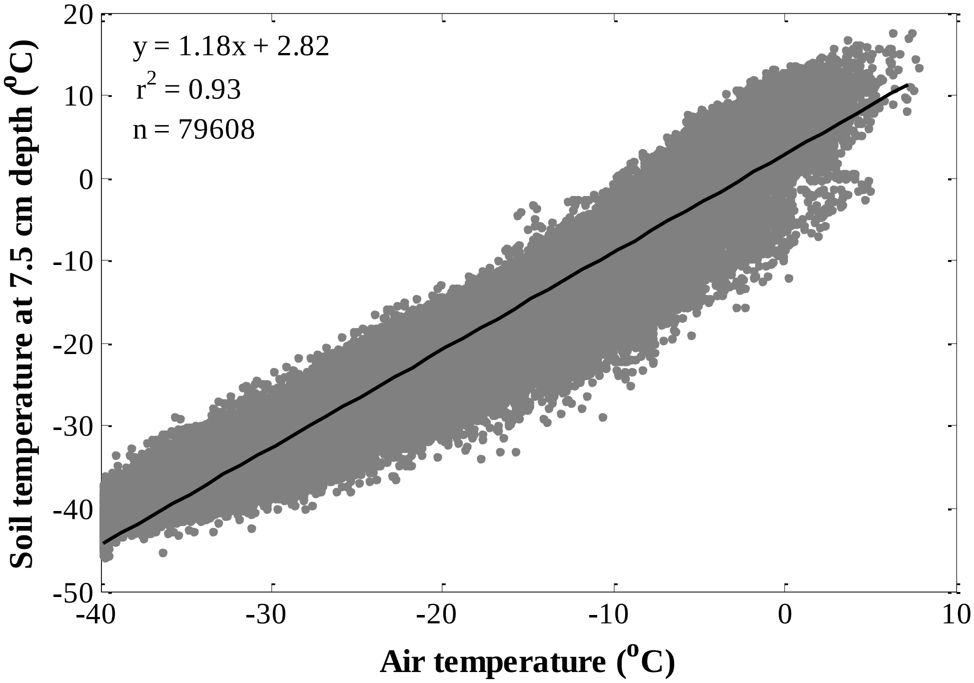

Figure 7.1: Correlation between hourly air temperature and hourly soil temperature at 7.5 cm depth at Marble Point from 1999 to 2007.

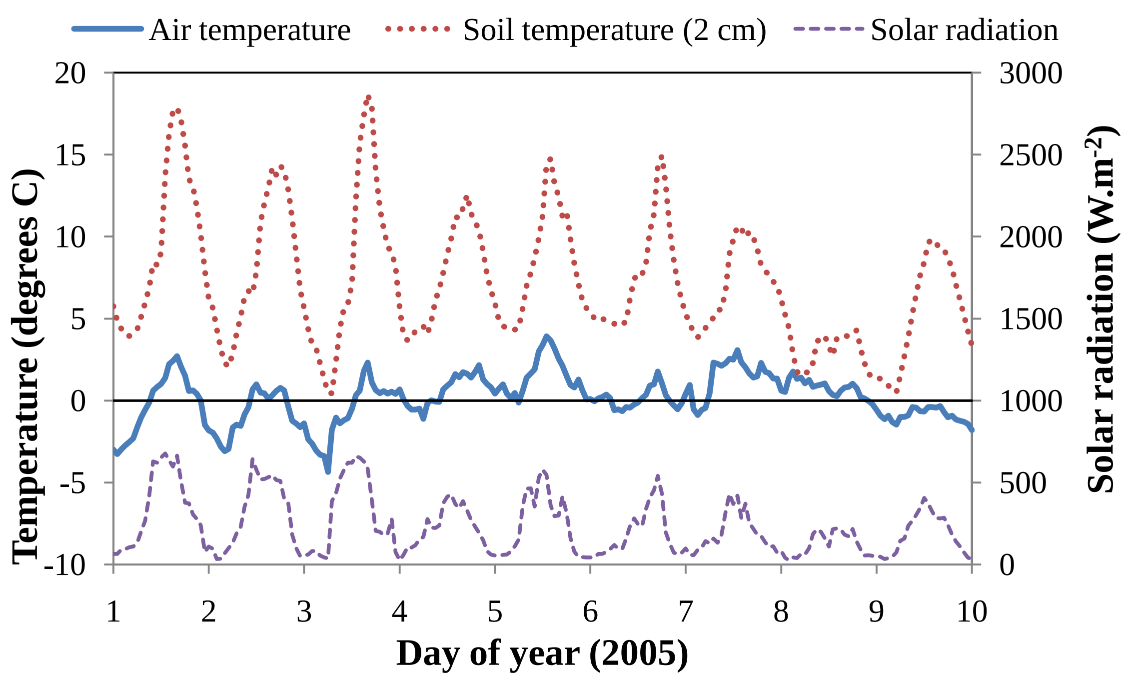

Figure 7.2: Air temperature, soil temperature (at 2 cm depth) and solar radiation at Granite Harbour from 1 – 10 January 2005.

In the winter (Jun – Aug), there was a strong correlation between air temperature and soil temperature at all sites ($0.76 \leq R^2 \leq 0.98$) except Granite Harbour ($0.24 \leq R^2 \leq 0.97$) (Table 7.1). The correlation was lowest at Granite Harbour in the winters of 2005 and 2006, possibly due to thick snow cover both years. The temperature signal at 2 cm depth at Granite Harbour was severely damped in the winter of 2005 and 2006 (e.g. Figure 7.3a), compared to 2007 when the soil temperature at 2 cm depth followed air temperature closely (Figure 7.3b). The correlation between air temperature and near-surface soil temperature was stronger at Granite Harbour when the winters of 2005 and 2006 were not taken into account. The strong correlations indicated that air temperature was a primary influence on soil temperatures during the winter, and that there was generally little snow cover at most of our sites.

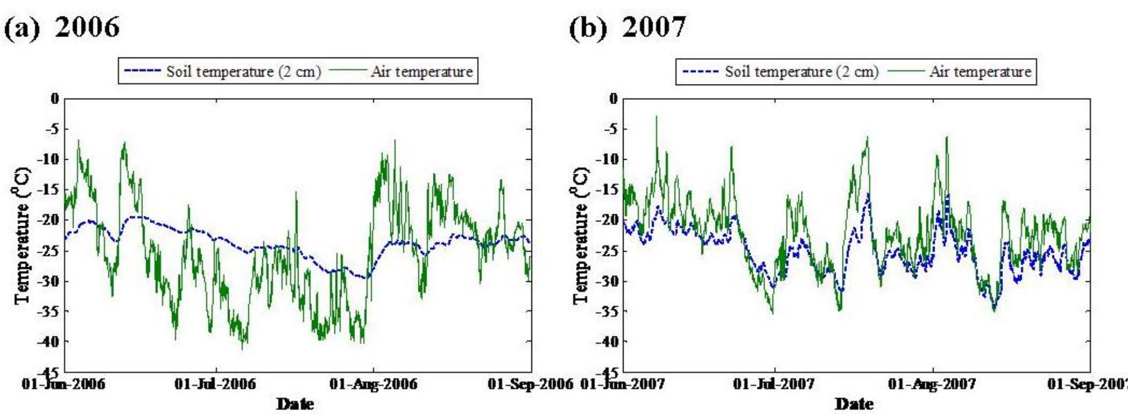

Figure 7.3: Air temperature and soil temperature (at 2 cm depth) at Granite Harbour for (a) the winter of 2006 and (b) winter of 2007.

7.3 Air temperature and incoming solar radiation

Air temperature was not well correlated with incoming solar radiation at any site over the long-term summer-time period ($0 \leq R^2 \leq 0.40$) (Table 7.2). However, on sunny summer days, there were occasions where air temperature at all sites followed a diurnal pattern (e.g. Scott Base, Figure 7.4) which correlated strongly with solar radiation (e.g. Figure 7.5). On 3 January 2004, the peak in air temperature coincided with a peak in solar radiation (Figure 7.4), and with low wind speeds. Occasionally, the air temperature did not have a midday peak corresponding with a peak of solar radiation (arrow, Figure 7.4). This occurred at all sites and usually coincided with a period of faster wind speeds, indicating that the interaction of solar radiation and wind speed may also influence the hourly and daily variation of air temperature during the summer period.

Table 7.2: Correlations between air temperature and incoming solar radiation during summer (1 Dec – 31 Jan) at each automated weather station.*

Summer	**R^2 value**						
	Minna Bluff	**Scott Base**	**Marble Point**	**Granite Harbour**	**Wright Valley**	**Victoria Valley**	**Mt Fleming**
1999-00	NE	0.04	0.20	NE	0.14	0.38	NE
2000-01	NE	0.14	0.28	NE	0.40	0.35	NE
2001-02	NE	0.15	0.11	NE	0.27	0.26	0.15
2002-03	0.03	0.00	0.04	NE	0.12	0.08	0.02
2003-04	0.13	0.09	0.12	—	0.29	0.26	0.15
2004-05	0.12	0.09	0.15	0.20	0.26	0.28	0.14
2005-06	0.09	0.04	0.16	0.20	0.35	0.36	0.16
2006-07	0.14	0.02	0.04	0.16	0.18	0.13	0.01

* *NE = Site not established and a dash (—) indicates system failure affecting the correlation calculation.*

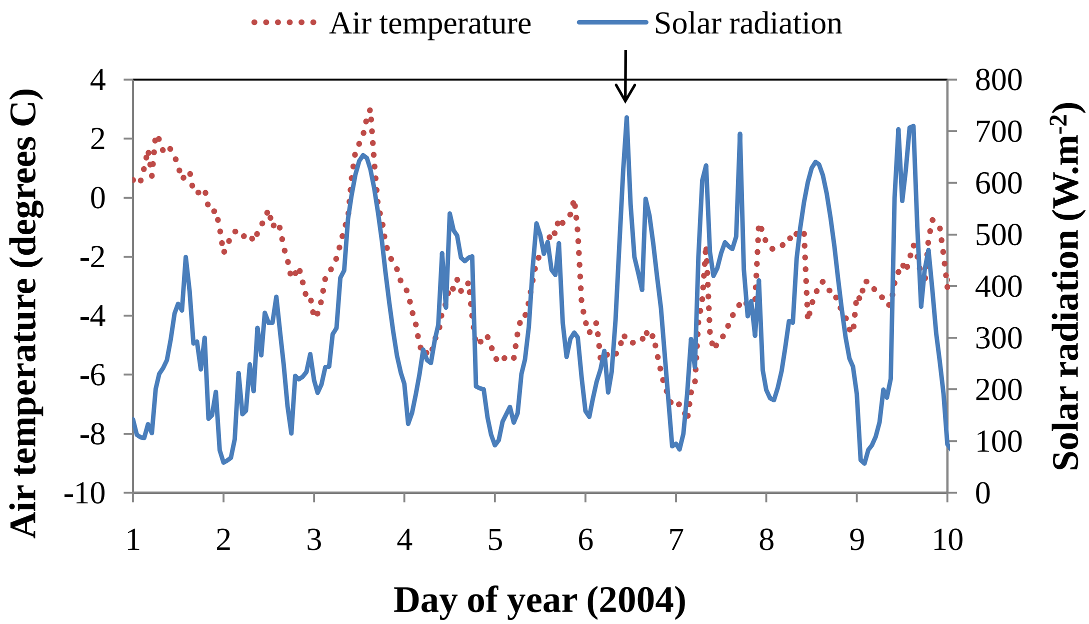

Figure 7.4: Solar radiation and air temperature at Scott Base from 1 – 10 January 2004. Arrow indicates an instance where midday peak in solar radiation did not correspond with a peak in air temperature.

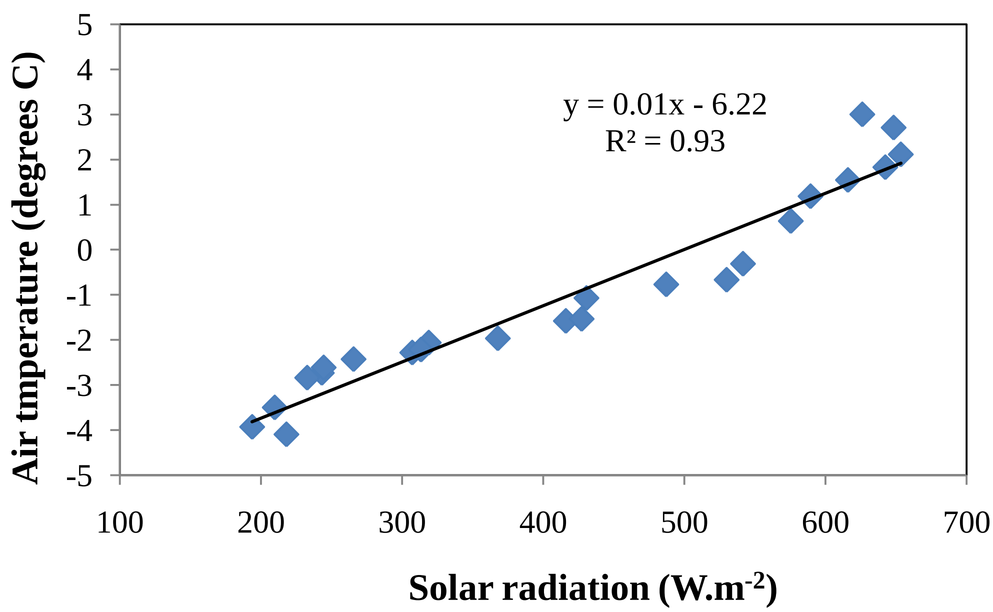

Figure 7.5: Correlation between incoming solar radiation and air temperature at Scott Base for the diurnal cycle on 3 January 2004.

7.4 Soil surface temperature and incoming solar radiation

The linear correlation between solar radiation and near-surface soil temperature during the summer ranged from non-existent to strong (Table 7.3). The strongest correlations usually occurred at Victoria Valley ($0.14 \leq R^2 \leq 0.76$) and Granite Harbour ($0.49 \leq R^2 \leq 0.82$). Poorer correlations occurred at Victoria Valley in the summers of 2002-03 and 2006-07 and at Granite Harbour in 2006-07. Near-surface soil temperatures were cooler in December 2002 and 2006 compared to other years, which may have been indicative of a cloudier summer. There was no significant correlation between near-surface soil temperature and incoming solar radiation at any other site ($0 \leq R^2 \leq 0.57$).

At the diurnal time scale, air and soil temperatures followed a diurnal pattern that coincided with the daily maxima in incoming solar radiation (Figure 7.2), which correlated strongly with solar radiation (e.g. Scott Base, Figure 7.6). This indicated the existence of a correlation between solar radiation and soil surface temperature, such as that found in preliminary analysis of this dataset by Balks *et al.* (2002) in the soils of Scott Base, Marble Point and Wright Valley. The strong correlation at the diurnal time-scale on clear-sky, sunny days was masked over the longer-term summer period. It was clear that when the solar radiation decreased, the soil temperature also decreased.

Table 7.3: Correlations between and near-surface soil temperature (1.3 – 7.5 cm depth) and incoming solar radiation during summer (1 Dec – 31 Jan) at each automated weather station*.

Summer	**R^2 value (soil depth)**						
	Minna Bluff (5 cm)	**Scott Base (1.3 cm)**	**Marble Point (7.5 cm)**	**Granite Harbour (2 cm)**	**Wright Valley (7.5 cm)**	**Victoria Valley (3 cm)**	**Mt Fleming (2 cm)**
1999-00	NE	0.48	0.40	NE	0.23	0.72	NE
2000-01	NE	0.43	0.19	NE	0.28	0.76	NE
2001-02	NE	0.50	0.32	NE	0.25	0.74	NE
2002-03	NE	0.30	0.10	NE	0.13	0.34	0.10
2003-04	0.34	0.42	0.29	—	0.26	0.68	0.01
2004-05	0.38	0.57	0.41	0.80	0.24	0.67	0.15
2005-06	0.35	0.37	0.40	0.82	0.25	0.69	0.14
2006-07	0.36	0.37	0.18	0.49	0.16	0.14	0.03

* *NE = Site not established and a dash (—) indicates system failure affecting the correlation calculation.*

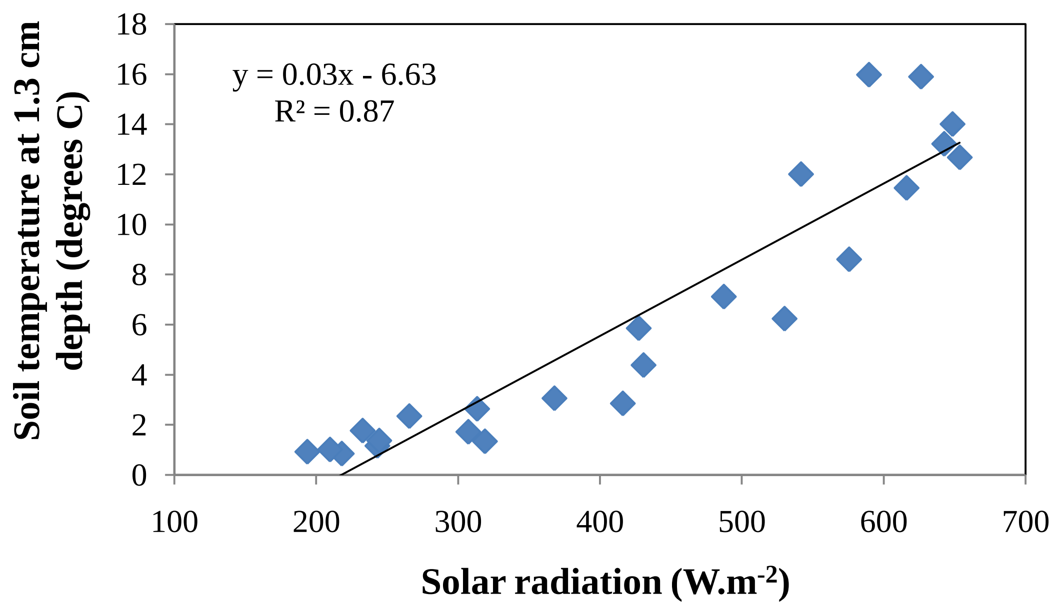

Figure 7.6: Correlation between solar radiation and soil temperature (at 1.3 cm depth) at Scott Base on 3 January 2004.

7.5 Air temperature and wind speed

When hourly wind speed and air temperature data were plotted for the full record at each site, there was no significant correlation ($0 \leq R^2 \leq 0.36$) (Table 7.4). During the summer, the correlation between air temperature and wind speed was even weaker ($0 \leq R^2 \leq 0.17$). Scott Base and Mt Fleming exhibited virtually no correlation between wind speed and air temperature.

Table 7.4: Correlations between air temperature and wind speed for all available data*, summer data (1 Dec – 31 Jan) and winter data (1 Jun – 31 Aug) at each automated weather station[#].

Time period	R^2 value						
	Minna Bluff	**Scott Base**	**Marble Point**	**Granite Harbour**	**Wright Valley**	**Victoria Valley**	**Mt Fleming**
Full record	0.05	0.00	0.02	0.19	0.04	0.36	0.03
Summer							
1999-00	NE	0.02	0.16	NE	X[a]	0.06	NE
2000-01	NE	0.03	0.04	NE	0.09	0.06	NE
2001-02	NE	0.02	0.04	NE	0.13	0.13	0.03
2002-03	0.12	0.00	0.01	NE	0.03	0.02	0.17
2003-04	0.09	0.01	0.02	—	0.08	0.05	0.03
2004-05	0.01	0.00	0.01	0.09	0.13	0.09	0.01
2005-06	0.01	0.00	0.01	0.03	0.08	0.05	0.09
2006-07	0.15	0.01	0.02	0.01	0.04	0.04	0.16
Winter							
1999	NE	0.26	0.16	NE	X	0.65	NE
2000	NE	0.07	0.29	NE	0.46	0.61	NE
2001	NE	0.07	0.11	NE	0.39	0.57	NE
2002	NE	0.07	0.19	NE	0.48	0.73	—
2003	0.42	0.02	0.13	—	0.40	0.66	—
2004	0.31	0.00	0.24	0.36	0.48	0.54	—
2005	0.57	0.15	0.26	0.25	0.45	0.61	—
2006	0.53	0.16	0.33	0.20	0.47	0.58	—
2007	0.13	0.03	0.20	0.25	0.43	0.57	0.06

** Up to eight years (1999-2007) where available. Full details in Table 1.1.*
[#] NE = Site not established and a dash (—) indicates system failure affecting the correlation calculation.
[a] No wind data.

The correlation between air temperature and wind speed was somewhat improved during the winter, though there was still a large range of correlation values ($0 \leq R^2 \leq 0.73$). The best correlations during the winter period occurred in the Wright and

Victoria Valleys. Though the correlation between wind speed and air temperature was sometimes high during the winter (e.g. Victoria Valley), the R^2 value may give a misleading picture of the correlation, due to the clustering of data points where wind speeds were low (< 5 $m.s^{-1}$) and air temperatures were cold (e.g. Victoria Valley, Figure 7.7), which was likely to have an impact on the calculated R^2 value.

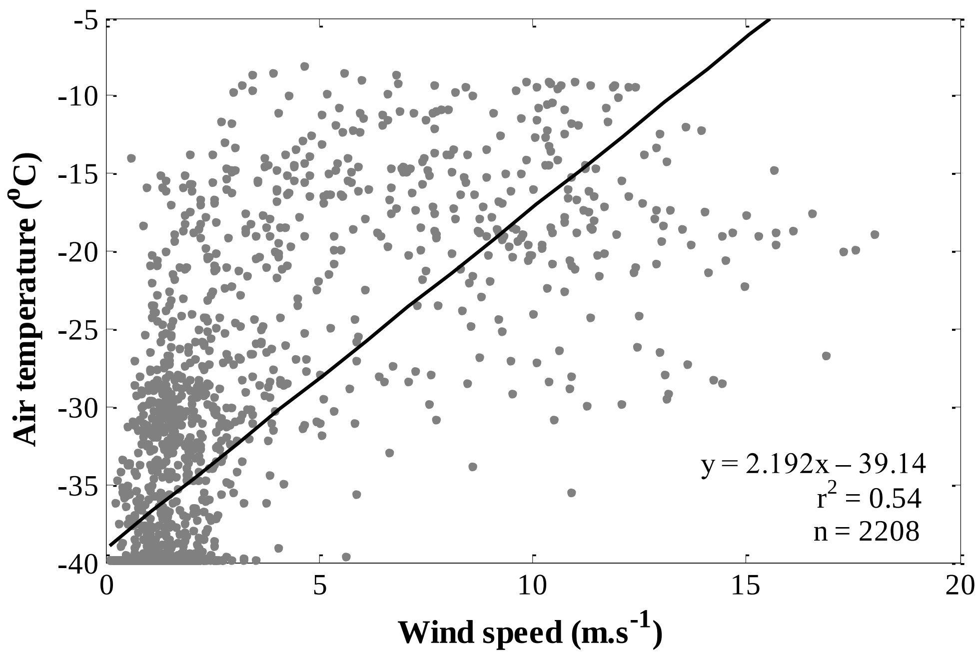

Figure 7.7: Correlation between wind speed and air temperature at Victoria Valley in winter 2004.

A time series of wind speed and air temperature at Marble Point in early June 2004 showed that increases in air temperature coincided with increases in wind speed (Figure 7.8). High speed wind events such as this do not occur for extended periods of time; for example, at Marble Point on 7 June 2004 (Day 158), wind speed was greater than 5 $m.s^{-1}$ for about six hours (Figure 7.8).

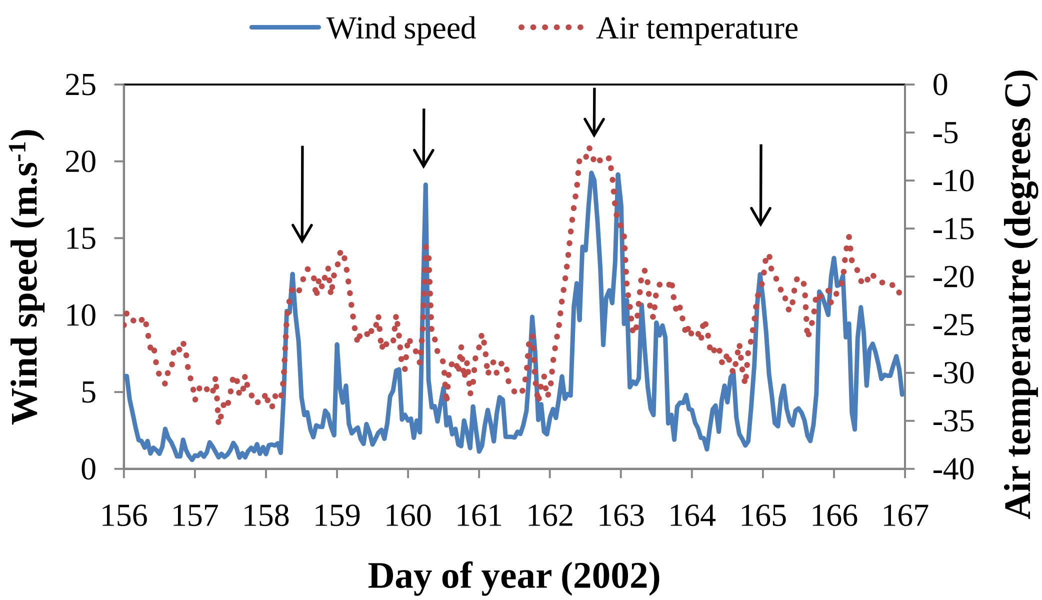

Figure 7.8: Wind speed and air temperature at Marble Point from 5 – 15 June 2004. Arrows denote examples where increases in air temperatures coincided with increases in wind speed.

7.6 Soil surface temperature and wind speed

There was no significant correlation between wind speed and soil surface temperature at any site over the full record ($0 \leq R^2 \leq 0.27$), during the summer ($0 \leq R^2 \leq 0.33$) or during the winter ($0 \leq R^2 \leq 0.59$) (Table 7.5). During the winter, the correlations were again best at Wright Valley and Victoria Valley. Time series of the hourly data (not shown) showed that there were occasions when increases in soil surface temperature coincided with increases in wind speed, much like air temperatures.

Table 7.5: Correlations between near-surface soil temperature (1.3 – 7.5 cm depth) and wind speed for all available data*, summer data (1 Dec – 31 Jan) and winter data (1 Jun – 31 Aug) at each automated weather station[#].

Time period	R^2 value						
	Minna Bluff (5 cm)	**Scott Base (1.3 cm)**	**Marble Point (7.5 cm)**	**Granite Harbour (2 cm)**	**Wright Valley (2 cm)**	**Victoria Valley (3 cm)**	**Mt Fleming (2 cm)**
Full record	0.01	0.00	0.01	0.00	0.24	0.27	0.04
Summer							
1999-00	NE	0.05	0.01	NE	X[a]	0.01	NE
2000-01	NE	0.06	0.00	NE	0.16	0.00	NE
2001-02	NE	0.12	0.00	NE	0.08	0.00	0.06
2002-03	0.12	0.11	0.01	0.03	0.04	0.02	0.33
2003-04	0.15	0.08	0.07	0.04	0.13	0.04	0.20
2004-05	0.11	0.06	0.02	0.11	0.14	0.04	0.08
2005-06	0.25	0.08	0.03	0.05	0.10	0.05	0.21
2006-07	0.06	0.12	0.03	0.04	0.05	0.09	0.29
Winter							
1999	NE	0.33	0.30	NE	X	0.49	NE
2000	NE	0.12	0.26	NE	0.48	0.53	NE
2001	NE	0.13	—	NE	0.40	0.46	NE
2002	NE	0.12	0.15	NE	0.47	0.59	—
2003	0.44	0.06	0.15	0.14	0.41	0.47	—
2004	0.36	0.02	0.18	0.25	0.48	0.46	—
2005	0.53	0.21	0.26	0.04	0.44	0.42	—
2006	0.44	0.23	0.29	0.02	0.47	0.27	—
2007	0.35	0.07	0.21	0.12	0.52	0.49	0.19

** Up to eight years (1999-2007) where available. Full details in Table 1.1.*
[#] NE = Site not established and a dash (—) indicates system failure affecting the correlation calculation.
[a] No wind data.

7.7 Multiple regression

A multiple regression, using Matlab v.2006b, was used to assess the combined impact of air temperature, incoming solar radiation and wind speed on near-surface soil temperature (1.3 – 7.5 cm). The combination of these three variables produced an excellent correlation with soil temperature ($0.88 \leq R^2 \leq 0.98$) (Table 7.6).

Table 7.6: Multiple regression equations and R^2 values for near-surface soil temperature (1.3 – 7.5 cm) as a function of air temperature, solar radiation and wind speed.

Site	**Multiple regression equation**	**R^2 value**
Minna Bluff	Soil temperature (5 cm) = 2.4712 + 1.0589 * Air temperature + 0.0115 * Solar radiation – 0.0946 * Wind speed	0.97
Scott Base	Soil temperature (1.3 cm) = -0.1930 + 1.0252 * Air temperature + 0.0174 * Solar radiation + 0.0100 * Wind speed	0.98
Marble Point	Soil temperature (7.5cm) = 1.0716 + 1.1049 * Air temperature + 0.0113 * Solar radiation – 0.1604 * Wind speed	0.95
Granite Harbour	Soil temperature (2 cm) = 4.0459 + 1.0428 * Air temperature + 0.0157 * Solar radiation – 1.3958 * Wind speed	0.88
Wright Valley	Soil temperature (7.5cm) = 2.1657 + 1.0662 * Air temperature + 0.0088 * Solar radiation – 0.3624 * Wind speed	0.96
Victoria Valley	Soil temperature (3 cm) = 1.1867 + 1.0865 * Air temperature + 0.0201 * Solar radiation – 0.4403 * Wind speed	0.97
Mt Fleming	Soil temperature (2 cm) = 3.6322 + 1.1501 * Air temperature + 0.0074 * Solar radiation – 0.0370 * Wind speed	0.96

The multiple regression equation was used to predict near-surface soil temperatures at all sites and compared to the observed, in order to check that the equation approximated both summer and winter soil temperature cycles accurately. At all sites, the multiple regression equation approximated the general pattern of soil temperature well throughout the whole year, but the peak in predicted soil temperature during the summer sometimes occurred before the peak in observed soil temperature. The multiple regression equations sometimes over-estimated the maximum and under-estimated the minimum soil temperatures during the summer (e.g. Victoria Valley, Figure 7.9a). During the winter, the multiple regression equation overestimated the peak soil temperatures (e.g. Victoria Valley, Figure 7.9b), but the timing of soil temperature fluctuations was essentially the same during the winter. It is important to note that these regression equations have not as yet been validated against an external dataset to prove their applicability.

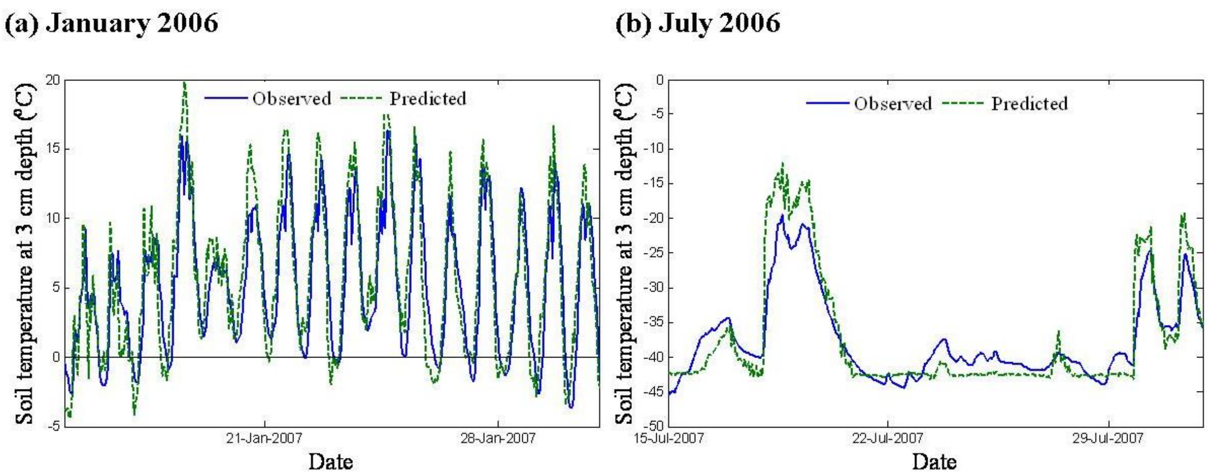

Figure 7.9: Observed and predicted soil temperature at 3 cm depth at Victoria Valley for (a) a summer period (1 – 15 Jan 07) and (b) a winter period (15 Jul 07 to 1 Aug 07). Soil temperatures were predicted using the multiple regression equation for Victoria Valley (Table 7.6).

7.8 Discussion

7.8.1 Relationship between air temperature and soil surface temperature

The strongest linear correlation between variables at sites in the McMurdo Sound region was between air temperature and soil surface temperature ($0.79 \leq R^2 \leq 0.95$). Soil temperature near the ground surface has been strongly linked to air temperature in New Zealand (Aldridge & Cook 1983), Utah, USA ($R^2 > 0.87$) (Bartlett *et al.* 2006), as well as in polar locations such as Barrow, Alaska (MacLean & Eyres 1985) and Boulder Clay, Antarctica ($R^2 > 0.9$) (Guglielmin 2004). Mean monthly soil temperature at 0.1 m depth in New Zealand soils had a linear correlation to mean monthly air temperature (Aldridge & Cook 1983). Mean annual ground surface temperature was linked directly to surface air temperature in Svalbard due to the exposed bedrock material with a lack of ground or snow cover (Bodri & Cermak 2007). Near-surface soil temperatures (0.1 m depth) and air temperature followed the same pattern at Emigrant Pass, Utah (Bartlett *et al.* 2006), which was also observed in near-surface soil temperatures at the seven sites in the McMurdo Sound region (Chapter 5).

The correlation between air temperature and soil temperature has been previously observed to be strongest at the soil surface, and decreased with increasing depth (MacLean & Eyres 1985, Bartlett *et al.* 2006). At Emigrant Pass, Utah, the air temperature and ground surface temperature was strongly correlated at 0.1 m (R^2 = 0.97), which was slightly reduced at 1.0 m depth (R^2 = 0.87) (Bartlett *et al.* 2006). A weaker correlation between air temperature and soil temperature with increasing depth was also observed at Victoria Valley, where the correlation between air temperature and soil temperature at 3 cm depth was always better than the correlation at 7.5 cm depth (Table 7.7). The decrease in correlation strength with depth presumably occurred at the other six sites in the McMurdo Sound region.

The decrease in correlation strength was explained at Barrow, Alaska as being due to the phase lag of the temperature with increasing depth (MacLean & Eyres 1985). With increasing depth the soil temperature was less sensitive to that day's temperature and was responding instead to temperatures over a longer time period (MacLean & Eyres 1985). For example, at about 10 cm depth, the soil temperature was an integrated response to air temperature over the last three days (MacLean & Eyres 1985). Bartlett *et al.* (2006) also noted that phase lag and attenuation of the surface temperature signal led to differences of ±10°C between air temperature and ground temperatures at about 1 m depth at the same point in time.

Table 7.7: Correlation (R^2) values between air temperature and soil temperature at 3 cm and 7.5 cm depths at Victoria Valley for the full record, each summer (1 Dec to 31 Jan) and each winter (1 Jun to 31 Aug).

Time period	**R^2 value**	
	Victoria Valley (3 cm)	**Victoria Valley (7.5 cm)**
Full record	0.93	0.87
Summer		
1999-00	0.62	0.36
2000-01	0.59	0.38
2001-02	0.55	0.46
2002-03	0.64	0.61
2003-04	0.62	0.57
2004-05	0.64	0.60
2005-06	0.69	0.67
2006-07	0.43	0.62
Winter		
1999	0.84	0.40
2000	0.91	0.45
2001	0.87	0.50
2002	0.86	0.61
2003	0.82	0.60
2004	0.90	0.71
2005	0.83	0.72
2006	0.77	0.73
2007	0.89	0.74

7.8.2 Relationship between solar radiation and air and soil surface temperature

Soil surface temperature was influenced by incoming solar radiation, which was a strong driver for the diurnal temperature cycles at the soil surface, despite not having a strong linear correlation with soil surface temperature over the long-term summer period ($0 \leq R^2 \leq 0.4$). The influence of solar radiation on the soil temperature cycle has been previously observed in soils of the McMurdo Dry Valleys (Campbell *et al.* 1997a, Campbell *et al.* 1998b) and at Scott Base, Marble Point and Wright Valley (Balks *et al.* 2002). Soil temperatures at Barrow, Alaska were negatively correlated with sky cover (MacLean & Eyres 1985), which may be considered a proxy for solar radiation. The results of MacLean & Eyres (1985) indicated that with more sky cover and therefore less incoming solar radiation, the soil temperature decreased.

Ground surface temperatures at Emigrant Pass, Utah followed the same pattern as air temperature during the night, but when the sun was out during the day, the ground surface temperature was more than 5°C warmer than air temperatures (Bartlett *et al.* 2006). At Pomquet station in Canada, air temperature close to the ground surface was warmer than at about 1.5 m above the ground surface due to the heating of the ground surface by solar radiation (Beltrami 2001). A similar pattern was observed in the soil and air temperatures at the seven sites in the McMurdo Sound region; shallow soil temperatures were often warmer than air temperatures at all sites during the summer (Figure 5.2, Figure 7.2) and sometimes cooler than air temperature during the winter (Figure 5.3). Differences between air and soil temperatures in summer were attributed to changes in solar radiation (Bartlett *et al.* 2006). This was also reflected in the correlation between air temperature and soil surface temperature, which was good during the summer ($0.21 \leq R^2 \leq 0.76$) and better during the winter ($0.76 \leq R^2 \leq 0.98$), excluding the presumed effects of snow cover at Granite Harbour in the winters of 2005 and 2006 (Table 7.1). The lower correlation between air temperature and soil surface temperature during the summer was indicative of the influence of solar radiation heating the soil surface. In the absence of solar radiation, air temperature became a more important influence on soil surface temperature.

The amount of energy absorbed from solar radiation is dependent on the albedo of the soil (Hillel 2004), with darker coloured surfaces absorbing more energy than lighter coloured surfaces (Oke 1987). It was suggested that the light coloured surface of soil at Northwind Valley led to cooler soils than at Coombs Hill, despite warmer air temperatures at Northwind (Campbell *et al.* 1997a). The cooler soil temperature was due to the difference in albedo between the sites (Campbell *et al.* 1997a). No albedo data was available for the sites in our soil climate monitoring network. Scott Base, which had a dark basaltic surface pavement, would be expected to have a lower albedo and therefore warmer summer soil temperatures than a light coloured surface, such as that at Marble Point. One would expect the relationship between solar radiation and soil temperature at the ground surface would be significant at a site with dark soil, due to increased absorption of solar radiation, but the relationship was usually worst at Scott Base.

7.8.3 Relationship between air and soil surface temperature and wind speed

A time series of wind speed and air temperature at all sites over an eight day period (15 – 22 July) in the winter of 2007 showed that, despite the poor correlation over long time scales, increases in air temperature during the winter often occurred at the same time (Figure 7.10). Minna Bluff was excluded due to missing data. The maximum wind speed for the seven day period occurred on 18 July 2007 at all sites. The first maximum wind speed occurred at Victoria Valley at 11am, followed by Wright Valley at 1pm, Mt Fleming at 3pm, Marble Point at 8pm, Granite Harbour at 9pm and Scott Base at 11pm. As shown in Figure 7.10, the air temperature usually rose during periods of high winds, except at Mt Fleming where the wind speed was usually high (>10 $m.s^{-1}$). The air temperature rose between 4 and 30°C during the storm event, with the largest air temperature increase occurring at Victoria Valley (Figure 7.10e).

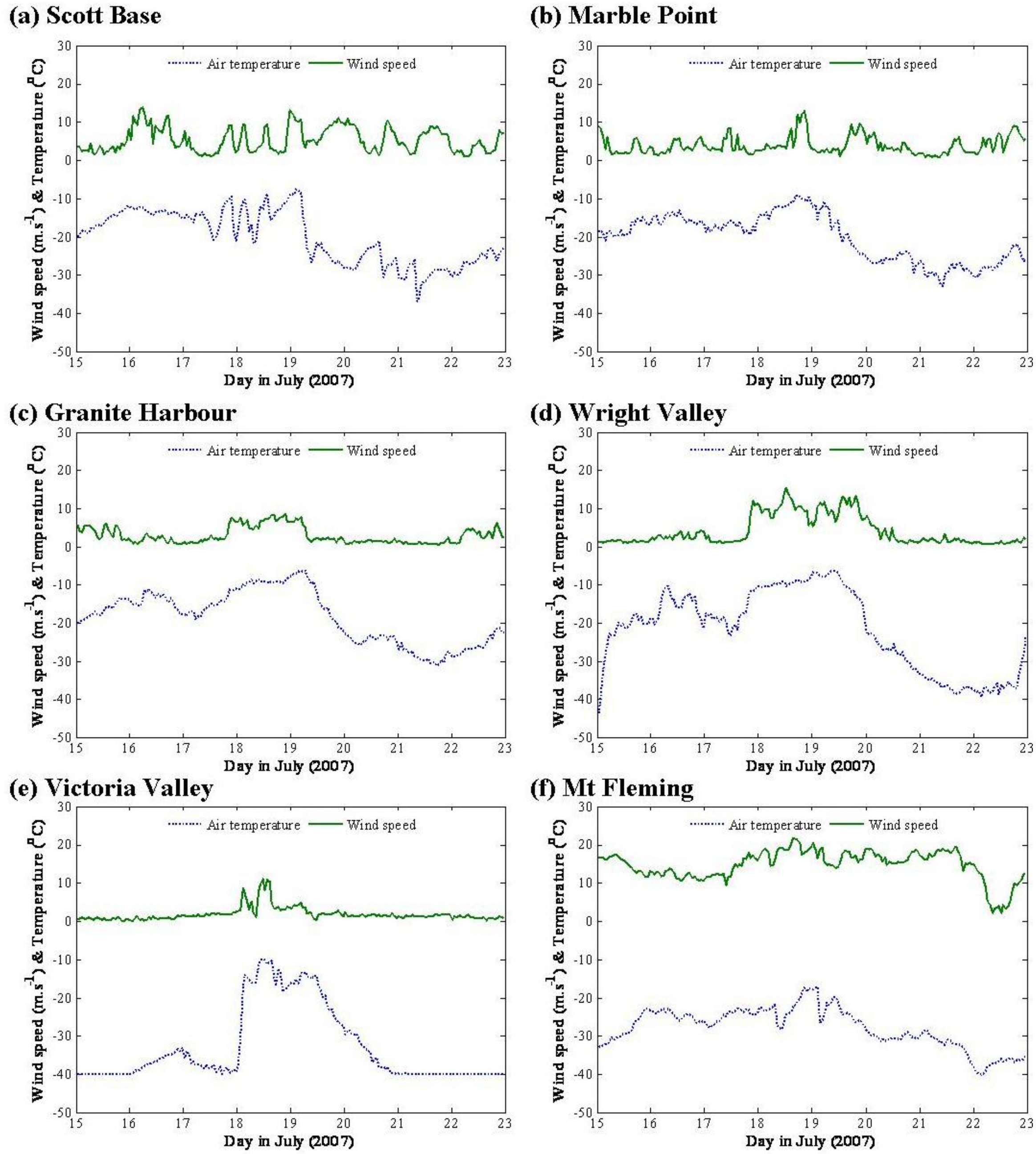

Figure 7.10: Wind speed and air temperature from 15 – 22 July 2007 at (a) Scott Base, (b) Marble Point, (c) Granite Harbour, (d) Wright Valley, (e) Victoria Valley and (f) Mt Fleming.

The high wind speed starting at Victoria Valley and progressing through Wright Valley and Marble Point indicated a katabatic wind event. However, the wind direction at most sites was reasonably variable (e.g. Victoria Valley, Figure 7.11a), lacking the characteristic constant wind direction typical of katabatic winds during the maximum wind speed event of 18 July 2007. The wind direction during the storm was approximately northerly at Scott Base (350°), westerly at Marble Point (250°), south-westerly at Victoria Valley (230°) and south-south-westerly at Mt Fleming (200°) (not shown). The only two sites displaying constant wind direction during the 15 – 22 July 2007 period were Wright Valley (230-240°) and Granite Harbour (220-240°) (Figure 7.11b). At Granite Harbour and the two valley sites, the wind speed was usually low (<5 m.s^{-1}) when not in a storm condition, whereas Mt Fleming, Scott Base and Marble Point had a more variable wind regime, both before and after the storm event. The difference in wind regimes was probably a reflection of the more exposed nature of the sites compared to Granite Harbour, Wright and Victoria Valleys. The occurrence of maximum wind speeds on the same day at all sites, including those well removed from the region of katabatic winds, and the lack of constant wind direction at most sites during maximum wind speeds suggested that the high wind speeds were the result of storm passage rather than katabatic winds.

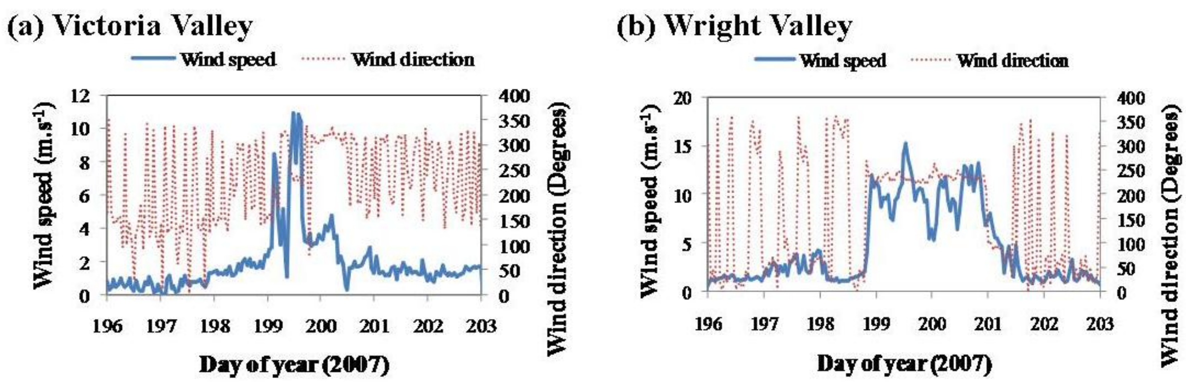

Figure 7.11: Wind speed and direction at (a) Victoria Valley and (b) Wright Valley from 15 – 22 July 2007.

Air temperatures have been previously shown to be sensitive to wind events (e.g. Doran *et al.* 2002a, Nylen *et al.* 2004). For example, high wind speeds in the dry valleys were associated with increased air temperature during katabatic wind events (Nylen *et al.* 2004). However, katabatic winds in the winter are the subject of conflicting reports. Katabatic winds have been stated to be stronger and more frequent during the winter (e.g. Hatherton 1990, Nylen *et al.* 2004). Contrastingly, Thompson *et al.* (1971) noted that there were only light winds in the Wright Valley during the winters of 1969 and 1970, despite previous belief that there would be strong katabatic winds. Doran *et al.* (2002a) noted that the variation in mean annual air temperature was primarily influenced by variations in winter temperatures, due to the warming of winter air temperatures due to the occurrence of katabatic winds. However, initial analysis of wind speeds at the seven McMurdo Sound stations indicated that the increases in wind speed occurring at all stations were due to the passage of winter storms.

7.8.4 Combined effects of above-ground climate variables on soil temperature

The influences of air temperature, solar radiation and wind speed on soil surface temperature occur simultaneously. Ground surface temperatures are an integrated response to surface factors such as air temperature, solar radiation, snow cover and vegetation (Beltrami 2001, Guglielmin 2004). A multiple regression at each site in the soil climate monitoring network produced a good correlation between the soil surface temperature (1.3 – 7.5 cm) and air temperature, solar radiation and wind speed ($0.88 \leq R^2 \leq 0.98$). Similarly, Balks *et al.* (1995) predicted soil surface temperature at Scott Base using a combination of air temperature and wind speed ($R^2 = 0.87$), while soil temperatures at Barrow, Alaska were related to mean daily air temperature, sky cover and hours where the sun was below the horizon (MacLean & Eyres 1985). The multiple regression model used at Barrow, Alaska became less reliable as the sun began to set (MacLean & Eyres 1985).

During the summer, the peak predicted soil temperature occurred before the peak in observed soil temperatures (e.g. Figure 7.9a). The maximum predicted soil temperature was sometimes warmer and the minimum usually cooler than the observed soil temperature during both summer and winter (e.g. Figure 7.9b). The soil surface temperature was variable between sites, and was between 1.3 and 7.5 cm depth. The time delay between predicted and observed soil temperature peaks during the summer, and the overestimation of peaks was therefore most likely a function of the depth at which the soil temperature was being estimated, and the associated attenuation of the temperature signal with increasing depth. There was no accounting for the thermal conductivity of the subsurface and the associated time lag for the peak in surface temperature to translate to depth when the multiple regression was calculated. As the surface temperature signal is attenuated with increasing depth (Hillel 2004), the peaks in soil temperature below the surface (e.g. 7.5 cm depth at Wright Valley) would be less than those at the surface, which was most likely why the multiple regression predicted a more variable soil temperature cycle than was observed.

7.9 Summary and conclusions

The strongest correlation between variables at the seven sites in the McMurdo Sound region was between air temperature and soil surface temperature over the whole record ($0.79 \leq R^2 \leq 0.96$), during the summer periods ($0.21 \leq R^2 \leq 0.76$) and during the winter ($0.76 \leq R^2 \leq 0.98$). Near-surface soil temperature was well correlated with solar radiation at Victoria Valley ($0.14 \leq R^2 \leq 0.76$) and Granite Harbour ($0.49 \leq R^2 \leq 0.82$) during the summer. At all other sites, there was no significant correlation between near-surface soil surface temperature and solar radiation ($0 \leq R^2 \leq 0.57$) during the summer, despite correlations that were occasionally strong on a diurnal basis (e.g. Figure 7.6). There was no significant correlation between air temperature and solar radiation ($0 \leq R^2 \leq 0.40$) at any site over the summer periods.

Though both air and soil temperature increases occurred at the same time during winter periods, there was no significant correlation between air temperature and wind speed (full record = $0 \leq R^2 \leq 0.36$, summer = $0 \leq R^2 \leq 0.17$, winter = $0 \leq R^2 \leq 0.73$) or between soil temperature and wind speed (full record = $0 \leq R^2 \leq 0.27$, summer = $0 \leq R^2 \leq 0.33$, winter = $0 \leq R^2 \leq 0.59$). Winter increases in air temperature and wind speed were often registered at all sites, and were attributed to the passage of winter storms.

A multiple regression was produced at each site predicting soil surface temperature (1.3 – 7.5 cm depth) as a function of air temperature, solar radiation and wind speed over the whole record ($0.88 \leq R^2 \leq 0.98$). The regression equations approximated the pattern of soil temperature well year round at all sites. Peak soil temperatures were overestimated by the regression equation in both summer and winter, and the predicted soil temperature peak occurred earlier than the observed soil temperature peak during the summer. The overestimation and timing differences between predicted and observed soil surface temperatures was probably due to the phase lag and attenuation of the temperature signal with increasing depth.

CHAPTER 8: SUMMARY AND CONCLUSIONS

8.1 Introduction

Eight years of hourly data from seven automated weather stations in the McMurdo Sound region were analysed, along with one year of six-hourly data from two 30 m deep permafrost temperature monitoring boreholes. The aim of this thesis was to use the data from soil and permafrost temperature monitoring networks to address five research questions. Each results chapter (Chapters 3 – 7) addressed one of the five research objectives outlined in Chapter 1. The principal findings of each chapter are summarised below in terms of each research objective, followed by a brief discussion of the implications and conclusions of the results. This chapter concludes with recommendations for further research.

8.2 Summary

8.2.1 Active layer depth

The research objective addressed in Chapter 3 was to determine the depth of thawing (active layer) each summer at each site, and describe how the active layer varied between summers and with changes in latitude and altitude. A multiple regression was used to determine the influence of above-ground climatic variables on active layer depth. The key outcomes of Chapter 3 were:

- Multiple regression showed that 73% of the variation in active layer depth (ALD) was explained by the combination of mean summer air temperature (MSAT), mean winter air temperature (MWAT), total summer solar radiation (TSSR) and mean summer wind speed (MSWS). *ALD = 222 + 5.69(MSAT) + 3.63(MWAT) – 10.6(TSSR) – 2.84(MSWS);*

- Active layer depth showed inter-annual variability but no significant increasing or decreasing trend over the eight years of available data;
- Active layer depth increased with decreasing latitude (R^2 = 0.94) and decreased with increasing altitude (R^2 = 0.95);
- Active layer depth was also influenced by local site characteristics, such as the percolation of meltwater at Granite Harbour causing a deeper active layer.

8.2.2 Permafrost temperature monitoring

The research objective addressed in Chapter 4 was to detail borehole drilling, ice-cemented core sampling and the installation of permafrost temperature monitoring equipment in the Wright Valley and at Marble Point. The research objective addressed in Chapter 5 was to describe the seasonal and annual temperature cycles, quantify the phase lag in transmission of surface temperature signals on a seasonal and annual basis, and investigate the depth of "Zero Annual Amplitude". The key outcomes of Chapters 4 and 5 were:

- Sixteen thermistors were installed to about 30 m depth in each permafrost temperature monitoring borehole at Marble Point and Wright Valley;
- One year of data (17 January 2007 – 18 January 2008) was available from each borehole, with the data for 2008 downloaded in January 2009;
- Depth of Zero Annual Amplitude was determined to be a flawed concept, because the accuracy of the sensor used influences the depth at which the annual temperature cycle can be observed;
- The sensors at Marble Point and Wright Valley were calibrated to ±0.1°C so an annual temperature cycle was observed at about 27 m depth in each hole;
- A new concept was proposed to replace the depth of 'Zero Annual Amplitude', instead referring to the depth at which the annual temperature range is ≤1°C, ≤0.5°C and ≤0.1°C;
- At Marble Point, an annual temperature range of ≤1°C occurred at 15.2 m, ≤0.5°C at 18.4 m and ≤0.1°C at 26.4 m;

- At Wright Valley, an annual temperature range of ≤1°C occurred at 14.0 m, ≤0.5°C at 17.2 m and ≤0.1°C at 25.2 m;
- Maximum and minimum surface temperatures in each permafrost temperature monitoring borehole took 12 – 13 months to penetrate to about 30 m depth at Marble Point and 11 – 12 months at Wright Valley;
- The summer maximum surface soil temperature (5 – 11 cm) took 15 – 22 days to penetrate to 75 – 90 cm depth;
- A single, large (~30°C) increase in surface soil temperature in the winter took 1-5 days to penetrate from the surface to 75 – 90 cm depth;
- The temperature range (maximum – minimum) decreased exponentially with depth at both the seasonal time scale ($0.40 \leq R^2 \leq 0.95$) and the annual time scale in each permafrost temperature monitoring borehole ($R^2 \geq 0.98$).

8.2.3 Mean annual and seasonal air and soil temperatures

Chapter 6 addressed the fourth research objective, which investigated the mean annual air and soil temperatures for evidence of warming or cooling trends from 1999-2007 and described the change in mean annual temperatures across latitude and altitude. The key outcomes of Chapter 6 were:

- There was no significant trend in mean annual air temperatures ($0 \leq R^2 \leq 0.2$) or mean annual soil temperatures ($0 \leq R^2 \leq 0.27$) to indicate warming or cooling over the eight year data record investigated;
- Mean annual and mean seasonal air and soil temperatures varied inter-annually;
- Mean annual and mean summer shallow soil temperatures (6.5 – 9 cm) were warmer than air temperatures due to heating by solar radiation;
- There was no correlation between mean annual or mean winter air temperatures with the Southern Annular Mode Index (SAMI);
- Mean summer air temperature correlated reasonably well with the SAMI ($0.61 \leq R^2 \leq 0.73$) at all sites except Victoria Valley;

- Mean annual air temperature and mean annual soil temperatures increased with decreasing latitude, and decreased with increasing altitude;
- Micro-climate and topography factors were likely to be more influential on mean annual temperatures than latitude;
- Winter air temperatures at Mt Fleming were warmer than those at Victoria Valley which was attributed to a frost hollow effect in Victoria Valley.

8.2.4 Relationships between near-surface soil temperatures and above-ground climate variables

Chapter 7 addressed the final research objective, which was to investigate the correlations between above-ground climate variables and near-surface soil temperatures and determine which correlations were significant (Chapter 7). The key outcomes of Chapter 7 were:

- The strongest correlation at all sites was between air and near-surface soil surface temperature (1.3 – 7.5 cm depth) ($0.79 \leq R^2 \leq 0.96$);
- There was no significant correlation between air temperature and incoming solar radiation ($0 \leq R^2 \leq 0.40$) over the summer (1 Dec to 31 Jan), despite occasions of strong correlation on a diurnal scale;
- Near-surface soil temperature (1.3 – 7.5 cm) was strongly correlated with incoming solar radiation over the summer (1 Dec to 31 Jan), at Victoria Valley ($0.14 \leq R^2 \leq 0.76$) and Granite Harbour ($0.49 \leq R^2 \leq 0.82$). The poor correlations occurred at Victoria Valley in the summer of 2002-03 and at both Victoria Valley and Granite Harbour in 2006-07, which was probably due to cooler December soil temperatures compared to other years;
- At all sites except Victoria Valley and Granite Harbour, there was no significant correlation between near-surface soil temperature and incoming solar radiation ($0 \leq R^2 \leq 0.57$);
- Diurnal cycles of air and soil temperatures during summer were driven by solar radiation;

- Multiple regression analysis showed that soil surface temperature (1.3 – 7.5 cm) correlated well with the combined effects of air temperature, solar radiation and wind speed ($0.88 \leq R^2 \leq 0.98$) at all sites;
- Multiple regression equations approximated the soil surface temperature pattern well in both summer and winter.

8.3 Discussion

Over the eight year record (January 1999 to January 2008) from seven automated weather stations in the McMurdo Sound region of Antarctica there were no significant warming or cooling trends in mean annual air temperature or active layer depth. There was inter-annual variability in air and soil temperatures that may have been part of a longer term cyclical pattern. Though no warming or cooling trend was observed in the McMurdo Sound region over our short time range, if the mean annual or seasonal air temperatures increase due to predicted 'global warming', it is clear that there will be ramifications for the subsurface temperature regime. Warmer air temperatures will result in warmer soil temperatures and active layer depth will increase, with an accompanying melting of the top of the permafrost.

The mean annual air temperature was shown to be primarily influenced by the winter air temperatures (Chapter 6), but the annual sinusoidal temperature curve showed that there were several spikes in surface temperature during the winter (Chapter 5), probably coinciding with the occurrence of winter storms. Presumably, differing frequencies of winter storms will impact on the mean annual air temperature, and thus the subsurface thermal regime.

The mean annual temperature measured by the deepest sensor in each permafrost temperature monitoring borehole (~27 m depth) was found to be within ±1°C of the mean annual air temperature measured by the automated weather stations nearby. Depths of "Zero Annual Amplitude" of 12 m in the Ross Sea Region of Antarctica (Guglielmin 2006) and 18 m depth in Svalbard (Isaksen 2000) have been previously reported. However, the depth of "Zero Annual Amplitude" was found to be a flawed concept, as it is sensitive to sensor accuracy. I observed mean annual temperature cycles at about 27 m depth in each borehole. As a larger database becomes available from the permafrost temperature monitoring boreholes, it will be important to investigate the mean annual temperatures at all depths for inter-annual variability and changes with depth.

Further investigation of the data from the permafrost temperature monitoring boreholes would yield information on the thermal conductivity of the bedrock. If the permafrost temperature monitoring network could be extended into other sites with different bedrock types, it would be interesting to compare the attendant thermal conductivities and investigate the depth to which the annual temperature cycle can be observed associated with different bedrock types.

8.4 Conclusions

It is important to understand how the Antarctic climate and subsurface thermal characteristics vary temporally and spatially before attempting to predict how the system will respond to global warming or cooling. Mean annual air and soil temperature, and subsequently the active layer depth, displayed inter-annual variability across the eight year record available. No significant trends were found in mean annual temperatures or active layer depth, indicating that at this short time scale, there was no evidence to support reported warming or cooling in Antarctica. Above-ground climatic variables influenced the subsurface thermal regime; for example, air temperature and soil surface temperature were strongly linked ($R^2 \geq 0.79$), and soil surface temperature was well approximated by the combined effects of air temperature, solar radiation and wind speed ($0.88 \leq R^2 \leq 0.98$). A multiple regression model combining the influence of mean summer air temperature, mean winter air temperature, total summer solar radiation and mean summer wind speed described 73% of the variability in active layer depth. The inter-annual variability observed indicated the need for a longer record to fully describe any trends in air temperatures.

8.5 Recommendations for further research

While several aspects have been covered in this thesis, there is still a vast amount of information available in the soil climate database which has not yet been explored. There are several options for further research to complement and build on the findings of this thesis.

A comparison of the mean annual temperatures from this soil climate monitoring network with those from the long term climate database for Scott Base (1953 – present), monitored by the National Institute for Water and Atmospheric Research (NIWA), would be beneficial to determine if the inter-annual variability observed was part of a cyclical trend. Comparison with a longer database would also provide a better picture of temperatures to determine the existence of any warming or cooling trends. It may be possible, using the longer database, to extend the existing eight year database backward and provide a longer time series for analysis.

It would be beneficial to extend the multiple regression model for active layer depth developed for the soil climate monitoring network. Using the regression model, together with climate observations, from other sites in the McMurdo Sound region would be valuable to verify the applicability of the model to sites outside the seven used to create it.

As more data becomes available from the two permafrost temperature monitoring boreholes, it will be interesting to use the data, in conjunction with the data from the soil climate stations, to investigate the influence of seasonal temperature changes on the subsurface thermal regime, and determine how quickly surface temperature changes are recorded by deeper sensors (e.g. deeper than 8 m). Also, investigation of the mean annual temperature with depth could be beneficial to understand if the deeper temperatures were responding to longer-term means or climate trends, for example, determining if the temperature measured by the deepest sensor (~27 m) is an integral the previous year's surface climate regime, or the last three years, or even longer term climate fluctuations.

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APPENDIX I: MEAN ANNUAL AND MONTHLY TEMPERATURE SPREADSHEETS

1. Introduction

This appendix provides the raw data for Chapter 6. The mean annual, mean summer, mean winter and mean monthly air temperatures are presented. The mean annual shallow soil, mid-depth soil and deep soil temperatures are also included. The results of significance testing are included on the mean annual tables.

2. Mean annual air and soil temperatures

Table 1: Mean annual air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	**Minna Bluff**	**Scott Base**	**Marble Point**	**Granite Harbour**	**Wright Valley**	**Victoria Valley**	**Mt Fleming**
1999	*NE*	-19.80	-16.89	*NE*	-21.71	-25.30	*NE*
2000	*NE*	-19.40	-17.73	*NE*	-19.59	-22.51	*NE*
2001	*NE*	-19.48	-18.50	*NE*	-20.14	-22.91	*NE*
2002	*NE*	-19.34	-18.51	*NE*	-20.25	-24.24	—
2003	—	-18.30	-18.02	—	-18.97	-22.22	—
2004	-20.52	-20.81	-19.52	-19.48	-21.10	-23.04	—
2005	-18.40	-24.93	-18.28	-18.12	-19.71	-23.01	—
2006	-19.61	-19.63	-18.50	-17.95	-20.98	-24.70	—
2007	—	-17.45	-16.28	-15.44	-18.09	-22.83	-23.43
Mean	-19.51	-19.91	-18.03	-17.75	-20.06	-23.42	–
Notation ($p<0.05$)	a	a	b	a	c	d	–

Table 2: Mean annual 'shallow' soil temperatures (6.5 – 8.9 cm depth) at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	**Minna Bluff (5 cm)**	**Scott Base (8.9 cm)**	**Marble Point (7.5 cm)**	**Granite Harbour (6.5 cm)**	**Wright Valley (7.5 cm)**	**Victoria Valley (7.5 cm)**	**Mt Fleming (7.5 cm)**
1999	*NE*	-18.61	-16.63	*NE*	-21.82	-23.03	*NE*
2000	*NE*	-18.18	-18.60	*NE*	-19.67	-21.75	*NE*
2001	*NE*	-18.45	-18.84	*NE*	-20.33	-22.34	*NE*
2002	*NE*	-18.30	-19.18	*NE*	-20.90	-24.71	—
2003	—	-17.53	-18.23	—	-19.10	-22.06	—
2004	—	-19.41	-19.16	-17.14	-21.10	-23.46	—
2005	—	-17.65	-18.13	-14.99	-20.00	-22.88	—
2006	-18.15	-18.21	-18.67	-14.80	-20.66	-24.94	—
2007	—	-16.41	-17.81	-14.23	-18.61	-22.41	-22.39
Mean	–	-18.09	-18.36	-15.29	-20.24	-23.07	–
Notation ($p<0.05$)	–	a	a	b	c	d	–

Table 3: Mean annual 'mid-depth' soil temperatures (39.4 – 45 cm depth) at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	**Minna Bluff (43 cm)**	**Scott Base (39.4 cm)**	**Marble Point (45 cm)**	**Granite Harbour (45 cm)**	**Wright Valley (45 cm)**	**Victoria Valley (45 cm)**	**Mt Fleming (45 cm)**
1999	*NE*	-18.25	-17.10	*NE*	-21.20	-23.19	*NE*
2000	*NE*	-17.91	-18.08	*NE*	-19.43	-21.95	*NE*
2001	*NE*	-18.47	-18.75	*NE*	-20.04	-22.43	*NE*
2002	*NE*	-18.12	-18.78	*NE*	-20.31	-23.74	—
2003	—	-18.03	-18.32	—	-19.13	-22.31	—
2004	—	-19.29	-19.05	-16.88	-20.58	-22.81	—
2005	—	-17.82	-18.16	-15.03	-19.77	-22.40	—
2006	-17.83	-17.97	-18.37	-14.74	-20.13	-23.66	—
2007	—	-16.49	-17.67	-14.02	-18.54	-22.40	-22.84
Mean	–	-18.04	-18.25	-15.17	-19.91	-22.76	–
Notation ($p<0.05$)	–	a	a	b	c	d	–

Table 4: Mean annual 'deep' soil temperatures (75 – 105 cm depth) at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	**Minna Bluff (96.5cm)**	**Scott Base (100.3cm)**	**Marble Point (105 cm)**	**Granite Harbour (90 cm)**	**Wright Valley (105 cm)**	**Victoria Valley (105 cm)**	**Mt Fleming (75 cm)**
1999	*NE*	-18.14	-17.57	*NE*	-20.81	-23.33	*NE*
2000	*NE*	-17.82	-17.87	*NE*	-19.38	-22.19	*NE*
2001	*NE*	-18.54	-18.79	*NE*	-19.87	-22.60	*NE*
2002	*NE*	-18.08	-18.65	*NE*	-19.99	-23.66	—
2003	—	-18.42	-18.55	—	-19.33	-22.57	—
2004	—	-19.25	-19.12	-16.67	-20.30	-22.85	—
2005	—	-17.84	-18.25	-14.87	-19.71	-22.48	—
2006	-17.76	-17.93	-18.33	-14.48	-19.88	-23.53	—
2007	—	-16.60	-17.74	-13.95	-18.70	-22.59	-22.87
Mean	–	-18.07	-18.32	-14.99	-19.77	-22.87	–
Notation ($p<0.05$)	–	a	a	b	c	d	–

3. Mean seasonal air temperatures

Table 5: Mean summer air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established.

Summer	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Bull Pass	Victoria Valley	Mt Fleming
1999-00	*NE*	-5.59	-2.93	*NE*	-1.12	-2.79	*NE*
2000-01	*NE*	-7.20	-4.82	*NE*	-2.18	-3.26	*NE*
2001-02	*NE*	-3.50	-1.17	*NE*	1.57	0.38	*NE*
2002-03	*NE*	-5.11	-3.62	*NE*	-0.68	-1.92	-13.69
2003-04	-4.47	-5.19	-2.94	-1.92	-0.20	-0.72	-12.79
2004-05	-2.51	-2.69	-1.53	-1.85	0.50	-0.54	-12.21
2005-06	-3.22	-4.24	-1.83	-2.49	0.64	-0.38	-12.03
2006-07	-2.99	-4.00	-1.97	-2.89	0.17	-1.45	-14.06

Table 6: Mean winter air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-26.69	-25.39	*NE*	-31.34	-35.07	*NE*
2000	*NE*	-27.00	-26.46	*NE*	-29.96	-34.07	*NE*
2001	*NE*	-27.63	-27.46	*NE*	-33.37	-35.65	*NE*
2002	*NE*	-31.30	-31.59	*NE*	-34.44	-36.93	—
2003	-27.01	-26.82	-27.09	—	-32.27	-36.55	—
2004	-32.01	-31.76	-31.09	-29.60	-31.89	-33.81	—
2005	-28.73	-28.35	-28.90	-28.65	-31.38	-34.49	—
2006	-26.23	-26.03	-26.17	-25.33	-30.40	-33.73	—
2007	-23.76	-23.96	-23.65	-22.14	-27.57	-34.62	-29.93

4. Mean monthly air temperatures

Table 7: Mean January air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-4.40	-1.85	*NE*	-0.13	-1.48	*NE*
2000	*NE*	-6.12	-3.12	*NE*	-1.31	-2.91	*NE*
2001	*NE*	-7.98	-5.76	*NE*	-2.62	-3.60	*NE*
2002	*NE*	-3.71	-1.45	*NE*	1.71	0.55	-12.06
2003	-3.41	-3.62	-2.86	-2.72	0.34	-0.69	-12.17
2004	-5.37	-6.14	-3.90	-4.99	-1.09	-1.20	-12.88
2005	-3.16	-2.22	-2.45	-2.72	0.26	-0.86	-12.49
2006	-4.35	-5.50	-2.59	-2.54	-0.23	-1.24	-12.69
2007	-1.21	-1.84	-0.45	-1.05	2.38	1.03	-15.34

Table 8: Mean February air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-11.25	-8.01	*NE*	-7.31	-9.82	*NE*
2000	*NE*	-12.80	-8.88	*NE*	-7.67	-9.15	*NE*
2001	*NE*	-9.60	-7.91	*NE*	-5.89	-7.40	*NE*
2002	*NE*	-10.11	-7.27	*NE*	-6.26	-7.60	-19.15
2003	-10.14	-11.38	-8.46	-8.26	-6.52	-7.66	-17.68
2004	-11.08	-11.87	-9.12	-9.81	-8.51	-8.98	-17.39
2005	-9.64	—	-8.49	-8.22	-8.21	-10.86	-18.21
2006	-9.66	-9.98	-8.10	-7.96	-6.79	-8.62	-18.07
2007	-11.14	-11.45	-9.08	-8.02	-8.83	-10.29	-12.05

Table 9: Mean March air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-21.20	-17.82	*NE*	-28.32	-33.05	*NE*
2000	*NE*	-18.42	-15.69	*NE*	-21.07	-23.31	*NE*
2001	*NE*	-21.90	-20.57	*NE*	-22.68	-23.03	*NE*
2002	*NE*	-17.38	-15.78	*NE*	-17.48	-22.24	-24.61
2003	-20.04	-21.61	-18.98	-12.63	-21.34	-27.43	-26.09
2004	-24.62	-24.00	-21.75	-21.98	-29.03	-30.64	-26.34
2005	-19.70	-18.72	-18.37	-17.43	-25.62	-32.06	-25.05
2006	-19.72	-20.59	-18.54	-16.70	-22.31	-26.92	-25.61
2007	-18.83	-19.32	-17.43	-15.45	-20.10	-28.83	-24.15

Table 10: Mean April air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-27.39	-25.61	*NE*	-35.05	-37.14	*NE*
2000	*NE*	-21.21	-19.55	*NE*	-28.96	-32.83	*NE*
2001	*NE*	-24.13	-23.86	*NE*	-27.92	-33.47	*NE*
2002	*NE*	-22.82	-22.32	*NE*	-30.02	-35.66	-28.84
2003	-26.57	—	-25.51	-21.63	-32.06	-35.92	-28.88
2004	-22.54	-22.74	-23.25	-22.84	-30.57	-35.39	-27.87
2005	-25.59	-25.61	-25.82	-25.26	-32.36	-36.01	-29.13
2006	-29.05	-27.93	-27.13	-25.49	-36.04	-38.48	-29.53
2007	-25.10	-24.02	-23.11	-21.94	-29.35	-34.38	-28.75

Table 11: Mean May air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-28.74	-28.41	*NE*	-37.56	-39.14	*NE*
2000	*NE*	-25.00	-24.11	*NE*	-32.75	-36.15	*NE*
2001	*NE*	-25.48	-24.57	*NE*	-27.13	-32.99	*NE*
2002	*NE*	-21.21	-20.30	*NE*	-24.89	-30.39	-27.53
2003	-21.86	-21.63	-21.44	-21.11	-23.05	-28.56	-28.74
2004	-28.22	-28.18	-27.44	-27.47	-35.55	-36.22	-31.65
2005	-21.53	-22.16	-22.27	-22.28	-26.20	-32.39	—
2006	-31.68	-30.56	-30.06	-28.64	-35.72	-36.38	-27.69
2007	-23.73	-21.80	-21.26	-20.17	-27.25	-32.18	-26.18

Table 12: Mean June air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*[a]	-25.48	-23.17	*NE*	-29.74	-35.89	*NE*
2000	*NE*	-26.99	-27.00	*NE*	-33.95	-34.26	*NE*
2001	*NE*	-23.66	-22.86	*NE*	-26.71	-33.67	*NE*
2002	*NE*	-30.09	-29.36	*NE*	-34.42	-35.70	-28.19
2003	-24.84	-25.26	-24.81	-23.61	-33.29	-36.92	—[b]
2004	-28.39	-27.80	-25.20	-23.41	-26.49	-29.36	-37.52
2005	-27.89	-27.48	-27.63	-28.33	-28.67	-33.41	—
2006	-24.59	-24.19	-23.40	-22.99	-26.95	-31.44	—
2007	-22.39	-22.26	-21.16	-20.31	-25.26	-31.38	-28.54

Table 13: Mean July air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-23.42	-22.28	*NE*	-26.67	-32.28	*NE*
2000	*NE*	-25.63	-25.03	*NE*	-25.80	-33.28	*NE*
2001	*NE*	-24.16	-24.49	*NE*	-31.45	-35.71	*NE*
2002	*NE*	-31.80	-32.54	*NE*	-33.40	-37.05	-32.43
2003	-23.72	-24.09	-24.00	-19.97	-29.22	-34.90	—
2004	-35.35	-35.21	-34.48	-33.79	-39.62	-38.27	-33.31
2005	-27.78	-27.47	-27.83	-28.33	-34.24	-35.32	—
2006	-33.05	-32.45	-32.27	-32.40	-38.43	-38.07	—
2007	-24.47	-24.48	-23.74	-22.98	-27.33	-36.19	-30.14

Table 14: Mean August air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-31.12	-30.62	*NE*	-37.52	-37.04	*NE*
2000	*NE*	-28.40	-27.37	*NE*	-30.25	-34.67	*NE*
2001	*NE*	-34.96	-34.87	*NE*	-41.73	-37.52	*NE*
2002	*NE*	-31.99	-32.79	*NE*	-35.51	-38.02	-33.66
2003	-32.35	-30.77	-30.53	—	-34.32	-37.85	-28.35
2004	-32.17	-32.16	-31.80	-31.41	-29.40	-33.72	-26.72
2005	-30.58	-30.09	-29.60	-29.27	-31.13	-34.70	-34.10
2006	-20.88	-21.38	-20.82	-20.50	-25.67	-31.58	-29.73
2007	-24.43	-25.08	-24.23	-23.06	-30.03	-36.18	-31.15

Table 15: Mean September air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-22.99	-22.68	*NE*	-27.00	-32.85	*NE*
2000	*NE*	-28.65	-27.82	*NE*	-26.86	-29.43	*NE*
2001	*NE*	-26.23	-27.06	*NE*	-31.96	-36.75	*NE*
2002	*NE*	-24.24	-24.55	*NE*	-29.54	-37.10	-25.87
2003	-25.11	-25.40	-23.67	—	-25.42	-27.55	-28.64
2004	-28.88	-28.58	-28.36	-27.98	-29.87	-33.97	-27.64
2005	-25.38	-26.55	-27.20	-25.94	-30.10	-35.54	-27.96
2006	-22.34	-24.17	-23.35	-22.76	-28.60	-31.82	-28.86
2007	—	-22.45	-21.62	-20.71	-25.52	-32.27	-29.51

Table 16: Mean October air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-18.61	-17.74	*NE*	-15.73	-22.52	*NE*
2000	*NE*	-23.25	-22.08	*NE*	-19.93	-24.31	*NE*
2001	*NE*	-20.56	-19.34	*NE*	-17.88	-22.37	*NE*
2002	*NE*	-18.97	-19.00	*NE*	-21.67	-31.28	-25.37
2003	-16.65	-17.72	-17.21	—	-15.25	-19.04	-26.55
2004	-19.31	-20.61	-19.73	-18.62	-18.37	-20.97	-25.41
2005	-18.26	-18.86	-18.33	-17.54	-15.03	-17.20	-24.29
2006	-20.39	-21.63	-20.65	-20.34	-21.02	-31.82	-25.73
2007	—	-21.92	-20.20	-18.44	-18.03	-21.03	-25.91

Table 17: Mean November air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-9.45	-8.00	*NE*	-4.62	-6.65	*NE*
2000	*NE*	-9.44	-7.99	*NE*	-4.57	-6.42	*NE*
2001	*NE*	-11.11	-9.10	*NE*	-6.16	-7.77	*NE*
2002	*NE*	-12.43	-11.01	*NE*	-9.13	-12.28	-21.07
2003	-10.21	-12.25	-10.43	—	-7.67	-9.10	-19.19
2004	-8.04	-9.05	-7.41	-6.52	-4.83	-6.62	-19.03
2005	-9.43	-10.99	-9.02	-9.28	-6.23	-7.68	-20.09
2006	-9.51	-10.79	-9.85	-9.66	-7.02	-15.02	-17.56
2007	—	-10.69	-10.06	-10.05	-6.97	-9.50	-18.71

Table 18: Mean December air temperatures at seven sites in the McMurdo Sound region of Antarctica from 1999-2007. NE = site not established, — = Incomplete record.

Year	Minna Bluff	Scott Base	Marble Point	Granite Harbour	Wright Valley	Victoria Valley	Mt Fleming
1999	*NE*	-5.06	-2.64	*NE*	-0.93	-2.67	*NE*
2000	*NE*	-6.40	-3.89	*NE*	-1.75	-2.92	*NE*
2001	*NE*	-3.24	-0.90	*NE*	1.42	0.22	*NE*
2002	*NE*	-6.61	-5.12	*NE*	-1.70	-3.16	-15.23
2003	-3.56	-4.25	-2.73	—	0.69	-0.24	-12.73
2004	-1.85	-2.96	-1.31	-0.97	0.74	-0.22	-11.92
2005	-2.28	-3.30	-1.89	-2.44	1.50	0.47	-11.38
2006	-5.10	-6.17	-4.59	-4.74	-2.03	-3.92	-12.35
2007	—	-3.83	-2.64	-2.72	-0.30	-1.99	-14.10

APPENDIX II: ACTIVE LAYER DEPTH DETERMINATION

1. Introduction

This appendix presents the figures used to create the active layer depths in each summer at each site in our study area (see Chapter 3). Active layer depth was calculated from the graphical interception of the maximum soil temperature profile with the 0°C isotherm. Where the maximum soil temperature profile crosses the 0°C isotherm more than once, the active layer depth was taken to be where the maximum soil temperature crossed the 0°C isotherm closest to the ground surface. Maximum soil temperatures were for the summer period, i.e. 1 Dec to 31 Jan.

2. Minna Bluff

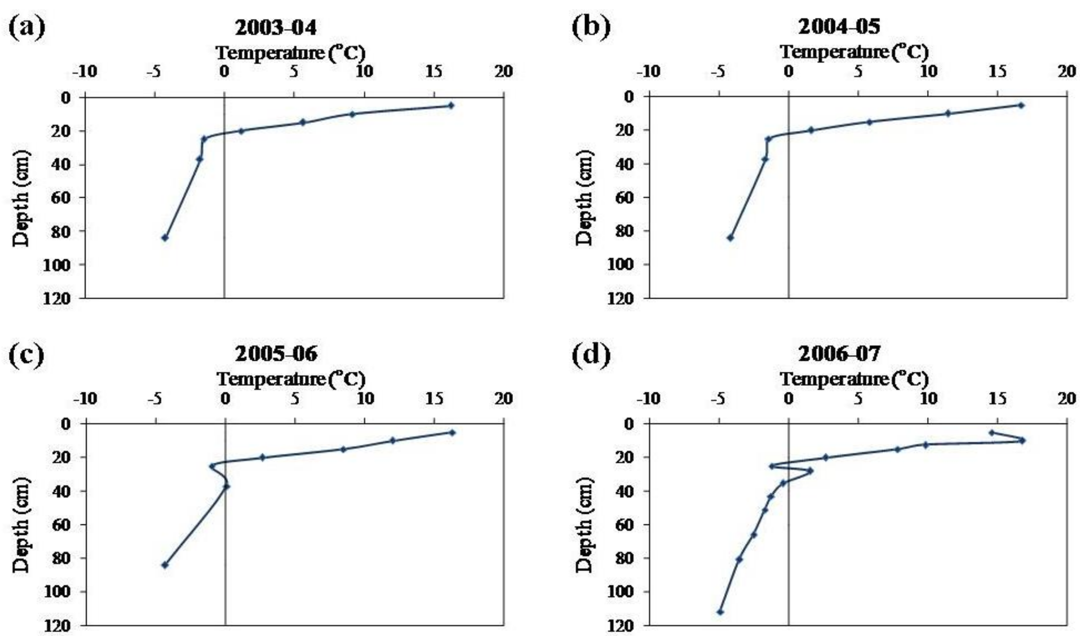

Figure 1: Maximum soil temperature profile at Minna Bluff for the summer of (a) 2003-04, (b) 2004-05, (c) 2005-06 and (d) 2006-07.

3. Scott Base

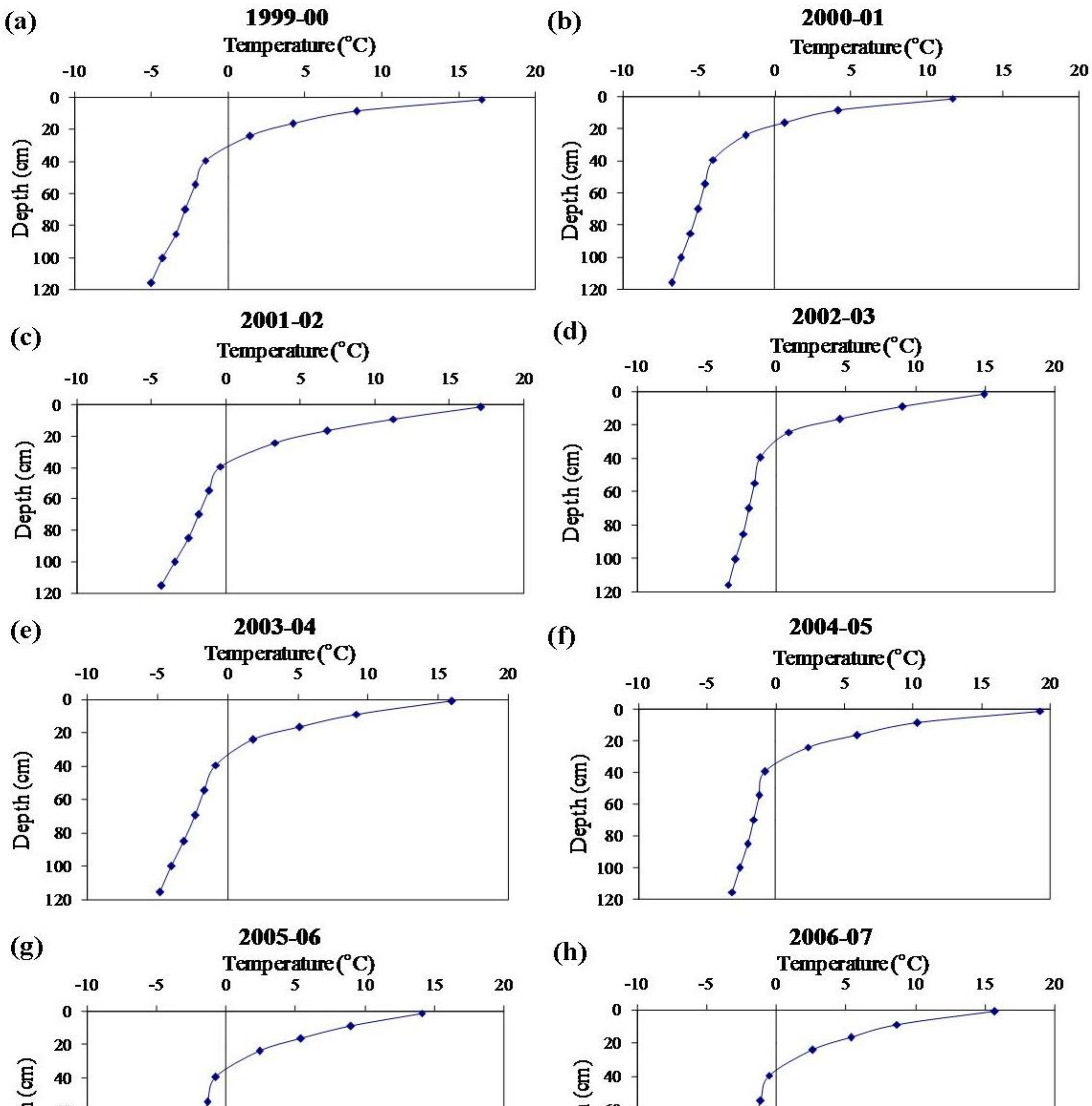

Figure 2: Maximum soil temperature profile at Scott Base for the summer of (a) 1999-00, (b) 2000-01, (c) 2001-02, (d) 2002-03, (e) 2003-04, (f) 2004-05, (g) 2005-06, (h) 2006-07.

4. Marble Point

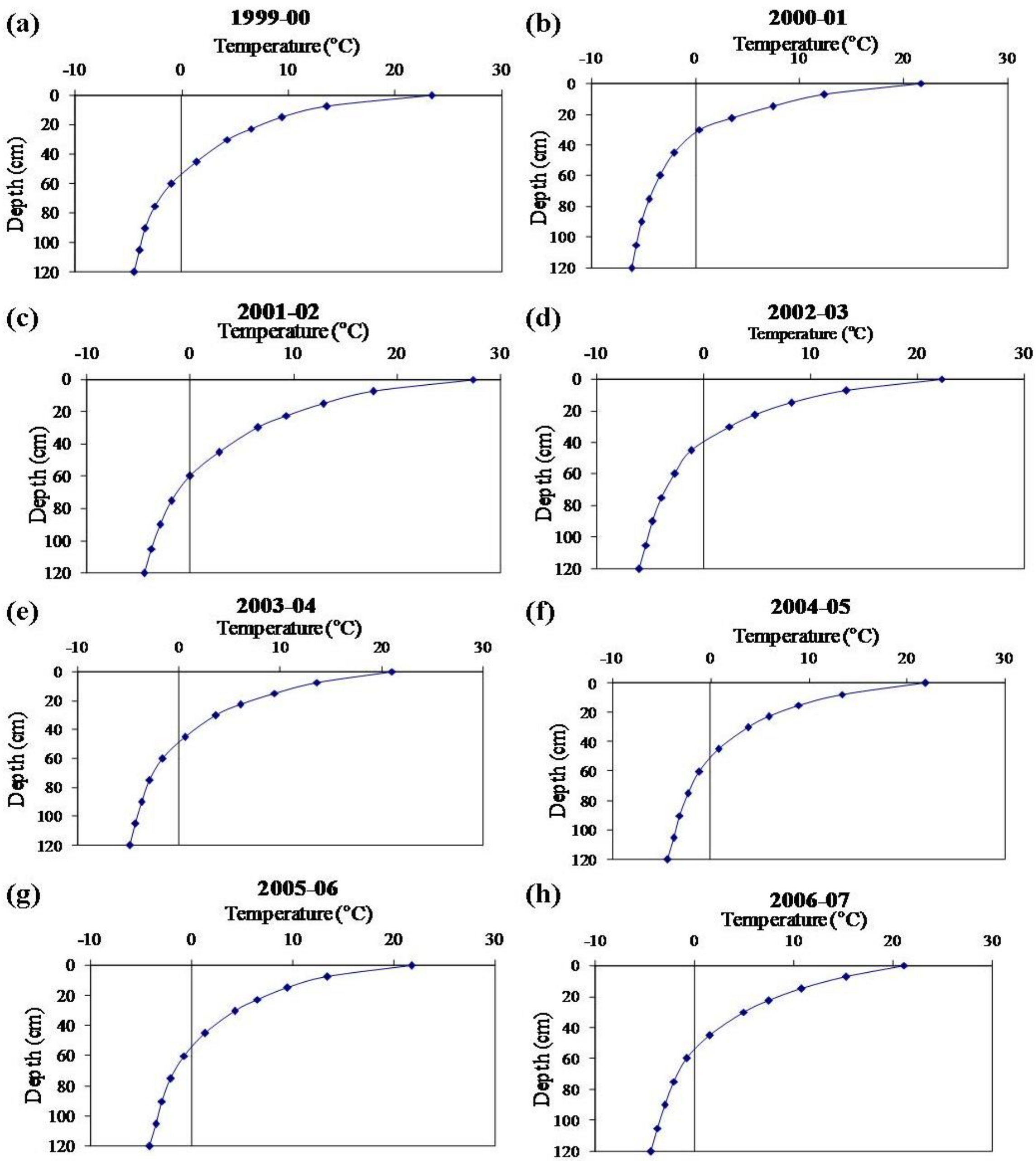

Figure 3: Maximum soil temperature profile at Marble Point for the summer of (a) 1999-00, (b) 2000-01, (c) 2001-02, (d) 2002-03, (e) 2003-04, (f) 2004-05, (g) 2005-06, (h) 2006-07.

5. Granite Harbour

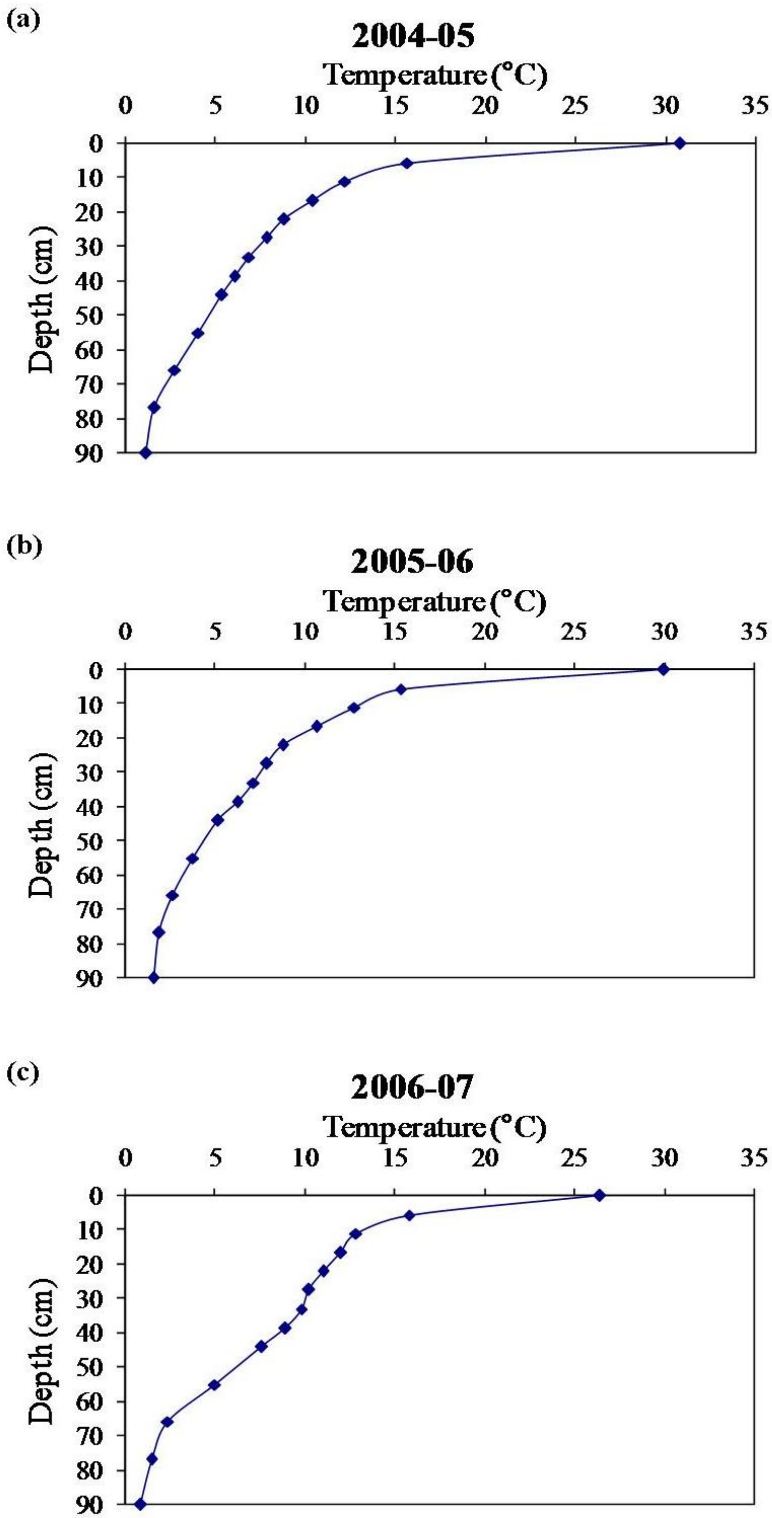

Figure 4: Maximum soil temperature profile at Granite Harbour for the summer of a) 2004-05, b) 2005-06, c) 2006-07.

6. Wright Valley

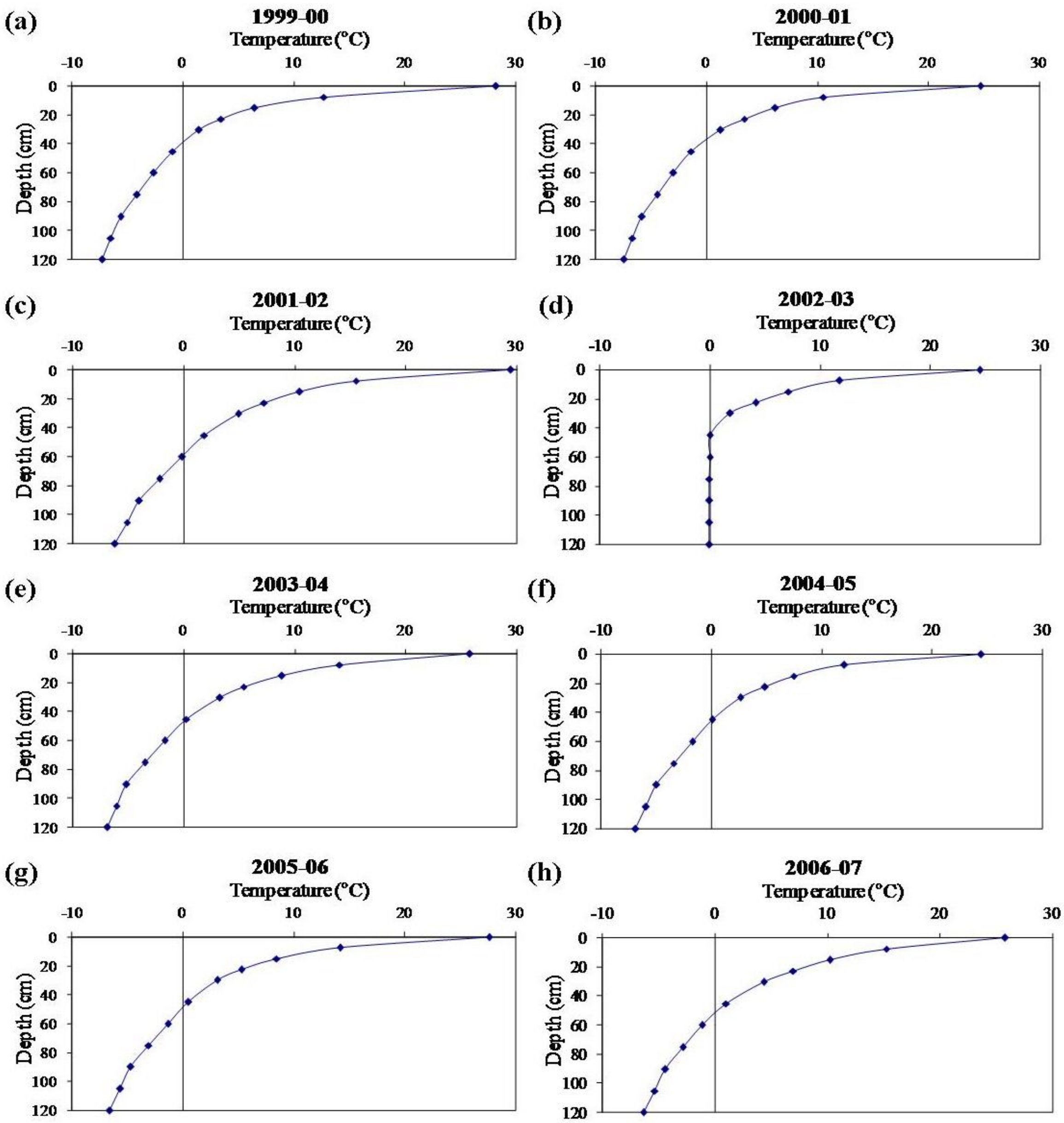

Figure 5: Maximum soil temperature profile at Wright Valley for the summer of (a) 1999-00, (b) 2000-01, (c) 2001-02, (d) 2002-03, (e) 2003-04, (f) 2004-05, (g) 2005-06, (h) 2006-07.

7. Victoria Valley

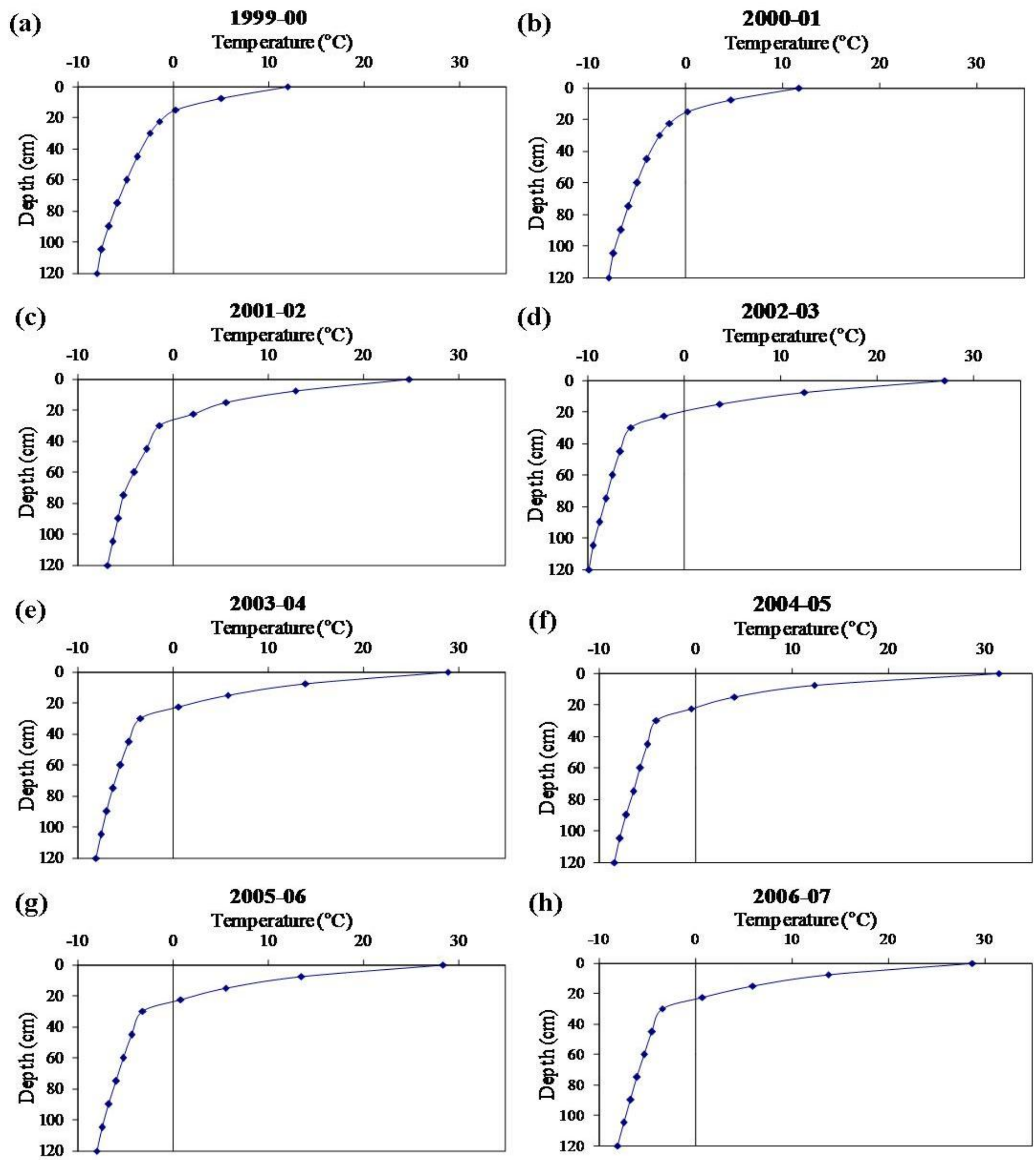

Figure 6: Maximum soil temperature profile at Victoria Valley for the summer of (a) 1999-00, (b) 2000-01, (c) 2001-02, (d) 2002-03, (e) 2003-04, (f) 2004-05, (g) 2005-06, (h) 2006-07.

8. Mt Fleming

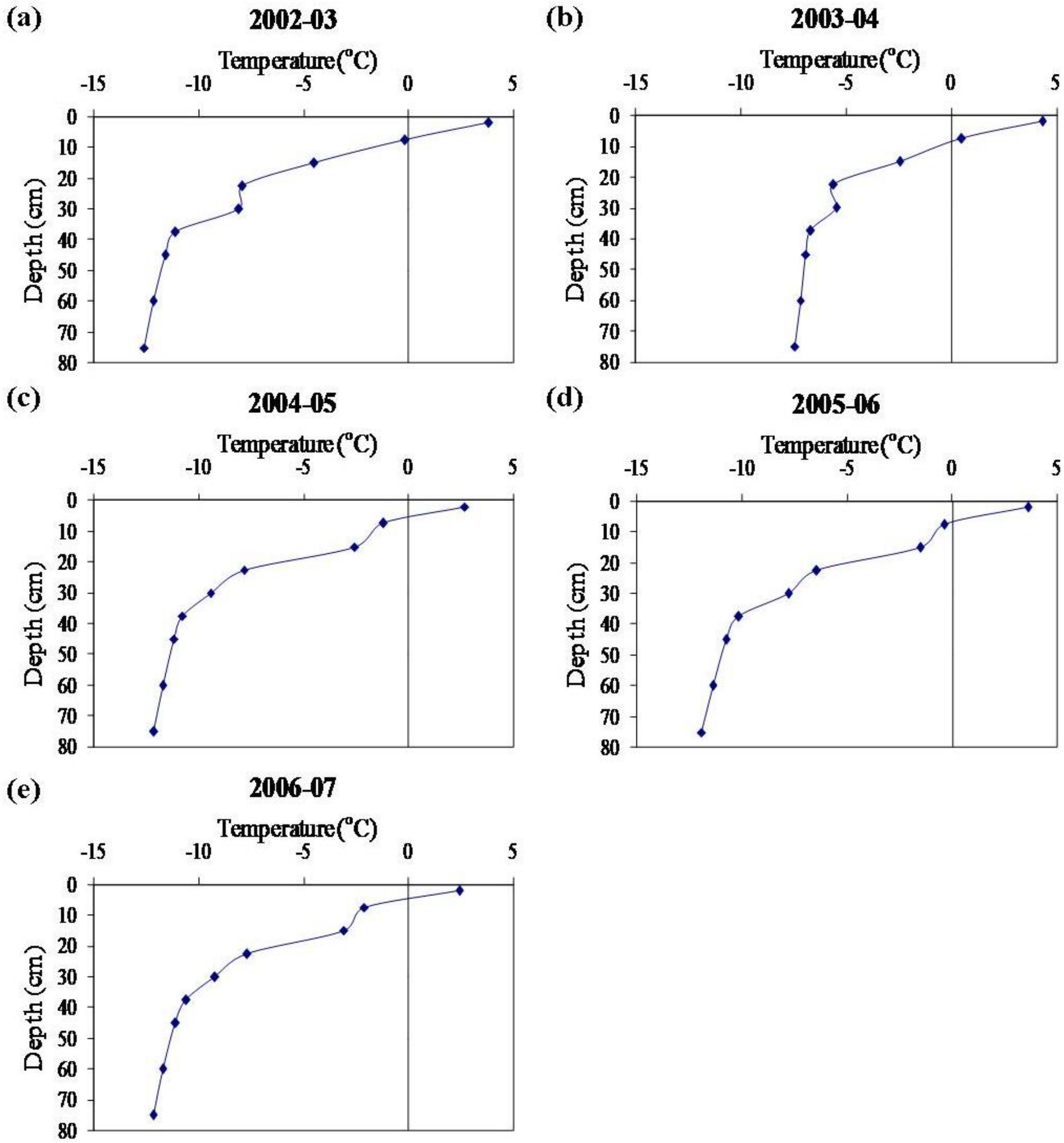

Figure 7: Maximum soil temperature profile at Mt Fleming for the summer of a) 2002-03, b) 2003-04, c) 2004-05, d) 2005-06, e) 2006-07.

APPENDIX III: SEASONAL PHASE LAG CALCULATIONS

1. Introduction

This appendix contains the details of maximum soil temperatures, date of maximum and associated phase lag from the surface at each depth of measurement (Chapter 5). Time lag was calculated for one summer only (1 December 2006 to 28 February 2007). Summer and winter temperature ranges (maximum – minimum) are plotted against depth.

2. Minna Bluff

Table 1: Maximum temperature and timing at each soil depth at Minna Bluff between 0:00am (midnight) 1 December 2006 and 11:00pm 28 February 2007.

Depth (cm)	Maximum temperature (°C)	Date of maximum	Time of day	Time lag from surface (hours)	Time lag from surface (days)
5	14.54	12/01/2007	1600	0	0.0
10	16.74	12/01/2007	1600	0	0.0
12.5	9.81	12/01/2007	1800	2	0.1
15	7.84	12/01/2007	1900	3	0.1
20	2.63	12/01/2007	2200	6	0.3
25	-1.22	1/02/2007	500	469	19.5
28	1.55	13/01/2007	0	8	0.3
35.5	-0.41	1/02/2007	100	465	19.4
43	-1.24	1/02/2007	300	467	19.5
51	-1.71	2/02/2007	300	491	20.5
66	-2.51	3/02/2007	300	515	21.5
81	-3.53	4/02/2007	200	538	22.4
112	-4.90	5/02/2007	1700	577	24.0

3. Scott Base

Table 2: Maximum temperature and timing at each soil depth at Scott Base between 0:00am (midnight) 1 December 2006 and 11:00pm 28 February 2007.

Depth (cm)	Maximum temperature (°C)	Date of maximum	Time of day	Time lag from surface (hours)	Time lag from surface (days)
1.3	15.71	12/01/2007	1100		0
8.9	8.68	9/01/2007	1800	0	0.0
16.5	5.36	13/01/2007	1800	31	1.3
24.1	2.65	13/01/2007	2000	33	1.4
39.4	-0.51	1/02/2007	1400	459	19.1
54.6	-1.11	3/02/2007	1100	504	21.0
69.8	-1.66	3/02/2007	1300	506	21.1
85.1	-2.26	3/02/2007	1300	506	21.1
100.3	-3.04	4/02/2007	1300	530	22.1
115.6	-3.80	6/02/2007	800	597	24.9

4. Marble Point

Table 3: Maximum temperature and timing at each soil depth at Marble Point between 0:00am (midnight) 1 December 2006 and 11:00pm 28 February 2007.

Depth (cm)	Maximum temperature (°C)	Date of maximum	Time of day	Time lag from surface (hours)	Time lag from surface (days)
0	21.10	11/01/2007	1600	0	0.0
7.5	15.24	11/01/2007	1700	1	0.0
15	10.79	11/01/2007	1900	3	0.1
22.5	7.48	11/01/2007	2200	6	0.3
30	4.95	13/01/2007	0	32	1.3
45	1.51	28/01/2007	200	394	16.4
60	-0.76	30/01/2007	700	447	18.6
75	-2.06	1/02/2007	400	490	20.4
90	-3.00	2/02/2007	500	515	21.5
105	-3.69	1/02/2007	2200	515	21.5
120	-4.36	3/02/2007	1000	546	22.8

5. Granite Harbour

Table 4: Maximum temperature and timing at each soil depth at Granite Harbour between 0:00am (midnight) 1 December 2006 and 11:00pm 28 February 2007.

Depth (cm)	Maximum temperature (°C)	Date of maximum	Time of day	Time lag from surface (hours)	Time lag from surface (days)
0	26.42	3/01/2007	1100		0.0
5.5	15.81	21/01/2007	2000		0.0
11	12.85	13/01/2007	2000	249	10.4
16.5	11.99	13/01/2007	2100	250	10.4
22	11.03	13/01/2007	2100	250	10.4
27.5	10.24	13/01/2007	2000	249	10.4
33	9.80	13/01/2007	2000	249	10.4
38.5	8.92	13/01/2007	2100	250	10.4
44	7.61	13/01/2007	2100	250	10.4
55	4.98	13/01/2007	2300	252	10.5
65.8	2.38	25/01/2007	900	526	21.9
76.8	1.49	25/01/2007	1100	528	22.0
90	0.86	29/01/2007	1100	624	26.0

6. Wright Valley

Table 5: Maximum temperature and timing at each soil depth at Wright Valley between 0:00am (midnight) 1 December 2006 and 11:00pm 28 February 2007.

Depth (cm)	Maximum temperature (°C)	Date of maximum	Time of day	Time lag from surface (hours)	Time lag from surface (days)
0	25.74	12/01/2007	1500	0	0
7.5	15.22	12/01/2007	1900	4	0.17
15	10.21	12/01/2007	2100	6	0.25
22.5	6.93	13/01/2007	100	10	0.42
30	4.36	13/01/2007	500	14	0.58
45	0.98	14/01/2007	800	41	1.71
60	-1.15	26/01/2007	1100	332	13.83
75	-2.85	28/01/2007	2000	389	16.21
90	-4.43	30/01/2007	1000	427	17.79
105	-5.37	1/02/2007	400	469	19.54
120	-6.33	2/02/2007	400	493	20.54

7. Victoria Valley

Table 6: Maximum temperature and timing at each soil depth at Victoria Valley between 0:00am (midnight) 1 December 2006 and 11:00pm 28 February 2007.

Depth (cm)	Maximum temperature (°C)	Date of maximum	Time of day	Time lag from surface (hours)	Time lag from surface (days)
0	28.76	11/01/2007	1500	0	0.0
7.5	13.78	12/01/2007	1900	28	1.2
15	5.90	12/01/2007	2200	31	1.3
22.5	0.69	12/01/2007	200	11	0.5
30	-3.47	26/01/2007	200	347	14.5
45	-4.54	26/01/2007	300	348	14.5
60	-5.38	1/02/2007	800	497	20.7
75	-6.07	1/02/2007	1000	499	20.8
90	-6.79	2/02/2007	900	522	21.8
105	-7.50	2/02/2007	2100	531	22.1
120	-8.13	3/02/2007	700	541	22.5

8. Mt Fleming

Table 7: Maximum temperature and timing at each soil depth at Mt Fleming between 0:00am (midnight) 1 December 2006 and 11:00pm 28 February 2007.

Depth (cm)	Maximum temperature (°C)	Date of maximum	Time of day	Time lag from surface (hours)	Time lag from surface (days)
2	1.52	8/12/2006	1500	0	0
7.5	-4.52	9/12/2006	1700	26	1.08
15	-4.99	9/12/2006	1800	27	1.13
22.5	-9.90	9/12/2006	2200	31	1.29
30	-11.51	10/12/2006	300	36	1.50
37.5	-13.17	10/12/2006	400	37	1.54
45	-13.77	10/12/2006	700	40	1.67
60	-14.31	27/12/2006	1000	451	18.79
75	-14.70	27/12/2006	1100	452	18.83

8. Summer soil temperature range (maximum – minimum) with depth

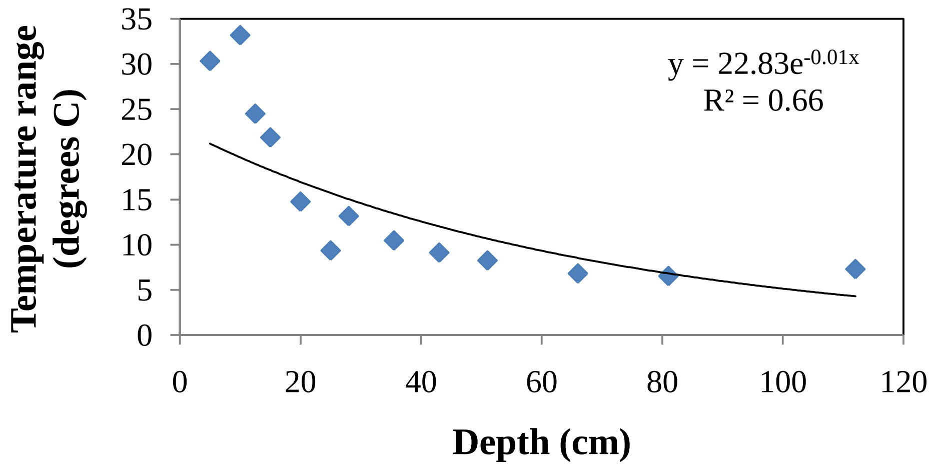

Figure 1: Summer temperature range (maximum – minimum) at Minna Bluff.

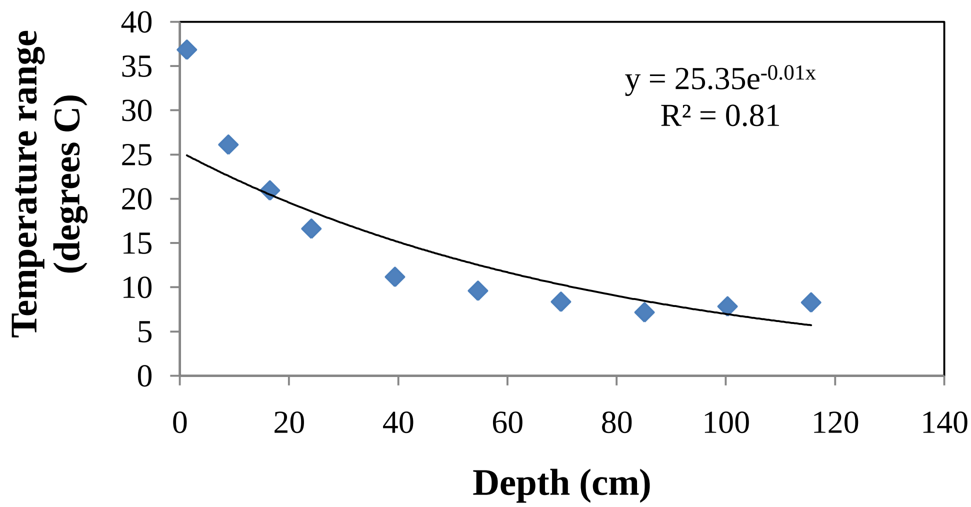

Figure 2: Summer temperature range (maximum – minimum) at Scott Base.

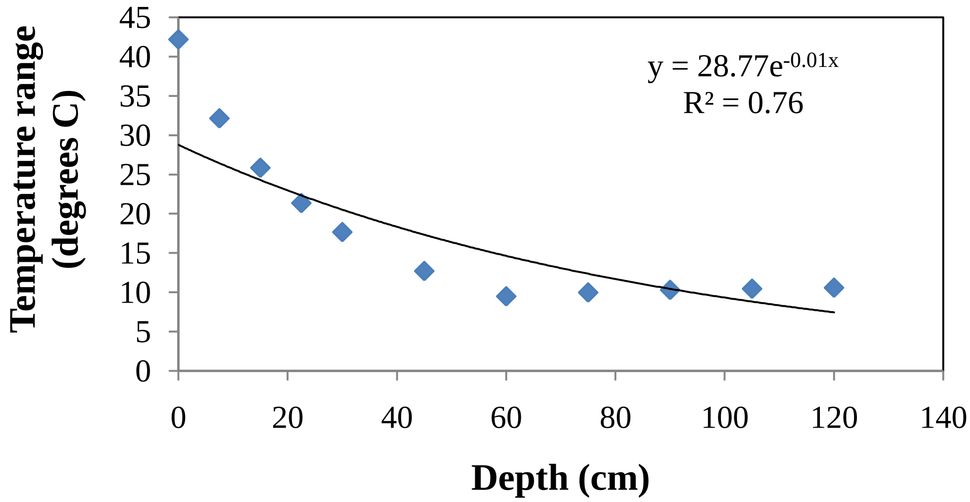

Figure 3: Summer temperature range (maximum – minimum) at Marble Point.

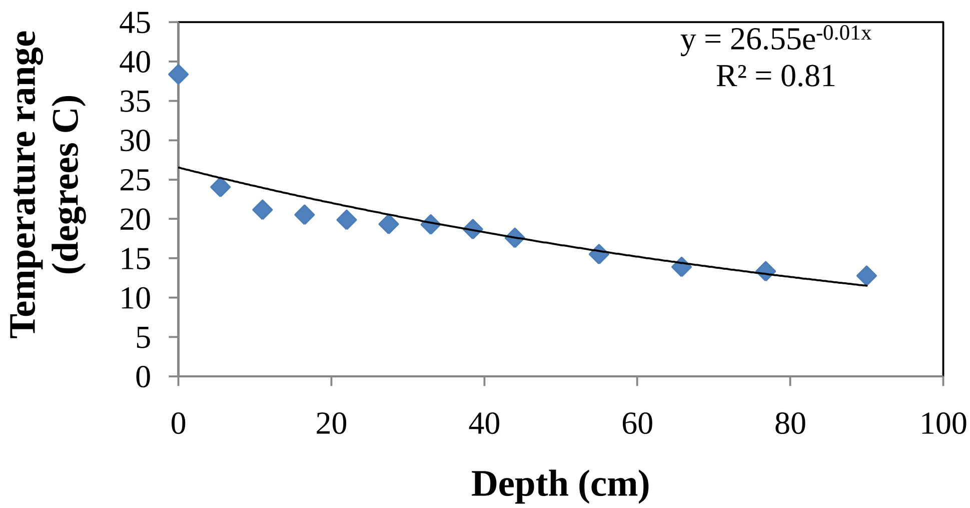

Figure 4: Summer temperature range (maximum – minimum) at Granite Harbour.

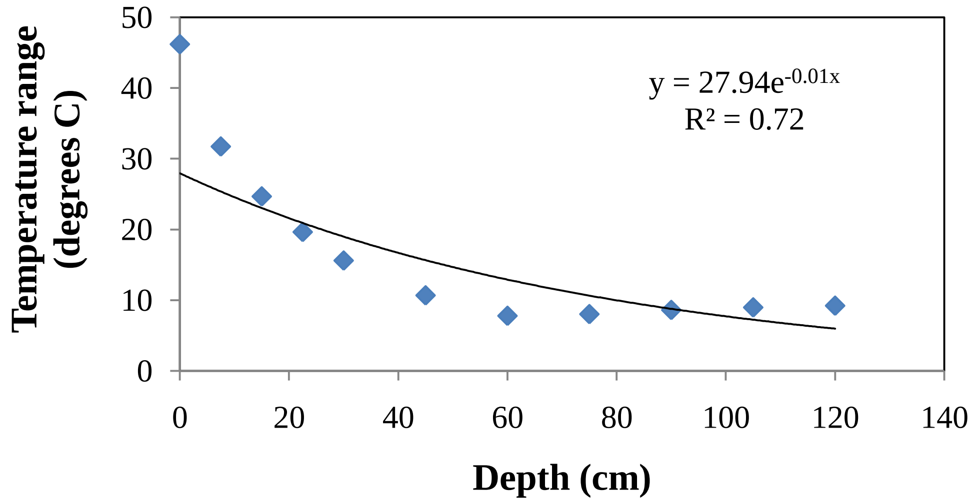

Figure 5: Summer temperature range (maximum – minimum) at Wright Valley.

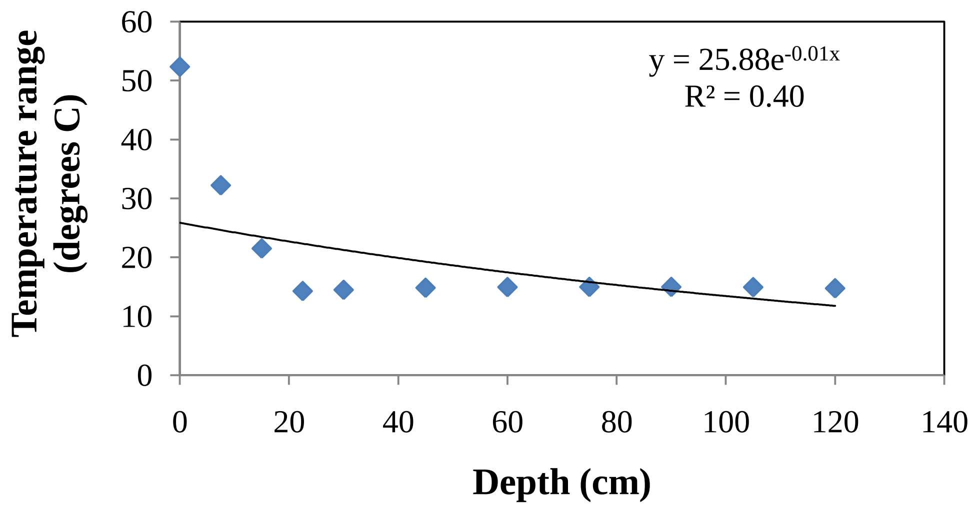

Figure 6: Summer temperature range (maximum – minimum) at Victoria Valley.

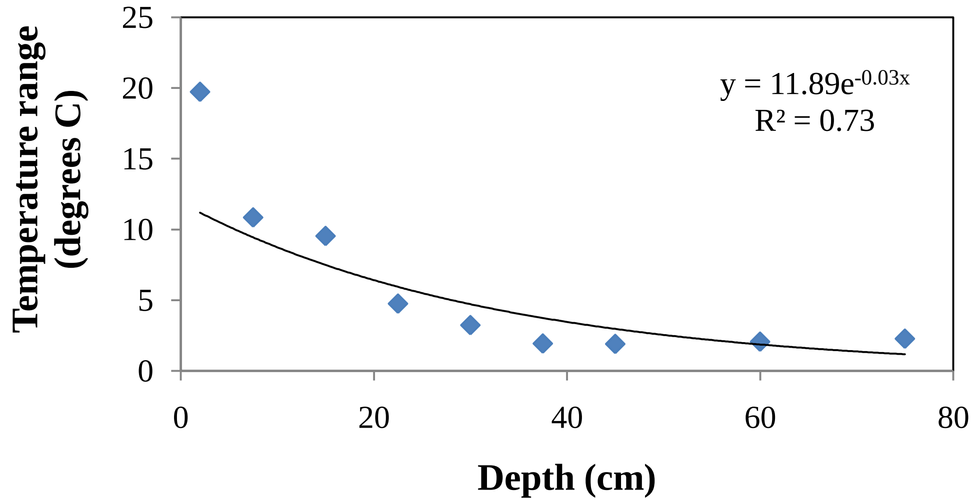

Figure 7: Summer temperature range (maximum – minimum) at Mt Fleming.

9. Winter soil temperature range (maximum – minimum) with depth

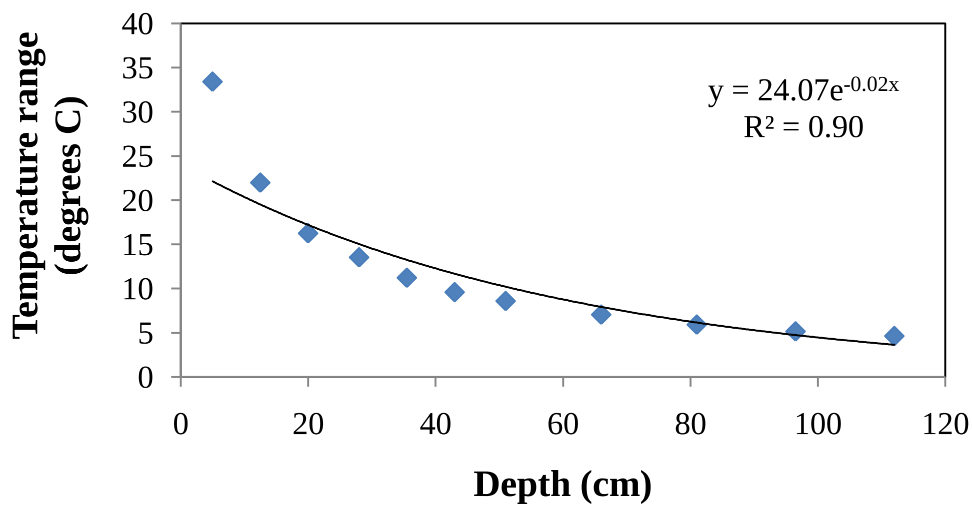

Figure 8: Winter temperature range (maximum – minimum) at Minna Bluff.

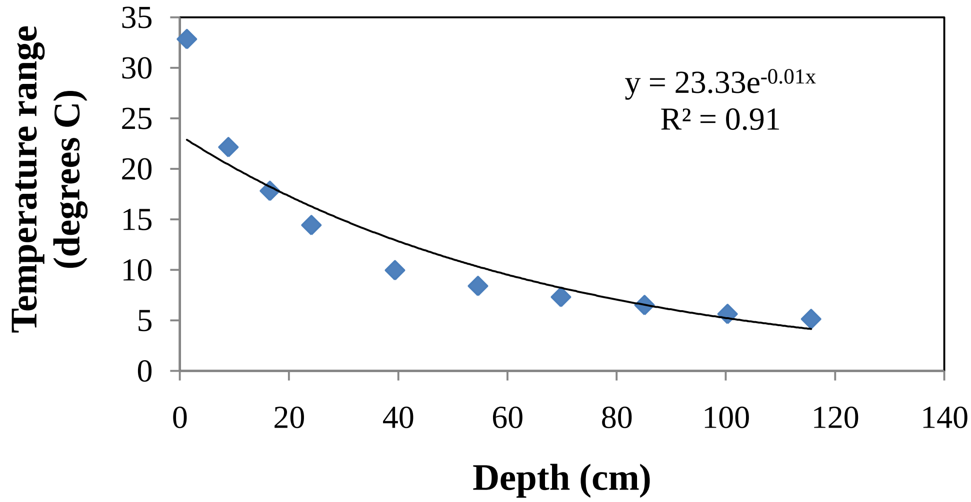

Figure 9: Winter temperature range (maximum – minimum) at Scott Base.

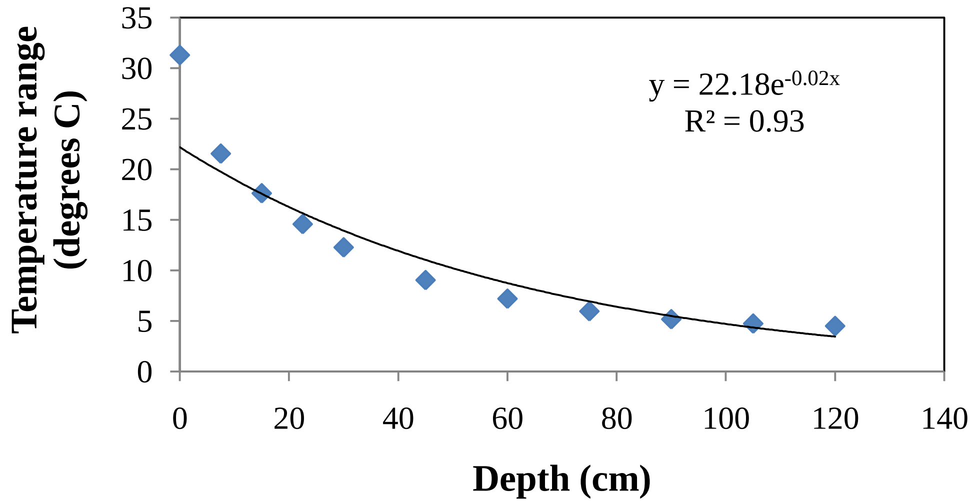

Figure 10: Winter temperature range (maximum – minimum) at Marble Point.

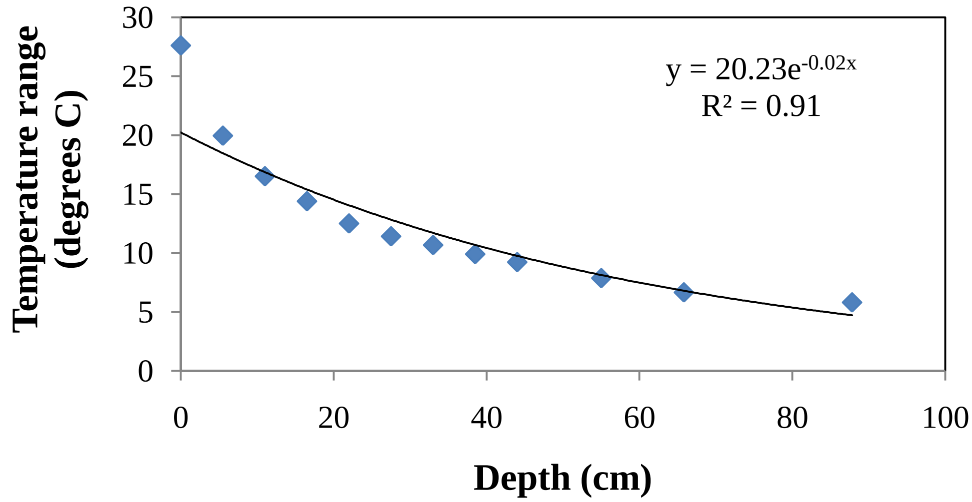

Figure 11: Winter temperature range (maximum – minimum) at Granite Harbour.

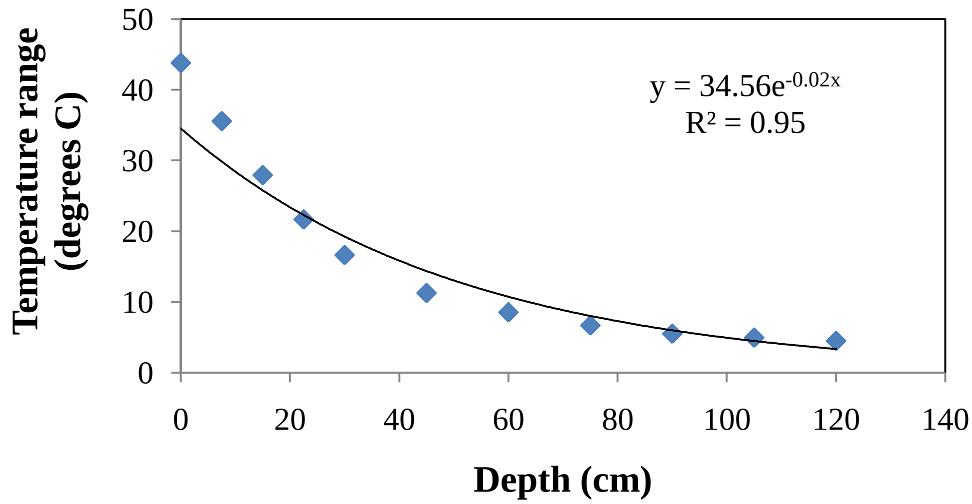

Figure 12: Winter temperature range (maximum – minimum) at Wright Valley.

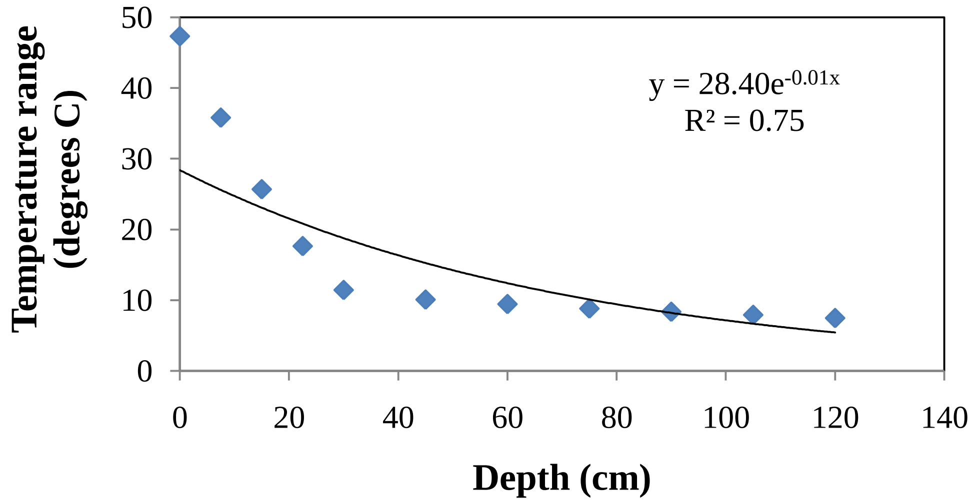

Figure 13: Winter temperature range (maximum – minimum) at Victoria Valley.

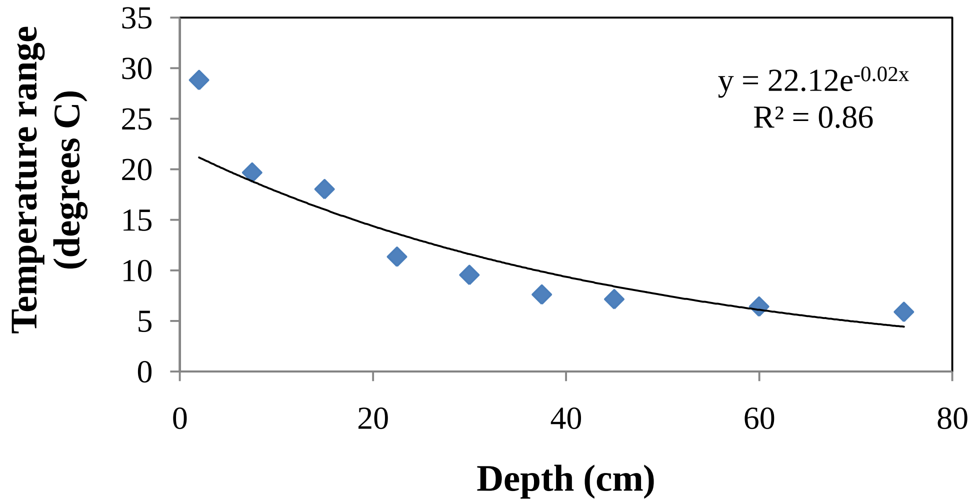

Figure 14: Winter temperature range (maximum – minimum) at Mt Fleming