The Effects of joint ENSO – Antarctic Oscillation Forcing on the McMurdo Dry Valleys, Antarctica

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Abstract

Stable oxygen analyses and snow accumulation rates from snow pits sampled in the McMurdo Dry Valleys have been used to reconstruct variations in summer temperature and moisture availability over the last four decades. The temperature data show a common interannual variability, with strong regional warmings occurring especially in 1984/1985, 1995/96 and 1990/91 and profound coolings during 1977/78, 1983/84, 1988/89, 1993/94, and 1996/97. Annual snow accumulation shows a larger variance between sites, but the early 1970's, 1984, 1997, and to a lesser degree 1990/91 are characterised overall by wetter conditions, while the early and late 1980's show low snow accumulation values. Comparison of the reconstructed and measured summer temperatures with the Southern Oscillation Index (SOI) and the Antarctic Oscillation (AAO) yield in statistically significant correlations, which improve when phase-relationships are considered. A distinct change in the phase relationship of the correlation is observed, with the SOI-AAO leading over the temperature records by 1 year before, and lagging by 1 year after 1988.

These results suggest that over the last two decades summer temperatures are influenced by opposing El Niño Southern Oscillation and AAO forcings and support previous studies that identified a change in the Tropical-Antarctic teleconnection between the 1980's and 1990's.

Introduction

The McMurdo Dry Valleys are an ecologically, glaciologically and climatically unique area in the Ross Sea region of Antarctica, and have been selected a study site for the Latitudinal Gradient Programme. Constituting the Taylor, Wright and Victoria Valleys (from south to north, Figure 1), the McMurdo Dry Valleys are the largest ice-free region on the white continent and hosts within one of the oldest landscapes on Earth (Sugden et al., 1995) an ecosystem that endures one of most extreme climate systems in Antarctica (Doran et al., 2002b). We present snow-pit data that demonstrate that this extreme climate, in particular summer temperature, is largely driven by an atmospheric teleconnection to a seemingly unlikely ocean-atmosphere dipole – the El Niño Southern Oscillation (ENSO) in the tropical Pacific and the Antarctic Oscillation.

Due to their proximity to McMurdo Station and Scott Base (Figure 1), the McMurdo Dry Valleys have been visited and studied relatively frequently in comparison to most other parts of East Antarctica since the Geophysical Year in 1957. However, only a few weather stations date from this time. Currently, data are available from Scott Base (1957-today), McMurdo Station (1957-today), Marble Point (1980-today), and a summer record from the former Vanda Station (1969-1991). Since 1980, the University of Wisconsin has maintained a growing network of automatic weather stations in Antarctica, and since 1993, the Long-Term Ecological Research (LTER) Programme has installed a number of weather stations within the McMurdo Dry Valleys, and incorporated earlier measurements, starting in 1986 at Lake Hoare in Taylor Valley (Doran et al., 2002b). In Victoria Valley, the first meteorological observations were made by LTER, commencing in 1996.

The combined data set shows, that the observed average annual temperature in the valleys ranged from –14˚C to –30˚C within less than 100km radius (Doran et al., 2002a). Overall, the valleys exhibit a south-north temperature gradient, with Taylor Valley being the warmest and Victoria Valley the coldest. Lake levels in the McMurdo Dry Valleys have been measured since the 1970's. Measurements from 1972/73 to 1980 indicate an overall increase of lake levels during this time period, which have been interpreted to reflect primarily warming of the McMurdo Dry Valleys (Chinn, 1981). In contrast, studies by Doran et al. (2002b) indicate an overall cooling of the McMurdo Dry Valleys since 1986. The trends vary with season, with a summer (December to February) cooling of -1.2K per decade and a stronger cooling during autumn (March to May) of -2.0K per decade. In addition, Doran et al. (2002b) observed a slight temperature increase of +0.6K and +0.1K per decade during winter (June to August) and spring (September to November), respectively, producing an annual trend of –0.7K per decade (Doran et al., 2002b). Furthermore, they report on a lake level decrease of Lake Hoare in Taylor Valley of ~0.60cm since 1986, following the lake level rise of ~0.60cm during 1972-1980 (Chinn, 1981). A longer-term warming has been reported in ocean temperatures. Jack and Budd (1998) compared sea-ice data from whaling records starting in the 1940s with satellite data available since 1973 and found that the sea ice edge retreated from 61°30"S to about 66°30"S in this time period. However, if only continuous data since 1973 are considered this trend is not significant.

The Antarctic Oscillation (AAO) (Thompson & Wallace, 2000) and the El Niño Southern Oscillation (ENSO) (Trenberth, 1997) are important drivers of Southern Hemispheric and Antarctic climate and oceanic variability on interannual to

decadal variability (Kwok & Comiso, 2002b; Kwok & Comiso, 2002a; Carleton, 2003; Ribera & Mann, 2003; Bertler et al., 2004a; Turner, 2004). Here we show new temperature and snow accumulation data that indicate that the combined forcing of AAO and ENSO are dominating summer temperatures in the McMurdo Dry Valleys.

Site and Sample Characterisation

Data from five snow pits are presented here (Table 1, Figure 1): Wilson Piedmont Glacier (WPG, ①), Victoria Lower Glacier I – ice divide (VLG_I, ②), Victoria Lower Glacier II - glacier tongue– (VLG_II, ③), Baldwin Valley Glacier (BVG, ④), and Polar Plateau (PP)near Shapeless Mountain (PP, ⑤). With the exception of the study site at the PP, all sites are situated on locally accumulating glaciers that are not part of the East Antarctic Ice Sheet. The sites vary in elevation and distance from the coast, ranging from 50 to 2400 m above sea level (asl) and 8 to 93 km, respectively. The snow profiles are between 0.8 and 4.2 m deep and provide a climate record for the last 8 to 41 years.

WPG is a low elevation site (50 m asl) and is situated only 7.5 km from the coast and is therefore expected to be particularly sensitive to precipitation from the seasonally open Ross Sea. The VLG I site is on an ice divide at 626 m asl which separates two ice masses, one moving into the valleys and another larger portion, feeding into WPG. VLG II is located on a glacier tongue descending into the valleys, while BVG is a small valley glacier feeding into Victoria Lower Glacier. The sampling location is at 1150 m asl and is surrounded by ice-free mountain peaks. Snow samples from PP, 20 km northwest of Shapeless Mountain at 2400 m asl, are studied to distinguish small-scale localised effects from regional climate pattern.

The snow samples were collected continuously down the snow pits with a 1cm resolution. The records were dated using seasonal signals in the aerosol concentration with a dating uncertainty of ±1year (Bertler et al., 2004b). Sodium and methylsulfonate were used to identify summer maxima. The annual layer count was independently verified for the VLG I record using gross beta radioactivity profiling from a nearby firn core, which detected the 1964/65 nuclear-testing fallout peak (Pourchet & Pinglot, 1979). This age benchmark lies within the dating uncertainty of the annual layer count when the younger part of core was matched with the high resolution snow pit data (Bertler et al., 2004b). Snow chemistry and isotopic ratios were measured on the same sample. Therefore, the age model developed for the chemistry record also applies for the isotope data. The oxygen isotope data for VLG I, measured at the Climate Change Institute, University of Maine, were analysed using a CO_2 dual-inlet system coupled to a Micromass Isoprime mass spectrometer with an accuracy of better than ±0.08‰. The oxygen isotope data for WLG, VLG II, BVG, and PP, measured at the Alfred Wegener Institute, were analysed using a MS Finnigan DeltaS with an accuracy of better than ±0.1‰. The main season for snow precipitation in McMurdo Sound is summer (Bromwich, 1988; Bertler et al., 2004a). The VLG I isotope record was therefore compared with summer temperature records from Scott Base and Lake Vida automatic weather stations and the dating fine tuned (Bertler et al., 2004a). Here, we apply the same strategy to WPG, VLG II, BVG and PP. The difference between annual layer count via snow chemistry did not exceed ±1year.

Temperature History of the McMurdo Region

The data show that WPG, VLG I & II, and BVG in Victoria Valley represent a common, regional climate history (Figure 2, Table 2). While PP experiences contemporary isotopic excursions to the sites in Victoria Valley, its isotopic range is subdued and overall isotopic values are more depleted. WPG shows the highest isotope values and largest range, which reflects its low-elevation, coastal location. Due to VLG II's proximity to the dry valleys, VLG II shows higher values and a larger range than VLG I. In general, BVG shows slightly more negative isotopic values than VLG and WPG but more enriched values than the high elevation and inland record from PP. Overall, the lower elevation sites closer to the coast show greater inter-annual isotopic variability than higher elevation sites, in particular PP.

The isotopic values were converted into temperature data via correlation with automatic weather station data. Since annual precipitation in the McMurdo Dry Valleys occurs predominantly during the summer (Bromwich, 1988), the isotope data were compared with the summer temperature records of December, January, February (DJF) from Scott Base and the LTER site Lake Vida. While Lake Vida is located in Victoria Valley, there is only a five years overlap with our isotope data. For this reason, we correlate the isotope records with the more distant Scott Base weather station data, which were also used to fine tune the age model of the snow pit data (Bertler et al., 2004a). The temperature values are calculated using the regression function

$T(°C) = 0.2239*\delta^{18}O − 0.6872$ (r=0.61, n=29, p<0.001, two-tailed student-t test) between annual Scott Base summer temperatures and annually re-sampled VLG I data. The calculated temperature data are then corrected for the difference in elevation to Scott Base with an atmospheric lapse rate of 0.6K/100m. The Scott Base weather station is located at 14m asl at 77.9°S and 166.7°E. The calculated isotope temperature records are shown in Figure 3 and summarised in Table 2.

In 1999 and 2000, a weather station was deployed at VLG I during the November and December months. A comparison between the VLG I weather station data and the concurrent LTER record from Lake Vida showed that averaged temperatures at VLG I were 4.7K and 4.6K colder during 1999 and 2000, respectively. Comparing the calculated VLG I isotope temperature record with the Lake Vida summer temperatures (overlap of five years), VLG I is on average 5.7K cooler, suggesting that our calibration of the calculated VLG I temperatures are in reasonable agreement with the weather station data. However, inter-annual variability between the two records is observed. It is important to note that the isotope temperature data records only temperature during snow precipitation and will therefore be biased to the frequency and timing of precipitation events, as well as specific climatic conditions during snow fall (eg. cloud cover).

Despite these differences, the temperature records inferred by isotopic ratios and weather stations exhibit a common interannual variability, with strong warmings occurring in 1984/1985, 1995/96 and 1990/91 and profound coolings during 1977/78, 1983/84, 1988/89, 1993/94, and 1996/97 (Figure 2 and 3). The comparison between the records shows that Scott Base and WPG exhibit the largest temperature variability, while Lake Vida (at 351 m asl) shows overall warmer temperatures despite its higher elevation. In comparison to the coastal and lower elevation sites, the temperature variability at VLG I and II and BVG are subdued. This could either reflect a true climate difference or diverse depositional environments and signal preservation characteristics. The strong correlation between the isotope records, e.g. VLG I and WPG (r=0.84, n=16, p<0.0001, two-tailed student-t test) and VLG I and

BVG (r=0.86, n=29, p<0.0001, two-tailed student-t test), suggests that the records represent a common, regional climate signal, and that the difference in temperature amplitude reflects a higher sensitivity of low elevation coastal sites, such as WPG. In view of the observed interannual variability contained in all records, the data series are too short to infer meaningful trends. As the polar plateau environment varies significantly from Scott Base and Victoria Valley (the correlation is not significant), the temperature transfer function was not applied to the PP data set.

Snow Precipitation in the McMurdo Dry Valleys

The McMurdo Dry Valleys are one of the driest deserts on Earth. Due to the proximity of the McMurdo Dry Valleys to the seasonally open Ross Sea, the valleys receive most of the precipitation during the short summer months (Bromwich, 1988). For this reason, fluctuations in precipitation has important implications for the McMurdo Dry Valleys ecosystem, as it changes the moisture availability in soils for micro organisms and plants, impacts on lake levels and their salinity, and eventually on the mass balance of the McMurdo Dry Valleys glaciers. Annual snow accumulation rates are calculated from density measurements (available for WPG, VLG I, and BVG) and annual snow layer thickness (Table 2, Figure 4). WLG shows the highest average annual accumulation of 5.2 cm water equivalent per year (cm weq/y) and the largest variability, ranging from 2.2 to 12.2 cm weq/y. VLG_I and BVG have an average of 3.7 and 3.2 cm weq/y, respectively and range from 1.3 to 8.2 cm weq/y and 0.9 to 9.3 cm weq/y, respectively.

Snow pit or ice core data provide only a minimum estimate for annual snow accumulation as they preserve net accumulation, which represents precipitated accumulation less sublimation and/or wind erosion. Therefore, particularly warm and/or windy years may result in underestimate of annual accumulation. While large interannual snow accumulation variability between the three sites is apparent (Figure 4), the early 1970's, 1984, 1997, and to a lesser degree 1990/91, are characterised by concurrent high snow accumulation, while the early and late 1980's show low snow accumulation values. As with the temperature records, the large interannual variability of the snow accumulation data does not allow us to infer meaningful trends.

The ENSO – AAO Climate Forcing in the McMurdo Region

A growing body of literature has identified strong teleconnections between ENSO and Antarctica. A comprehensive review is provided by Turner (2004). A commonly used index for ENSO is the Southern Oscillation Index (SOI), which represents the normalised difference in surface pressure between Darwin and Tahiti, with positive extremes representing La Niña and negative extremes indicating El Niño time periods (Parker, 1983). Applying Trenberth's definition of El Niño and La Niña events (Trenberth, 1997), Turner (2004) showed that since 1950 ENSO was in El Niño mode for ~31%, in La Niña mode for 23%, and in neutral mode for 56%.

In the McMurdo Region, Bertler et al. (2004a) used ERA-40 reanalysis and snow pit data from VLG I to show that the McMurdo Dry Valleys experienced frequently warmer temperatures during La Niña and cooler temperatures during El Niño events due to an ENSO driven change in the position of the Amundsen Sea Low, which is a semi-permanent low pressure system centred north of Marie Byrd Land in the Ross/Amundsen Seas. During La Niña periods, the Amundsen Sea Low is strengthened and situated north of the Ross Ice Shelf in the Ross Sea, enhancing

marine air mass intrusion into the McMurdo Dry Valleys region. During El Niño events, the Amundsen Sea Low is weakened and shifts eastwards up to 1400km towards Marie Byrd Land (Chen et al., 1996; Cullather et al., 1996). Bromwich et al. (1993) showed that the juxtaposition of the Amundsen Sea Low off Marie Byrd Land caused katabatic surges across the Ross Ice Shelf. These katabatic surges imported colder air masses from West Antarctica into the western Ross Sea and hence the McMurdo Dry Valleys, causing a regional cooling (Bertler et al., 2004a). Fogt and Bromwich (2006) showed that the ENSO – Antarctic teleconnection is strongest during the Southern Hemispheric spring (Sep-Nov) and summer (Dec-Feb), while autumn (Mar-May) and winter (Jul-Aug) show no significant correlation. Furthermore, they found that during the 1980's the ENSO connection was weaker during spring due to interferences of the AAO with the Pacific South American (PSA) pattern (Mo & Ghil, 1987). The PSA, a large blocking high pressure system, develops by upper level divergence initiated from tropical convection and is therefore tied to ENSO (Renwick & Revell, 1999). During the 1990's the spring ENSO teleconnection was amplified as the PSA and AAO were in phase (Fogt & Bromwich, 2006). In contrast, the summer months the AAO and PSA remained in phase in during both decades, maintaining a strong ENSO – Antarctic teleconnection (Fogt & Bromwich, 2006).

We compare the summer SOI (Dec-Jan SOI values) and the measured / reconstructed summer temperature records from the McMurdo Region (Figure 3). Positive temperature excursions frequently coincide with positive SOI values (La Niña), and cold summer temperatures in the McMurdo Dry Valleys with negative SOI data (El Niño). This relationship is captured in the ERA-40 reanalysis data and is robust for the 1990's but is only marginally significant during the 1980's (Bertler et al., 2004a). This suggests important additional forcing mechanisms driving the regional temperature variability.

The AAO is defined as the leading mode of Empirical Orthogonal Function analysis of monthly mean 700 hPa geopotential height anomalies during 1979-2000 period. It is a measure of the strength of the polar vortex and has a 4-5year frequency. Times of high AAO index indicate a strong circumpolar vortex in combination with low-amplitude Rossby waves in the polar front, with the opposite situation occurring during times of low AAO (Thompson & Wallace, 2000; van der Broeke & Van Lipzig, 2004). Kwok and Comiso (2002b) demonstrate that during times of high AAO index most of East Antarctica experiences a cooling while the Antarctic Peninsular experiences a warming. Thompson & Solomon (2002) found that tropospheric AAO is coupled to the stratosphere and suggest that the trend towards high AAO polarity over the last two decades is connected to stratospheric cooling caused by stratospheric ozone loss over the Antarctic. Van den Broeke and van Lipzig (2004) argued that the reason for the winter cooling over East Antarctic during high AAO index is caused by a greater thermal isolation of Antarctica due to decreased meridional flow and intensified temperature inversion on the ice sheet due to weaker near-surface winds. They demonstrate that a strengthening circumpolar vortex leads to a pronounced deepening of the Amundsen Sea Low and a 10m wind flow anomaly across West Antarctica descending the Ross Ice Shelf, with an associated cooling of the region. In a seasonal AAO regression slope of surface pressure and surface temperature, van den Broeke and van Lipzig (2004) find that all seasons show statistically significant cooling across large areas of East Antarctica in response to a strengthening AAO. However, the response is most pronounced during autumn and winter and weaker during spring and summer, which contrasts the ENSO teleconnection found by Fogt

and Bromwich (2006), which is strong during spring and summer, and not statistically significant during autumn and winter.

Patterson et al. (2005) employed deuterium excess data to trace the origin of precipitating air masses in the McMurdo Dry Valleys and concluded that that during El Niño events these air masses travel from Marie Byrd Land across West Antarctica and are therefore colder upon arrival in the McMurdo Dry Valleys. During La Niña years, they are derived from the Ross Sea and are therefore warmer (Patterson et al., 2005). As a result, we expect the McMurdo Dry Valleys to experience drier conditions during El Niño years than during La Niña. However, the ENSO influence on sea-ice and sea surface temperature in the Ross Sea are negatively correlated with warmer sea-surface temperatures and reduction of sea ice during El Niño events, and the opposite during La Niña events (Ledley & Huang, 1997; Kwok & Comiso, 2002b; Kwok & Comiso, 2002a; Yuan, 2004). In addition, there are many influences on sea-ice that are seemingly unrelated to ENSO, such as katabatic storms, which tend to break up sea-ice and maintain polynas. These will impact on moisture source availability and hence precipitation in the McMurdo Dry Valleys. In addition, Van den Broeke and van Lipzig (2004) found that during periods of high AAO index, western Marie Byrd Land and the Ross Ice Shelf experience a 30% decrease in precipitation. However, the McMurdo Dry Valleys region lies outside the area of 99% significance.

In summary, ENSO and AAO appear to have spatially and temporally varying influences on the McMurdo Dry Valleys temperature and precipitation. During times of positive SOI (La Niña), the McMurdo Dry Valleys frequently experience warmer conditions, while times of positive AAO (enhanced polar vortex) promote cooling and vice versa. Furthermore, the ENSO forcing is strongest during spring and summer, while the AAO forcing appears stronger during autumn and winter. Combined the two forcings have the potential to partially off-set or enhance their influence on the McMurdo Dry Valleys. Over the last two decades, a trend towards more negative SOI and positive AAO has been observed. In contrast, summer SOI and AAO indices are slightly positively correlated since 1979 (r=0.45, n=21, p=0.04, two-tailed student-t test), which should lead to opposing temperature forcing during summer. To assess the combined influence of SOI and AAO on the McMurdo Dry Valleys summers, we subtract from the standardised summer SOI the standardised summer AAO and compare their combined index (SOI_{DJF}-AAO_{DJF}) with the standardised Scott Base summer temperature and standardise VLG I isotope temperature over the common time period of 1979 to 1999 (Figure 5). The correlation between SOI_{DJF}-AAO_{DJF} and Scott Base summer temperatures results in a weak, but statistically significant, positive relationship of r=0.39 (n=20, p=0.09, two-tailed student-t test). In contrast, the comparison between the accumulation data and the SOI_{DJF}-AAO_{DJF} time series does not yield in a statistically significant correlation. While high accumulation years are all accompanied by SOI_{DJF}-AAO_{DJF} peaks, the low accumulation years are not accompanied by low SOI_{DJF}-AAO_{DJF} values (Figure 5). Within the limitation of our accumulation data, it appears that while SOI and AAO are influencing moisture variability, other drivers or postdepositional influences are of equal or greater importance.

At closer investigation, the poor correlation between SOI_{DJF}-AAO_{DJF} and the temperature records, is caused by a change in the phase relationship, with the SOI_{DJF}-AAO_{DJF} leading by one year before 1987 and lagging by one year after 1989 and zero-lag during 1988 (Figure 5).

When this lead/lag phase relationship is taken into consideration, a stronger correlation is obtained (Figure 5, dashed line). The correlation coefficient between the lead/lag-adjusted SOI_{DJF}-AAO_{DJF} and Scott Base summer temperature increases to r=0.64 (n=18, p=0.002, two-tailed student-t test) and VLG isotope temperature to r=0.59 (n=18, p=0.005, two-tailed student-t test), confirming that the ENSO and the AAO play a dominant role in the interannual variability of McMurdo Dry Valleys summer temperatures.

The data discussed here are not sufficient to determine whether the change in the phase relationship is part of a multidecadal oscillation or a change in the ENSO-AAO – McMurdo Dry Valleys summer temperature teleconnection. However, a variety of changes in the ENSO – Antarctic relationship between the 1980's and 1990's have been observed elsewhere. In Marie Byrd Land, the SOI–snow precipitation correlation changed from positive in the 1980's to negative in the 1990's (Bromwich et al., 2000). In addition, the positive SOI–ERA-40 reanalysis temperature correlation in the western Ross Sea during the 1980's is only marginally significant and increases strongly in the 1990's (Bertler et al., 2004a), while Fogt and Bromwich (2006) find a distinct contrast during the spring months between the SOI and high latitude teleconnection in the 1980's and the 1990's. Furthermore, it is important to determine whether the phase change is due to a change in the seasonality of the ENSO and/or AAO forcing, leading to an apparent +/- 1year phase difference. Intriguingly ENSO's influence on Antarctica is only statistically significant during summer and autumn (Fogt & Bromwich, 2006), while AAO's influence is strongest during spring and winter (van den Broeke & Van Lipzig, 2004).

Our results highlight the need for more longer, well dated, high resolution proxy data from the Antarctic continent and their integration with paleoclimate models. Multidisciplinary efforts such as the Latitudinal Gradient Programme are well suited to encourage cross-collaboration that will help improve our understanding of the dynamic Antarctic – Tropical Dipole.

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Figures and Tables

Table 1: Overview of the snow pit characteristics. WPG = Wilson Piedmont Glacier, VLG = Victoria Lower Glacier (accumulation zone), VLG II = Victoria Lower Glacier (glacier tongue), BVG = Baldwin Valley Glacier, PP = Polar Plateau (near Shapeless Mountain)

Site	Location Lat/long	Elevation (m)	Distance to coast (km)	Pit depth (m)	Record Length
WPG*	S 77°16.000' E 163°15.000'	50	7.5	2.80	15yr 1984-1999
VLG#	S 77°19.810' E 162°31.991'	624	22.5	4.10	27yr 1971-1998
VLG II*	S 77°20.8185' E 162°29.5367'	550	27.5	0.80	8yr 1991-1999
BVG*	S 77°19.836' E 162°32.019'	1100	30.0	4.20	41yr 1958-1999
PP*	S 77°21.092' E 159°52.226'	2400	92.5	1.80	16yr 1985-2001

\# measured at Climate Change Institute, University of Maine, USA
* measured at Alfred Wegener Institute, Germany

Table 2: Overview of the calculated average, maximum, and minimum summer isotope temperatures, isotope values, and annual snow accumulation. Values have been calculated over the available length of each record.

Site	$\delta^{18}O$ (‰) Average / Max / Min	$T_{\delta18O}$ (°C) Average / Max / Min	Snow Accumulation (cm water equivalent / y) Average / Max / Min
WPG	-23.9 / -15.0 / -32.0	-6.3 / -4.3 / -8.1	5.2 / 12.2 / 2.2
VLG	-27.7 / -20.9 / -33.7	-10.6 / -9.1 / -11.9	3.7 / 8.2 / 1.3
VLG II	-27.5 / -21.5 / -32.2	-10.1 / -8.7 / -11.1	-
BVG	-28.8 / -15.1 / -37.3	-13.7 / -12.6 / -15.5	3.2 / 9.3 / 0.9
PP	-34.9 / -32.3 / -41.7	**-**	-

Figures
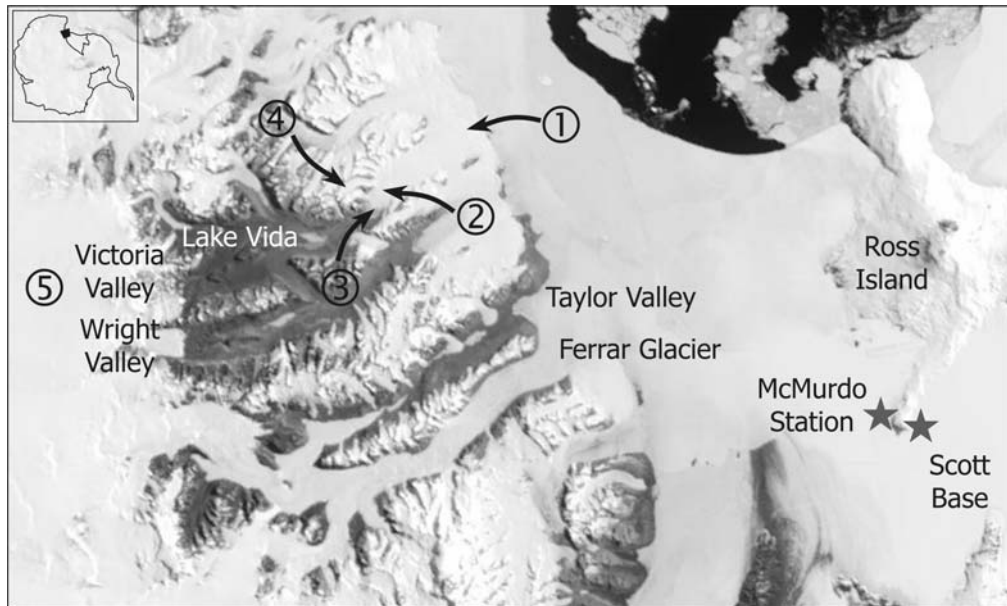
Figure 1: Location of the study sites: Wilson Piedmont Glacier (WPG, ①), Victoria Lower Glacier – ice divide (VLG_I, ②), Victoria Lower Glacier II - glacier tongue– (VLG_II, ③), Baldwin Valley Glacier (BVG, ④), and Polar Plateau near Shapeless Mountain (PP, ⑤).
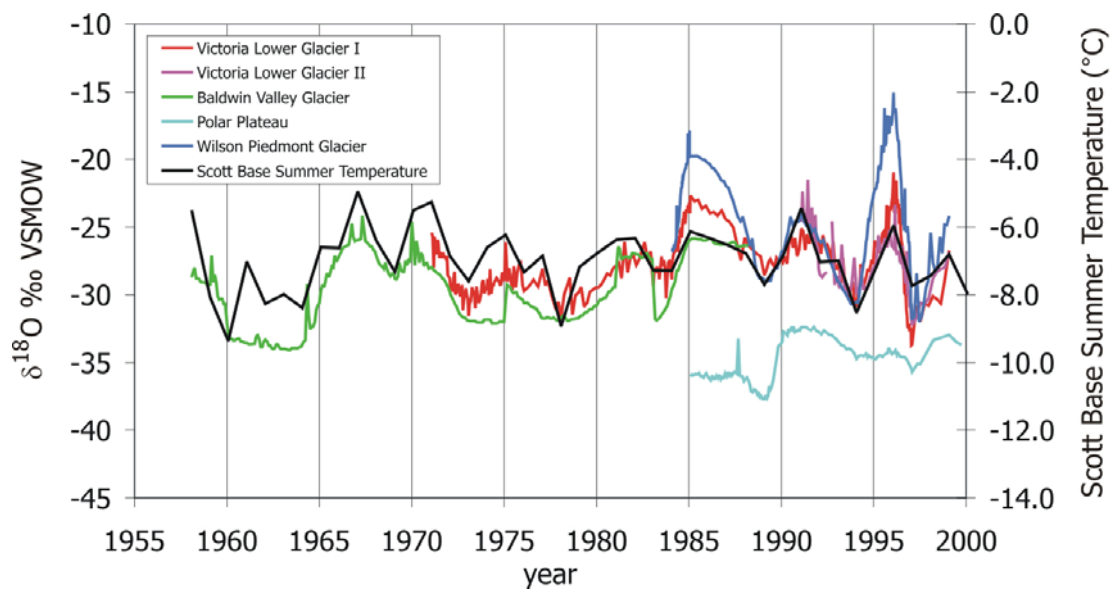
Figure 2: Isotope records from four snow pits (WPG, VLG_I, VLG_II, BVG, and PP) compared with Scott Base summer temperature automatic weather station data.
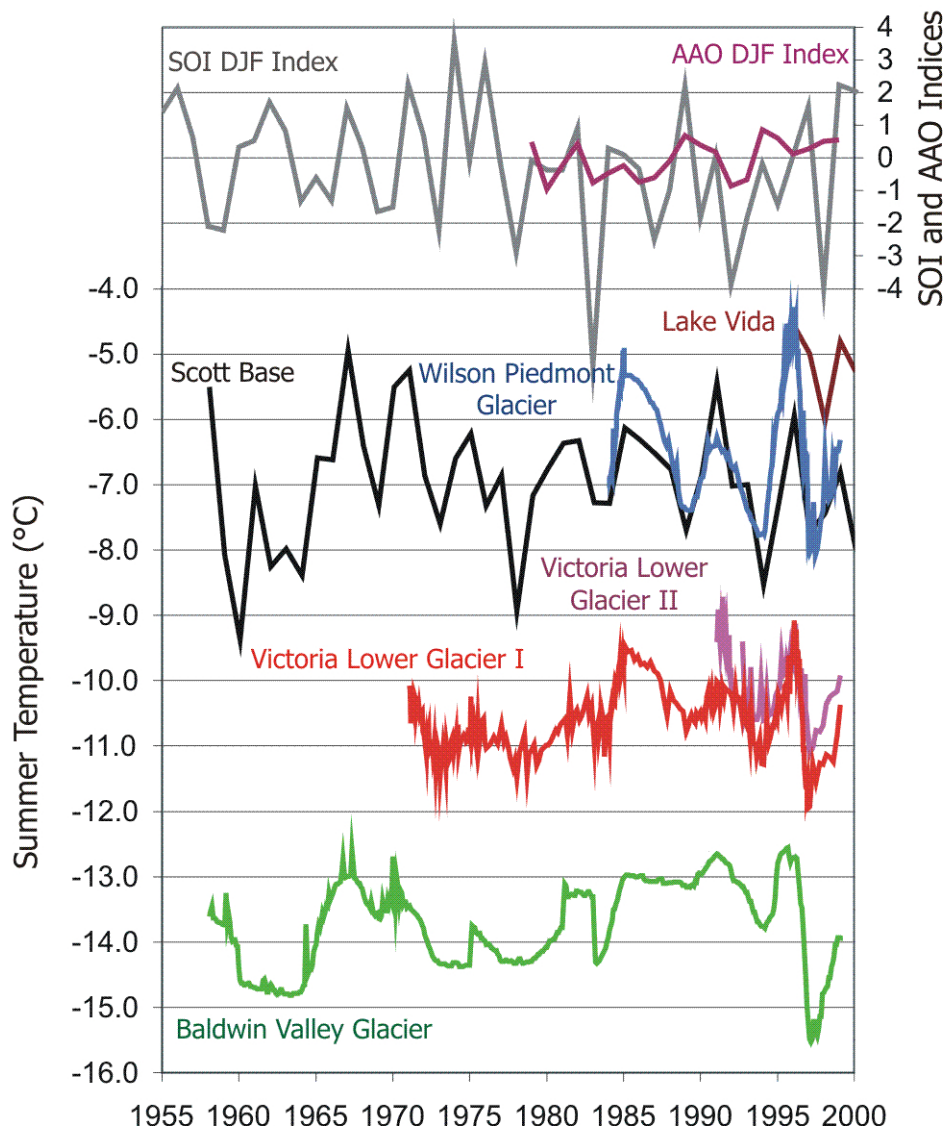
Figure 3: Calculated temperature records from WPG, VLG I and II, and BVG compared with Scott Base summer temperature and the summer (Dec-Feb) indices of SOI and AAO
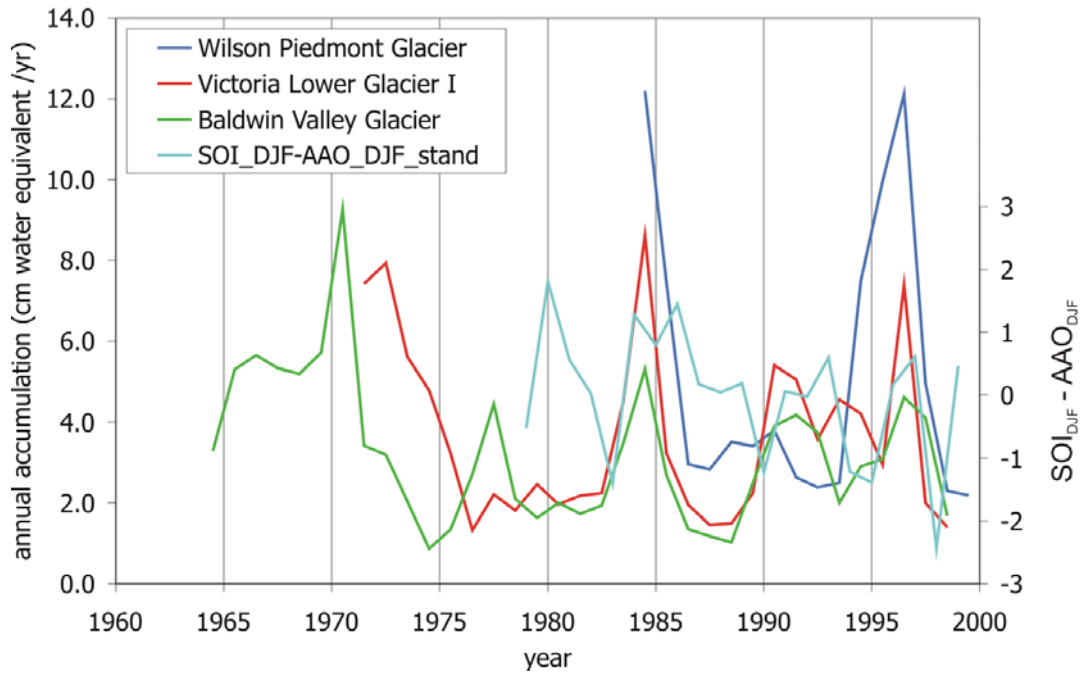
Figure 4: Annual snow accumulation data from WPG, VLG I, and BVG compared with the SOI_{DJF}-AAO_{DJF} index.
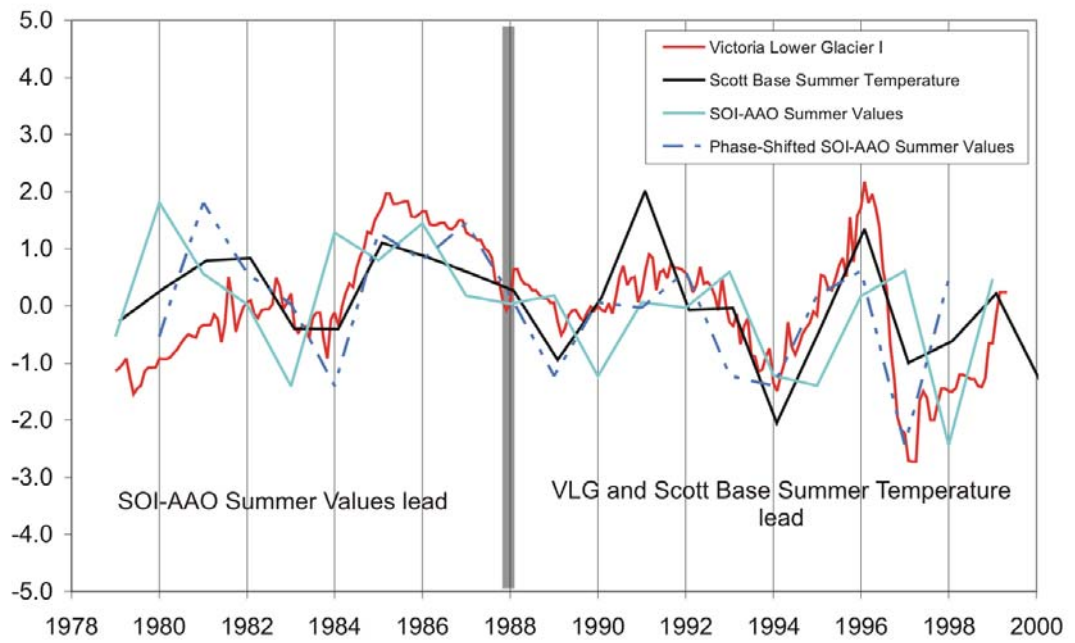
Figure 5: Comparison between standardised VLG I isotope data, Scott Base summer temperature, SOI_{DJF}-AAO_{DJF} index and phase-shifted SOI_{DJF}-AAO_{DJF} index.