Creating a Composite Temperature Series for Dunedin

December 2010

Figure 1: Looking southwest towards the Musselburgh climate station (agent number 15752) in 1997.

NIWA has previously analysed temperature trends from data at seven locations which are geographically representative of the country: Auckland, Wellington, Masterton, Nelson, Hokitika, Lincoln (near Christchurch) and Dunedin (see http://www.niwa.co.nz/our-science/climate/nz-temp-record/review/changes/seven-stations-series). The calculation of climate trends ideally requires very long records of temperature measured with comparable instruments at the same site unaffected by changes in the local environment. Since such undisturbed and very long records do not exist in New Zealand, it is necessary to combine records from different nearby sites, and adjust for the effect of any changes unrelated to the broad-scale climate, such as site moves or instrument changes.

In February 2010, NIWA documented the adjustments in use at that time (see web link above). These adjustments to the multiple sites comprising the 'seven-station' series were calculated by Salinger *et al.* (1992), using the methodology of Rhoades and Salinger (1993), which extended the early work on New Zealand temperatures by Salinger (1981). Subsequent to 1992, the time series have been updated regularly, taking account of further site changes as circumstances required.

The present document revisits and describes in greater detail the process by which a composite temperature series has been developed for Dunedin. The primary purpose is to demonstrate in an intuitive way how to estimate adjustments to temperature series when combining data from different sites, or when there are changes in exposure or instrumentation at a given site. The focus in this document is on annual mean temperature[1]. The data from different sites should not simply be appended without adjustment, since significant biases can be introduced when measurement sites are moved.

[1] Mean temperature is defined as the average of the daily-maximum and daily-minimum temperature. Further research will determine adjustments to monthly temperatures, including maximum and minimum temperatures separately, and apply statistical methods (e.g., RHtest, Wang et al., 2007) to identify other change-points in the data.

Table 1: Information about Dunedin climate observations:
(Column 1) the site label used in the text;
(Column 2) the site name, and (in parentheses) the 'agent number' used by the NIWA Climate Database (CliDB) to identify the station;
(Column 3) additional remarks about the site location, and (in parentheses) the full period of available temperature record;
(Column 4) altitude of site in metres above sea level;
(Column 5) previous (as of February 2010) period for which the site contributed to the composite time series used by NIWA;
(Column 6) previous temperature adjustment, taken from the February 2010 'Schedule of Adjustments' in 'The NIWA "Seven-Station" Temperature Series';
(Column 7) new period for which the site contributes to the composite time series; and
(Column 8) revised temperature adjustment to be applied (with respect to Musselburgh EWS, Site 6), as discussed in the text.

Site Label	Site Name (Agent Number)	Location (Full Period of Record)	Height (m a.s.l.)	Previous Period	Prev. Temp. Adjust. (°C)	Revised Period	Revised Temp Adjust.[2] (°C)
Site 1	Leith Valley (5380)	Northeast facing slope of Leith Valley, Dunedin. (May 1886 to Jan 1913)	108	May 1886 to Jan 1913	+0.3	Jan 1900 to Dec 1912[3]	+0.25
Site 2	Botanical Gardens (5375)	Near curator's house in Botanical Gardens, Dunedin. (Jan 1913 to Nov 1942)	73	Feb 1913 to Sep 1940	−0.1	Jan 1913 to Nov 1942	−0.14
				Oct 1940 to Nov 1942	+0.6		
Site 3	Beta Street (5379)	Water reservoir, Belleknowes, Dunedin (Sep 1940 to Dec 1947)	210	Dec 1942 to May 1947	+0.6	Dec 1942 to May 1947	+0.59
Site 4	Musselburgh (5402)	South of Musselburgh Pumping Station, Dunedin (Jan 1947 to Oct 1960)	2	Jun 1947 to Oct 1960	−0.2	Jun 1947 to Oct 1960	−0.14
Site 5	Musselburgh (5402)	Northwest of Musselburgh Pumping Station, Dunedin (Oct 1960 to Aug 1997)	4	Nov 1960 to Aug 1997	0.0	Nov 1960 to Aug 1997	−0.07
Site 6	Musselburgh EWS[4] (15752)	Musselburgh, same enclosure as Site 5, automated (Sep 1997 to present)	4	Sep 1997 to present	0	Sep 1997 to present	**0.00**

[2] Air temperatures are recorded to the nearest 0.1 °C in CliDB, but each revised adjustment used in the composite temperature record has been calculated to two decimal places, in order to minimise the accumulation of round-off errors. This should not however be interpreted as an indication of the accuracy of the adjustment.
[3] There is lower confidence in the adjustment applied to the data prior to 1913.
[4] EWS stands for "Electronic Weather Station". In the NIWA Climate Database, the acronym AWS (Automatic Weather Station) is also used when referring to automated measurement sites. AWS refers to a MetService site, and EWS to a NIWA site. The data loggers are quite different in the two networks, and the sensors are often different also.

Calculation of Adjustments

Table 1 summarises the information about the local sites used to develop the composite temperature series for the Dunedin location. A comparison is provided between the adjustments in use as at February 2010 (labelled 'Previous Temperature Adjustment'), and the new ones derived in this document (labelled 'Revised Temperature Adjustment'). The previous adjustments were calculated to one decimal place, whereas the revised adjustments are specified to two decimal places. Table 1 lists six different sites[5] as contributing to the composite Dunedin temperature series. Thus, there are five change-points, and the temperature records must be closely examined before and after the change-dates, in order to identify potential biases.

In the process of documenting the revised adjustments for all the 'seven-station' series, it was recognised that there was lower confidence in New Zealand's early temperature measurements, and there were fewer comparison sites from which to derive adjustments for non-overlapping temperature series. Thus, a decision has been made not to include temperatures prior to 1900. Furthermore, if there were site changes around 1910 for which an adjustment could not be estimated accurately, then the time series was truncated at that point. In the case of Dunedin, there was a site change (Site 1 to Site 2) in 1913. The adjustment required to account for this site change has been calculated by comparison with other climate stations (below) and is included in Table 1, but the value is uncertain because many of the comparison stations underwent changes at about the same time. So the revised Dunedin series derived here begins in 1900, but should be used with caution prior to 1913. When calculating century-scale trends, there is actually little difference between the 1909-2009 trend and the 1913-2009 trend (see last section of main text).

It is common practice to adjust all the historical measurements to be consistent with the current open site, which is then called the "reference site" (Aguilar *et al.*, 2003). This practice is followed for Dunedin, where the reference site is Musselburgh EWS (Figure 1), labelled Site 6 in Table 1. Figure 2 provides a map locating the Dunedin sites of Table 1, and also the more distant comparison sites discussed in the subsequent text.

The sites contributing to the Dunedin series generally have complete data during the relevant periods, with a few minor exceptions. The handling of suspect and missing data is described in Appendix 1.

Adjustment for Site Change in 1997

We will work backwards in time from the current open site: Musselburgh EWS (Site 6). This station is located in a grassed area, 35 m northwest of the Musselburgh Pumping Station, Dunedin. The pumping station is in a long-established, flat suburban area and is 800 m from the south coast of Otago Peninsula (Figure 1 and Figure 2)[6]. Musselburgh EWS opened in August 1997. The site contributes temperatures to the Dunedin composite temperature series from September 1997.

[5] One of the nominal 'site changes' is actually an instrument change (manual to automatic) at the same physical site and one is a small shift in the location of the instrument enclosure.

[6] For further information on the situation of the Dunedin stations, see Brown (2006).

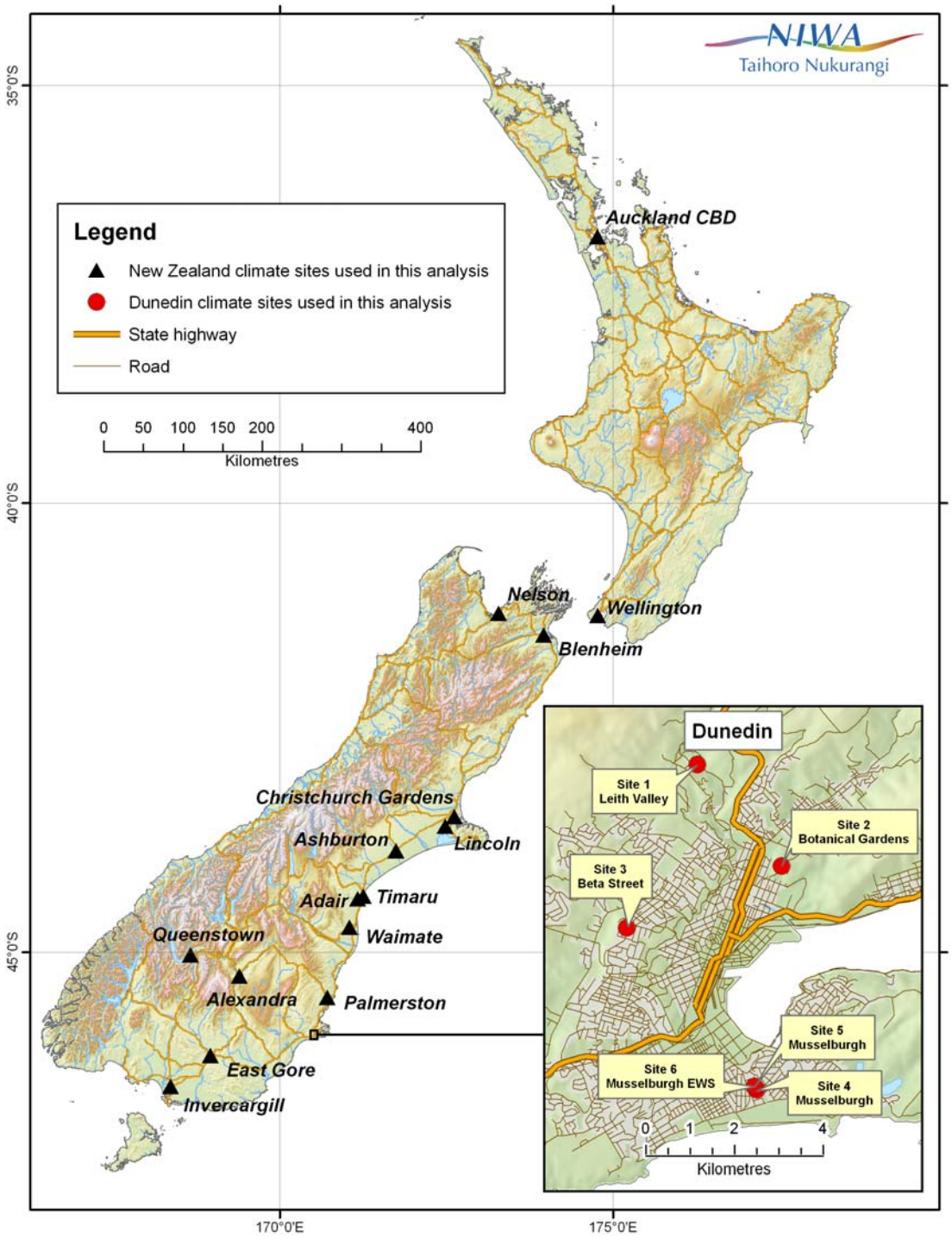

Figure 2: Map showing sites of temperature records referred to in this document. The inset map locates the Dunedin sites.

For the period November 1960 to August 1997, the Dunedin composite temperatures are provided by the Musselburgh station (Site 5), a manual station located in the same enclosure as the current Musselburgh EWS. The manual station closed in early September 1997 at about the time the EWS opened.

There being no overlap between these two stations, it is necessary to estimate the effect of the change by comparing temperatures before and after the change with measurements at other climate stations. The comparison stations used in developing

the previous composite temperature series were not documented by Salinger (1981), so for the present work they have been selected independently. Comparison stations were chosen subjectively, based on a number of factors:

- availability of annual temperature data for a reasonable period—preferably 10 years—before and after the change;
- absence of any indication of a site change or instrumentation change at the comparison station;
- proximity, geographic similarity and climatic similarity to the candidate stations (i.e., the two stations between which the change is to be estimated);
- a high correlation between temperatures at the comparison station and temperatures at the candidate stations.

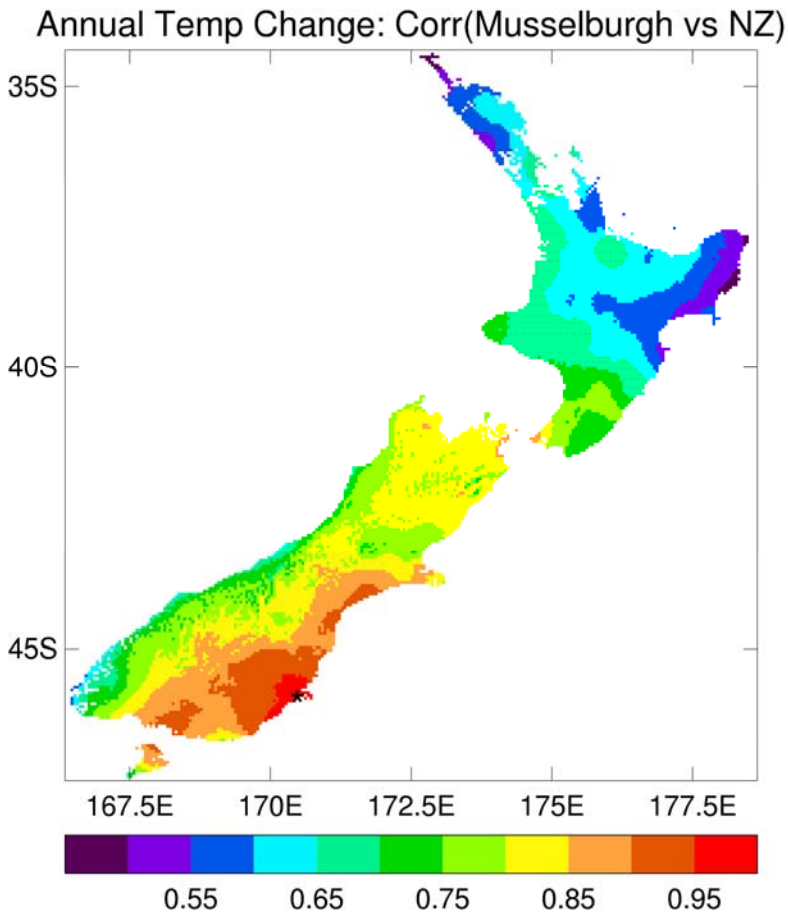

Figure 3: Map of correlation between interannual temperature changes at the Musselburgh EWS grid-point (Site 6, location marked by asterisk) near Dunedin, 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

As background information for the selection of comparison stations, Figure 3 shows the correlation of mean temperature interannual differences at the Virtual Climate Station (VCS) grid cell containing Musselburgh EWS (Site 6) with interannual differences at all other locations on the VCS grid from 1972 until 2008 (i.e., 1972-73

difference, 1973-74, … , 2007-08)[7]. This map gives a good indication of the locations at which temperatures are likely to be highly correlated with the sites comprising the Dunedin composite series.

Not surprisingly, interannual temperature variations at Dunedin correlate highly with those in the Otago region as a whole, the correlation coefficient typically being over +0.90. Temperature variations in Dunedin also correlate well with those in Southland and south Canterbury (typically >+0.85), and also with north Canterbury, Marlborough, Nelson and Wellington regions (typically >+0.80), so if necessary, stations in these more distant regions can be used.

For the 1997 site change, the comparison stations chosen were Invercargill Aero (5814)[8], Palmerston (5323), Timaru 2 (5095) and Ashburton Council (4778). The comparison period was 1987–2007 (10 years before and after the instrumentation change, not including the change year). The closeness of the match between each comparison station and the candidate stations contributing to the composite series was quantified using the correlation coefficient of the first-difference series of annual temperatures over the comparison period, excluding any differences affected by the change (Aguilar *et al.*, 2003). For the four comparison stations used here, the correlations were 0.86, 0.89, 0.82 and 0.82, respectively.

Figure 4 shows annual temperatures at Musselburgh during the comparison period along with annual temperatures at Invercargill Aero, Palmerston, Timaru 2 and Ashburton Council. The temperature change is estimated relative to each comparison station in turn. Before the instrumentation change in 1997, Musselburgh (Site 5) was on average 1.19 °C warmer than Invercargill Aero. After the instrumentation change, Musselburgh EWS (Site 6) was on average 1.03 °C warmer than Invercargill Aero. Therefore, the comparison with Invercargill Aero results in the estimate that Musselburgh EWS (Site 6) was 0.16 °C cooler than Musselburgh (Site 5).

A similar procedure was followed for the other three comparison sites. The comparison with Palmerston results in the estimate that Musselburgh EWS (Site 6) was 0.05 °C warmer than Musselburgh (Site 5). The comparison with Timaru results in the estimate that Musselburgh (Site 5) was neither warmer nor cooler than Musselburgh EWS (Site 6). Finally, the comparison with Ashburton Council results in the estimate that Musselburgh EWS (Site 6) was 0.18 °C cooler than Musselburgh (Site 5).

Averaging the four differences[9] (−0.16 °C, 0.05 °C, 0.00 °C and −0.18 °C), we estimate that Musselburgh EWS after the instrumentation change was 0.07 °C cooler

[7] Over the past few years, NIWA research scientists have developed gridded data sets of daily climate parameters, on a 0.05° latitude by 0.05° longitude grid covering the whole country (a total of approximately 11,500 grid-points). The "Virtual Climate Station" (VCS) data set for daily maximum and minimum temperatures begins on 1 January 1972, and interpolates data from between 150 and 200 climate stations using a sophisticated interpolation technique developed at the Australian National University in Canberra (Tait 2008).

[8] A number in parentheses after a climate station name indicates the CliDB agent number.

[9] The offsets from each of the comparison stations could be combined in some way other than a simple average. For example it is common to weight the contribution from each comparison station by its first-difference correlation coefficient (Aguilar *et al.*, 2003). In this case, the comparison stations have similar correlation coefficients, so a weighted average would not be significantly different from a simple average.

than Musselburgh before the instrumentation change. The final adjustment of temperatures at Musselburgh (Site 5) to make them homogeneous with the Musselburgh EWS (Site 6) is −0.07 °C. This is slightly different from the adjustment of 0.0 °C applied to this station in the previous series.

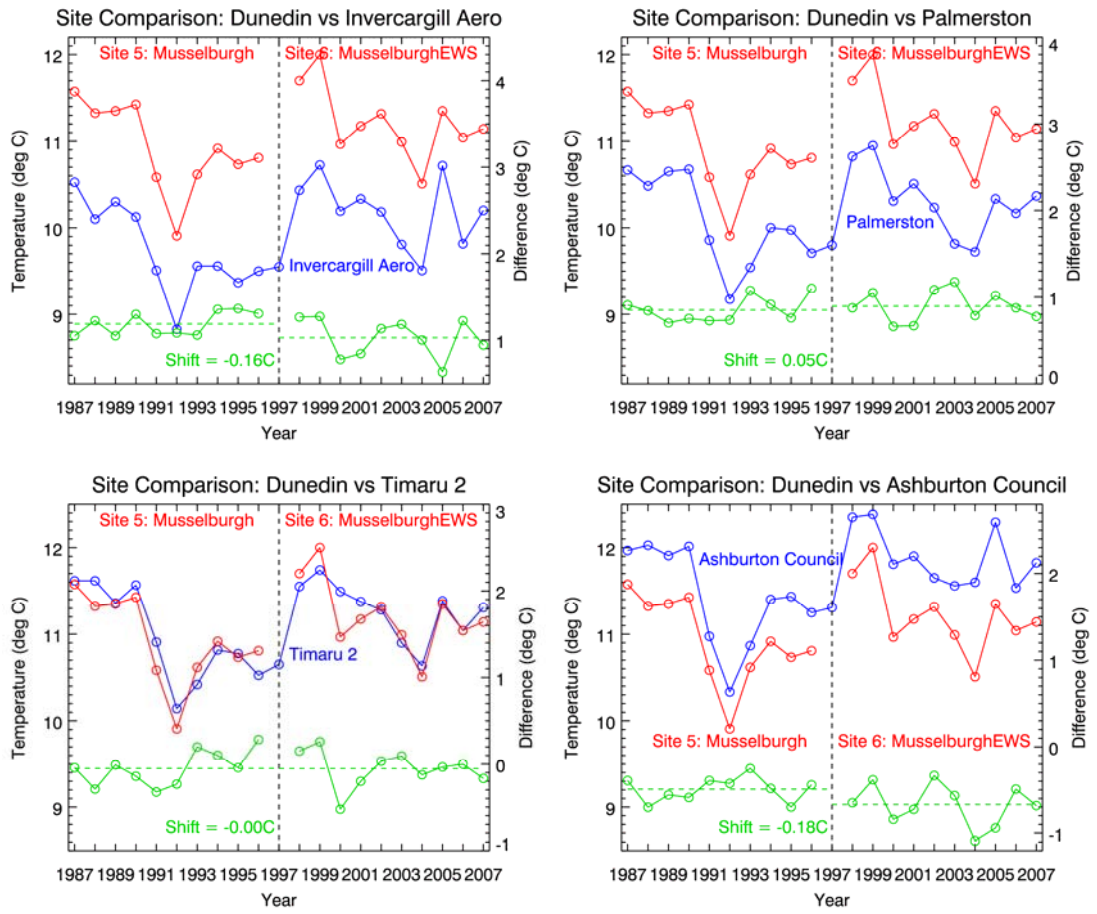

Figure 4: Annual mean temperature series at Musselburgh (Site 5, red line on the left of each plot) and Musselburgh EWS (Site 6, red line on the right of each plot) compared with several stations: Invercargill Aero, Palmerston, Timaru 2, and Ashburton Council. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Site 5/6 minus comparison station) using the right-hand ordinate scale. The year of the site change, 1997, is indicated by a vertical dashed line. The mean differences for the periods before and after the site change are indicated by dashed green lines.

Adjustment for Site Change in 1960

In October 1960, the climate station enclosure at the Musselburgh site was moved from south of the pumping station (Site 4) to northwest of the pumping station (Site 5). There is no overlap period for these two sites, but we can estimate the change in temperature by comparison with other sites. The comparison period was 1950–1970, excluding the change year, and the comparison stations were Invercargill Aero (5814), Waimate (5102), Adair (5088) and Wellington Kelburn (3385). Wellington is some 600 km from Dunedin, but its climatic similarity is indicated by a high correlation between Wellington and Dunedin annual temperatures (e.g., for the gridded dataset shown in Figure 3, the correlation coefficient is +0.89). For the 1960

site-change comparisons, the first-difference correlation coefficients were 0.91, 0.90, 0.85 and 0.83, respectively. Figure 5 presents the four comparisons.

By comparison with Invercargill Aero, the Musselburgh northwest site (Site 5) was 0.06 °C cooler than the Musselburgh south site (Site 4). By comparison with Waimate, Musselburgh northwest was 0.07 °C cooler than Musselburgh south. By comparison with Adair, Musselburgh northwest was 0.06 °C cooler than Musselburgh south. Finally, by comparison with Wellington, Kelburn, Musselburgh northwest was 0.09 °C cooler than Musselburgh south.

Averaging the four differences (−0.06 °C, −0.07 °C, −0.06 °C and −0.09 °C), we estimate that Musselburgh northwest (Site 5) was 0.07 °C cooler than Musselburgh south (Site 4). The previous series had a larger cooling of 0.2 °C (to one decimal place) associated with this change, however the smaller revised value is more in line with expectations for a small change in instrument location. The final adjustment required to make observations at Musselburgh south (Site 4) consistent with those at Musselburgh EWS (Site 6) is − 0.07 − 0.07 = −0.14 °C.

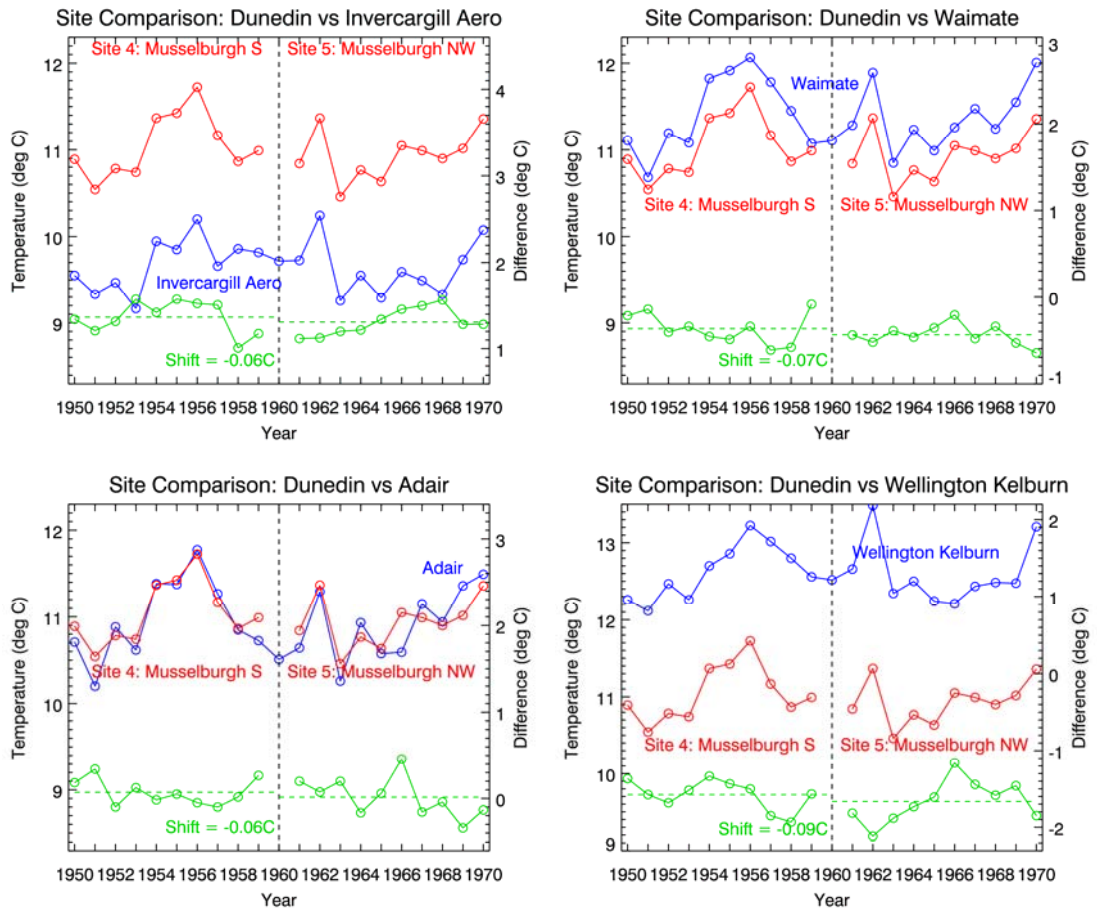

Figure 5: Annual-mean temperature series at Musselburgh south (Site 4, red line on the left of each plot) and Musselburgh northwest (Site 5, red line on the right of each plot) compared with Invercargill Aero, Waimate, Adair and Wellington Kelburn. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Site 4/5 minus comparison station) using the right-hand ordinate scale. The year of the site change, 1960, is indicated by a vertical dashed line. The mean differences for the periods before and after the site change are indicated by dashed green lines.

Adjustment for Site Changes in 1942 and 1947

From December 1942 to November 1947, the composite Dunedin temperatures are provided by the Dunedin Beta Street station (Site 3). The relatively short record from this station fills the gap between the longer records at Dunedin Botanical Gardens (Site 2), which operated from January 1913 to November 1942, and Musselburgh (Sites 4–6). The Beta Street site was at a higher elevation (210 m) than either Botanical Gardens (73 m) or Musselburgh (2–4 m) and, as we shall see, some 0.7-0.8 °C cooler than either.

There is some confusion regarding the source of the data for the previous Dunedin composite series during the period of overlap between Botanical Gardens and Beta Street, i.e., from October 1940 to November 1942. According to the "Schedule of Adjustments", Beta Street data were used during this period with an adjustment of +1.3 °C, and then from December 1942 with an adjustment of +0.6 °C. However there is no indication in the station metadata, or the data themselves, that could justify such a large change in the adjustment. A re-examination of the data suggests that the Botanical Gardens temperatures were used during this period, but adjusted by +0.6 °C as if they were from Beta Street. Whatever the correct explanation, there has clearly been an error in preparing the previous composite series, resulting in the values being approximately 0.6 °C too high in 1941 and 1942.

The re-examination of the data also uncovered an error in the previous time series in the 1947 annual mean, which is approximately 0.6 °C too low.[10]

The adjustments for the site changes in 1942 and 1947 are estimated below by comparison with other stations. With Beta Street being substantially cooler than either Botanical Gardens or Musselburgh, and being occupied for a short time, the main concern in setting these adjustments is to minimise the error introduced into the offset between the longer records at Botanical Gardens and Musselburgh. This was achieved, first, by using all six complete years (1941–1946) available at Beta Street. Thus the comparisons for the 1942 change are based on 1931–1940 data from Botanical Gardens and 1941–1946 data from Beta Street, and the comparisons for the 1947 change are based on 1941–1946 data from Beta Street and 1948–1957 data from Musselburgh. Second, the same comparison stations were used in both comparisons, so that exactly the same data appear in the "after" part of the first comparison as in the "before" part of the second.

The comparison stations were chosen according to the usual considerations of homogeneity and similarity to the candidate stations, with the additional requirement that the same stations be suitable for both comparisons. The stations selected were East Gore (5759), Alexandra (5576) and Wellington Kelburn (3385). For the 1947 site-change comparison, the first-difference correlation coefficients for the three comparison stations were 0.85, 0.85 and 0.84, respectively; for the 1942 site-change comparison they were 0.93, 0.85 and 0.95.

A larger set of comparison stations was also considered, comprising the three above plus Queenstown (5446), Christchurch Gardens (4858) and Blenheim (4331). The

[10] The origin of the incorrect value in 1947 is unknown, however it may have involved duplication of the 1946 value, which is the same to two decimal places at 10.18 °C.

latter stations were apparently homogeneous over the period spanned by both comparisons, but had lower correlation coefficients and larger scatter in the "before" and "after" temperature differences. The results from comparisons with the larger set of stations will be mentioned briefly for an indication of the sensitivity of the shifts to station selection.

The 1947 site change

Figure 6 compares annual temperatures at Dunedin Beta Street (Site 3) and Musselburgh (Site 4) from 1941 to 1957 with temperatures from the three comparison stations.

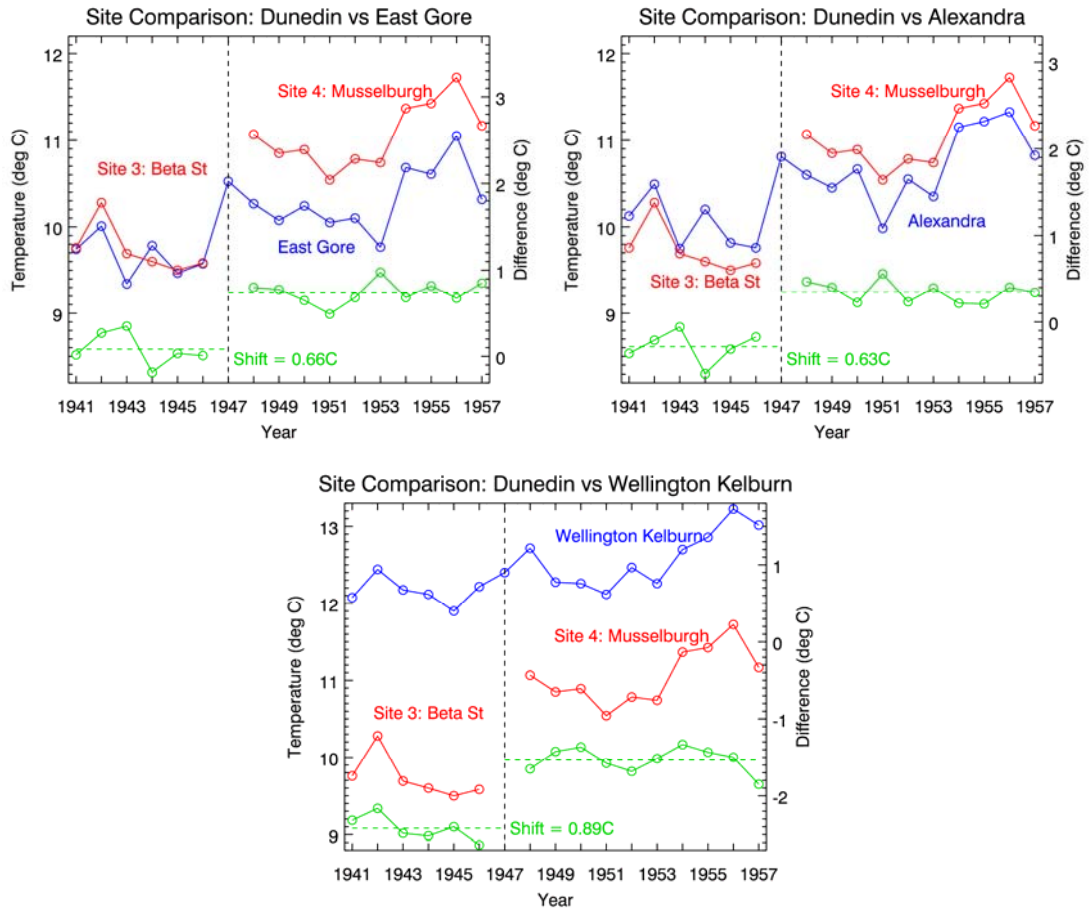

Figure 6: Annual-mean temperature series at Dunedin Beta Street (Site 3, red line on the left of each plot) and Musselburgh (Site 4, red line on the right of each plot) compared with East Gore, Alexandra and Wellington Kelburn. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Site 3/4 minus each comparison station) using the right-hand ordinate scale. The year of the site change, 1947, is indicated by a vertical dashed line. The mean differences for the periods before and after the site change are indicated by dashed green lines.

By comparison with East Gore, Musselburgh was 0.66 °C warmer than Beta Street. By comparison with Alexandra, Musselburgh was 0.63 °C warmer than Beta Street. Finally, by comparison with Wellington Kelburn, Musselburgh was 0.89 °C warmer than Beta Street.

By averaging the three differences (0.66 °C, 0.63 °C and 0.89 °C) we estimate that Musselburgh (Site 4) was, on average, 0.73 °C warmer than Beta Street (Site 3). The estimate from the larger set of six comparison stations is 0.70 °C.

There is additional evidence against which our estimate of the difference between sites can be tested. There were approximately 300 days of overlap between the temperature records from Beta Street and Musselburgh. (The overlap is from January to December 1947, but with incomplete months at each end and a period of missing data in April–May.) Brown (2006)[11] compared the daily data and estimated that Musselburgh was 0.65 °C warmer than Beta Street. Our own comparison (not shown) based on monthly data gives a mean difference of 0.53 °C. Since these comparisons are based on less than one year's data, they may not be very accurate. In addition, Brown (2006) installed temperature-logging instruments at the two sites for two years (October 2002 to October 2004) and found *median* differences in daily minimum and maximum temperature of 0.5 and 1.1 °C, respectively. Assuming that the median difference is equal to the mean difference (which may not be a good approximation, as Brown's Figure 5.9 suggests some skewness in the distribution of minimum temperature differences[12]) the implied difference in mean temperature is 0.8 °C. Since this comparison involved the current Musselburgh site, northwest of the pumping station, but with similar instruments at both sites, it is equivalent to a comparison of Beta Street (Site 3) with Musselburgh between 1960 and 1997 before the EWS was installed (Site 5), for which our estimate of the difference is 0.73 − 0.07 = 0.66 °C. None of these additional estimates is reliable enough to be adopted in place of the one derived from the comparison stations, however they do support the comparison result to within ~ 0.2 °C.

The final adjustment required to make observations at Beta Street (Site 3) consistent with those at Musselburgh EWS (Site 6) is therefore: − 0.07 − 0.07 + 0.73 = +0.59 °C.

The 1942 site change

Figure 7 compares annual temperatures at Dunedin Botanical Gardens (Site 2) and Dunedin Beta Street (Site 3) from 1931 to 1946 with temperatures from the three comparison stations.

By comparison with East Gore, Beta Street was 0.63 °C cooler than Botanical Gardens. By comparison with Alexandra, Beta Street was 0.64 °C cooler than Botanical Gardens, By comparison with Wellington Kelburn, Beta Street was 0.92 °C cooler than Botanical Gardens.

Averaging the individual estimates of the shift (−0.63 °C, −0.64 °C and −0.92 °C) we estimate that Beta Street (Site 3) was, on average, 0.73 °C cooler than Botanical Gardens (Site 2). From the larger set of six comparison stations, we estimate that it was 0.71 °C cooler.

[11] See Brown (2006) Section 5.6 and Table 5.6.

[12] Salinger (1977) discussed the difference between the Dunedin mean temperature calculated as the average of the daily maximum and minimum and that calculated as the average of 24 hourly values. He found the diurnal cycle was not symmetrical, with the 24-hourly average being about 0.2 °C lower than the max/min average.

From October 1940 until November 1942 (25 months, since January 1942 is missing at Beta St), monthly mean temperatures are available at both Botanical Gardens and Beta Street. This overlap allows us to make a separate estimate of the difference between the two sites (Figure 8). The mean difference is −0.72 °C. This estimate differs from the one derived from the three-station comparison by only 0.01 °C and therefore supports that result.

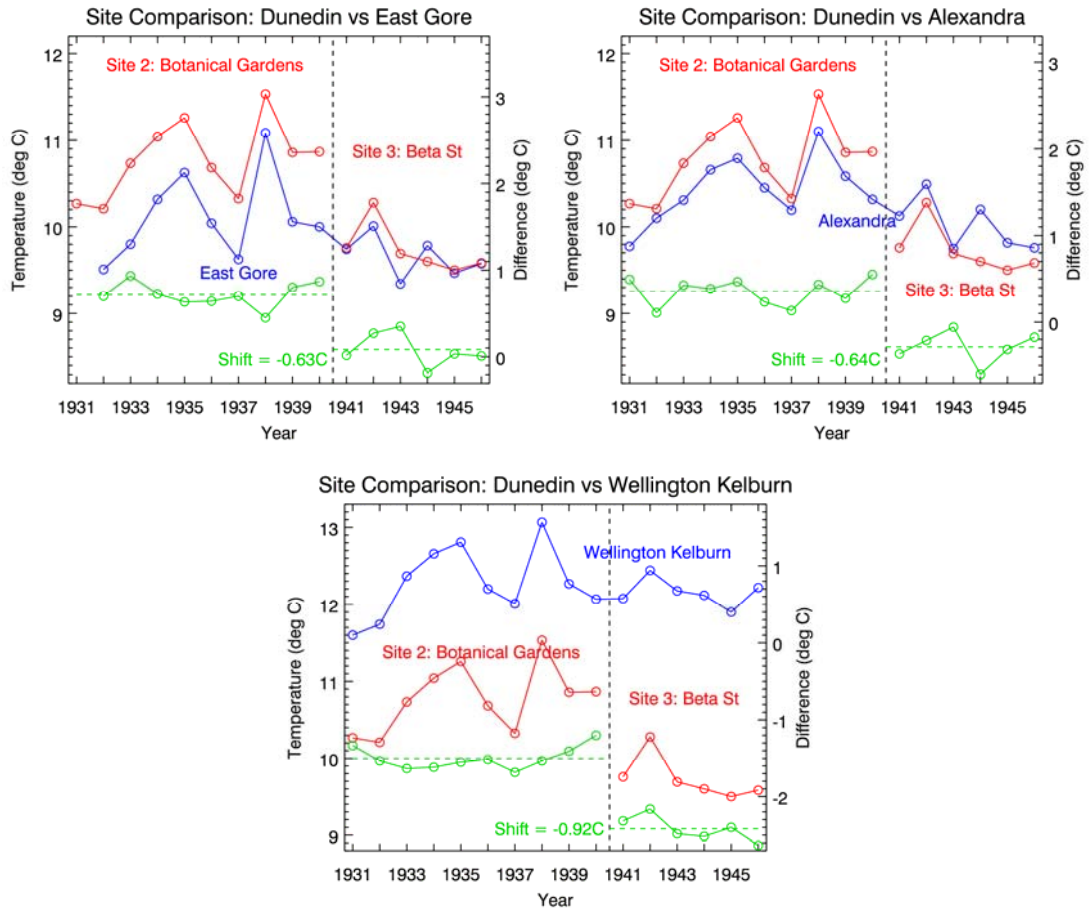

Figure 7: Annual-mean temperature series at Dunedin Botanical Gardens (Site 2, red line on the left of each plot) and Beta Street (Site 3, red line on the right of each plot) compared with East Gore, Alexandra and Wellington Kelburn. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Site 2/3 minus each comparison station) using the right-hand ordinate scale. The date of the site change, between 1940 and 1941, is indicated by a vertical dashed line. The mean differences for the periods before and after the site change are indicated by dashed green lines.

The final adjustment required to make observations at Botanical Gardens (Site 2) consistent with those at Musselburgh EWS (Site 6) is therefore: − 0.07 − 0.07 + 0.73 − 0.73 = −0.14 °C. Note that although there is a spread in the estimated adjustments of about 0.3 °C between the three comparison sites, there is almost exact site-by-site compensation between the Site 2 to Site 3 adjustment (Figure 7) and the subsequent Site 3 to Site 4 (Figure 6) adjustment. Therefore, we are confident that Site 2 (Botanical Gardens) and Site 4 (Musselburgh) are closely equivalent in their annual mean temperatures.

Adjustment for Site Change in 1913

The composite Dunedin temperatures from January 1900 until December 1912 are provided by the Leith Valley station (Site 1), located near the meteorological observer's house on the northeast-facing slope of Leith Valley. It was closed at the beginning of February 1913. The overlap between this site and the Botanical Gardens site is only one month, which is not long enough to usefully compare temperatures at the two sites, so again the change in temperature is estimated by comparison with other sites. The comparison period was limited by the availability of data and was from 1904 to 1920, i.e., eight years before and after the site change at 1912/1913.

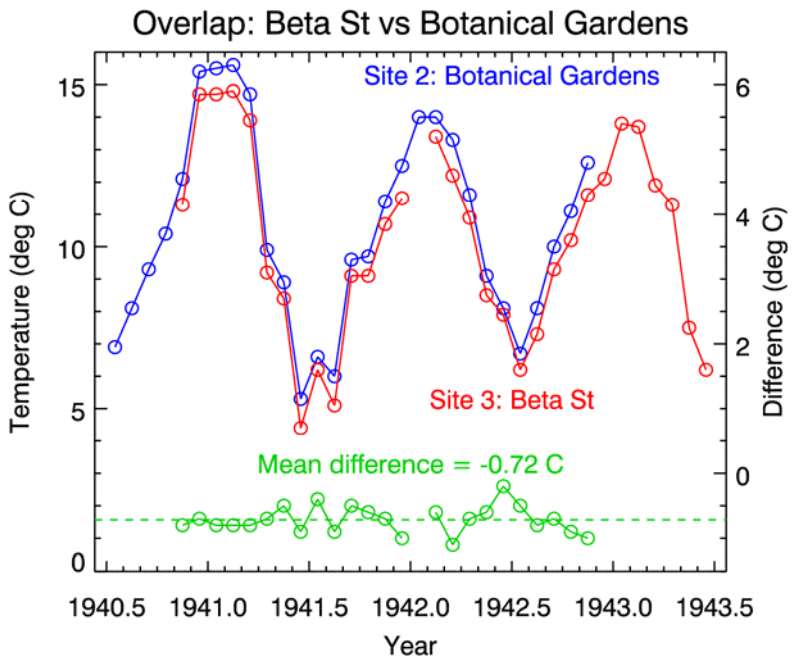

Figure 8: Monthly mean temperature series for Dunedin Botanical Gardens (Site 2, blue line) and Dunedin Beta Street (Site 3, red line) during their overlap period. The monthly difference, Site 3 minus Site 2, is indicated by the solid green line, using the right-hand ordinate scale, and the mean monthly difference is indicated by the dashed green line.

Selection of good comparison stations becomes more difficult earlier in the series, as the stations become sparser and the data quality generally lower. The stations selected were Christchurch Gardens (4858), Lincoln (4881), Nelson (4244) and Albert Park, Auckland (1427). Although they are distant from Dunedin (particularly Albert Park) these stations all show a reasonably high correlation with Dunedin, with a stable temperature difference before and after the shift. The first-difference correlation coefficients of the comparison stations with the candidate stations for this period are 0.97, 0.95, 0.86 and 0.86, respectively. However, both Lincoln[13] and Albert Park[14]

[13] At the Lincoln station there was a marked cooling in 1915–1916. There was no documented site change at this time, but it is suspected that the cooling was caused by development of the land around Lincoln College. The Lincoln document estimates the magnitude of the cooling to be 0.52 °C. Therefore for the present comparison, temperatures from 1916 have been shifted by +0.52 °C to correct for the site change.

[14] The Albert Park measurement site was moved in 1909 from the Auckland Museum to Albert Park. According to the Auckland document the new site was 0.09 °C cooler than the old site. Therefore, for

had inhomogeneities during the comparison period requiring adjustments to their data for the purpose of the comparison. This reduces the confidence in the final result.

Figure 9 compares annual temperatures at Leith Valley (Site 1) and the Botanical Gardens (Site 2) with those at the comparison stations. From Christchurch Gardens, we estimate that the Botanical Gardens site was 0.19 °C warmer than Leith Valley. Comparisons with Lincoln, Nelson and Albert Park result in estimates of 0.46 °C 0.35 °C and 0.56 °C, respectively. After averaging the four differences, we estimate that Botanical Gardens (Site 2) was, on average, 0.39 °C warmer than the Leith Valley (Site 1).

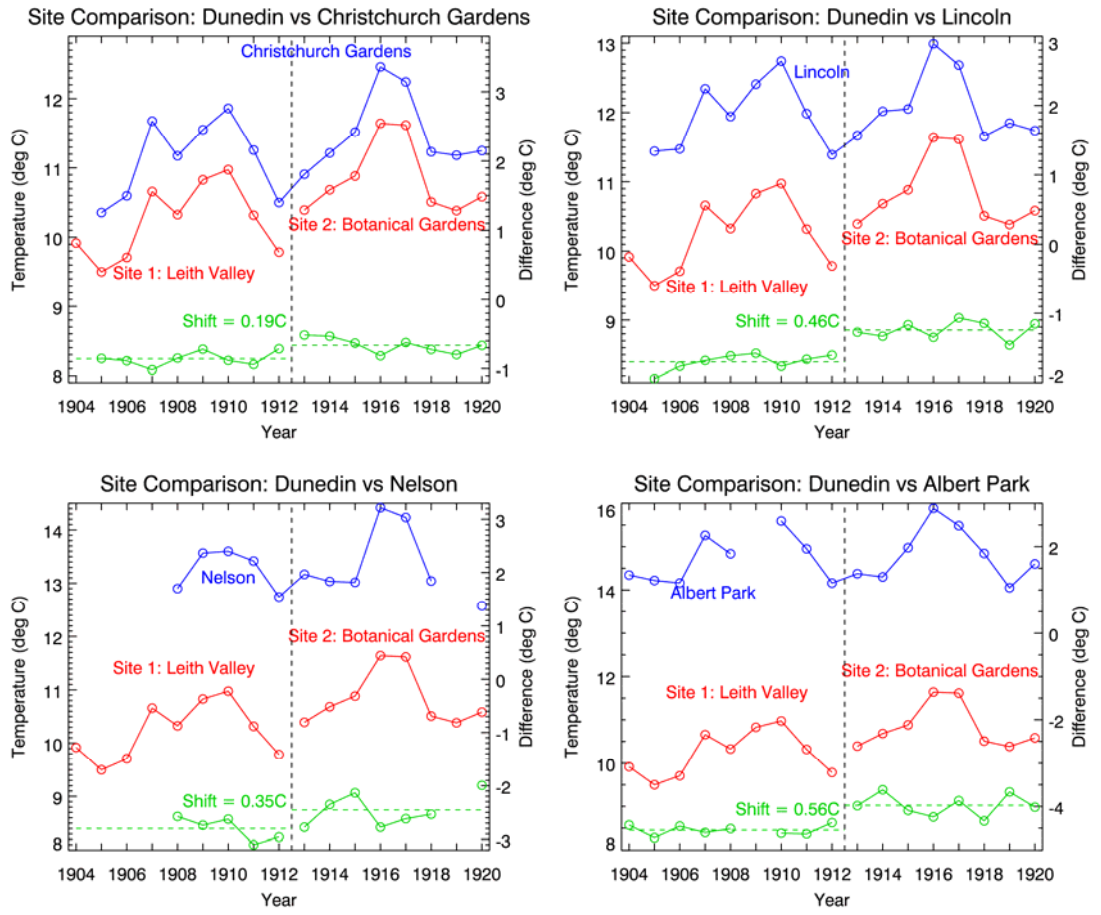

Figure 9: Annual-mean temperature series at Leith Valley (Site 1, red line on the left of each plot) and Dunedin Botanical Gardens (Site 2, red line on the right of each plot) compared with Christchurch Gardens, Lincoln, Nelson and Albert Park. See footnotes in the text for information about adjustments applied to Lincoln and Albert Park. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Site 1/2 minus each comparison station) using the right-hand ordinate scale. The year of the site change, 1913, is indicated by a vertical dashed line. The mean differences for the periods before and after the site change are indicated by dashed green lines.

the present comparison, temperatures before 1909 have been shifted by −0.09 °C to correct for the site change.

The final adjustment required to make observations at Leith Valley (Site 1) consistent with those at Musselburgh EWS (Site 6) is therefore: -0.07 -0.07 +0.73 -0.73 +0.39 = 0.25 °C.

Putting the Time Series Together

The various adjustments described above can be applied successively to the Dunedin temperature records. The resultant annual time series from 1900 to 2009 is shown in Figure 10, with a comparison to the previous Dunedin series. A linear trend has been fitted to each series over the period 1913–2009. Expressed in units of degrees per century, the linear trend in the revised series is 0.62 (±0.32) °C /century, as compared to 0.63 (±0.32) °C /century for the trend calculated from the seven-station time series published in February 2010.[15]

As discussed in the section on "Calculation of Adjustments", the series before 1913 is considered less reliable because of uncertainty in estimating the effect of the shift from Site 1 to Site 2. However for completeness we have also calculated the trend for the period 1909–2009; it is 0.58 (±0.30) °C for both the previous and revised series.

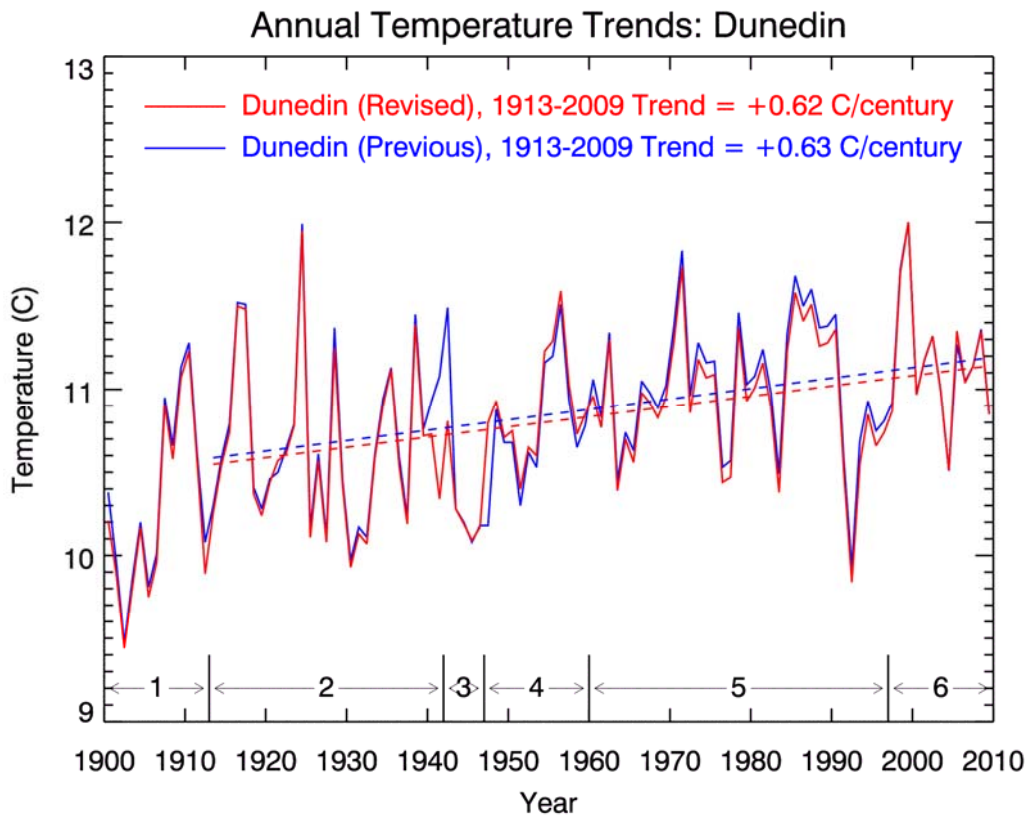

Figure 10: Comparison of the revised composite series of annual mean air temperatures for Dunedin (red line) to the previous NIWA Dunedin series (blue line) from 1900 to 2009. The dashed lines show the fitted linear trends from 1909 to 2009. Dunedin site labels from Table 1 are displayed at the bottom of the plot.

[15] The uncertainty here (±0.32 °C) defines the standard 95% confidence interval on the linear trend fitted to the adjusted time series, and does not include any consideration of uncertainty about each adjustment. Further research is underway to quantify how the accumulating adjustments influence the trend estimates.

Figure 11 repeats the graph of the revised composite annual mean temperature series for Dunedin, and compares the composite with the unadjusted raw multi-site temperatures. For the period 1997–2009 the two series are identical, since this period is covered by the reference site (Musselburgh EWS, Site 6) for which no adjustment is applied. The cumulative adjustments relative to the reference site are also shown in Figure 11, and correspond to those in the final column of Table 1.

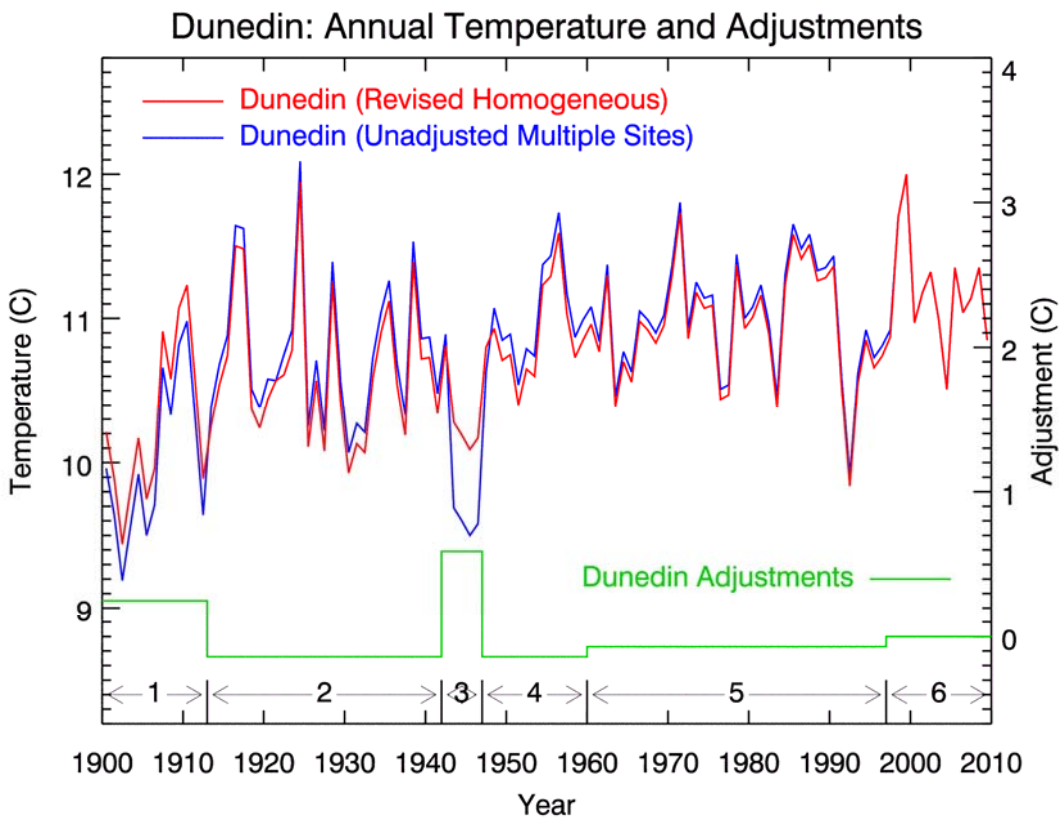

Figure 11: Comparison of the revised composite temperature series for Dunedin (red line), with an unadjusted composite series (blue line) from 1900 to 2009. Numbers near the bottom of the plot denote the site labels of Table 1, with vertical lines marking the time periods over which each site contributes to the composite series. The green line (using right-hand ordinate scale) indicates the adjustment for each period.

Once the temperatures from the Dunedin sites have been adjusted for consistency with Musselburgh EWS (Site 6), and then combined, we have a series dating back to 1913, and before that with lower reliability. Simply appending the raw data from the Dunedin records without correcting for known site changes would result in an inhomogeneous history of temperature, unsuitable for the analysis of trends.

Further Information

Further technical information on different approaches to homogeneity adjustment of climate data can be found in the references below (Peterson *et al.*, 1998; Rhoades and Salinger, 1993; Wang *et al.*, 2007).

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Appendix 1

Treatment of missing and suspect data

We could calculate annual-mean temperatures at each station only for those years with no missing monthly data, but this would discard potentially useful information. Instead, if monthly data are missing at a station for only a small number of months in a given year, we estimate the annual mean temperature in that year by a procedure that uses the temperatures from the remaining months. The procedure is described in Appendix 2 of "Creating a Composite Temperature Series for Masterton" and was applied to the data used in constructing the Dunedin series, both the data from Dunedin stations themselves and the comparison-station data. In general (with one exception, for Dunedin Botanical Gardens in 1921, described below) the maximum number of missing months allowed in any year was three. In practice most applications of the procedure involved missing data for just a single month.

The procedure to account for missing monthly data requires a monthly climatology for the station in question. This was generally calculated from 30 years of data at that station, over a period spanning the year(s) to be filled. Note that the climatology is needed only to define the *variation* in temperature during a typical year, not the absolute value, so the procedure is not sensitive to the range of years over which the climatology is calculated.

In April–August 1921 at the Botanical Gardens station (Site 2), the monthly-mean, daily-maximum temperatures in CliDB were unusually low, by several degrees Celsius. Fouhy et al. (1992) note that there were bad maximum temperature data in 1921 (though they are unclear as to what months were affected). For the present work, the mean daily maximum temperatures for each month in the period April–August 1921 were set to missing and the annual temperature was then calculated from the remaining data using a 1910–1939 climatology.

Other years for which an annual-mean temperature was calculated with missing monthly data were:

Dunedin composite series

1900 (October), 1909 (August), 1912 (November), 1952 (February).

Site change 5→6 (1997)

Palmerston (5323): 2004 (April).

Timaru 2 (5095): 1993 (September)

Site change 4→5 (1960)

Invercargill Aero (5814): 1954 (November)

Site changes 2→3 and 3→4 (1940 and 1947)

Dunedin Beta Street (Site 3): 1942 (January)

East Gore (5759): 1931 (December)

Queenstown (5446): 1953 (September), 1957 (September, October)

Alexandra (5576): 1947 (February)

Site change 1→2 (1913)

Christchurch Gardens (4858): 1905 (December), 1906 (April).

Appendix 2

Dunedin versus neighbouring stations

The 100-year trend in the Dunedin composite temperature series, at approximately 0.6 °C/century, is the lowest of the trends at the locations comprising the "7 station" series. It is lower by ~ 0.3 °C/century than the trend in the 7-station mean[16]. It is reasonable to ask whether other stations in the region also show a below-average trend.

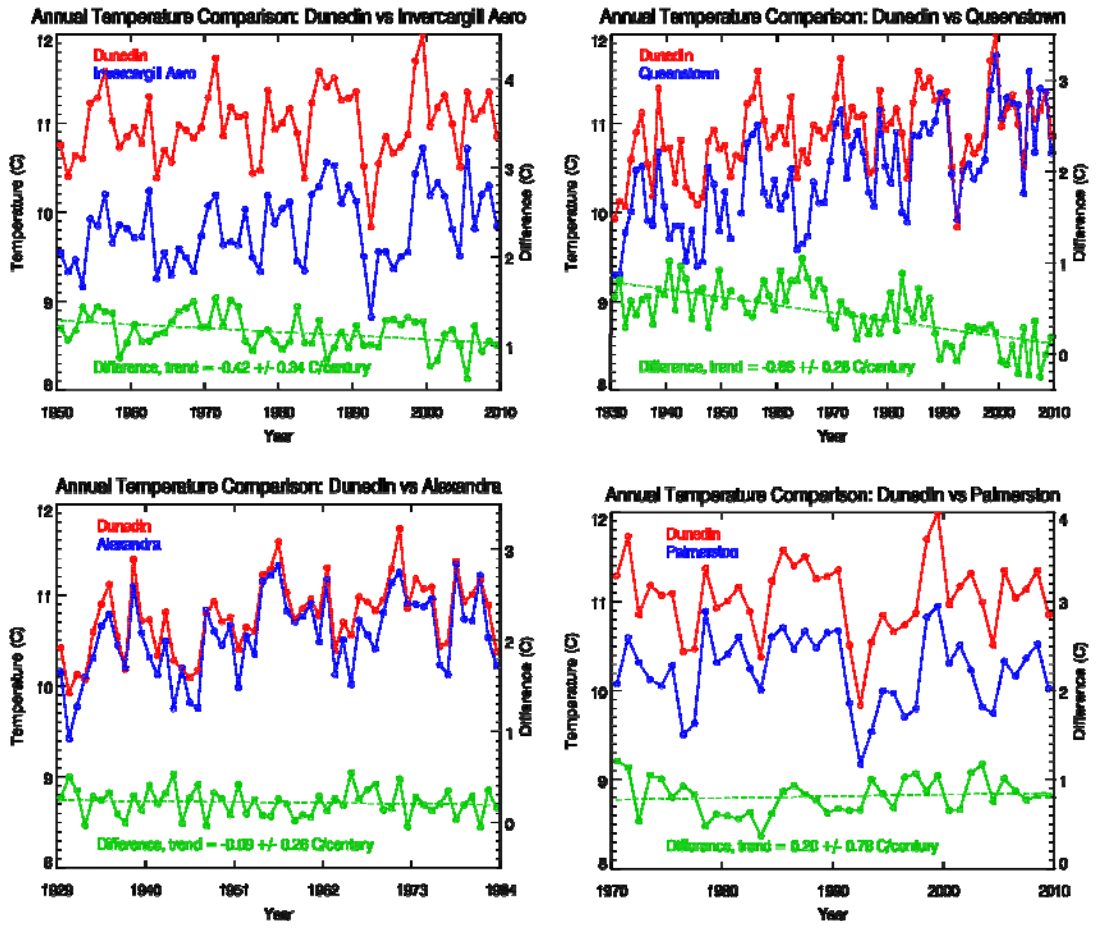

Figure A2.1: Comparison of the revised composite temperature series for Dunedin (red line), with time series of annual mean temperature (blue line) at stations in the southern half of the South Island: Invercargill Aero, Queenstown, Alexandra and Palmerston. The solid green line represents the difference (Dunedin minus the other station) using the right-hand ordinate scale. The dashed green line represents a linear trend fitted to the difference time series; the legend indicates the slope of the trend line and its associated uncertainty[17].

Figure A2.1 shows the Dunedin series compared with temperature series from several other climate stations in the southern half of the South Island. The stations have been

[16] The final value of the trend in the 7-station mean depends on the current revision and is not available at the time of writing.

[17] The uncertainty here is twice the standard error of the slope in the least squares linear fit to the difference time series, with the effective sample size reduced to allow for the lag-one serial autocorrelation (Santer et al., 2008, Equations 4–6).

chosen to have a long record (at least 40 years) with no evidence of significant inhomogeneities; no adjustments have been applied to the data from them.

Invercargill Aero (5814) is cooler than Dunedin, but the temperature difference (Dunedin minus Invercargill Aero) decreased between 1950 and 2009, with a trend of −0.42 ± 0.34 °C/century. Comparing Dunedin with Queenstown (5446), there is a larger trend of the same sign (−0.86 ± 0.28 °C/century, 1930–2009). The comparisons with Alexandra (5576) and Palmerston (5323) result in trends that are smaller in magnitude and not statistically significant (Alexandra: −0.09 ± 0.20 °C/century, 1929–1983; Palmerston +0.20 ± 0.78 °C/century, 1930–2009). So two of these stations, with record lengths of 60 years or more, show statistically significant negative trends in the difference (i.e., the stations in question have warmed relative to the Dunedin composite series) and for Queenstown the magnitude of the trend in the difference is approaching 1 °C/century.

The reasons for these differences are not obvious. For Queenstown, a trend due to urbanisation is a possibility, as Queenstown, Otago, is a resort town that has grown rapidly (urban population 10,416 at 2006[18]). The Queenstown climate station is on a small grassy patch adjacent to a road intersection, ~ 200 m southeast of the central business district. Large trees in the reserve on the other side of the road have grown over the years and periodically been cut back. Brown (2006) notes that this station has warmed relative to other Central Otago stations since 1950 and relative to Queenstown Aero (5450) since 1970, and argues that this is a result of localised environment change around the station. However our own investigation indicates that Queenstown Aero temperatures shifted by approximately +0.5 °C relative to other stations around 1976, coinciding with a note in CliDB that the thermometers were installed in the enclosure on 21 July 1976 (almost 8 years after the station opened). Considering only data from 1977 to the cessation of climate observations at Queenstown Aero in 1992, we find a statistically insignificant cooling of Queenstown relative to Queenstown Aero. This comparison argues against the existence of a local warming influence at the Queenstown station, at least since 1977. So the factors contributing to the warming trend at Queenstown relative to Dunedin and other Otago stations remain unclear. It is possible that it results from real climatic differences, as Queenstown is quite differently situated from the other stations, being at high elevation (398 m above sea level) in a mountain valley and near a large alpine lake.

The Invercargill Aero station is at Invercargill Airport, in a rural area 1–2 km from Invercargill, Southland, (urban population 48,300 at 2009[19]) and is unlikely to have been affected by increasing urbanisation. However it may have been affected by airport development.

To summarise, the evidence from other climate stations in Otago and Southland suggests that warming elsewhere in the region is similar to or exceeds that observed in the Dunedin temperature series. A more careful assessment of possible environmental influences on the other stations would be worthwhile.

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[18] 2006 Census Data, Final counts, Otago Region. Cited population is the sum total of Frankton (Quickstats about Frankton), Kelvin Heights (Quickstats about Kelvin Heights), Sunshine Bay (Quickstats about Sunshine Bay), Queenstown Bay (Quickstats about Queenstown Bay) and Queenstown Hill (Quickstats about Queenstown Hill)

[19] "Subnational Population Estimates: At 30 June 2009". Statistics New Zealand. 23 October 2009. http://www.stats.govt.nz/methods_and_services/access-data/tables/subnational-pop-estimates.aspx.