Report on the Review of NIWA's 'Seven-Station' Temperature Series

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Contents

Summary of NIWA's "Seven-Station" Temperature Series, December 2010

NIWA has re-analysed temperature trends from data at seven locations which are geographically representative of the country: Auckland, Masterton, Wellington, Nelson, Hokitika, Lincoln (near Christchurch) and Dunedin. The revised temperature series supersedes the previous version posted in February 2010. Extensive documentation has been prepared that describes in detail how composite temperature series have been developed at each of the seven locations.

This "Overview" document provides a less technical summary of the key results, and gives a broader scientific perspective to assist interpretation of the revised seven-station temperature series.

Key Points

- For each of the seven locations, temperature records from a number of local sites have been merged together to form a long time series. When merging different temperature records like this, it is necessary to adjust for climatic differences between sites to avoid significant biases being introduced. Adjustments may also be needed even if the site does not physically move, because changes in exposure or instrumentation at a given site can also bias the temperature measurements.

- The key result of the re-analysis is that the NZ-wide warming trend from the "seven-station" series of about 0.9 °C/century is virtually the same in the revised series as in the previous series. In terms of the detail for individual sites, the 100-year trend has increased slightly at some sites, and decreased slightly at some others.

- The variations in time of New Zealand temperature are consistent with completely independent measurements of regional sea temperatures. There is also a strong correlation between variations in New Zealand temperature and prevailing wind flow, which relates closely to the abrupt warming in the mid 20th century, and the slower rate of warming since about 1960.

- The spatial pattern in the warming is consistent with changes in sea surface temperature around New Zealand, with greatest warming in the north of the country (Auckland) and least warming (but still significant) in the southeast (Dunedin).

Further discussion of these points is given below.

Brief History

The concept of the seven-station temperature series was originally developed as part of Dr Salinger's 1981 PhD thesis (Salinger, 1981). He recognised that, although the absolute temperatures varied markedly from point-to-point across the New Zealand landscape, the variations from year to year were much more spatially uniform, and only a few locations were actually required to form a robust estimate of the national temperature anomaly. In an appendix to that thesis, Salinger calculated adjustments for many sites across New Zealand, in order to correct for site moves or other inhomogeneities.

During the early 1990s, the seven-station series was revised and updated as a research activity within climate research programmes undertaken by the NZ Meteorological Service and NIWA under contract to the Foundation for Research, Science and Technology. Station histories and site changes in the series were documented by Fouhy *et al*., 1992. The homogenisation procedures were described along with the resulting time series data for each station by Salinger *et al*., 1992. This latter document did not, however, provide any tables of adjustments.

In February 2010, NIWA published the adjustments in use at that time (see web link above). We also placed a document on our website detailing the adjustments for site changes at Hokitika and the reasons for them. Because of the interest generated by this document, NIWA produced similar documents for the other six locations used in the "seven-station" temperature series. These documents were peer reviewed and published on the NIWA website.

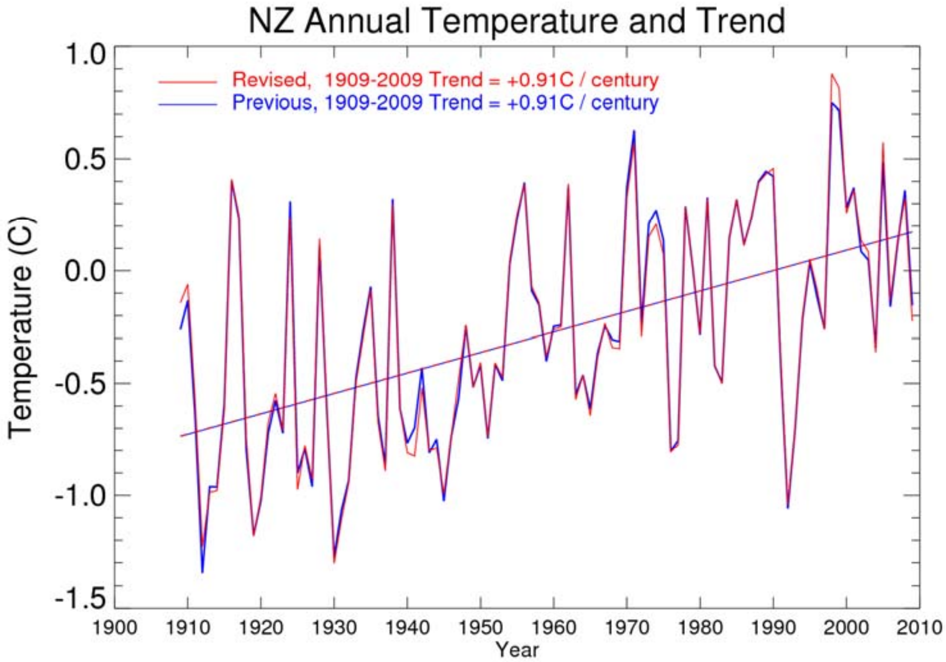

Figure 1: Comparison of the revised seven-station series with the previous one, plotted as anomalies from the 1971-2000 climatology. Averaged over the seven locations, the revised New Zealand trend is +0.91 °C/century compared with the previous estimate of +0.91 °C/century. The 95% confidence interval on the calculated linear trend is ±0.29 °C/century.

Have our estimates of overall temperature trend changed?

Figure 1 shows a graph of the previous (February 2010) and revised (December 2010) annual temperature series, averaged over the seven locations. Table 1 summarises the century-scale warming trends up to 2009 for each site separately. For four of the sites, the trend calculation starts from 1909; for the other three sites, a later year is used because of lower confidence in the very early data. Trends for individual stations vary between the previous and revised temperature series, some being slightly higher and some being slightly lower. The trend for the seven-station average has changed minimally, showing that the previous result was robust.

Table 1: Long-term trends in annual mean temperature, in °C/century, comparing results from the previous series with the revised seven-station series. The period of the trend calculation is 1909 to 2009 except where a different start year is noted.

Station (start year)	Previous Series Trend (°C/century)	Revised Series Trend (°C/century)
Auckland (1910)	1.34	1.53
Masterton (1912)	0.80	0.88
Wellington	0.79	0.86
Nelson	0.81	0.76
Hokitika (1913)	1.07	1.11
Lincoln	0.99	0.83
Dunedin	0.58	0.58
Seven-Station Average	0.91	0.91*

* This is the trend of the seven-station composite series (Figure 1), not the average of the 7 individual trends (which have different starting years). It is coincidental that the previous and revised trends agree exactly to the second decimal place. For example, had we chosen the period 1913-2009, the trends would be 0.95 °C/century (Previous) and 0.97 °C/century (Revised).

The 95% confidence intervals on the trends is approximately ±0.3 °C/century (see individual station documents for specific values). This represents the two standard deviation uncertainty on the least squares linear fit to the composite series. It does not include any consideration of uncertainty about each adjustment separately. Further research is underway to quantify how the accumulating adjustments influence the uncertainty in the trend estimates.

The individual station documents show the trends separately for each composite series. These documents also show how the adjustments vary over time, and compare the adjusted series with the raw station data. As has been commented on elsewhere, most early sites in New Zealand were in warmer locations than current sites (e.g., Albert Park versus Auckland Aero, Thorndon versus Kelburn in Wellington). This finding is not unusual in the global context (Tuomenvirta, 2001), and is likely a consequence of early settlers siting their settlements in the 'best' (i.e., warmest) local micro-climate.

What is the effect of urban heating in Auckland?

The trends calculated above do not make any allowance for urban heating effects. The only location which we consider has been significantly influenced in this way is Auckland, and the Auckland document includes a long discussion of the issue. The key points are:

- The Albert Park record shows no differential warming relative to other sites in the northern North Island after the mid-to-late 1950s, so any non-climatic warming is prior to this time.
- The CBD lies on the northern edge of the Auckland isthmus, and there is a strong coastal influence from the warmer waters of the East Auckland Current to the east of the northern North Island. That is, we expect the northern part of the isthmus (Albert Park) to be warmer than further south (like Mangere or Auckland airport). This is not an indicator of urban warming.
- Nevertheless there is evidence that Albert Park warmed relative to other locations in the area between about 1928 and 1960 due to tree growth in the park and increased urbanisation around the park. The warming due to these effects over the three decades is estimated in the Auckland document at about 0.3 °C. Such a warming would increase the apparent 1909–2009 trend at Auckland by 0.38 °C.[1]
- However, the overall seven-station trend is relatively insensitive to a change at one site. For example, if we reduce the Auckland trend from 1.53 °C/century to 1.15 °C/century, this only reduces the overall seven-station trend to 0.85 °C/century (from 0.91 °C/century). Completely omitting the Auckland station from the seven-station series gives a trend over the remaining 6 stations of 0.81 °C/century.

What else has changed from the previous seven-station series?

Besides the revised estimates of warming trends, there have been some structural changes in the make-up of the "seven-station" series. The same 7 locations are used (there are no others available that have records extending back to around 1900), but in some cases we have changed the sites contributing to the composite series. For the Auckland composite series, the Auckland Aero automatic weather station (identified by 'agent number' 1962 in the NIWA Climate Database) is used in preference to the Mangere EWS station (agent 22719) after 1998. For Nelson, the Appleby automatic stations are replaced by the Nelson Aero sites after 1996. These changes are to circumvent some recent reliability problems encountered in the observations.

The other main change is the starting year of the published time series. The early temperature records are less reliable, and there are very few comparison sites pre-1910 to confidently determine site adjustments. We have not used data prior to 1900, and produced the seven-station average from 1909 onwards. Table 2 shows the revised starting date in the new composite temperature series.

[1] This was calculated as follows: start with the adjusted Auckland temperature series. For the period 1928-1957, successively reduce the annual temperatures by 0.01 °C more each year than the previous year; for the period 1958 onwards, reduce temperatures by a constant 0.30 °C.

Table 2: The starting date of the composite temperature series, for the previous and revised NIWA seven-station" series.

Location	Previous Series	Revised Series
Auckland	June 1853	September 1909
Masterton	January 1906	February 1912
Wellington	March 1862	June 1906
Nelson	July 1862 *1	October 1907 *2
Hokitika	January 1867 *3	September 1912
Lincoln	January 1864	January 1905
Dunedin	January 1853	January 1900

*1 Includes gap of missing data January 1881 to September 1907.
*2 There is presently no annual value in 1919 in the revised series (because of 5 missing months)
*3 Includes gap of missing data January 1881 to December 1893.

What is driving the temperature trend? – Temporal patterns

Figure 2 shows the time variation of the annual-average NOAA ERSSTv3 sea surface temperatures (SSTs)[2], averaged over a box (160-190°E, 30-50°S, see Figure 4) around New Zealand, compared with the annual seven-station air temperature series. The variation in time is very similar, showing how strongly New Zealand is influenced by its oceanic environment. The land temperature interannual variations are more extreme than those in the ocean, and the long-term trend is slightly higher; this is expected because of the large ocean heat capacity and is predicted by climate models (Sutton *et al.*, 2007).

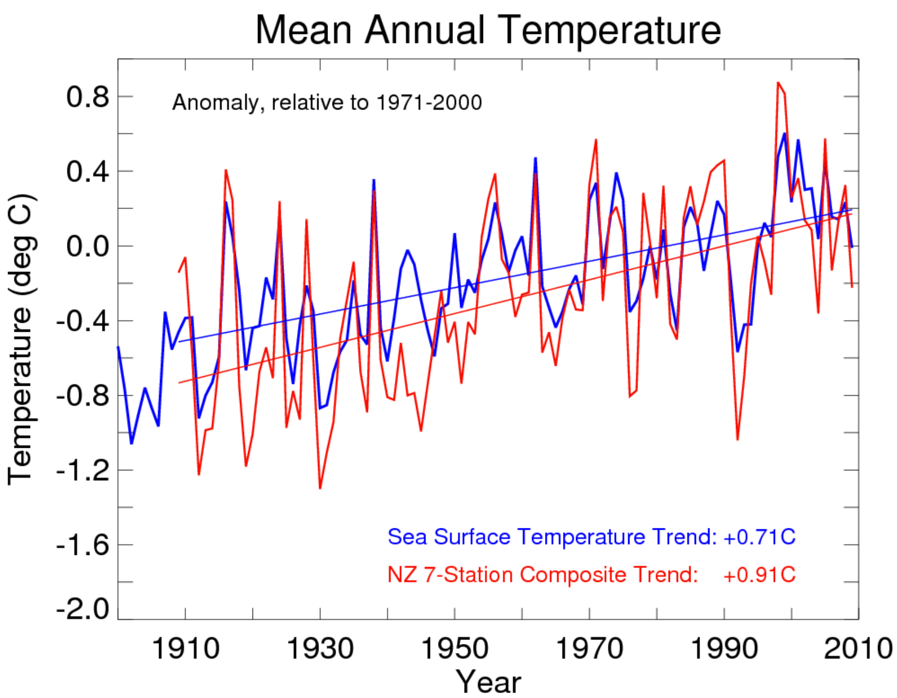

Figure 2: Annual time series NOAA sea surface temperatures (blue line) and NIWA's seven-station composite series (red line), expressed as anomalies relative to the 1971-2000 climatological average. Linear trends over the period 1909-2009, in °C/century, are noted under the graph.

[2] http://www.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php

Although a linear trend has been fitted to the seven-station temperatures in Figure 2, we know that the variations in time are not completely uniform. For example, a markedly large warming occurred through the period 1940-1960. These higher frequency variations can be related to fluctuations in the prevailing north-south air-flow across New Zealand. Figure 3 shows such a comparison, where the Northerly Flow Index is calculated from the Chatham Islands minus Hobart pressure difference (the reverse of the more commonly used Trenberth Southerly Index (Trenberth, 1976)). Again, there is very strong agreement between the seven-station temperatures and completely independent surface pressure measurements. Temperatures are higher in years with stronger northerly flow (more positive values of the Index), and lower in years with stronger southerly flow (more negative values of the Index). One would expect this, since southerly flow transports cool air from the Southern Oceans up over New Zealand.

The unusually steep warming in the 1940-1960 period is paralleled by an unusually large increase in northerly flow during this same period. On a longer timeframe, there has been a trend towards less northerly flow (more southerly) since about 1960. However, New Zealand temperatures have continued to increase over this time, albeit at a reduced rate compared with earlier in the 20th century. This is consistent with a warming of the whole region of the southwest Pacific within which New Zealand is situated.

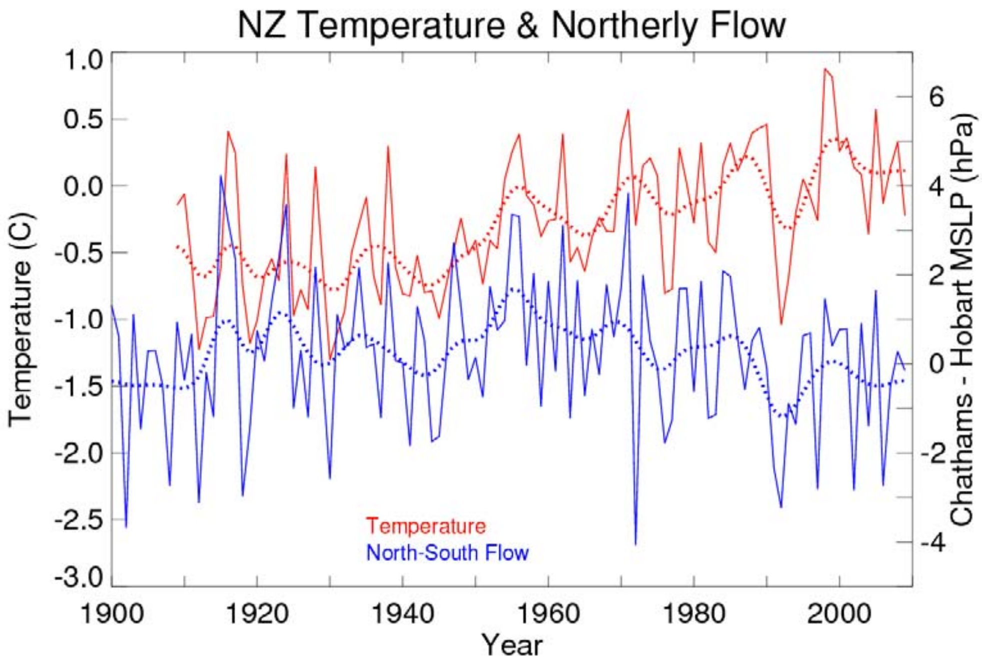

Figure 3: Annual time series of a Tasman Sea Northerly Flow Index (blue line, right-hand axis) and NIWA's seven-station composite temperature series (red line, left-hand axis), expressed as anomalies relative to the 1971-2000 climatological average. The dotted lines are low-pass filtered series which highlight the decadal and longer-term trends. The zero lines of each series have been offset for ease of comparison.

What is driving the temperature trend? – Spatial patterns

There is a marked difference between the trends at Auckland and at Dunedin. Even allowing for some reduction in the Auckland trend due to urban heating or sheltering, the trends are still very different. Figures 4 and 5 show this north-to-south variation is readily understandable in terms of the regional patterns of sea surface temperature (SST) trends. Figure 4 shows the SST trends over 1909-2009, matching the period we have quoted for the seven-station series. (Note that the 2° latitude-longitude boxes encroach over New Zealand if there is a sufficient ocean fraction, but the data do not contain any land-based observations.)

Figure 4 shows enhanced rates of warming (in units of °C/decade) down the Australian coast and to the east of the North Island, and much lower rates of warming south and east of the South Island. Figure 5 gives a broader spatial picture at much higher resolution (but a shorter period, since 1982). It is apparent that sea temperatures are increasing north of about 45 °S; they are increasing more slowly, and actually decreasing in recent decades, off the Otago coast and south of New Zealand.

This regional pattern of cooling (or only slow warming) to the south, and strong warming in the Tasman and western Pacific can be related to increasing westerly winds and their effect on ocean circulation. Thompson and Solomon (2002) discuss the increase in Southern Hemisphere westerlies and the relationship to global warming; Roemmich *et al.* (2007) describe recent ocean circulation changes; Thompson *et al.* (2009) discuss the consequent effect on sea surface temperatures in the Tasman Sea.

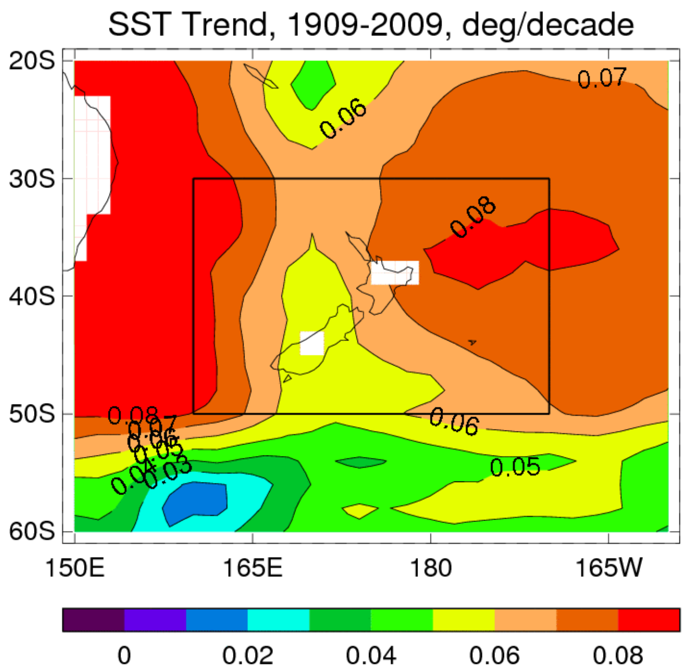

Figure 4: Trends in sea surface temperature, in °C/decade over the period 1909-2009, calculated from the NOAA_ERSST_v3 data-set (provided by NOAA's ESRL Physical Sciences Division, Boulder, Colorado, USA, from their web site at http://www.esrl.noaa.gov/psd/). The data values are on a 2° latitude-longitude grid. The box around New Zealand denotes the region used to produce the area-averaged sea temperatures plotted in Figure 2. (See Smith *et al.* (2008) for a description of the ERSST v3 product.)

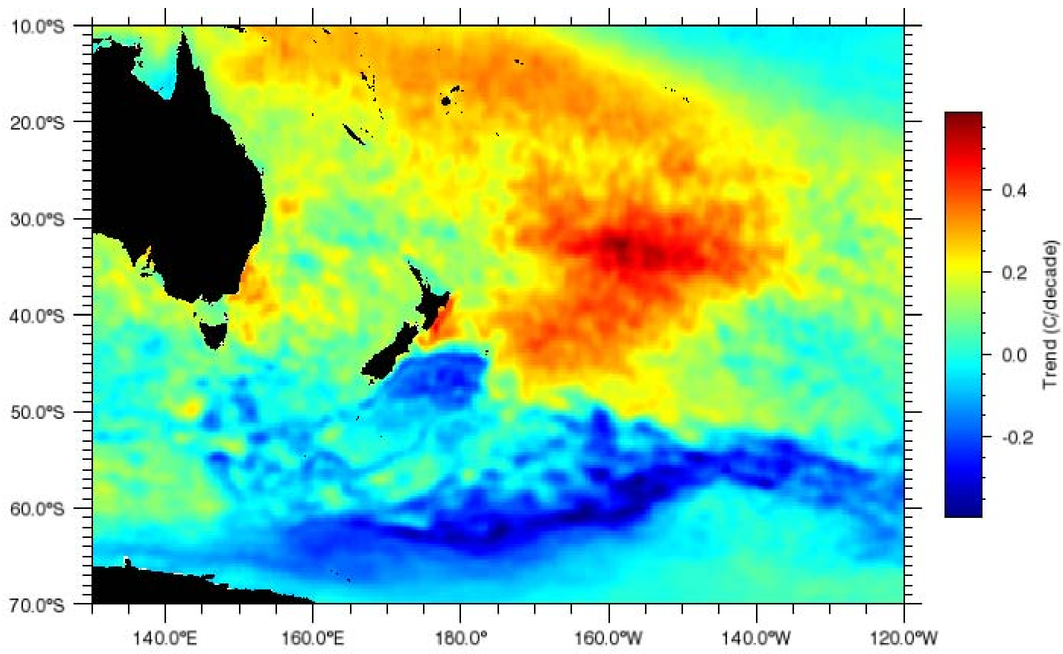

Figure 5: Trends in sea surface temperature, in °C/decade over the period 1982-2009. The data are again taken from NOAA, but are based on daily interpolated satellite measurements over a much finer 0.25° grid.[3]

Further Research

The revised New Zealand temperature series discussed here will inevitably undergo small changes in the future. NIWA scientists are continuing to research past variations and changes in New Zealand temperatures and other facets of climate and their causes. New results will be reported as they become available.

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[3] See http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php. This product is the result of an objective analysis, an optimum interpolation rather than a pure satellite retrieval, so as to correct for issues like the effect of the Mt Pinatubo eruption aerosols on satellite detected radiances. It is described in Reynolds *et al.* (2007).

Why and how we adjust temperature series

Adjusting time series is standard practice in climatology and other technical fields. For example, when investigating the feasibility of wind power at some location, no engineer would ever take a wind time series from another location and apply it without adjustment to the site under consideration.

In building long time series of temperatures from several nearby sites, a few basic principles need to be recognised:

- Micro-climates exist: Within a general region, taking Wellington as an example, there are many micro-climates, and thus temperatures vary from place to place. This is because of Wellington's varied topography, meaning that the sites have different exposures and aspects and are at different altitudes. All these factors can influence the measured temperature. There is no such thing, therefore, as "the" Wellington temperature; there are many Wellington temperatures, and they are all different. Joining the raw unadjusted temperature records from two different sites, such as Thorndon (a warm sea-level site in the CBD) and Kelburn (a colder higher altitude suburb), would give a completely false picture of any long-term trends.

- Neighbouring sites vary together: Comparison of temperatures from neighbouring sites shows again and again that trends and interannual variations at nearby sites are very similar. So although the base level temperatures may be different at two sites (due to micro-climate effects), the variations are almost in 'lock-step', with occasional exceptions. (See examples in the seven-station documents and on the NIWA website.)

If it were not for this 'lock-step' variation, it would not be appropriate to join temperature records from different sites at all. But once such parallel variation is recognised, it is a simple matter in principle[4] to adjust temperatures from one site to the same base level as at another site. These adjustments are sometimes termed offsets or corrections. This does not mean the measured values are incorrect; merely, that they were not taken at the desired location.

The offsets adjust temperature records from multiple sites to be consistent with a selected reference site. That is, we build a temperature series as if we had measurements from the reference site over the entire period of record. For example, the Wellington reference site is Kelburn. The actual period of record at Kelburn can be extended using records from nearby sites, provided we adjust for their relative climatic differences. A warmer site than Kelburn (e.g., Thorndon) will have its temperatures adjusted downwards. A colder site than Kelburn would have its temperatures adjusted upwards.

The details of the methods used to identify the necessary adjustments are provided in the individual reports on the locations used in producing NIWA's "seven-station" temperature series.

[4] It would be almost as simple in practice too, were it not for missing data.

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National Institute of Water & Atmospheric Research Ltd
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New Zealand

Peer Review of the NIWA "Seven-station" series: Temperature Data for Auckland, Wellington, Dunedin, Nelson, Masterton and Lincoln ("Christchurch")

Dear David,

This Bureau of Meteorology peer review of the National Institute of Water & Atmospheric Research Ltd (NIWA) "seven station" series is a scientific review of the station reports for the Auckland, Wellington, Dunedin, Nelson, Lincoln ('Christchurch') and Masterton sites as provided by NIWA to the Australian Bureau of Meteorology. In this context 'scientific review' means a critical inspection/examination of the station reports taking into account the range of supporting evidence provided. The ideas, methods and conclusions of the papers are assessed for scientific error, internal consistency, clarity and scientific logic.

The data and methodology provided in the reports from NIWA are taken as an accurate representation of the actual analyses undertaken. We are not in a position to question all of the underlying analyses and data that have contributed to the final results, such as methods used to compile raw data taken at stations. We do, however, perform some independent analyses as appropriate to the aims of the review as outlined above.

The review does not constitute a reanalysis of the New Zealand 'seven station' temperature record. Such a reanalysis would be required to independently determine the sensitivity of, for example, New Zealand temperature trends to the choice of the underlying network, or the analysis methodology. Such a task would require full access to the raw and modified temperature data and metadata, and would be a major scientific undertaking. As such, the review will constrain itself to comment on the appropriateness of the methods used to undertake the 'seven station' temperature analysis, in accordance with the level of the information supplied.

In general, the evidence provided by NIWA supports the homogeneity corrections that have been applied to the temperature record to create the 'seven station' series. The scientific papers clearly report on major issues which have been identified in the metadata and past scientific literature. It is also clear that a number of significant adjustments (as identified by NIWA in the reports) are clearly required for the raw/composite station series owing to inhomogeneities which would otherwise artificially bias results.

Yours sincerely,

Neil Plummer
Acting Assistant Director (Climate Information Services)
14/12/2010

Creating a Composite Temperature Series for Auckland

December 2010

Figure 1: Looking west toward the automatic weather station at Auckland Aero (agent number 1962). (MetService, 2009)

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 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.

This present document revisits and describes in greater detail the process by which a composite station series has been developed for Auckland. The primary purpose is to demonstrate in an intuitive way how to estimate adjustments to temperature records 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 <u>not</u> 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 minimum temperature. Further research will determine adjustments to monthly maximum and minimum temperatures separately, and apply statistical methods (e.g., RHtests, Wang *et al*., 2007) to identify other change-points in the data.

Table 1: Information about Auckland 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 record;
(Column 4) altitude of site in metres above sea level;
(Column 5) previous period of record (as of February 2010) 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 of record for which the site contributes to the composite time series; and
(Column 8) revised temperature adjustment to be applied (with respect to Auckland Aero AWS, Site 5), as discussed in the text.

Site Label	Site Name (Agent Number)	Location (Full Period of Record)	Height (m a.s.l.)	Previous Period	Previous Temp. Adjust. (°C)	Revised Period	Revised Temp. Adjust. (°C)
Site 1	Albert Park (1427)	Government Domain, Auckland. (May 1868 to Mar 1883)	77[2]	May 1868 to Mar 1883	-0.5	Not Used	-0.62[3]
Site 2	Albert Park (1427)	Museum, corner of Princes and Shortland Streets, Auckland. (Apr 1883 to Aug 1909)	38	Apr 1883 to Aug 1909	-0.5	Not Used	-0.71[4]
Site 3	Albert Park (1427)	Albert Park, Auckland. (Sep 1909 to Dec 1989)	49	Sep 1909 to Dec 1950	-0.5	Sep 1909 to Dec 1950	-0.62
Site 3	Albert Park[4] (1427)	Albert Park, Auckland. (Sep 1909 to Dec 1989)	49	Jan 1951 to Dec 1975	-0.6	Jan 1951 to Mar 1976	-0.65
Site 4	Mangere (1945)	Mangere treatment plant, Manukau. (Feb 1959 to Jul 1998)	2	Jan 1976 to Jul 1998	0.0	Apr 1976 to Jul 1998	0.01
Site 5	Auckland Aero AWS[5] (1962)	Auckland Airport, Manukau. (Jun 1962 to present)	33	Aug 1998 to Apr 2002	0.0	Aug 1998 to present	**0.00**
Site 6	Mangere EWS (22719)	Mangere treatment plant, Manukau. (May 2002 to present)	5	May 2002 to present	0.0	Not Used	N/A

[2] The elevation of Site 1 is uncertain. Hector (1869-1885) gives the elevation as 79m, while NZ Meteorological Service staff later estimated the elevation as 60m. Salinger (1981) lists the elevation as 77m.
[3] We have included the estimated adjustment of Sites 1 and 2 in this Table for ease of comparison with previous estimates (column 6). The correction is derived in the Appendix. We do not, however, have high confidence in the adjustments estimated for very early temperature data, and so have "not used" (column 7) these early adjusted temperatures in the revised NIWA temperature series for Auckland.
[4] In November 1950 there was a change in the type of screen used at the Albert Park site, from louvred to Bilham type.

Calculation of Adjustments

Table 1 summarises the information about the local sites used to develop the composite temperature series for the Auckland 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.[6] Table 1 lists six different sites as contributing to the composite Auckland temperature series, and one change in the type of screen[7] used. Thus, there are at least seven change-points, and the temperature record 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 was made <u>not</u> to include temperatures prior to 1900. Furthermore, if there were site change adjustments around 1910 that were difficult to quantify, then the time series was truncated at that point. In the case of Auckland, the revised series begins with Site 3 in 1909. In the interests of completeness, adjustments are still estimated for the earlier sites, but discussion of them is relegated to the Appendix, along with other more technical comments.

It is common practice to adjust all the historical measurements to be consistent with the current open site (Aguilar *et al*., 2003). In previous temperature adjustments, a relatively new station, Mangere EWS (Site 6, agent number 22719), was the current open site, and was used to complement the long time series from Mangere (Site 4, agent 1945). In the present report, Mangere EWS is not used for reasons explained in Appendix 2. Therefore, here we reference the temperature adjustments to Auckland Aero Automatic Weather Station (AWS) (Site 5, agent 1962) which is still open. It is labelled Site 5 in Table 1 and shown in Figure 1.[8] Figure 2 provides a map locating the local Auckland sites of Table 1, and also a number of the more distant comparison sites discussed in the following text.

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[5] Auckland Aero is the reference site for the Auckland region. Other Auckland sites are adjusted to be consistent with this reference site. The choice of reference site does not affect the trend of the temperature series; it only affects the offset.

[6] Calculation to two decimal places has been done to minimise the accumulation of round-off errors. This should not be interpreted as an indication of the accuracy of the adjustment. Air temperatures are recorded to the nearest 0.1 °C on the NIWA Climate Database.

[7] The louvred wooden enclosure that houses the thermometers and other meteorological equipment at a measuring site.

[8] The final adjusted temperature series should therefore be thought of as representing historical temperatures at Auckland Aero from 1909 onwards.

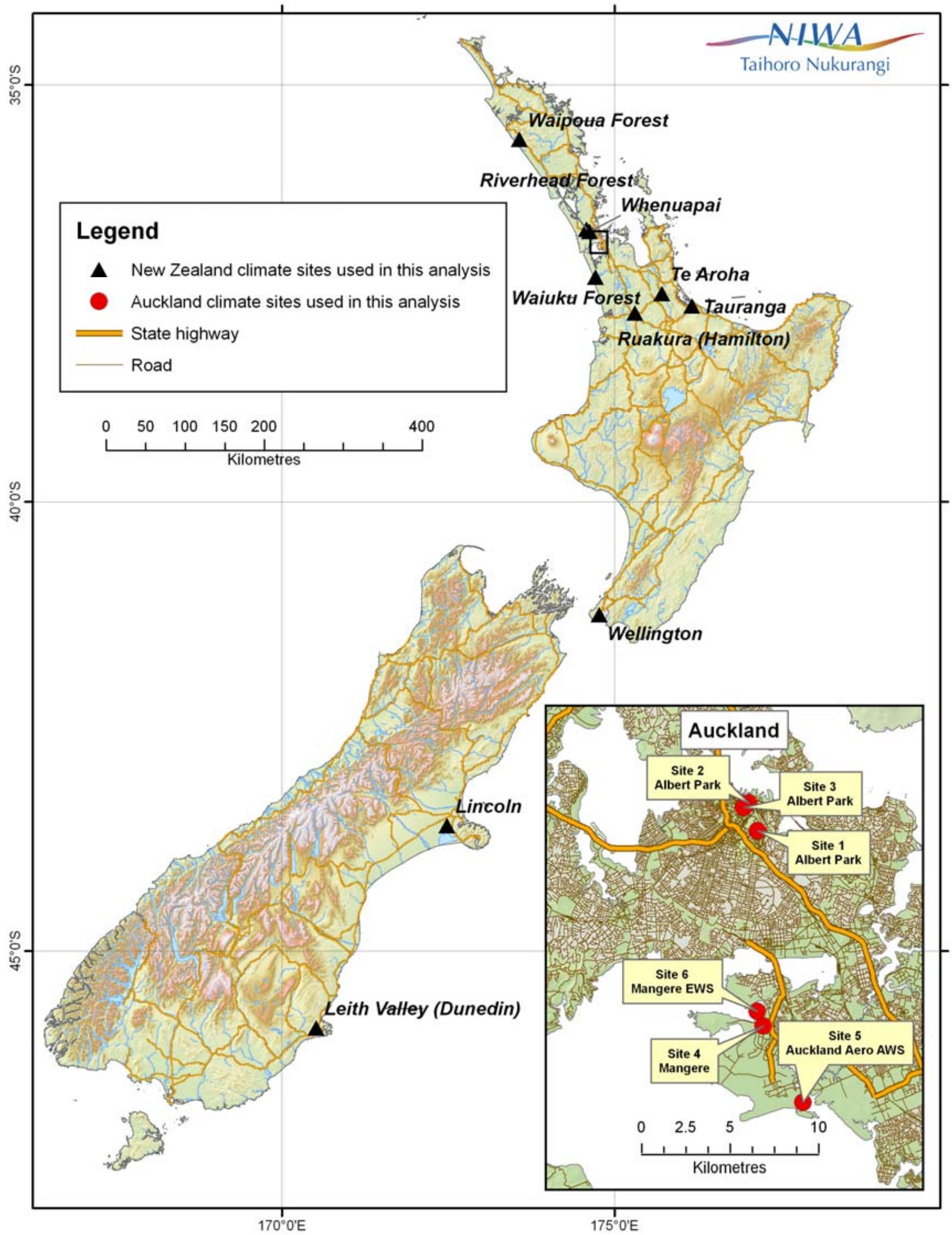

Figure 2: Map showing sites of temperature records referred to within this document. The inset map locates the local Auckland sites.

Adjustment for Site Change in 1998

We will work backwards in time from the current open site: Auckland Aero AWS (Site 5, agent 1962). This station is located south of the eastern end of the runway at Auckland Airport (Figure 1). It is situated on well-managed grass which, apart from the airport to the northeast, is in a rural setting adjacent to Manukau Harbour.

The previous station used for the composite Auckland temperature series was Mangere (Site 4, agent 1945) located on the grounds of the Mangere water treatment plant, Manukau City. This station provided data for the present composite Auckland series for the period April 1976 until July 1998. The station was closed at the beginning of August 1998. The Auckland Aero site could potentially have been used for the composite series from an earlier date, but the Auckland Aero temperature series has a significant data gap from 1993-1994. By using Mangere we avoid having to fill that missing data period.

Annual mean temperatures are available at both the Auckland Aero AWS site and the Mangere site from 1963 until 1997. This overlap allows us to directly compare temperatures at the two sites. We can then determine what adjustment may be necessary in order to make observations at Mangere (Site 4) consistent with those at Auckland Aero AWS (Site 5). Figure 3 shows the overlapping annual mean temperatures[9] at Auckland Sites 4 and 5.

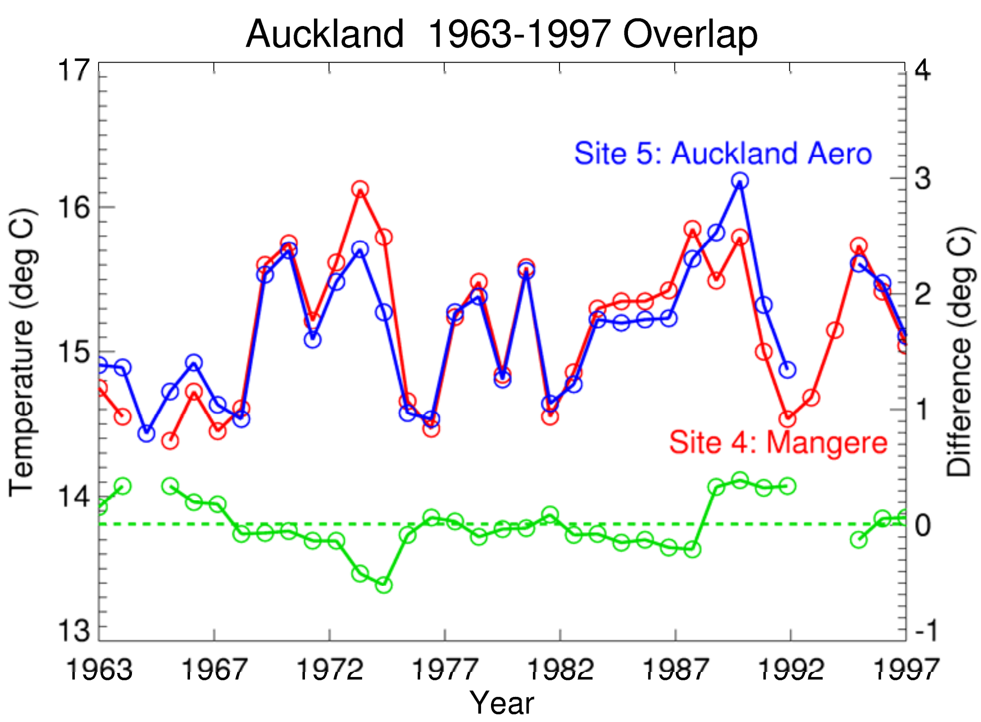

Figure 3: Annual mean temperature series for Mangere (Site 4, agent 1945, red line) and Auckland Aero AWS (Site 5, agent 1962, blue line) from 1963 to 1997. The annual difference, Site 5 minus Site 4, is plotted by the green solid line, using the right-hand ordinate scale, and the mean annual difference is shown, in green, by the dashed line.

From 1963 until 1997, annual mean temperatures at Auckland Aero AWS varied between 0.39 °C warmer and 0.52 °C cooler than those at Mangere. On average, the Auckland Aero site was 0.01 °C warmer than the Mangere site. Therefore, temperatures at Mangere should be adjusted *upwards* by 0.01 °C in order to be

[9] The monthly mean air temperature is missing from Mangere for 1 month in November 1975. The annual mean temperature for this year has been estimated from the existent months in that year. Please refer to Appendix 1 for details.

homogenised with the Auckland Aero AWS reference station.[10] This adjustment of 0.01 °C is consistent with that listed in the February 2010 'Schedule of Adjustments' (offset of 0.0 °C, column 6 of Table 1).

Adjustment for Site Change in 1975/76

From January 1951 until 1976, the composite Auckland temperatures were provided by the Albert Park site (Site 3, agent 1427) using a Bilham-type screen. The Albert Park station was located in an enclosure on the grounds of Albert Park, a large reserve within the Auckland CBD. As a consequence of repeated vandalism, the station was converted to a rainfall-only site in January 1990 and was closed in March 1994. In the previous composite Auckland temperature series, temperatures were provided by Albert Park until December 1975 and then afterwards from the rural Mangere site (Site 4, agent 1945)[11]. In the present composite series we have delayed the transition date by 3 months to April 1976 to avoid a move of the Mangere station in March 1976.

Mean temperatures are available at both the Albert Park site and the Mangere site from 1962 until 1986[12]. This overlap allows us to directly compare temperatures at the two sites. We can then determine what adjustment may be necessary in order to make observations at Albert Park (Site 3) consistent with those at Mangere (Site 4). Figure 4 shows the overlapping annual mean temperatures at Auckland Sites 3 and 4 over a 25-year overlapping period[13].

Ten-year overlap periods before and after the site change in 1976 are used here for consistency with other adjustment calculations. From 1966 until 1986, annual mean temperatures at Albert Park were between 0.40 °C and 0.95 °C warmer than those at Mangere. On average, the Albert Park site was 0.66 °C warmer than the Mangere site. Therefore, temperatures at Albert Park need to be *decreased* by 0.66 °C in order to be consistent with those at Mangere. The final adjustment of temperatures at Albert Park (Site 4, 1951–1976) to the Auckland Aero (Site 5) reference site should be: 0.01 -0.66 = -0.65 °C. This is only slightly larger than the February 2010 'Schedule

[10] This trivially small adjustment could be set to zero. However, even though the estimated adjustment is effectively zero, it has a non-zero uncertainty associated with it, which should be retained for a full assessment of uncertainties in the final trend.

[11] The choice of 1976 as the year for a change from Albert Park to Mangere, as the contributing record to the homogeneous 'Auckland' temperature series, was made for convenience. In the original Auckland series developed in the Salinger 1981 thesis, the data cut-off for trend analyses was 1975. In 1991 when new adjustments were developed (Salinger *et al.*, 1992), Albert Park had closed and so there was no option but to choose another site. Mangere was a sensible choice, and could have been used from 1962 onwards instead of 1976. (From 1960 to 1961, no temperature measurements were made on Sundays or public holidays at Mangere.) However, Figure 4 shows this would have made minimal difference to the Auckland temperature trend from 1960.

[12] Monthly mean air temperatures are missing from Mangere for November 1975. Monthly mean air temperatures are missing from Albert Park in October 1978, December 1984, January and June 1985. Nine months are missing in 1987 at Albert Park. Annual mean temperatures have been estimated from the existent months in those years with no more than 3 missing months, using the climatology for each station. Please refer to Appendix 1 for details.

[13] Only the 21-year period 1966-1986 is used here for calculating the adjustment. For completeness, Mangere temperatures are shown back to the first complete year of its record.

of Adjustments' value of -0.6 °C[14]. It would clearly be erroneous to append the Mangere site temperature record to the Albert Park site record without adjustment when there is such a clear and consistent offset between the two sites due to differing geography and environments.[15]

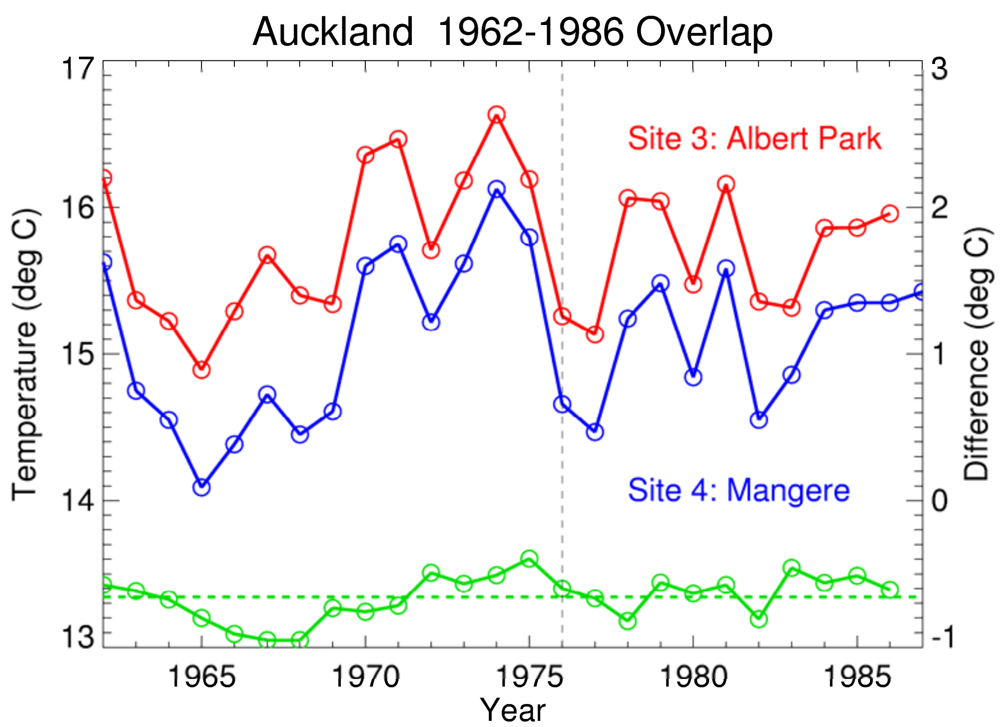

Figure 4: Annual mean temperature series for Albert Park (Site 3, agent 1427, red line) and Mangere (Site 4, agent 1945, blue line) from 1962 to 1986. The annual difference, Site 4 minus Site 3, is plotted by the green solid line, using the right-hand ordinate scale, and the mean annual difference is shown, in green, by the dashed line.

[14] If a shorter overlap of 11 years (1971 to 1981) is used, then the average temperature difference between the sites is -0.59 °C (which would then agree with the February 2010 'Schedule of Adjustments' value).

[15] It may seem surprising that Albert Park is as much as 0.6 to 0.7 °C warmer than Mangere, when the sites are only about 12 km apart and Albert Park is at a higher altitude (Table 1). However, the northern side of the Auckland isthmus (where the CBD is situated) is warmer than any other part of the Auckland region (see Appendix 6), as a result of proximity to the warmer Waitemata Harbour and sheltering from the prevailing west-southwesterly winds. Temperature measurements were made at Mechanics Bay (agent 1428) over 1948-1962, when flying boats were in operation at that site off Tamaki Drive. (Since that time, Mechanics Bay has been filled in and is now reclaimed land). We can compare annual temperatures at Mechanics Bay with those at Owairaka (Mt Albert, towards the southern edge of the Auckland isthmus) and at Albert Park. For the period 1949-1961 (except for 1958, missing at Owairaka), we find that Mechanics Bay has an average of 15.88 °C, Albert Park 15.58 °C and Owairaka 14.71 °C. Thus, Mechanics Bay at sea level is the warmest location of all, about 0.3 °C warmer than Albert Park, which in turn is about 0.9 °C warmer than Owairaka. In later years, when Mangere opened, it was also warmer than Owairaka, but only by about 0.2 °C.

Adjustment for Screen Change in 1950/51

From 1909 until 1950, climate measurements took place at Albert Park in Auckland (Site 3) using a louvred Stevenson screen. In order to measure air temperature accurately, a screen is needed to avoid direct radiation effects, and to provide shelter from precipitation. At the same time the screen should allow airflow over the thermometers. In November 1950 the screen was replaced with an improved Bilham type screen. Such a change in screen type can result in a bias in the temperature data, and is investigated here. (See Appendix 3 for further discussion.) There is no overlap period during which both screen types were used. In such situations, it becomes necessary to compare the before and after temperatures with observations at other stations (comparison sites), in order to determine any potential change in temperature associated with the change of screen type.

Figure 5 shows the correlation of mean temperature interannual differences at the Virtual Climate Station (VCS) grid point containing Auckland Aero (Site 5) with interannual differences at all other locations on the VCS grid from 1972 until 2008 (i.e., 1972-73 difference, 1973-74, … , 2007-08).[16] Auckland Sites 1 to 6 are all less than 20 km from the Auckland Aero site, and so the temperatures at these sites are likely to be well correlated. The map in Figure 5 gives a clear indication of more distant locations at which temperatures are likely to correlate strongly with the sites making up the Auckland composite series.[17]

Not surprisingly, temperature variations at Auckland correlate strongly with those in the Auckland region as a whole, and indeed much of the western North Island, the correlations typically being over +0.95 (a value of +1 indicates perfect correlation). Interannual temperature variations at Auckland also correlate well with those at Masterton (+0.91), Kelburn (+0.88), and Appleby (+0.91).

[16] 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).

[17] The stations to be used in comparisons (‘comparison stations’) ideally ought to have experienced the same broad climatic influences as the Auckland sites (‘candidate stations’), but should have a homogeneous record of temperature over the period of comparison (Aguilar *et al.*, 2003). The homogeneity of comparison stations is assessed by analysing ‘metadata’ from station histories and looking for stations at which no significant site changes occurred during the period of comparison. This becomes more difficult in earlier years, when fewer climate stations were in operation and station histories are often less complete. Comparison stations may differ from those used in Salinger (1981) if metadata indicate that a site change may have occurred during the period of comparison.

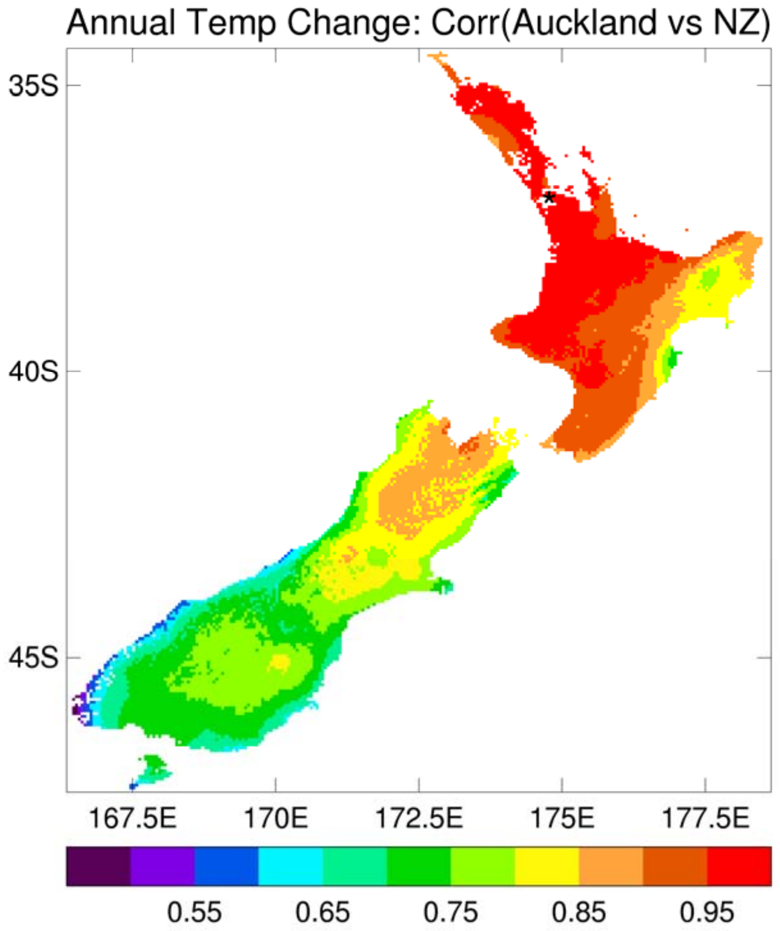

Figure 5: Map of correlation between interannual temperature changes at the grid-point nearest to Auckland Aero (Site 5, location marked by asterisk) near Auckland, 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

Figure 6 compares annual temperatures over the period 1940–1960 (10 years before and after the screen change) at Albert Park with five comparison stations with overlapping records. These sites were chosen on the basis of the completeness of the overlapping record, with a target of 20 years overlap. In addition the comparison station was required to have a high correlation (> 0.9) with Albert Park temperature variations. Suitable comparison stations were found to be Waipoua Visitor Centre (agent 1155), Riverhead Forest (agent 1405), Waiuku Forest (agent 2011), Te Aroha (agent 1565), and Hamilton, Ruakura (agent 2101) with correlations with Albert Park of 0.90, 0.92, 0.94, 0.93, 0.91 respectively.[18] Riverhead Forest was used only between the years 1945 to 1960 in order to avoid the screen change there in 1944. Other potential comparison sites which had site changes themselves during the 20 year period (Waihi, Tauranga) were avoided in the analysis. Wellington was not used because it displayed a weaker correlation (0.64) with Albert Park than with the other

[18] Monthly mean air temperatures are missing from Waipoua for 2 months in 1952, 1 month in each of 1955, 1956 and 1960, Te Aroha for 1 month in each of May 1951, July 1953, May 1955, December 1958, and for 1 month at Ruakura in January 1946. Annual mean temperatures have been estimated from the existent months in those years. Please refer to Appendix 1 for details. Please also refer to Footnote #8 in the Nelson review document for information on how these correlations are calculated across a site change boundary.

five comparison sites for this time period. The comparison stations are compared with Albert Park to determine appropriate corrections for the enclosure change in 1950.

Before the screen change in 1951, Albert Park (Site 3) was on average 1.23 °C 0warmer than Waipoua (Figure 6, top). After the screen change, Albert Park was on average 1.27 °C warmer than Waipoua. Thus, when compared with Waipoua, Albert Park before the screen change was 0.04 °C cooler than after the screen change.

This process of comparison is now repeated for the other stations in Figure 6. Before the screen change in 1951, Albert Park (Site 3) was on average 1.94 °C warmer than Riverhead Forest (Figure 6, middle left). After the screen change, Albert Park (Site 3) was on average 1.85 °C warmer than Riverhead Forest. Thus, when compared with Riverhead Forest, Albert Park before the screen change was 0.09 °C warmer than after the screen change. Before the screen change, Albert Park was on average 1.21°C warmer than Waiuku Forest (Figure 6, middle right). After the screen change, Albert Park was on average 1.04 °C warmer than Waiuku Forest. Thus, when compared with Waiuku Forest, Albert Park before the screen change was 0.17 °C warmer than after the screen change.

Before the screen change, Albert Park was on average 0.73 °C warmer than Te Aroha (Figure 6, lower left). After the screen change, Albert Park was on average 0.92 °C warmer than Te Aroha. Thus, when compared with Te Aroha, Albert Park before the screen change was 0.19 °C cooler than after the screen change.

Finally, before the screen change, Albert Park was on average 2.20 °C warmer than Hamilton, Ruakura (Figure 6, lower right). After the screen change, Albert Park was on average 2.38 °C warmer than Hamilton, Ruakura. Thus, when compared with Hamilton, Ruakura, Albert Park before the screen change was 0.18 °C cooler than after the screen change.

After averaging the five shifts (0.04 °C, -0.09 °C, -0.17 °C, 0.19 °C and 0.18 °C), we estimate that Albert Park before the screen change was 0.03 °C cooler than after the screen change[19]. Thus the effect of the screen change on the mean temperature was very small. The final adjustment of temperatures at Albert Park before the screen change (Site 3, 1909–1950) to Mangere (Site 4) should be: 0.01 -0.66 + 0.03 = -0.62 °C. After rounding to one decimal place, this is -0.6 °C which is slightly larger than the February 2010 'Schedule of Adjustments' value of -0.5°C.

Site Adjustments Prior to 1910

Temperature data prior to the start of Site 3 in September 1909 are not included in the revised composite series for Auckland. However, see Appendix 4 for a discussion of estimated adjustments for Sites 1 and 2.

[19] This trivially small adjustment could be set to zero. However, even though the estimated adjustment is effectively zero, it has a non-zero uncertainty associated with it, which should be retained for a full assessment of uncertainties in the final trend. Moreover, larger adjustments are required for the maximum and minimum temperature series (not discussed here, but see Appendix 3), and the adjustment for the mean temperature must be consistent (i.e., the average of the maximum and minimum adjustments).

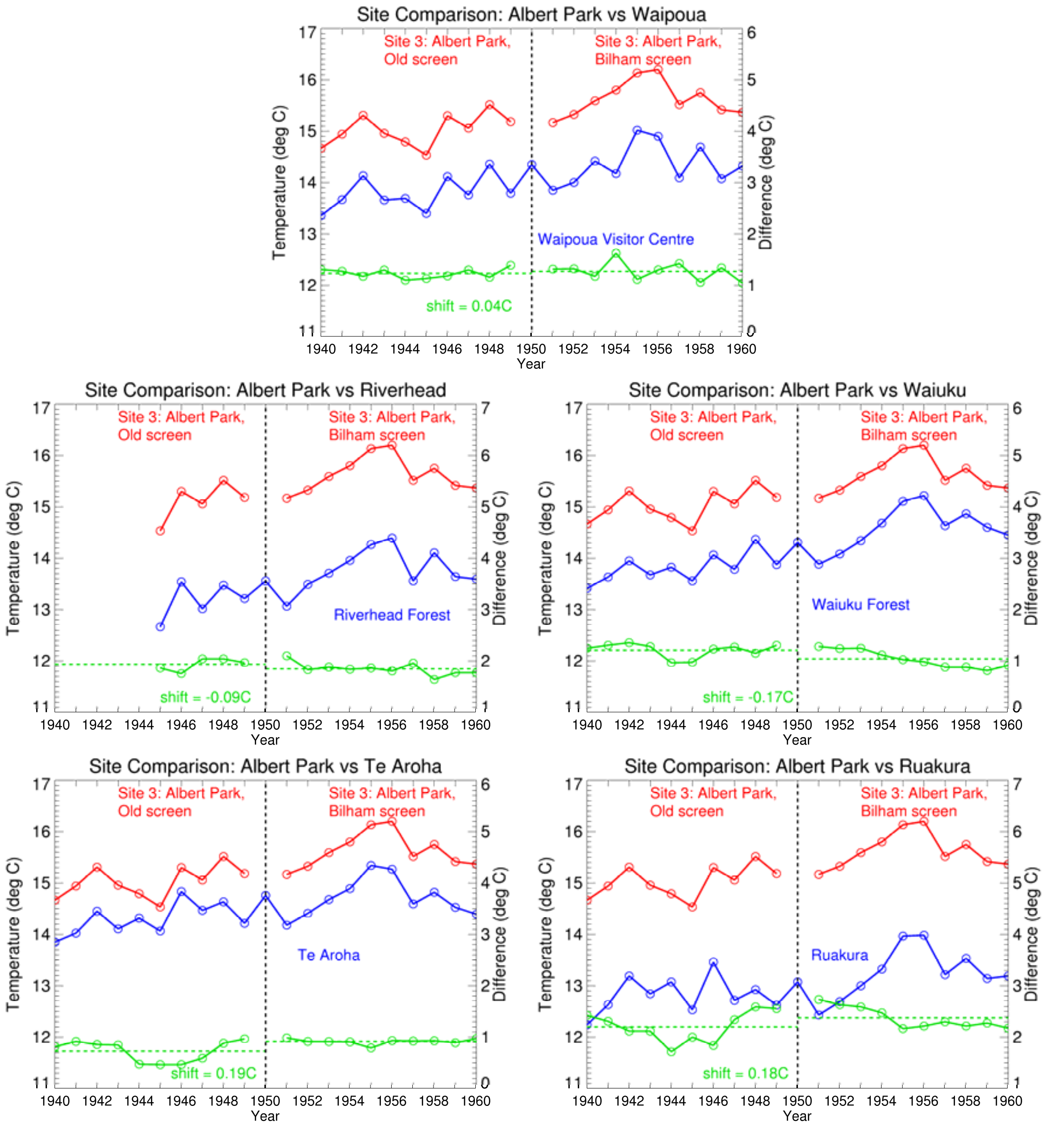

Figure 6: Comparisons of annual mean temperature series at Albert Park (Site 3, agent 1427, red lines on each plot) before and after the screen change in 1950/51 with Waipoua Visitor Centre (agent 1155), Riverhead Forest (agent 1405), Waiuku Forest (agent 2011), Te Aroha (agent 1565), Hamilton, Ruakura (agent 2101), from 1941 to 1960. The solid blue lines in each plot show the temperatures at these comparison stations. The differences (Albert Park minus each of the other stations) are indicated by the green solid lines, using the right-hand ordinate scale, and the mean differences (before and after the screen change) are shown by the dashed lines. The year of the screen change at Albert Park, 1951, is indicated by the vertical dashed line in the centre of each plot.

Putting the Time Series Together

The various adjustments described above can be applied successively to the Auckland temperature record. The resulting annual time series from 1900 to 2009 is shown in Figure 7, including a comparison with the previous Auckland time series used by NIWA[20]. A linear trend has been fitted to each series. The linear trend is 1.53 (± 0.32) °C /century[21]. The previous trend was 1.34 °C /century. Note that the revised series uses Auckland Aero AWS from August 1998 onwards, whereas the series published in February 2010 used Auckland Aero AWS only up to April 2002, and Mangere EWS thereafter. A start date of 1910 was used for the trend in Figure 7 so that the less reliable data prior to the site change in September 1909 did not influence the trend. If the 1909 year was included, the previous trend changed slightly to 1.29 °C /century (no annual value has been calculated for 1909 in the revised series since there are 4 missing months that year).

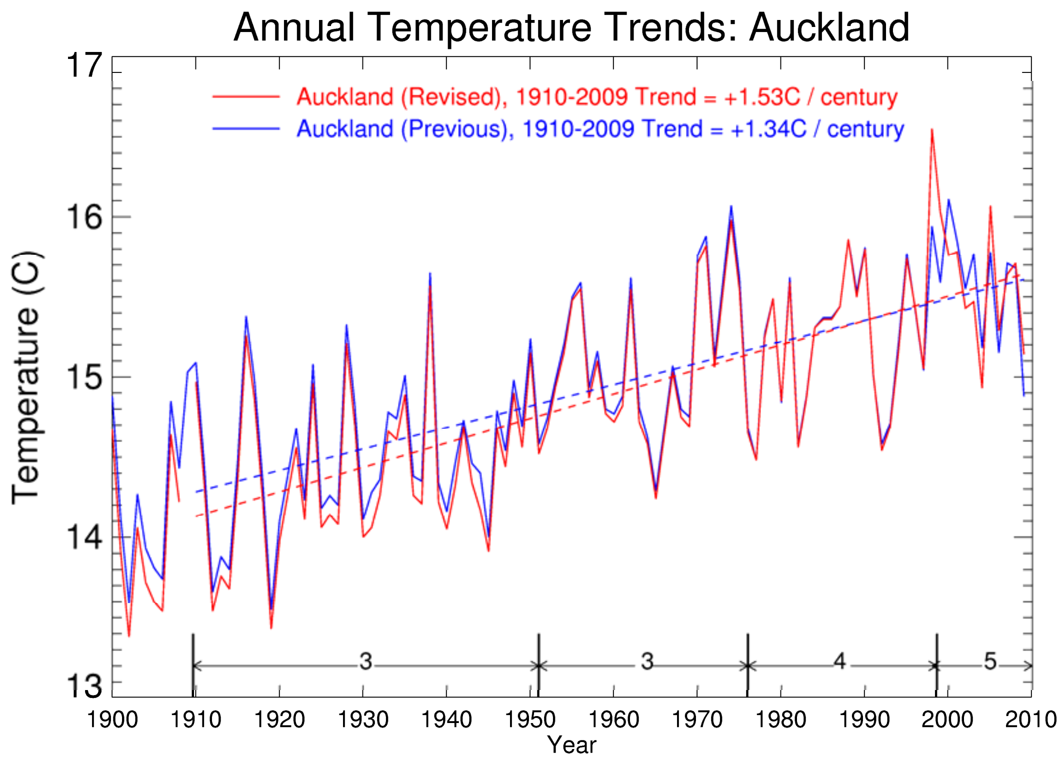

Figure 7: Comparison of the revised composite series of annual mean air temperatures for Auckland (red line) to the previous NIWA Auckland series (blue line) from 1900 to 2009. The dashed lines show the fitted linear trends from 1910 to 2009. Auckland site labels from Table 1 are displayed at the bottom of the plot.

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[20] The present analysis shows a higher temperature for 1998 than the previous record; this was globally one of the warmest years of the 20th Century. This has a small effect on the trend (0.06 °C /century). The Auckland annual temperatures 1998-2004 in the spreadsheet published February 2010 are incorrect, owing to an error in compiling the data for the spreadsheet.

[21] The uncertainty is the 2-standard deviation uncertainty estimate of the least squares linear fit to the composite temperature time series.

Figure 8 repeats the graph of the revised composite annual mean temperature series for Auckland, and compares the composite with the unadjusted raw multi-site temperatures. For the period 1998-2010 the two series are identical, since this period is covered by the Auckland reference site (Auckland Aero, Site 5) for which no adjustment is applied. The adjustments are also shown in Figure 8, in green. The adjustments are cumulative relative to Auckland Aero Site 5, and correspond to those in the final column of Table 1.

The trend over 1909-2009 for the revised composite Auckland series is now substantially larger than at any of the other seven-station-series locations, and also larger than trends in surrounding sea surface temperature.[22] This suggests there could be some residual non-climatic warming in the Auckland record, after adjustment for the sudden discontinuities. Appendix 5 discusses long-term biases in the Auckland record. Our conclusions, which are still preliminary at this stage, are that the warming trend in Figure 7 of +1.5°C/century may be too high by about 0.3°C per century.

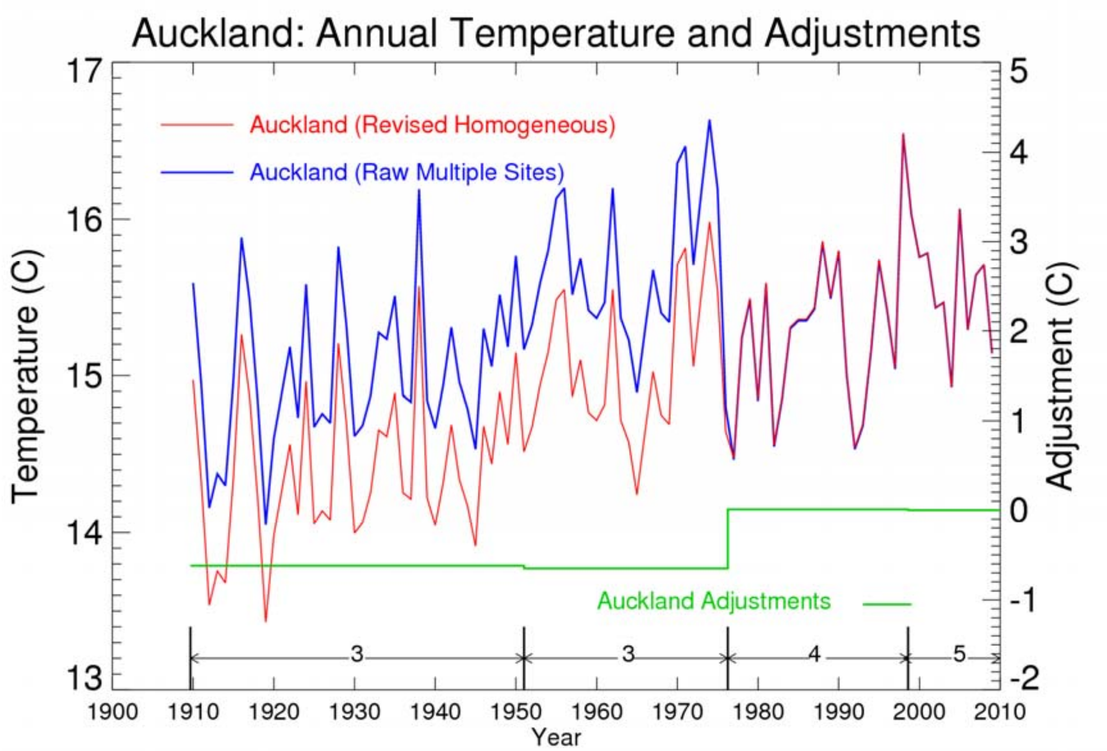

Figure 8: Comparison of the revised composite temperature series for Auckland from 1910 to 2009 (red line), with the raw multi-site series (Sites 3-5, blue line). The green line (using right-hand axis) indicates the cumulative step adjustments to each site as shown at the bottom of the graph, and corresponds to the adjustments in the right-hand column of Table 1.

[22] See review documents for the other 6 locations comprising the "seven-station" series, and the overview or synthesis document, where further discussion is given of spatial and temporal trend patterns.

Further Information

Further technical information on different approaches to homogeneity adjustment of climate data can be found in the references below (Aguilar *et al*., 2003; Peterson *et al*., 1998; Rhoades and Salinger 1993).

Date: Document originally created 29 October 2010, and revised 13 December 2010 following review from the Australian Bureau of Meteorology.

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Appendix 1

Technical note on the treatment of missing data

Annual values could be calculated and plotted for only those years with no missing months, but this would potentially discard a lot of useful information. If only a small number of months are missing from a station in a given year, we can estimate the annual mean temperature in that year by calculating the annual anomaly from the existent months.

First, climatologies and anomalies from climatologies are calculated for each calendar month over a thirty year period when available. An annual climatology for the whole period is then calculated by averaging the monthly climatologies. The annual anomaly is then calculated for each year across the period, by averaging the anomalies of the non-missing months. Finally, the annual mean temperature for the missing years is estimated by adding each calculated annual anomaly to the annual climatology. Examples are shown in detail in Appendix 2 of the NIWA review document for Masterton: ‘Creating a Composite Temperature Series for Masterton’.

Appendix 2

Adjustment for Mangere EWS in 2002

Mangere EWS (agent 22719) is a new station located in a well-exposed area on the grounds of the Mangere water treatment plant, Manukau City (Figure 2), close to where the earlier Mangere site (agent 1945) was located. This is a rural area. Mangere EWS first opened in April 2002, and 2003 is the first complete year when annual mean temperatures are available in the NIWA Climate Database. While it is not used in the present analysis, in the previous analysis Mangere EWS contributed temperatures to the composite temperature series for Auckland from May 2002 onward.

Annual mean temperatures are available at both the Auckland Aero AWS and the Mangere EWS from 2003 until 2009. This overlap allows us to directly compare temperatures at the two sites. We can then determine what adjustment may be necessary in order to make observations at Mangere EWS (Site 6) consistent with those at Auckland Aero AWS (Site 5). Figure A2.1 shows the overlapping annual mean temperatures at Auckland Sites 5 and 6.

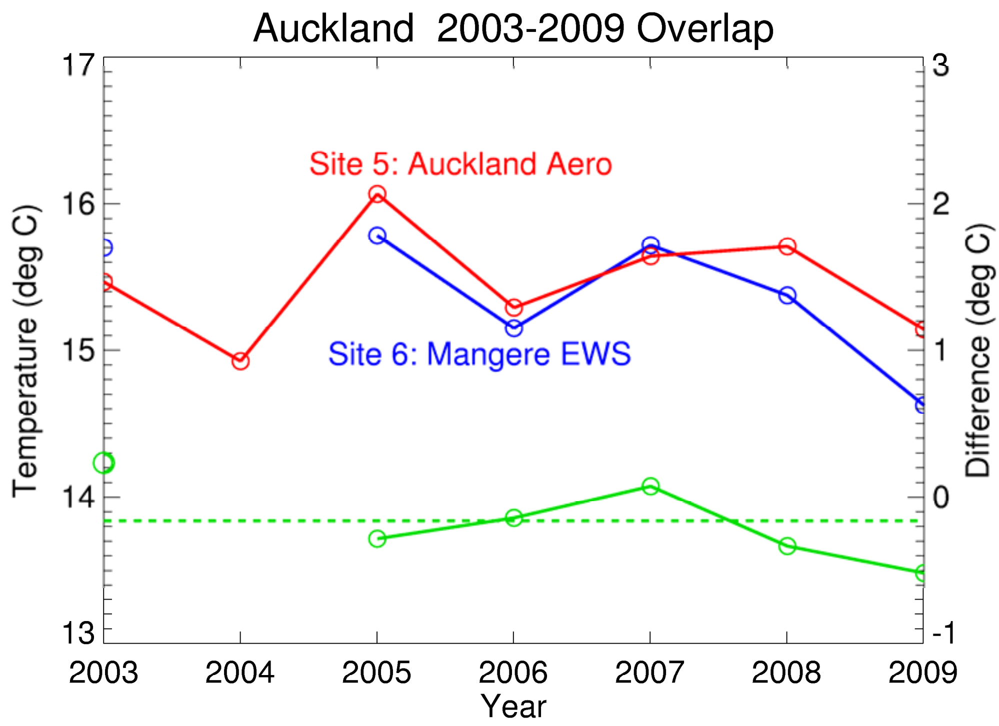

Figure A2.1: Annual mean temperature series for Auckland Aero AWS (Site 5, agent 1962, red line) from 2003 to 2009, and Mangere EWS (Site 6, agent 22719, blue line) from 2005 to 2009 and for the year 2003 (blue circle). The annual difference, Site 6 minus Site 5, is plotted by the green solid line, using the right-hand ordinate scale, and the mean annual difference is shown, in green, by the dashed line. Data are unavailable at Mangere EWS for 2004.

In 2004, three months (February, March, April) were missing from the Mangere EWS series. These data have not been infilled with climatological data due to the short period of the climatology available for this station. From 2003 until 2009 (leaving out 2004), annual mean temperatures at Auckland Aero AWS varied between 0.23 °C cooler and 0.52 °C warmer than those at Mangere EWS. On average, the Auckland Aero site was 0.16 °C warmer than the Mangere EWS site. However, close examination of the monthly temperatures shows that there is a marked change in the difference between these sites after mid-2008. In the first five years of the overlap (2003–2007) the average difference between the sites is 0.03 °C (Auckland Aero warmer than Mangere); while in the last two years (2008–2009) Auckland Aero is on average 0.43°C warmer than Mangere. A subsequent field check found that the Mangere EWS temperature sensor was indeed reading too low, and it was replaced in June 2009. Based on a comparison of monthly mean temperatures with Auckland Aero, the Mangere EWS series should be adjusted up 0.6 °C between May 2008 and June 2009[23]. The effect on annual temperatures is less since the correction is needed for only a part of each year.

[23] This instrument error at Mangere EWS was picked up by NIWA staff in mid-2009 from a comparison of nearby sites, as described above. The corrections applied at the time, which were incorporated into the version of the “7-station” series published in February 2010 were: add +0.2 °C for May 2008, and then +0.5 °C for June 2008 to June 2009 inclusive. The revised analysis in this document suggests a slightly larger correction should have been applied. Note that because we cannot

Therefore, annual mean temperatures at Mangere EWS between 2003 and 2007 (i.e., before the fault with the thermometer) should be adjusted up 0.03 °C to be consistent with Auckland Aero AWS. This adjustment of 0.0 °C to 1 decimal place is consistent with that listed in the published 'Schedule of Adjustments'.

However, annual mean temperatures at Mangere EWS between 2008 and 2009 should be *increased* by 0.43 °C in order to be consistent with Auckland Aero and earlier measurements at Mangere EWS. This adjustment is due to the instrument fault at Mangere EWS. It is not listed explicitly in the February 2010 published 'Schedule of Adjustments', but was corrected for at the time.

In order to minimise uncertainties in the Auckland composite series, the Auckland Aero AWS has been used in place of Mangere EWS in the present document for the composite series. At some future date, when the Mangere EWS climatology is better established, its use in the composite series may be reinstated.

Appendix 3

Further discussion of 1950/51 Albert Park screen change

Hessell (1980) considered the effect of the screen change at Albert Park in 1950 by comparing the average temperature for five years either side of the screen change at Albert Park. He found a 0.5 °C increase. He did note that the 0.5 °C "may include a short period synoptic scale secular increase". However, without considering other sites, he went on to attribute 0.4 °C to the screen change. When we repeat that analysis here, we also find a 0.5 °C temperature increase at Albert Park after 1950. However it can be seen in Figure 6 that the temperature at other nearby sites also increased in a similar fashion.

In Figure A3.1 we show in more detail a comparison with Riverhead Forest and with Waiuku Forest, which also increased by 0.5 °C after 1950. This makes it clear that the 0.5 °C change was <u>largely</u> due to the "short period synoptic scale secular increase" referred to by Hessell (1980) and had little to do with the change in screen. This emphasises the need to refer temperature changes to comparison sites when an overlap is unavailable.

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be certain of the exact correction (particularly on a daily basis), the NIWA Climate Database still contains the temperatures as measured.

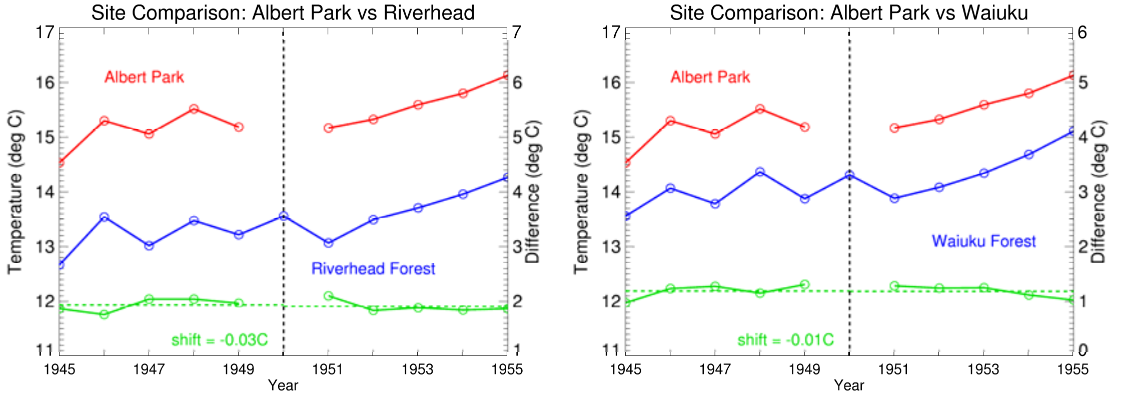

Figure A3.1: Comparisons of annual mean temperature series at Albert Park (Site 3, agent 1427, red lines on the left of each plot) with Riverhead Forest (agent 1405) and Waiuku Forest (agent 2011) from 1945 to 1955, which is the same period as Hessell (1980). The solid blue line shows the temperatures at these comparison stations. The differences (Albert Park minus each of the other stations) are indicated by the green solid lines, using the right-hand ordinate scale, and the mean differences (before and after the site change) are shown by the dashed lines. The year of the screen change, 1950, is indicated by the vertical dashed line in the centre of each plot. Temperatures at both Riverhead Forest and Waiuku Forest increase after 1950 in a similar way to Albert Park.

Although the screen change had a minimal effect on the mean temperature, there were measurable effects on the maximum and minimum temperature series. The effect is clearest on the maximum temperatures, shown in Figure A3.2. Just as there was a change to a Bilham screen in 1950 at Albert Park, there had been a similar screen change in 1944 at Riverhead Forest. For this reason, the comparison in Figure A3.1 does not extended prior to 1945. However, Figure A3.2 illustrates a longer period that encompasses the screen changes at both sites. Higher maximum temperatures are observed with the new screen. Prior to 1945, Albert Park has a higher annual-average maximum than Riverhead (by +0.27 °C over 1935-44). When Riverhead changed to a Bilham screen, its maximum temperature increased (by +0.43 °C over 1944-50) to be above that for Albert Park. Then, when Albert Park received its new screen, its maximum temperature rose (by +0.36 °C over 1951-60) to again be warmer than Riverhead.

So there is an increase of about 0.4 °C in maximum temperature with the introduction of the Bilham screen. Conversely, the minimum temperature decreases, and the net result on the mean temperature is therefore quite small.

The original comparison of the Bilham screen with the unmodified Stevenson screen is described in Bilham (1937). The two screen designs were tested at Kew Observatory during 1932 and 1933. Over this period, the Bilham screen temperatures (relative to the older design) were: 0.31 °F higher for the maximum (i.e., +0.17 °C), 0.14 °F lower for the minimum (-0.08 °C), and 0.09 °F higher for the mean (+0.05 °C).

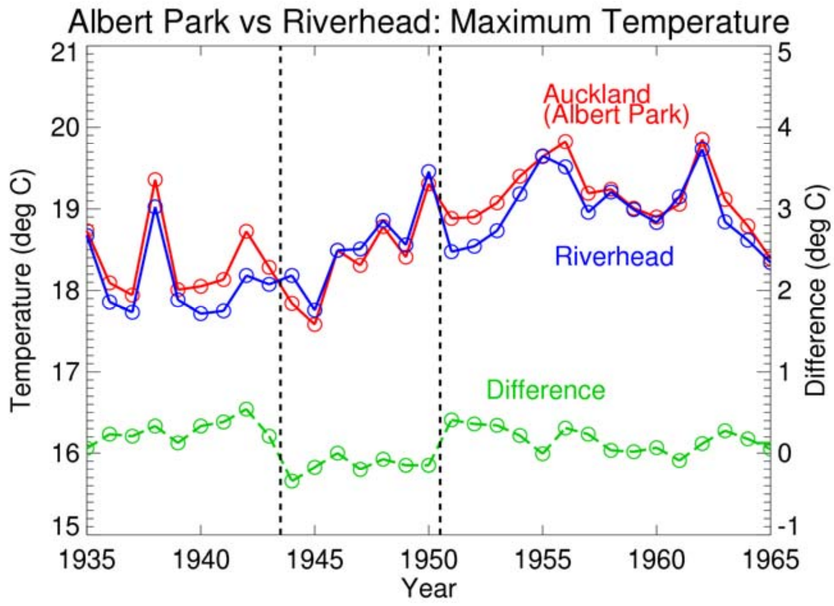

Figure A3.2: Comparison of annually averaged maximum temperature series at Albert Park (Site 3, agent 1427, red line) with Riverhead Forest (agent 1405, blue line) from 1935 to 1965. The difference (Albert Park minus Riverhead) is indicated by the green dashed line, using the right-hand ordinate scale. The years of the screen changes are indicated by the vertical dashed lines: between 1943 and 1944 for Riverhead, and between 1950 and 1951 for Auckland Albert Park. In both cases maximum temperatures increase with the change to a Bilham screen.

Appendix 4

Adjustment for Site Change in 1909

From April 1883 until August 1909, temperature measurements for the Albert Park site (Site 2 in Table 1) were observed from the roof of the Museum at the corner of Princes and Shortland streets, Auckland. The NZ Meteorological Service historical notes dated 29th May 1936 comment that "the station had the usual drawbacks associated with the roofs of buildings". In September 1909 the site changed to the Albert Park enclosure. There is no overlap period for these two sites, but we can estimate the difference in temperature by comparison with other sites.

Figure A4.1 compares annual temperatures at the Museum (Site 2) and Albert Park (Site 3) with stations in Lincoln and Dunedin 4 or 5 years before and after the site change[24], from 1905 to 1913. Before the 1909 site change, the Museum was, on average, 2.91 °C warmer than Lincoln (Figure A4.1, left). After the 1909 site change, temperatures at Albert Park were, on average, 2.82 °C warmer than Lincoln. Therefore, by comparison to Lincoln, the Museum site is estimated as being 0.09 °C warmer than the Albert Park enclosure.

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[24] In this instance, a longer period before and after the site change was not possible owing to changes at the comparison sites or missing data.

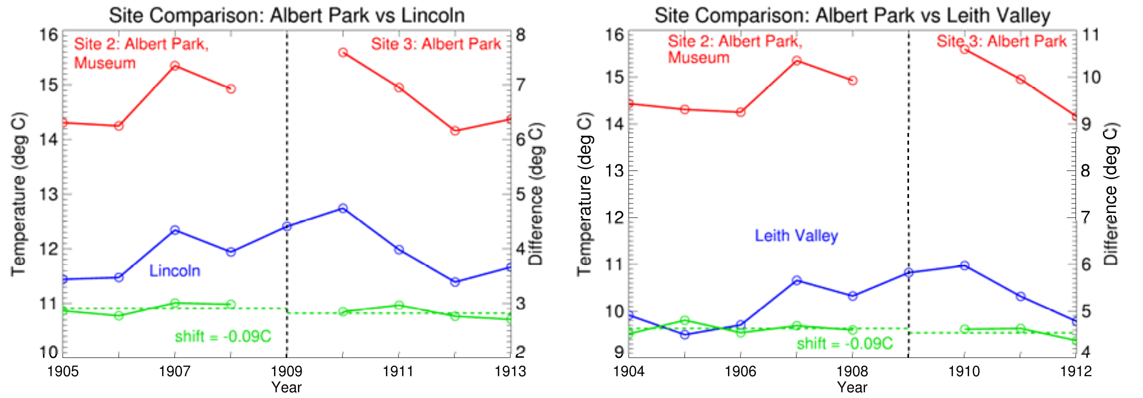

Figure A4.1: Comparisons of annual mean temperature series at the Museum (Site 2, agent 1427, red lines on the left of each plot) and Albert Park (Site 3, agent 1427, red lines on the right of each plot) with Lincoln (agent 4881) from 1905 to 1913, and Dunedin, Leith Valley (agent 5380) from 1904 to 1912. The solid blue line shows the temperatures at these comparison stations. The differences (Museum/Albert Park minus each of the other stations) are indicated by the green solid lines, using the right-hand ordinate scale, and the mean differences (before and after the site change) are shown by the dashed lines. The year of the site change from the Museum to Albert Park, 1909, is indicated by the vertical dashed line in the centre of each plot.

Repeating the same comparison process with Leith Valley, Dunedin (Figure A4.1, right), we also find that the Museum site was 0.09 °C warmer than Albert Park[25].

After averaging the two identical shifts (0.09 °C and 0.09 °C), we estimate that the Museum (Site 2) was, on average, 0.09 °C warmer than Albert Park (Site 3).[26] The final adjustment required to make observations at the Museum (Site 2) consistent with those at Auckland Aero (Site 5) should therefore be: 0.01 -0.66 + 0.03 -0.09 = -0.71 °C. In the ‘Schedule of Adjustments’, the adjustment of -0.71 °C has been applied to temperatures at the Museum (Site 2) from January 1900 onwards.

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25 Monthly mean air temperatures are missing from Dunedin for 1 month in August 1909 and November 1912. Annual mean temperatures have been estimated from the existent months in those years. Please refer to Appendix 1 for details.

26 In the Hokitika document (posted February 2010 on the NIWA website), it was noted that measured Hokitika temperatures were too warm during 1894-1912 due to a cramped meteorological enclosure near a building. A correction was estimated by comparison with Christchurch Gardens (implying the pre-1912 mean temperatures at Hokitika were 1.24 °C too warm), and with Auckland (implying the pre-1912 temperatures at Hokitika were 1.06 °C too warm). However, the Auckland comparison assumed no temperature discontinuity at Auckland across the Museum to Albert Park site shift (consistent with the adjustments published at the time; see column 6 of Table 1). The revised adjustment described above leads us to conclude that the Auckland-Hokitika comparison would imply the pre-1912 temperatures at Hokitika were 1.15 °C too warm (a slightly better agreement with the 1.24°C from the Christchurch-Hokitika comparison).

Adjustment for Site Change in 1883

From May 1868 until March 1883, temperature measurements for the Albert Park site (Site 1 in Table 1) were observed at the Government Domain, Auckland. The NZ Meteorological Service historical notes of 1936 caution that "A louvred screen was used but it was probably of a massive type and in some respects unsatisfactory. The temperature records suggest this". In April 1883 the site changed to the roof of the Museum, at a lower altitude. There is no overlap period for these two sites, but we can estimate any potential change in temperature by comparison with other sites.

When stations which had been shifted during the period of interest were eliminated, only a single station had a record with more than 2 years either side of the site change: Wellington at the Bolton Cemetery. The correlation coefficient between this station and Albert Park was 0.75 over a 20 year overlap period. Lincoln has 2 years of data before the change and Dunedin, Roslyn two years after the change, but this period of comparison data is not sufficient for a robust difference estimate. Figure A4.2 compares annual temperatures at the Domain (Site 1) and the Museum (Site 2) with the station in Wellington for the 10 years before and after the site change, from 1873 to 1893[27]. Before the 1883 site change, the Domain was, on average, 2.17 °C warmer than Wellington (Figure A4.2). After the 1883 site change, temperatures at the Museum were, on average, 2.26 °C warmer than Wellington. Therefore, by comparison with Wellington, the Domain site was 0.09 °C cooler than the Museum site.

The final adjustment required to make observations at the Domain (Site 1) consistent with those at Auckland Aero (Site 5) should therefore be: 0.01 -0.66 + 0.03 -0.09 + 0.09 = -0.62 °C. Owing to the greater uncertainty in early temperature measurements, the revised Auckland time series does not use this early data, but we have nevertheless included our estimated adjustment in Table 1. However, note that both the original adjustment (i.e., from Salinger *et al*., 1992, given in column 6 of Table 1) and this revised adjustment suggest that temperatures at the Domain and Albert Park are homogeneous (i.e., very little offset between the pre-1883 and post-1909 mean temperatures).

[27] Monthly mean air temperatures are missing from Wellington in January, February and March 1884. The annual mean temperature has been estimated from the existent months in that year. Please refer to Appendix 1 for details. The effect of infilling was to modify the temperature change by 0.01 ^{o}C.

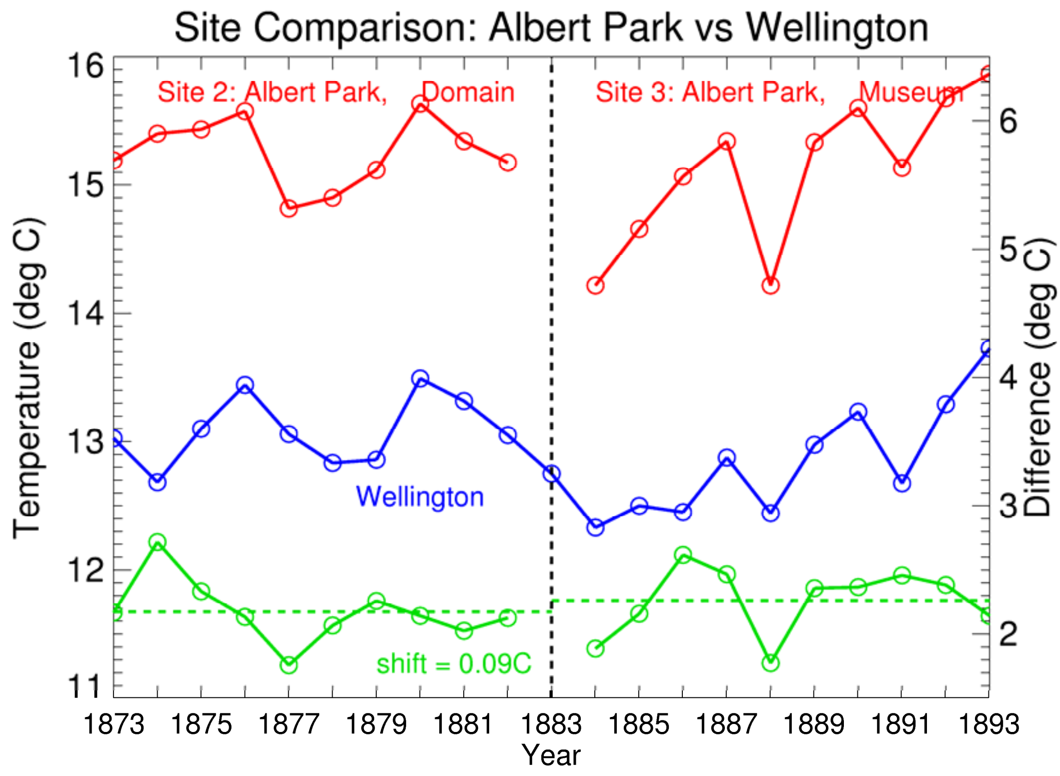

Figure A4.2: Comparisons of annual mean temperature series at the Domain (Site 1, agent 1427, red lines on the left of the plot) and the Museum (Site 2, agent 1427, red lines on the right of the plot) with Wellington, Bolton Street Cemetery (agent 3390, blue line). The differences (Domain/Museum minus Wellington) are indicated by the green solid lines, using the right-hand ordinate scale, and the mean differences (before and after the site change) are shown by the dashed lines. The year of the site change from the Domain to the Museum, 1883, is indicated by the vertical dashed line in the centre of each plot.

Appendix 5

Technical note on sheltering/urban heating effects at Albert Park

The 100-year trend in the Auckland composite temperature series is substantially higher than the warming trends found at the other six locations of the "7-station" series. An obvious question to ask, therefore, is whether the Auckland series has been affected by environment influences such as urban heating or sheltering because of tree growth. It is noted in the NZ Meteorological Service station histories (Fouhy *et al.*, 1992) that trees around the site cut off a certain amount of sunshine and had a considerable effect on wind flow. Just how this (or urban growth) affected the temperature series is not easy to determine. Salinger (1981, Appendix C) claimed that the trees "reached their maximum height in 1930 and it is not expected that they will further affect the exposure." However, the heights of buildings in the Auckland CBD have increased steadily over the years, and it is feasible that this has led to additional sheltering post-1930.[28]

[28] Wind-run data can be helpful in assessing sheltering. Hessell (1980, Figure 3) showed a graph of Albert Park wind data from 1918, although the NIWA climate database does not currently have digitised monthly wind-run data prior to 1946.

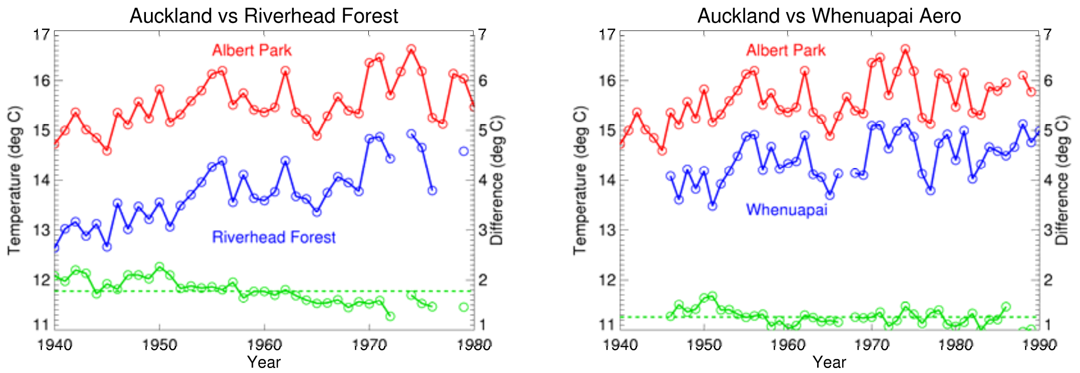

Figure A5.1: Comparison of composite annual temperatures for Auckland Albert Park with Riverhead Forest from 1940 to 1980 (left panel), and Whenuapai Aero from 1940 to 1990 (right panel). The green line indicates the temperature difference, Albert Park minus the other site. Riverhead Forest and Whenuapai are the only sites within 50 km of Albert Park with temperature series prior to 1948 (Riverhead starting in 1928, and Whenuapai in 1945).

It is important to compare the composite series with other long series where possible, but sites close to Auckland with such a long series are lacking. Figure A5.1 compares annual mean temperatures at Albert Park with two other local sites with shorter records: Riverhead Forest (agent 1405) and Whenuapai Aero (agent 1410), which both lie on the northern side of Auckland City (see Figure 2). The difference between Albert Park and Riverhead Forest trends down over time (green line, Figure A5.1), indicating that Riverhead is warming faster than Albert Park.[29] For Whenuapai, there is no trend relative to Albert Park over the period of overlapping record. It has already been noted that post-1960 there is no relative trend between Mangere and Albert Park either. On the other hand, distant sites such as Kelburn or Appleby clearly have smaller warming trends than Albert Park over the 20th century.

The approach usually taken to diagnose the source of non-climatic warming is to examine the trends in maximum and minimum temperature separately. If urban heating was affecting the temperature series, we might expect to see this most strongly in the minimum temperatures increasing faster than those at a rural site. If sheltering was the dominant influence, we might expect to see a decreasing minimum and increasing maximum relative to an unaffected series.

Two sites some distance from Auckland have records that seem reasonable from 1928 onwards: Te Aroha and Waipoua Forest. Two further sites in the northern North Island, Ruakura[30] near Hamilton and Tauranga[31], were considered as comparison

[29] The stronger warming trend at Riverhead Forest relative to Albert Park is due to the trend in the minimum temperature. Forested sites in New Zealand are often noticeably warmer than non-forested ones.

[30] The temperature record at Ruakura, near Hamilton, starts in November 1906, but is missing (climate station closed) during September 1913 to March 1921. Moreover, there were several early site moves (in 1928, 1936 and 1939), and Salinger (1981) considered the Ruakura record to be of dubious value before October 1939.

[31] Tauranga Aero (agent 1612) moved from the Judea site (2.5 miles southwest of Tauranga Post Office) to a farm at Te Puna (5.5 miles west of Tauranga) in September 1940, and then to the aerodrome in February 1941, at which time a Bilham screen was also introduced. There was a site move to a different location within the airport grounds in November 1971, and the station closed at the end of February 1989.

sites, but their early records are rather dubious because of site changes. Figure A5.2 compares mean, minimum and maximum temperatures at Albert Park with those at Te Aroha[32] and Waipoua Forest. The Te Aroha measurements were taken in the domain of this small town, and the record is considered reliable from 1928 onwards with no significant site change. The Te Aroha temperatures prior to 1928, although shown in Figure A5.2 for completeness, should not be used for assessing temperature trends due to the problems described in the footnote.

Figure A5.2 suggests greater warming in the maximum temperatures at Auckland relative to the other two sites. A linear trend has been fitted to the difference curves for the period 1928-1960. The maximum temperature at Albert Park increases faster than at Te Aroha and Waipoua, by about +0.2 °C per decade over 1928-1960. Conversely, the minimum temperature at Albert Park increases more slowly than that at the two comparison sites. In the case of Te Aroha, the net effect on the mean temperature is +0.09 °C/decade relative warming at Albert Park; for Waipoua, the relative trends in maximum and minimum cancel out.

This result would suggest a sheltering influence could be affecting the Albert Park record through at least the period 1928-1960. If the Te Aroha differential is taken as an approximate measure of the sheltering effect, then the Albert Park record of mean temperature shows warming by about 0.3 °C more than it ‘should’ over 1928-1960 (and maximum temperature by twice the amount). Before 1928, it is difficult to draw a conclusion, although it should be noted that the trend in the actual temperatures (as opposed to the differential with another site) is smaller pre-1928 than post-1928.[33]

Reducing the Auckland warming by 0.3 °C would reduce its century trend and bring it more in line with those at other New Zealand locations. However, further research is required to provide more confident bounds on the correction of the early Auckland record for non-climatic warming.

[32] The Te Aroha record started in April 1888, with a gap of 12 years 1896-1907, and closed in October 1999. However, the record prior to 1928 had many problems. The very early observations 1888-1895 were probably under non-standard conditions and biased high. From 1907 to 1922, temperatures were recorded to the nearest degree Fahrenheit only, and during 1913-1922 over half the daily minimum temperatures listed end in zero (i.e., a multiple of 10°F). It is recorded that in January 1923 asphalt was removed from around the screen. Several instances of faulty thermometers were reported subsequently in the 1920s. Missing values become frequent towards the end of the record (1970s onwards), and shortly before the station closure the inspector’s report notes “Not a satisfactory station. No Met301 [the monthly return of daily observations] sighted for many years.”

[33] Using the previous Auckland mean temperature series (February 2010 version, equivalent to the revised series up to the screen change in 1950/51), the linear trend over 1909-1930 is +0.02 °C/decade, in contrast to +0.16 °C/decade for the period 1928-1960.

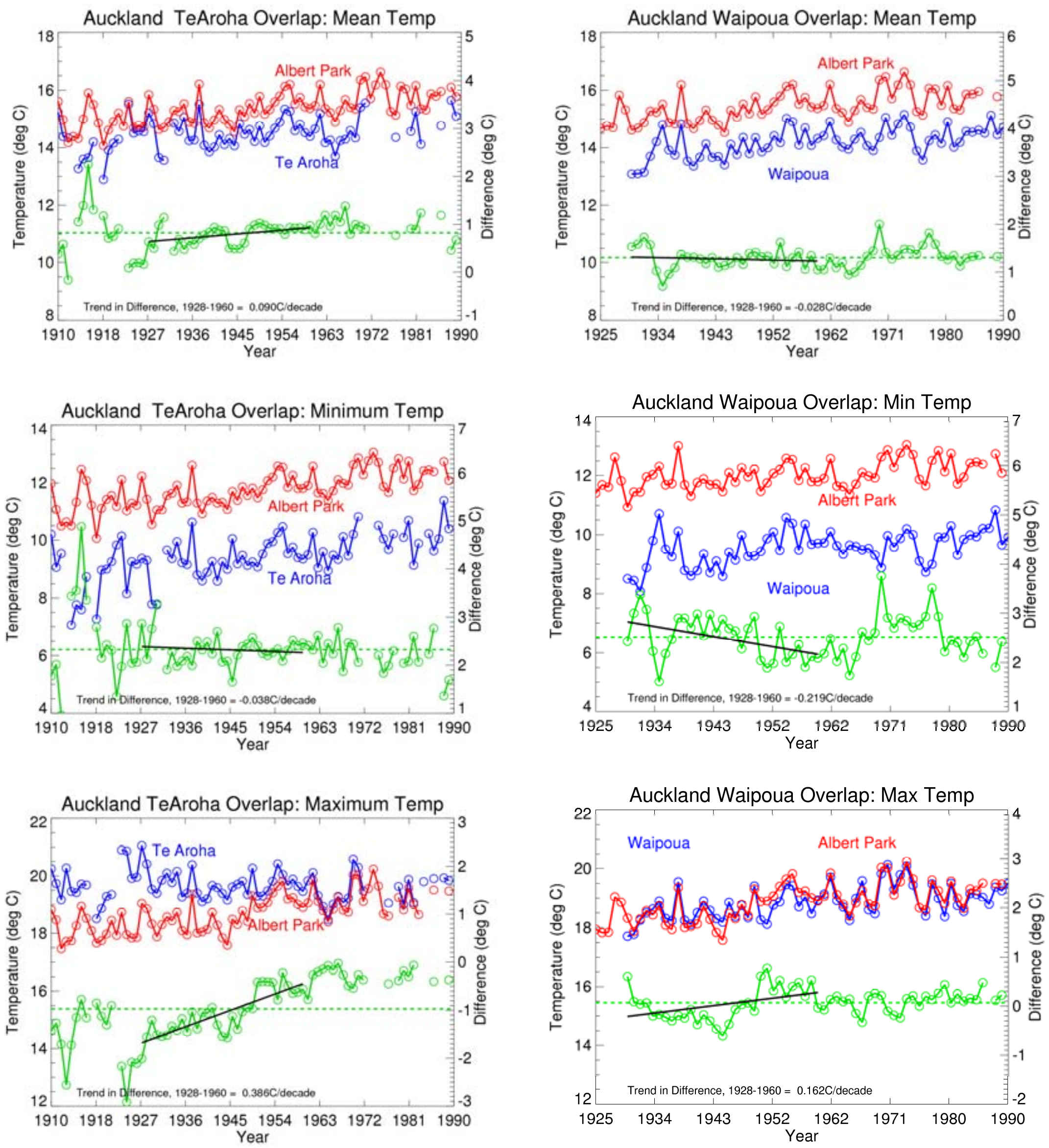

Figure A5.2: Comparison of annual temperatures at Auckland Albert Park with those at Te Aroha (agent 1565, left-hand panels) and at Waipoua Forest (agent 1155, right-hand panels): mean (top), minimum (centre) and maximum (bottom) temperature. In all cases, Albert Park is shown in red and the other site in blue, and for ease of comparison the temperature range is fixed at 10 °C. The difference, Albert Park minus “other site”, is in green, with an expanded (right-hand side) scale of 6 °C. A linear trend is fitted to a selected portion of the difference curve (black line), and the calculated slope noted at the bottom of each plot.

Appendix 6

Further discussion of Albert Park temperatures vs other Auckland sites

We conclude this discussion of the Auckland temperature record with two further figures that point to Albert Park being warmer than Mangere, even without any urban or sheltering effects. Figure A6.1 is taken from a NIWA sea surface temperature climatology[34], showing that sea surface temperatures are at least 0.5 °C higher to the east of Northland and Auckland relative to the western coast. The higher temperatures offshore to the east are contributed by the East Auckland Current, which originated as a branch of the southward-flowing East Australian Current, which separates and then crosses the Tasman Sea before flowing around North Cape.

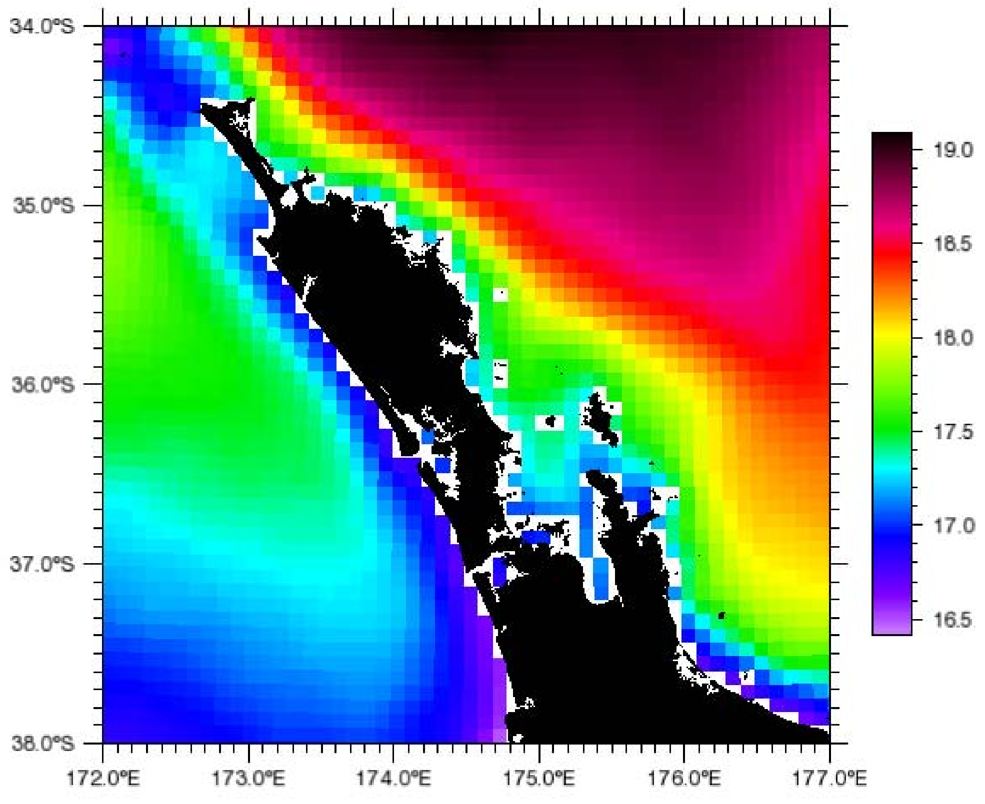

Figure A6.1: Annual mean sea surface temperatures around the northern part of the North Island, based on satellite observations over the period 1993-2002.

The proximity to the warmer waters of the East Auckland Current leads us to expect higher temperatures on the eastern side of the northern North Island. This opinion is reinforced by Figure A6.2, taken from the Hessell's (1988) study of the climate of Auckland. The highest values of mean temperature occur in a narrow coastal strip down the eastern side of the Auckland region. Thus, there is clearly a coastal effect,

[34] Uddstrom and Oien (1997) originally produced a 5-year climatology, extended here with a further 5 years.

making the northern side of the Auckland isthmus warmer than the southern side. Auckland City may be subject to an additional urban effect (darkest shading in Figure A6.2, partly obscured by labels) that elevates the CBD temperatures even further.

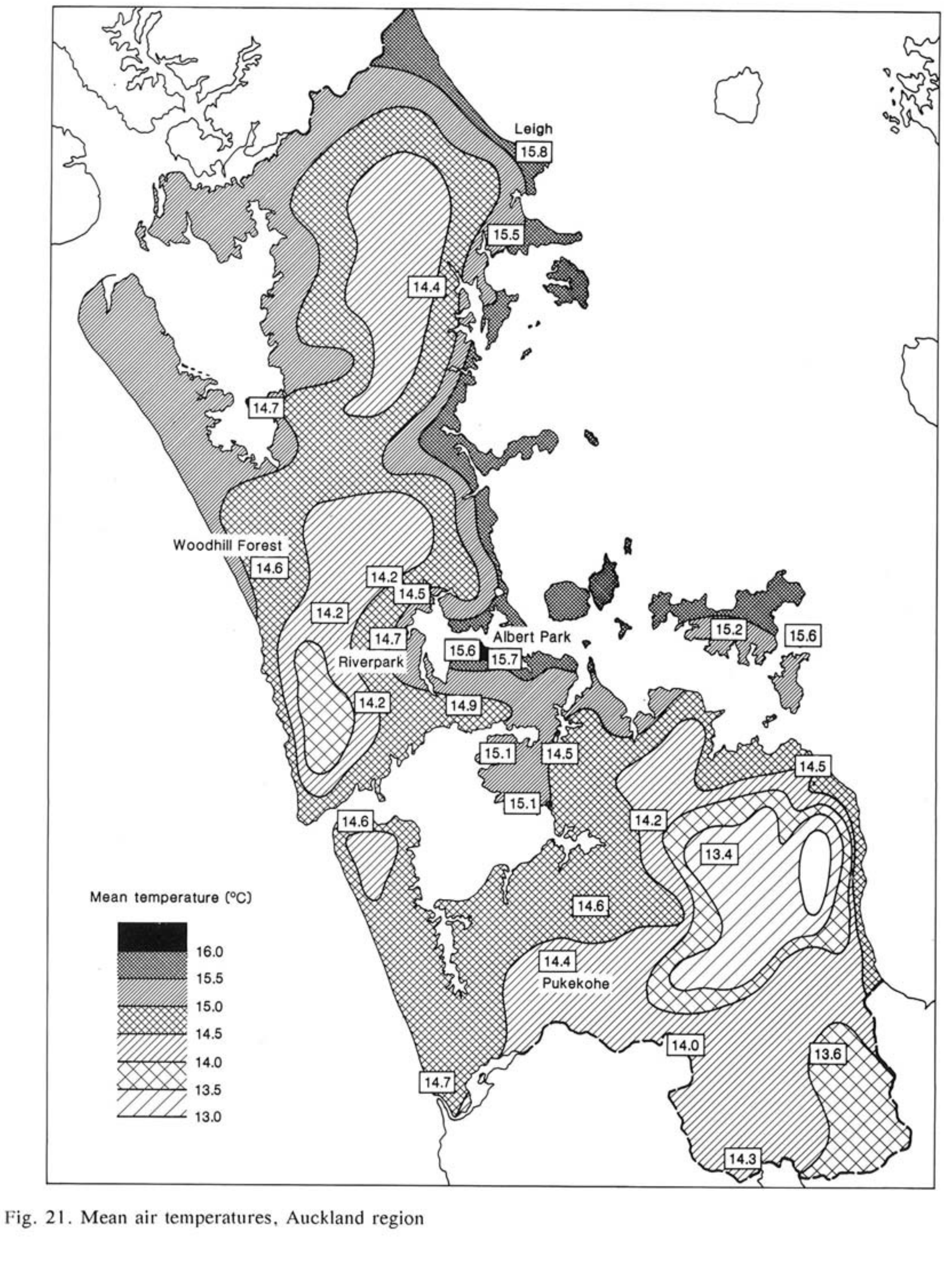

Figure A6.2: Map of annual-average mean temperatures in the wider Auckland region, from Hessell (1988).

Creating a Composite Temperature Series for Masterton

December 2010

Figure 1: Looking east toward the automatic weather station at East Taratahi near Masterton (agent number 2612) in 2007.

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.

This present document revisits and describes in greater detail the process by which a composite station series has been developed for Masterton. The primary purpose is to demonstrate in an intuitive way how to estimate adjustments to temperature records 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 <u>not</u> 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., RHtests, Wang *et al.*, 2007) to identify other change-points in the data.

Table 1: Information about Masterton 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 record;
(Column 4) altitude of site in metres above sea level;
(Column 5) previous period of record (as of February 2010) 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 of record for which the site contributes to the composite time series; and
(Column 8) revised temperature adjustment to be applied (with respect to East Taratahi, Site 7), as discussed in the text.

Site Label	Site Name (Agent Number)	Location (Full Period of Record)	Height (m a.s.l.)	Previous Period	Previous Temp. Adjust. (°C)	Revised Period	Revised Temp Adjust. (°C)
Site 1	Waingawa (2473)	Church Street, Masterton.[2] (Jan 1906 to Oct 1910)	115	Jan 1906 to Oct 1910	-0.5	Not Used	N/A
Site 2	Waingawa (2473)	Private residence of observer, Masterton. (Nov 1910 to Feb 1911)	115[3] estimated	Nov 1910 to Feb 1911	-0.5	Not Used	N/A
Site 3	Waingawa (2473)	The Manse, Masterton. (Mar 1911 to Jan 1912)	115	Mar 1911 to Jan 1912	-0.5	Not Used	N/A
Site 4	Waingawa (2473)	Worksop Road, Masterton. (Feb 1912 to Apr 1920)	115	Feb 1912 to Apr 1920	-0.5	Feb 1912 to Apr 1920	-0.55
Site 5	Waingawa (2473)	Essex Street, Masterton. (Jun 1920 to Nov 1942)	115[3]	Jun 1920 to Sep 1942	-0.2	Jun 1920 to Sep 1942	-0.34
Site 6	Waingawa (2473)	Waingawa substation. (Oct 1942 to Mar 1991)	114	Oct 1942 to Dec 1990	0.0	Oct 1942 to Dec 1990	-0.08
Site 7	East Taratahi AWS (2612)	8 km southeast of Masterton. (Jan 1982 to Oct 2009)	91	Jan 1991 to Oct 2009	0.0	Jan 1991 to Oct 2009	**0.00**
Site 8	Martinborough EWS (21938)	Provisional replacement site.[4] (Apr 2001 to present)	20	Nov 2009 to present	-0.3	Nov 2009 to present	-0.28

[2] From 1884, rainfall observations were made either at the private residence of the observer or at the office of the 'Wairarapa Daily Times' in Church Street, but probably the latter. A new observer, from the staff of the newspaper, commenced observations of air temperature in 1906, presumably still at the newspaper office.
[3] The elevation of Site 2 is not entered in the original station records, but it is likely to be similar to those of the other sites in Masterton, so an estimate of 115 m above sea level (m a.s.l.) has been provided. In the original records, there is some variability in the reported elevations of the Essex Street site (Site 5), which range from 100 m to 118 m a.s.l.
[4] The East Taratahi station was operated by MetService NZ, and closed down at the end of October 2009. In anticipation of this closure, MetService had opened a new station, Masterton Aero (agent

Calculation of Adjustments

Table 1 summarises the information about the local sites used to develop the composite temperature series for the Masterton 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.[5] Table 1 lists eight different sites as contributing to the composite Masterton temperature series. Thus, there are at least seven change-points, and the temperature record 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 was made <u>not</u> to include temperatures prior to 1900. Furthermore, if there were site changes around 1910 that were difficult to justify, then the time series was truncated at that point. In the case of Masterton, the revised series begins with Site 4 in 1912. In the interests of completeness, adjustments are still estimated for the earlier sites, but discussion of them is relegated to Appendix 1, along with other more technical comment.

It is common practice to adjust all the historical measurements to be consistent with the current open site (Aguilar *et al.*, 2003). However, the current open site, Martinborough EWS (Electronic Weather Station), labelled Site 8 in Table 1, is considered a provisional replacement only. Masterton Aero (agent 36735) is much closer to the other Masterton sites than Martinborough, and will be reconsidered when a longer record is available.

Therefore, measurements will be adjusted for consistency with East Taratahi AWS (Automatic Weather Station), which is labelled Site 7 in Table 1 and shown in Figure 1.[6] Figure 2 provides a map locating the local Masterton sites of Table 1, and also a number of the more distant comparison sites discussed in the subsequent text.

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number 36735) in March 2009. Temperature comparisons made for this short overlap period showed that the difference varied with the month of the year (East Taratahi had a larger amplitude to its annual cycle), and so NIWA National Climate Centre scientists considered Masterton Aero unsuitable as a replacement for East Taratahi. NIWA also operated a nearby station, Masterton Te Ore Ore (agent 7578), but unfortunately this was closed in September 2009; it restarted immediately on the same site but with different instrumentation as a 'Compact Weather Station' (CWS, agent 37662), so again there is a problem of homogeneity of record. Martinborough, on the other hand, has 9 years of overlap (2001-2009), from which site differences can be assessed. The use of Martinborough as a replacement for East Taratahi will be re-assessed when another year or so of data are available; in the meantime, all sites will continue to be adjusted relative to East Taratahi.

[5] Calculation to two decimal places has been done to minimise the accumulation of round-off errors. This should not be interpreted as an indication of the accuracy of the adjustment. Air temperatures are recorded to the nearest 0.1 °C on the NIWA Climate Database.

[6] The final adjusted temperature series should therefore be thought of as representing historical temperatures at East Taratahi from 1912 onwards. Adding 0.28 °C to <u>all</u> data values would lead to a temperature series representative of the warmer Martinborough site, with slightly higher temperatures but exactly the same long-term trend as East Taratahi.

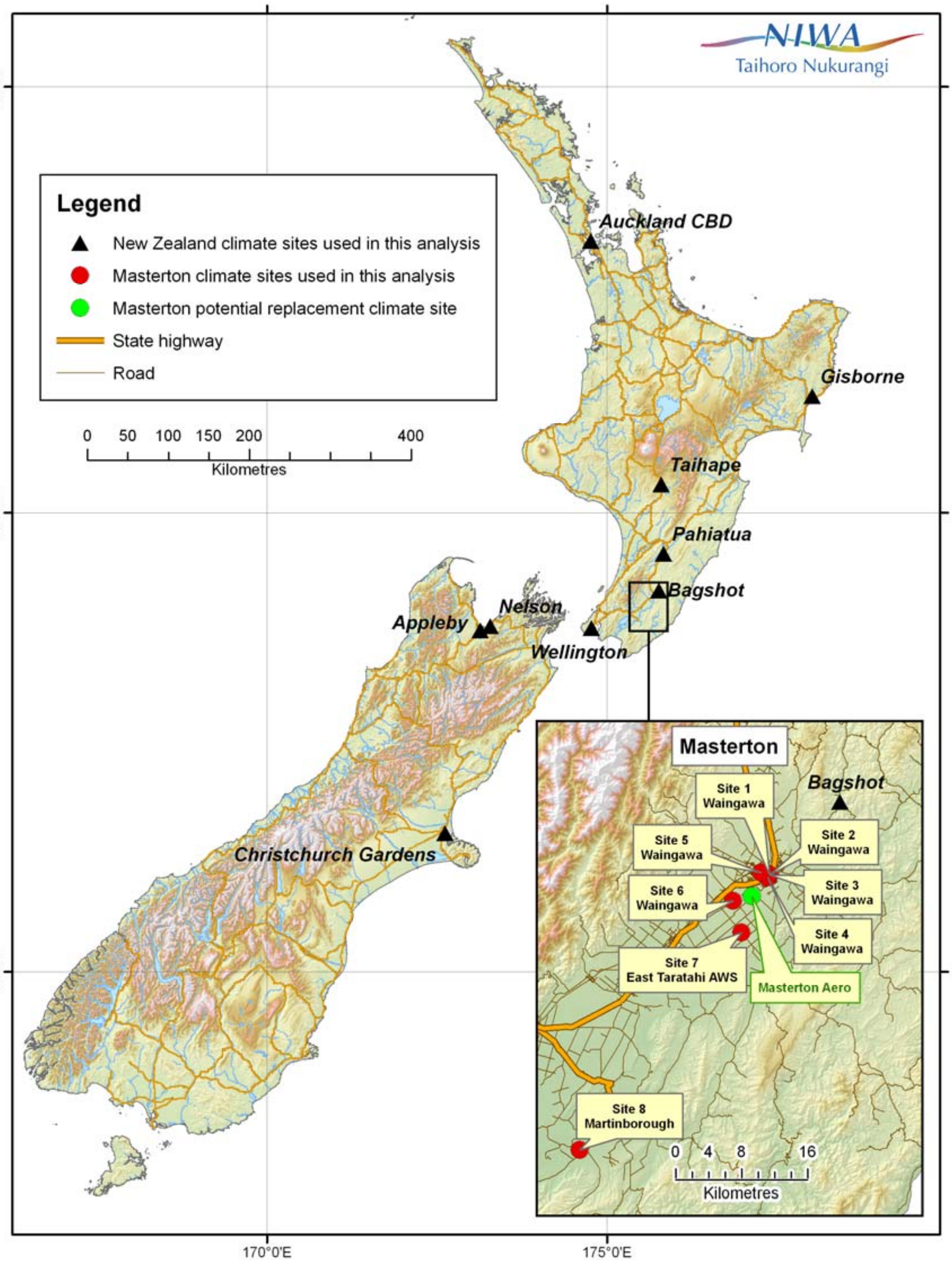

Figure 2: Map showing sites of temperature records referred to elsewhere within this document. The inset map locates the local Masterton sites.

Adjustment for Site Change in 2009

We will work backwards in time from the current open site: Martinborough EWS (Site 8, agent number 21938). This station is located in a well-exposed area on the southern outskirts of Martinborough. Martinborough EWS first opened in April 2001 and contributes temperatures to the composite temperature series for Masterton from November 2009 onward after the closure of East Taratahi (see Footnote 4 from Table 1).

From January 1991 until October 2009, the composite Masterton temperatures were provided by the East Taratahi AWS (Site 7, agent number 2612, Figure 1). The East Taratahi station was located in an area of mainly flat farming land, 8 km southeast of Masterton. This station closed at the beginning of November 2009.

Annual mean temperatures are available at both the East Taratahi AWS and the Martinborough EWS for 2002 and from 2004 until 2008.[7] This overlap allows us to directly compare temperatures at the two sites. We can then determine what adjustment may be necessary in order to make observations at Martinborough EWS (Site 8) consistent with those at East Taratahi AWS (Site 7). Figure 3 shows the overlapping annual mean temperatures at Masterton Sites 7 and 8.[8]

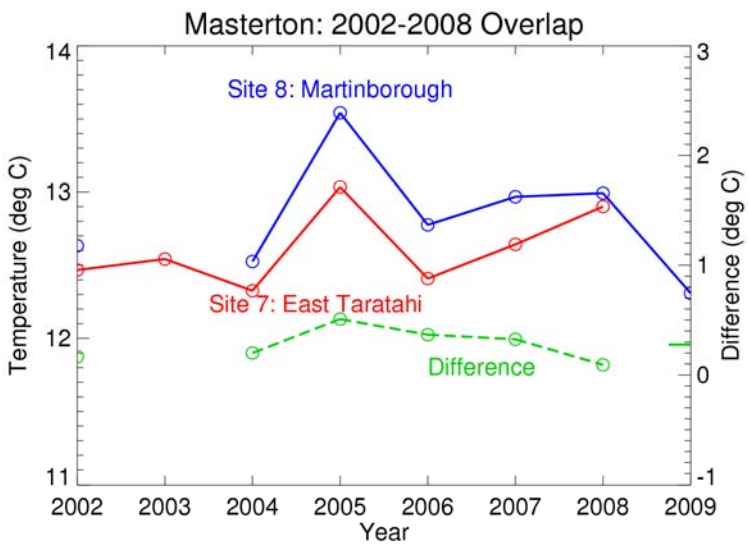

Figure 3: Annual mean temperature series for East Taratahi AWS (Site 7, agent 2612, red line), and Martinborough EWS (Site 8, agent 21938, blue line), from 2002 to 2009. The annual difference, Site 8 minus Site 7, is plotted by the green dashed line, using the right-hand ordinate scale, and the mean annual difference is indicated by a short solid green line on the right side of the plot. Circles (e.g., in 2002) indicate the annual values, which is helpful when missing data causes a gap in the lines.

[7] Martinborough has 4 months missing in both of the years 2001 and 2003, so we have not attempted to estimate an annual value for these years. We have estimated annual values only when there are no more than 3 missing months in the year, as explained in Appendix 2.

[8] Annual mean temperatures during this analysis have been calculated to several decimal places from the monthly mean temperatures in CliDB, in order to minimise round-off errors.

In the overlap period for 2002 and 2004-2008, annual mean temperatures at the Martinborough site were between 0.09 °C and 0.51 °C warmer than those at the East Taratahi site. On average, the Martinborough site was 0.28 °C warmer than the East Taratahi site. Therefore, annual temperatures at Martinborough EWS ought to be *decreased* by 0.28 °C in order to be consistent with those at East Taratahi AWS.[9] This adjustment of -0.28 °C is consistent with that listed in the February 2010 'Schedule of Adjustments' of -0.3 °C (rounded to one decimal place).

Adjustment for Site Change in 1990/91

From October 1942 until December 1990, the temperatures used for the composite temperature series for Masterton were observed at the Waingawa climate station (Site 6 in Table 1, agent number 2473). This station was established on 12 September 1942 at the Waingawa substation of the New Zealand Electricity Department, 2 km southwest of Masterton. The thermometers resided in an enclosure which was located next to the residence of the overseer of the substation. This station closed in April 1991 and was replaced by the automatic weather station at East Taratahi.

There is an overlap period from January 1982 until March 1991, during which time both the East Taratahi and Waingawa sites were in operation. There are a number of missing monthly temperatures at one or other of these sites during this period. For example, an air bubble was present in the minimum thermometer at Waingawa (Site 6) from February to April in 1986. At East Taratahi (Site 7), six months of monthly mean temperatures are unavailable between December 1985 and June 1986, partly because sheep ate through the temperature probe cable.

Nevertheless, we can calculate annual values for most years (see Appendix 2), with the exception of 1986. Therefore we can again directly compare temperatures at the two sites, and then determine what adjustment may be necessary in order to make observations at the Waingawa substation (Site 6) consistent with those at East Taratahi AWS (Site 7). Figure 4 shows the annual mean temperatures at Masterton Sites 6 and 7 during the overlapping years.

Over the eight overlapping years, the difference between annual mean temperatures at Waingawa (Site 6) and East Taratahi (Site 7) was between +0.23 °C and -0.23 °C. On average, Waingawa (Site 6) was 0.08 °C warmer than East Taratahi (Site 7). Therefore annual mean temperatures at Waingawa (Site 6) ought to be *decreased* by 0.08 °C to be consistent with East Taratahi (Site 7). The adjustment for Waingawa (Site 6) in the February 2001 'Schedule of Adjustments' was given as 0.0 °C.

[9] As noted previously, East Taratahi is the 'Reference' site for Masterton. Data from all other sites will be adjusted relative to the East Taratahi record.

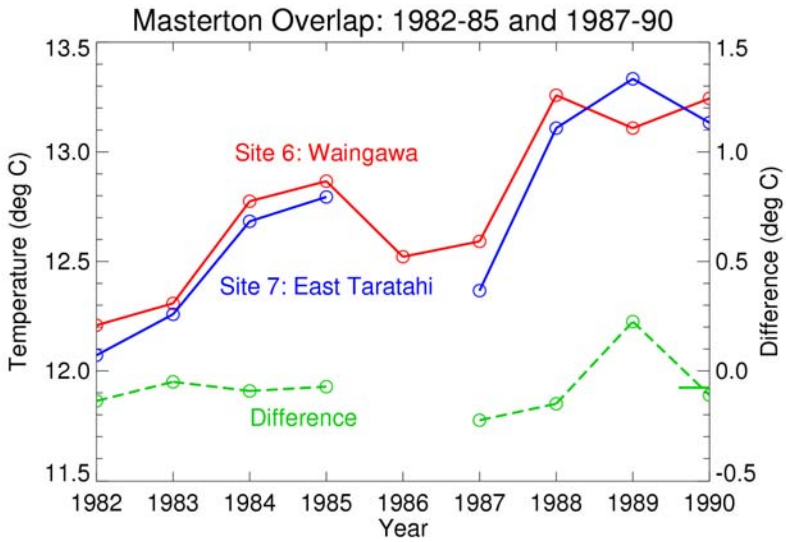

Figure 4: Annual mean temperature series for Waingawa (Site 6, agent 2473, blue line) and East Taratahi AWS (Site 7, agent 2612, red line) from 1982 to 1990. The annual difference, Site 7 minus Site 6, during overlapping years is plotted by the green dashed line, using the right-hand ordinate scale, and the mean annual difference is shown by a short solid green line on the right side of the plot.

Adjustment for Site Change in 1942

From 1920 until 1942, climate observations took place at Essex Street in Masterton (Site 5). This site closed at the beginning of December 1942, so monthly mean temperatures at Sites 5 and 6 overlap for only a short period.[10] In such situations, it becomes necessary to compare temperatures at the two sites to observations at other stations, in order to determine any potential change in annual mean temperature associated with the change of site.

Figure 5 shows the correlation of mean temperature interannual differences at the Virtual Climate Station (VCS) grid point containing the East Taratahi AWS (Site 7) with interannual differences at all other locations on the VCS grid from 1972 until 2008 (i.e., 1972-73 difference, 1973-74, … , 2007-08).[11] Masterton Sites 1 to 6 are all less than 10 km from the reference East Taratahi site (Site 7), and so we would expect them to be well correlated. If more distant sites are required for comparison purposes,

[10] In the original meteorological returns, monthly mean temperature at the Waingawa substation (Site 6) in October 1942 was 0.1 °F (0.06 °C) cooler than at Essex Street (Site 5), while in November 1942, the monthly mean at the substation was 0.1 °F warmer than at Essex Street. However, a much longer period of comparison is necessary in order to calculate the difference between annual mean temperatures at the two sites.

[11] 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).

then Figure 5 gives an excellent indication of locations at which temperatures are likely to correlate strongly with the Masterton record.[12]

Not surprisingly, interannual temperature variations at Masterton correlate strongly with those in the Wairarapa region as a whole, the correlation typically being over +0.95.[13] Temperature variations at Masterton also correlate well with those over much of the North Island (+0.92 for Wellington, +0.91 for Auckland), and with Nelson-Marlborough (+0.93 for Nelson Appleby), and even with Lincoln (+0.90). Correlations are poorer with the other two members of the seven-station series (+0.64 for Hokitika, +0.72 for Dunedin).

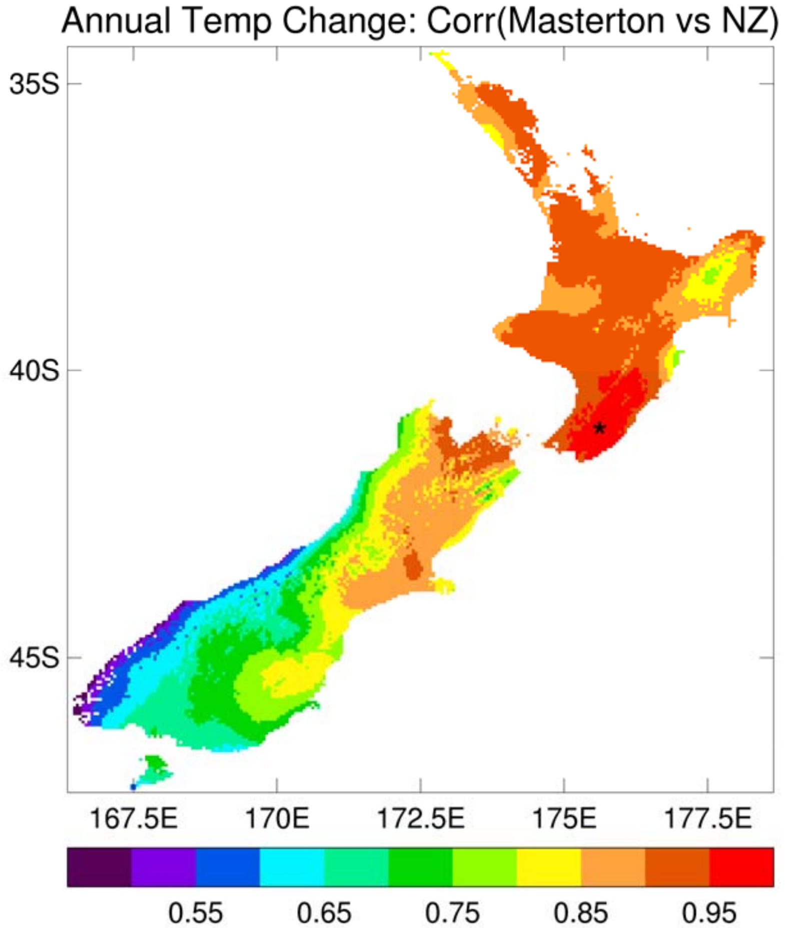

Figure 5: Map of correlation between interannual temperature changes at the East Taratahi grid-point (Site 7, agent 2612, location marked by asterisk) near Masterton, 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

[12] The stations to be used in comparisons ('comparison stations') ideally ought to have experienced the same broad climatic influences as the Masterton sites, and should have a homogeneous record of temperature over the period of comparison (Aguilar et al. 2003). The homogeneity of comparison stations is assessed by analysing 'metadata' from station histories and looking for stations at which no significant site changes occurred during the period of comparison. This becomes more difficult in earlier years, when fewer climate stations were in operation and station histories are often less complete. Comparison stations may differ from those used in Salinger (1981) if metadata indicate that a site change may have occurred during the period of comparison.

[13] A correlation of +1.0 indicates perfect agreement; i.e., that the interannual temperature variations at two sites match perfectly (except for a constant offset and multiplicative factor).

Figure 6 compares annual temperatures at Waingawa with temperatures at six other stations (see Figure 2 for location map). Annual temperatures are ignored in 1942, since the Waingawa site moved in the latter part of that year. Any temperature shift between Waingawa Site 5 (Essex Street) and Site 6 (Waingawa substation) can be identified by comparing them against a comparison site before and after 1942.

Bagshot Station (Figure 6, upper left) is the site closest to Waingawa, and was situated in the Whangaehu Valley in Wairarapa, approximately 17 km northeast of the Waingawa substation and 13 km northeast of Essex Street (see Figure 2). During the ten years before the 1942 site change, 1932 to 1941, Site 5 was on average 0.53 °C warmer than Bagshot Station. During the ten years after the site change, 1943 to 1952, Site 6 was on average only 0.25 °C warmer than Bagshot.[14] Thus when compared with Bagshot, where there was no site change, the Site 5 (Essex Street) was 0.28 °C warmer than Site 6 (Waingawa substation).

This process of comparison is then repeated for the other stations in Figure 6.[15] Before the 1942 site change, Site 5 was on average 0.08 °C cooler than Kelburn in Wellington (Figure 6, upper right). After the site change, Site 6 was on average 0.34 °C cooler than Kelburn. Thus when compared with Kelburn, the earlier Site 5 (Essex Street) was 0.26 °C warmer than Site 6 (Waingawa substation).

The Pahiatua measurements were taken in the Mangamutu Domain of the township of Pahiatua, about 60 km northwest of Waingawa in the Manawatu-Wanganui district of the southwest North Island. Before the site change, Site 5 was on average 0.17 °C warmer than Pahiatua (Figure 6, centre left), while after the 1942 site change, Site 6 was on average 0.03 °C <u>cooler</u> than Pahiatua. Therefore, when compared with Pahiatua, the Essex Street site was 0.21 °C warmer[16] than the Waingawa substation.

Before the site change, Site 5 was on average 1.87 °C warmer than Taihape[17], while after the site change, the Site 6 was on average only 1.45 °C warmer than Taihape (Figure 6, centre right). Thus when compared with Taihape, the Essex Street site was 0.42 °C warmer than the Waingawa substation.

Before the site change, Site 5 was on average 0.20 °C cooler than Appleby (Figure 6, lower left), while after the 1942 site change, Site 6 was on average 0.34 °C cooler

[14] Monthly mean air temperatures are missing from Waingawa for a single month in each of 1945, 1946 and 1947. Annual mean temperatures have been estimated from the eleven existent months in these years. Refer to Appendix 2 for details. Note, also, that in these comparisons with other sites, we only present results for the mean temperature. However, shifts in maximum and minimum temperatures were also analysed, along with inter-site correlations that helped in selecting the best comparison sites.

[15] In July 1949, trees and shrubs were cut back to improve the exposure of the Kelburn site. In November 1950, a Bilham screen was installed at Albert Park. The periods of comparison between each of these stations and Waingawa have therefore been slightly truncated in order to maintain homogeneous comparisons.

[16] The temperature differences appearing in the text (0.17 °C, 0.03 °C, 0.21 °C) have been rounded to two decimal places, but the summation (0.17 + 0.03) is calculated with extra significant figures.

[17] Taihape is located on the central plateau of the North Island, about 150 km north of Waingawa but still well correlated; the correlation of mean temperature interannual differences is above +0.9 since 1972 according to Figure 5, and was +0.91 over the period 1932-1950 examined in Figure 6.

than Appleby.[18] Therefore, when compared with Appleby, the Essex Street site was 0.14 °C warmer than the Waingawa substation.

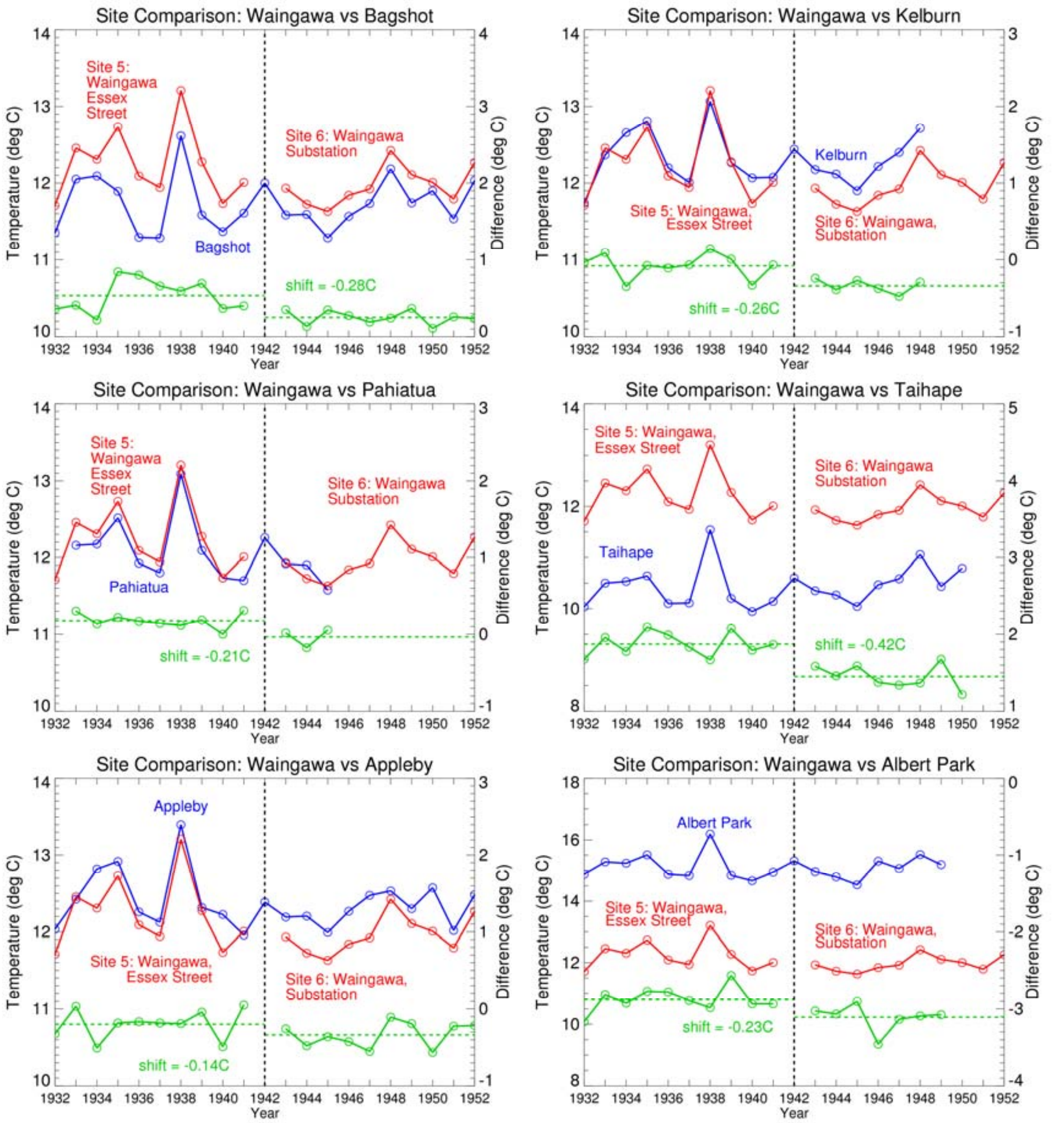

Figure 6: Comparisons of annual mean temperature series at Essex Street (Site 5, agent 2473, red lines on the left of each plot) and Waingawa substation (Site 6, agent 2473, red lines on the right of each plot) with Bagshot Station (agent 2446, blue line in upper left plot), Wellington Kelburn (agent 3385, blue line in upper right plot), Pahiatua (agent 2385, blue line in centre left plot), Taihape (agent 3669, blue line in centre right plot), Appleby (agent 4239, blue line in lower left plot) and Albert Park in Auckland (agent 1427, blue line in lower right plot), from 1932 to 1952. The differences (Waingawa minus each of the other stations) are indicated by the green solid lines, using the right-hand ordinate scale, and the mean differences relative to each Masterton site are shown by the green dashed lines. The magnitude of the mean shift across 1942 is displayed in green, while the year of the site change at Waingawa, 1942, is indicated by the vertical dashed line in the centre of each plot.

[18] A single month of mean air temperatures is missing from Appleby in each of 1942, 1943, 1944 and 1949. Annual mean temperatures have been estimated from the eleven existent months in each of these years. Please refer to Appendix 2 for details.

Finally, before the site change, Site 5 was on average 2.88 °C cooler than Albert Park, while after the site change, Site 6 was on average 3.11 °C cooler than Albert Park (Figure 6, lower right). Thus when compared with Albert Park, Essex Street Site 5 was 0.23 °C warmer than Waingawa substation Site 6.

After averaging the six shifts (-0.28 °C, -0.26 °C, -0.21 °C, -0.42 °C, -0.14 °C and -0.23 °C), we conclude that the Essex Street site was 0.26 °C warmer than the Waingawa substation.[19] Thus, the Site 5 temperatures must be reduced by 0.26 °C before joining them to the Site 6 record. The final cumulative adjustment of temperatures at Essex Street (Site 5) to East Taratahi AWS (Site 7) should therefore be: -0.08 - 0.26 = -0.34 °C. The magnitude of this adjustment is greater than that of the -0.2 °C adjustment from the February 2010 'Schedule of Adjustments'.

Adjustment for Site Change in 1920

From February 1912 until April 1920, temperatures were observed in Worksop Road in Masterton (Site 4 in Table 1).[20] The station was moved to Essex Street (Site 5) in May 1920. We have no overlap period for Sites 4 and 5, but we can once again estimate any potential change in temperature by comparison with other sites.

Figure 7 compares annual temperatures at Worksop Road (Site 4) and Essex Street (Site 5) with stations in Thorndon (Wellington), Auckland, Christchurch and Taihape from 1912 to 1927.[21]

Rather than go through all the before and after comparisons of Waingawa with each comparison site, we refer the reader to Figure 7, and present just the overall estimate

[19] We also considered using only the first four sites of Figure 6 to estimate the 1942 adjustment. Appleby had the problem that its minimum temperature correlation with Waingawa was poorer than the other 5 sites (+0.70 versus at least +0.84 or better), and the shift diagnosed in the minimum temperature at Waingawa was +0.19°C using Appleby, as against a shift of between -0.12 °C and -0.20 °C using the other 5 sites. The issue with Auckland was its much greater distance from Waingawa than the other sites, and it also had the poorest (equal to Appleby) correlation with Waingawa in its maximum temperatures. If Appleby and Auckland were removed, the overall shift at the 1942 site change works out to be -0.29 °C. In the end, we have decided to use the slightly more conservative shift from the 6-station average. There is the added advantage that the Auckland Albert Park site is common to the 1920 set of comparison stations.

[20] Salinger (1981) noted that by comparison to observations at other stations, the Masterton temperature record prior to 1920 was only 'fair' and should be viewed with caution.

[21] Technical Comment: In making comparisons with other sites, our approach throughout these station documents is to endeavour to compare 10 years before and 10 years after any site change (subject to additional site changes), as in Figure 6. However, differences between distant stations can be sensitive to atmospheric circulation (prevailing wind flow), and in 1928 there appears to have been a shift in circulation regime: 1928 was a year of anomalous northeasterly flow, and Waingawa recorded its 4th highest annual rainfall in the 65 years of record. Including the additional 3 years 1928-1930 in the comparison of Figure 7 makes no difference with the other 'easterly' site of Christchurch (shift is -0.06 °C instead of -0.05 °C), but causes a large divergence with the Albert Park and Taihape comparisons. (The Thorndon record ends in 1927, so it is not affected.) Since we actually want to know how temperatures at the east coast site of Waingawa varied before and after 1920, it is preferable to avoid comparison with non-east coast sites during a period in which they are responding quite differently; a comparison over such a period would only introduce greater uncertainty into the estimated adjustment.

of the shift at 1920. All four panels of Figure 7 are consistent in showing that the Waingawa Essex St site is cooler than the Worksop Road site.

The four shifts calculated are: -0.20 °C (Thorndon), -0.37 °C (Albert Park), -0.05 °C (Christchurch) and -0.20 °C (Taihape). We conclude that Essex Street (Site 5) was, on average, 0.21 °C cooler than Worksop Road (Site 4). The final adjustment required to make observations at Worksop Road (Site 4) consistent with those at East Taratahi AWS (Site 7) should therefore be: -0.08 - 0.26 - 0.21 = -0.55 °C. This cumulative adjustment is very close to the -0.5 °C in the February 2010 'Schedule of Adjustments'.

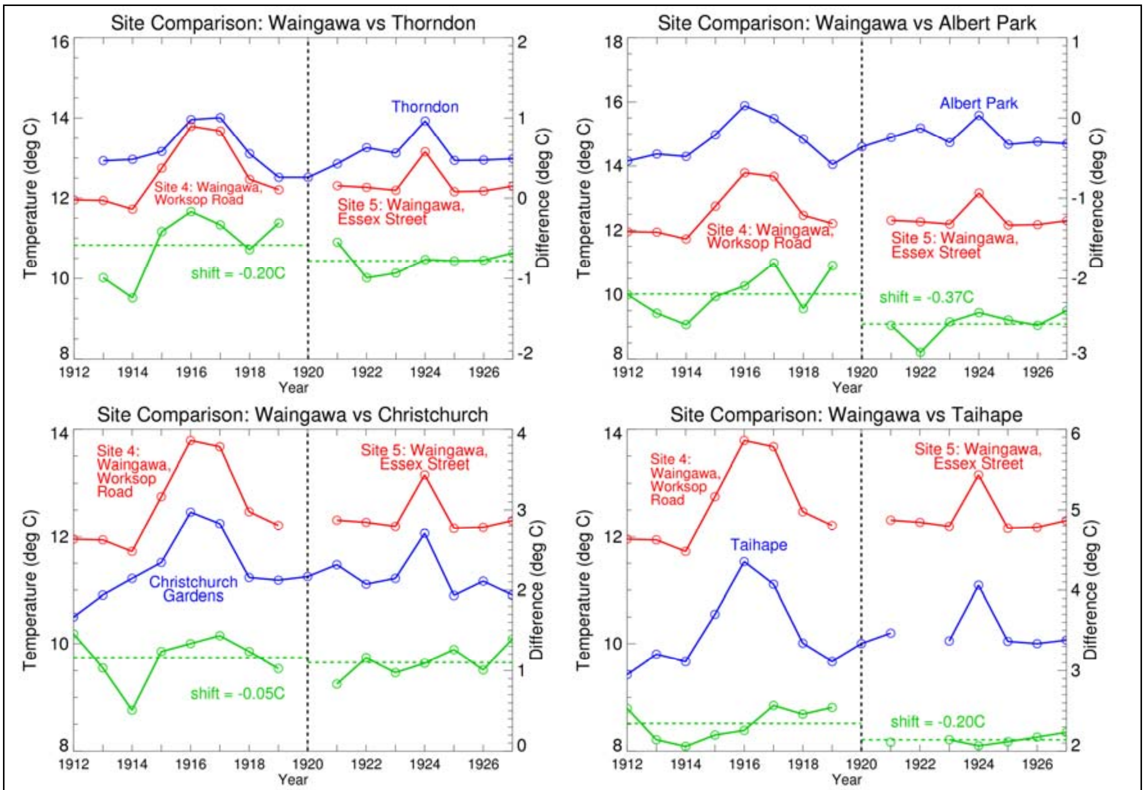

Figure 7: Comparisons of annual mean temperature series at Waingawa Worksop Road (Site 4, agent 2473, red lines on the left of each plot) and Waingawa Essex Street (Site 5, agent 2473, red lines on the right of each plot) with Thorndon (agent 3391, blue line in upper left plot), Albert Park (agent 1427, blue line in upper right plot), Christchurch Gardens (agent 4858, blue line in lower left plot) and Taihape (agent 3669, blue line in lower right plot) from 1913 to 1927. The differences (Waingawa minus each of the other stations) are indicated by the green solid lines, using the right-hand ordinate scale, and the mean differences relative to each Masterton site are shown by the green dashed lines. The magnitude of the mean shift across 1920 is displayed in green, while the year of the site change at Waingawa, 1920, is indicated by the vertical dashed line in the centre of each plot.

Site Adjustments Prior to 1912

Temperature data prior to the start of Site 4 in February 1912 are not included in the revised composite series for Masterton. However, see Appendix 1 for a discussion of estimated adjustments for Sites 1 to 3.

Putting the Time Series Together

The various adjustments described above can be applied successively to the Masterton temperature records. The resultant annual time series from 1912 to 2009 is shown in Figure 8, with a comparison with the previous Masterton series.[22] A linear trend has been fitted to each series. Expressed in units of degrees per century, the linear trend in the revised series is 0.88 (±0.34) °C /century, as compared with 0.80 (±0.34) °C /century for the trend calculated from the previous Masterton time series published in February 2010.[23]

Once the temperatures from the Masterton sites have been adjusted for consistency with East Taratahi AWS (Site 7), and then combined, we have a series dating back to 1912. However, simply appending the raw data from the Masterton records without correcting for known site changes would result in an inhomogeneous history of temperature, unsuitable for the analysis of long-term trends.

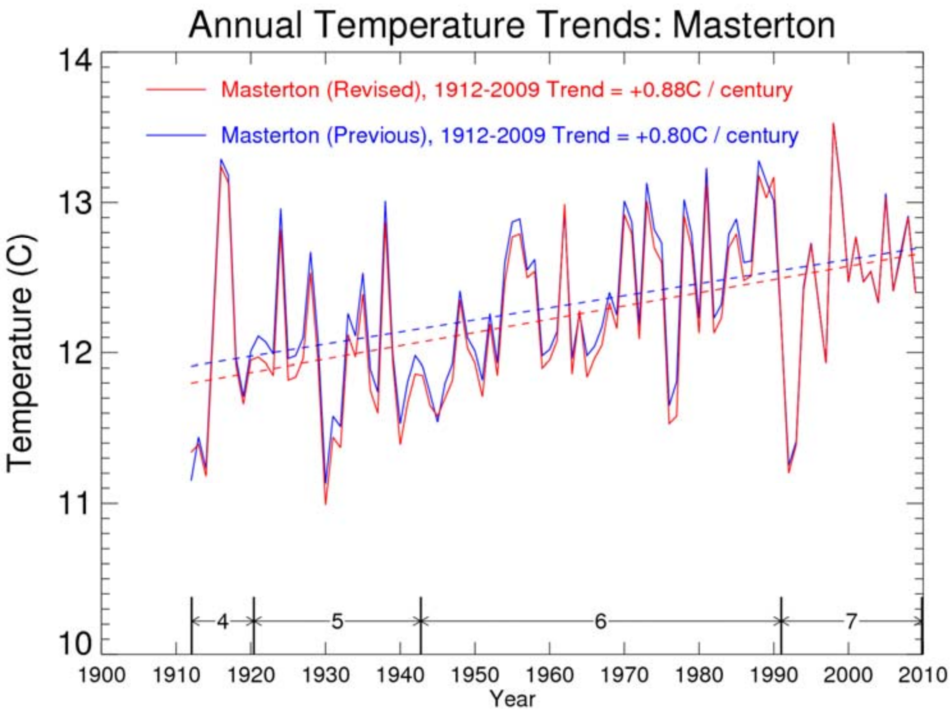

Figure 8: Comparison of the revised composite series of annual mean air temperatures for Masterton (red line) to the previous NIWA Masterton series (blue line) from 1912 to 2009. The dashed lines show the fitted linear trends from 1912 to 2009. Masterton site labels from Table 1 are displayed at the bottom of the plot. Masterton Sites 1, 2 and 3 have been omitted from the revised temperature series, as discussed in the text, while Site 8 (Martinborough EWS) begins in November 2009.

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[22] In the revised composite temperature series for Masterton shown in Figure 8, annual mean temperatures in years containing up to three missing months have been estimated from the composite 1971-2000 climatology for Masterton. The methodology for these estimates is described in Appendix 1.

[23] The uncertainty here (±0.35 °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 9 repeats the graph of the revised composite annual mean temperature series for Masterton, and compares the composite with the unadjusted raw multi-site temperatures. For the period 1991-2009 the two series are identical, since this period is covered by the Masterton reference site (East Taratahi, Site 7) for which no adjustment is applied. The estimated adjustments are also shown in Figure 9. The adjustments are cumulative relative to East Taratahi Site 7, and correspond to those in the final column of Table 1.

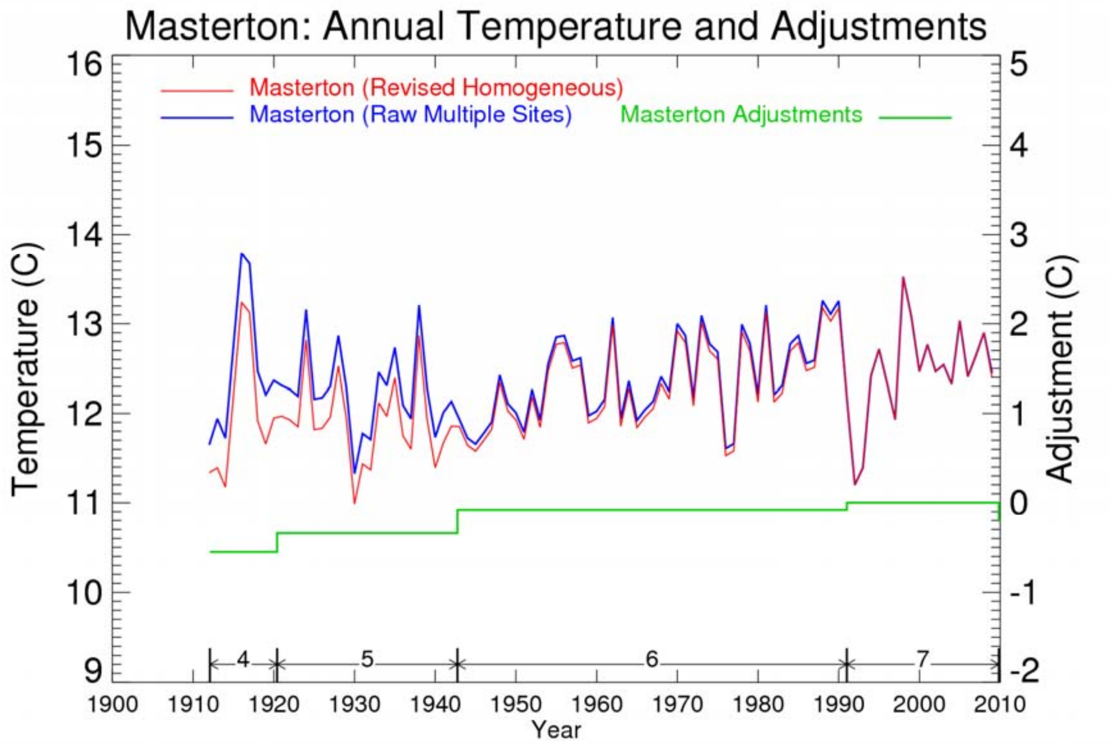

Figure 9: Comparison of new composite temperature series for Masterton from 1912 to 2009 (red line), with the raw multi-site series (Sites 4-7, blue line). The green line (using right-hand axis) indicates the cumulative step adjustments to each site as shown at the bottom of the graph, and corresponds to the adjustments in the right-hand column of Table 1.

Further Information

Further technical information on different approaches to homogeneity adjustment of climate data can be found in the references below (Aguilar *et al.*, 2003; Peterson *et al.*, 1998; Rhoades and Salinger 1993).

Date: Document originally created 20 August 2010, and revised 13 December 2010 following review from the Australian Bureau of Meteorology.

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Appendix 1

Site Adjustments Prior to 1912

From the end of March 1911 until January 1912, temperatures were observed at the Manse in Masterton (Site 3). Mr A. H. Vile of the 'Wairarapa Age' measured temperatures at his residence in Masterton (Site 2) from the end of October 1910 until March 1911.

From January 1906 until October 1910, temperatures were observed by a member of the staff of the 'Wairarapa Daily Times' in Masterton (Site 1). Monthly minimum and mean temperatures are unavailable in July and August of 1908, when the thermometer was exposed in the open. Monthly temperatures are also unavailable in September 1907 and October 1908. No regular observations took place in June, July and August of 1910, and the observer resigned towards the end of October 1910.

It is difficult to calculate any annual adjustments which might be necessary for Masterton Sites 2 and 3, since both sites were in operation for less than a year. However, we can still investigate any potential adjustment necessary for Site 1, by comparing observations at both Site 1 and Worksop Road (Site 4) with temperatures measured at other stations during the periods before and after the site changes in 1910, 1911 and 1912.

Comparisons with stations in Nelson, Gisborne and Christchurch indicate Worksop Road (Site 4) was warmer than Masterton Site 1 (Figure A1.1).[24] By taking an average of the three shifts shown in Figure 7 (+0.57 °C, +0.71 °C and +0.43 °C), we can estimate that Site 4 was 0.57 °C warmer than Site 1.[25] Temperatures at Site 1 should therefore be increased by 0.57 °C for consistency with Site 4. The cumulative adjustment necessary for Site 1 to be made consistent with East Taratahi AWS (Site 7) is therefore: -0.08 - 0.26 - 0.21 + 0.57 = +0.02 °C. In the February 2010 'Schedule of Adjustments', an equal adjustment of -0.5 °C had been applied to each of the Masterton Sites 1, 2, 3 and 4. However, our analysis here suggests that at least Site 1 was considerably warmer than Site 4.

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[24] Due to the four months missing from Masterton Site 1 in 1907 and 1908, annual mean temperatures were estimated from the available months at this site in these years. The annual mean temperature at Masterton Site 4 in 1912 has been estimated from the February to December temperatures in that year, because January 1912 readings were taken from Masterton Site 3. Since a monthly maximum temperature is missing from Christchurch Gardens in December 1905 and April 1906, the annual mean temperatures were estimated at this station in these years, though 1905 is not used in the comparison to Masterton Site 1. Please refer to Appendix 2 for details of the methodology used to estimate annual mean temperature in years missing up to three months of data.

[25] It must be noted that before the early site changes, the periods of comparison with Nelson, Gisborne and Christchurch are only two to four years. These periods are each followed by a two-year gap, because Masterton Sites 2 and 3 have been excluded. This leads to some uncertainty over the magnitude of any constant difference in temperatures between Masterton Sites 1 and 4.

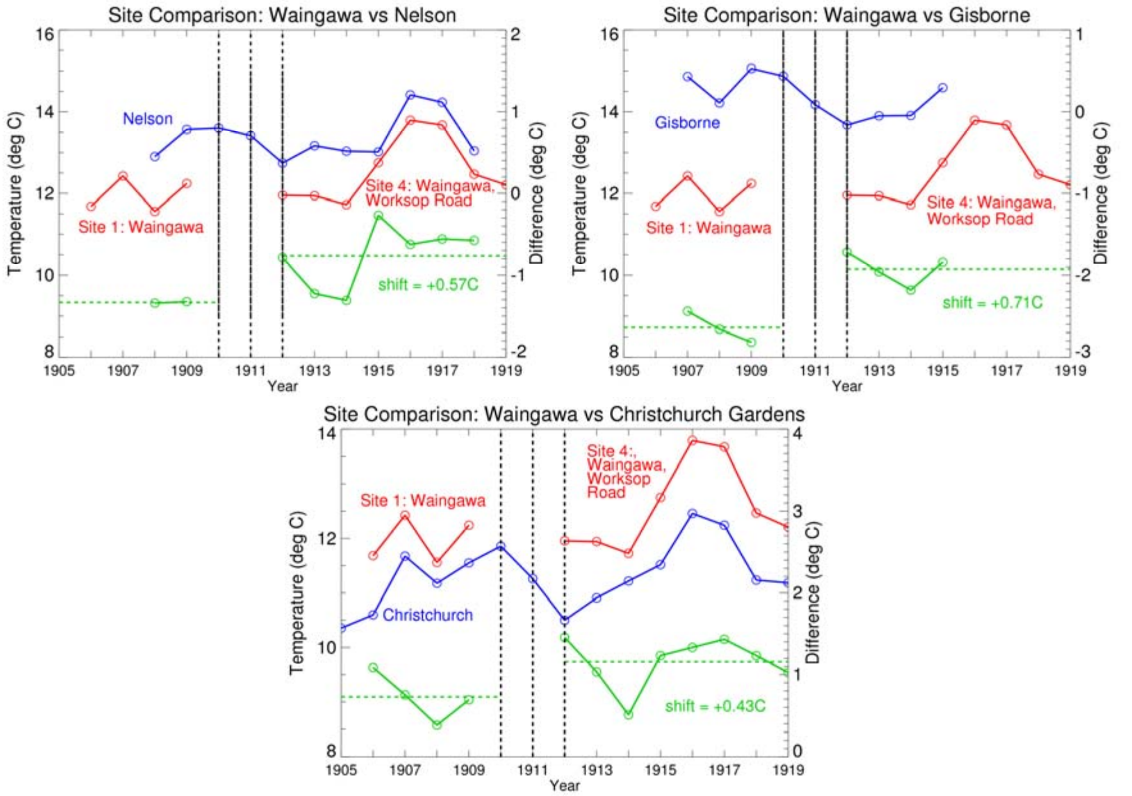

Figure A1.1: Comparisons of annual mean temperature series at Masterton Site 1 (Waingawa, agent 2473, red lines on the left of each plot) and Masterton Site 4 (Waingawa, Worksop Road, agent 2473, red lines on the right of each plot) with Nelson (agent 4244, blue line in upper left plot), Gisborne Aero (agent 2807, blue line in upper right plot) and Christchurch Gardens (agent 4858, blue line in lower plot) from 1905 to 1919. The differences (Waingawa minus each of the other stations) are indicated by the green solid lines, using the right-hand ordinate scale, and the mean differences relative to each Masterton site are shown by the green dashed lines. The magnitude of the mean shift from Site 1 to Site 4 is displayed in green, while the years of site changes at Waingawa (1910, 1911, and 1912) are indicated by the vertical dashed lines in the centre of each plot.

Appendix 2

Technical note on the treatment of missing data

We could choose to calculate and plot annual values for only those years with no missing months, but this would potentially discard a lot of useful information. If only a small number of months are missing from a station in a given year, we can estimate the annual mean temperature in that year by calculating the annual anomaly from the existent months.

Maximum and mean monthly air temperatures are unavailable at the Waingawa substation (Site 6) in July 1945, August 1946 and August 1947, partly because a new maximum thermometer was required in July 1945. In order to determine the adjustment necessary for the change of site in 1942, we need to estimate annual mean temperatures at the Waingawa substation in 1945, 1946 and 1947.

First, climatologies and anomalies are calculated for maximum temperatures at Waingawa in each calendar month from 1943 to 1972. This is the 30-year period following the 1942 site change at Waingawa. An annual climatology for the whole 1943-72 period is then calculated by averaging the monthly climatologies. The annual anomaly is then calculated for each year from 1943 to 1972, by averaging the anomalies of the non-missing months. The annual maximum temperature for the missing years is then estimated by adding each calculated annual anomaly to the annual climatology. This process is then repeated for minimum temperatures over the same period. Finally, the annual mean temperature in the missing years is calculated by taking the average of the annual maximum and minimum temperatures. This method takes advantage of all the monthly temperature data available at the station.

To use Appleby station (agent 4239) as a reference station for the 1942 site change at Waingawa, annual mean temperatures at Appleby in 1942, 1943, 1944 and 1949 were estimated from the eleven existent months in each of those years, using the methodology described above. A 30-year climatology from 1932 to 1961 was used, since annual mean temperatures began at Appleby in 1932.

Annual mean temperatures at the early Masterton sites in 1907, 1908 and 1912 were estimated by the same method, using shorter climatologies from Masterton Sites 1 and 4. Also, a monthly maximum temperature is unavailable at Christchurch Gardens in December 1905 and April 1906. The annual mean temperatures at Christchurch Gardens in 1905 and 1906 were therefore estimated using a 30-year climatology from 1905 to 1934, since annual mean temperatures began at the Magnetic Observatory in Hagley Park in 1905.

For the revised composite Masterton record, annual mean temperatures in years containing up to three missing months have been estimated from the composite 1971-2000 climatology for Masterton. The methodology for these estimates is the same as that described above, except that missing annual mean temperatures have been estimated solely from the existent monthly mean air temperatures, rather than the monthly maxima and minima.

Creating a Composite Temperature Series for Wellington

December 2010

Figure 1: Looking west toward the climatological enclosure at Kelburn in Wellington (November 2000).

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.

This present document revisits and describes in greater detail the process by which a composite station series has been developed for Wellington. The primary purpose is to demonstrate in an intuitive way how to estimate adjustments to temperature records 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 stations 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., RHtests, Wang *et al.*, 2007, see Appendix 3) to identify other change-points in the data.

Table 1: Information about Wellington 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 record;
(Column 4) altitude of site in metres above sea level;
(Column 5) previous period of record (as of February 2010) 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 of record for which the site contributes to the composite time series; and
(Column 8) revised temperature adjustment to be applied (with respect to Kelburn, 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	Previous Temp. Adjust. (°C)	Revised Period	Revised Temp. Adjust. (°C)
Site 1	Knowles Observatory (3383)	Midway between the shore of Wellington Harbour and the base of the Tinakori Range. (Feb 1862 to Oct 1868)	27	Mar 1862 to Oct 1868	-0.5	Not Used	N/A
Site 2	Bowen St (3389)	Grounds of the old museum. (Nov 1868 to Oct 1869)	18	Nov 1868 to Oct 1869	-0.5	Not Used	N/A
Site 3	Bolton St Cemetery (3390)	Government Astronomical Observatory. (Nov 1869 to May 1906)	43	Nov 1869 to May 1906	-0.5	Not Used	N/A
Site 4	Buckle St (3431)	Mount Cook, south Wellington. (Jun 1906 to Jul 1912)[2]	34	Jun 1906 to Jun 1912	-0.6	Jun 1906 to Jun 1912	-0.73
Site 5	Thorndon (3391)	Thorndon Esplanade. (Jul 1912 to Dec 1927)	3	Jul 1912 to Dec 1927	-0.8	Jul 1912 to Dec 1927	-0.89
Site 6	Kelburn (3385)	Wellington Botanic Garden. (Dec 1927 to Aug 2005)	125	Jan 1928 to Aug 2005	0.0	Jan 1928 to Aug 2005	**0.00**
Site 7	Kelburn AWS[3] (25354)	Wellington Botanic Garden. (April 2004 to present)	125	Sep 2005 to present	0.0	Sep 2005 to present	-0.06

[2] A meteorological return from Buckle Street (Site 4) for July 1912 is available in the paper archives. Thus, there is one month of overlap with Thorndon, which is not recorded in CliDB.
[3] AWS denotes Automatic Weather Station, and is part of the observation network operated by MetService NZ. The NIWA Climate Database also uses other abbreviations such as EWS, for Electronic Weather Station: this is also an 'automatic' station, but is operated by NIWA and has a different set of sensors and data logging software.

Calculation of Adjustments

Table 1 summarises the information about the local sites used to develop the composite temperature series for the Wellington 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.[4] Table 1 lists six different sites, and a change to an automatic weather station (labelled as Site 7). Thus, seven temperature series contribute to the Wellington series, and the temperatures 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 was made <u>not</u> to include temperatures prior to 1900. Furthermore, if there were site changes around 1910 that were difficult to justify, then the time series was truncated at that point. In the case of Wellington, the revised series begins with Site 4 in 1906. In the interests of completeness, adjustments are still estimated for the earlier sites, but discussion of them is relegated to Appendix 1 and 2, along with other more technical comment.

It is common practice to adjust all the historical measurements to be consistent with the current open site (Aguilar *et al.,* 2003). However, in the case of the Wellington sites, the automatic site has only been operating for a few years and the long-running Kelburn manual site (Figure 1, labelled Site 6 in Table 1, agent number 3385) is still currently used as the ‘Reference’ site. Thus, Kelburn (Site 6), the ‘Reference’ site, will by definition have zero adjustment. Measurements made at the other Wellington stations (Sites 1, 2, 3, 4, 5 and 7 in Table 1) will all be adjusted for consistency with Kelburn (Site 6).[5]

Figure 2 provides a map locating the local Wellington sites of Table 1, and also a number of the more distant comparison sites discussed in the subsequent text.

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[4] Calculation to two decimal places has been done to minimise the accumulation of round-off errors. This should not be interpreted as an indication of the accuracy of the adjustment. Air temperatures are recorded to the nearest 0.1 °C on the NIWA Climate Database.

[5] We could easily choose to adjust the temperature records to a different site. This would make no difference to the <u>trend</u> or variability, which is what we are trying to work out. However, the absolute temperatures would change; for example, they would be higher for a warmer reference site in the Wellington CBD, but still retain the same trend in time.

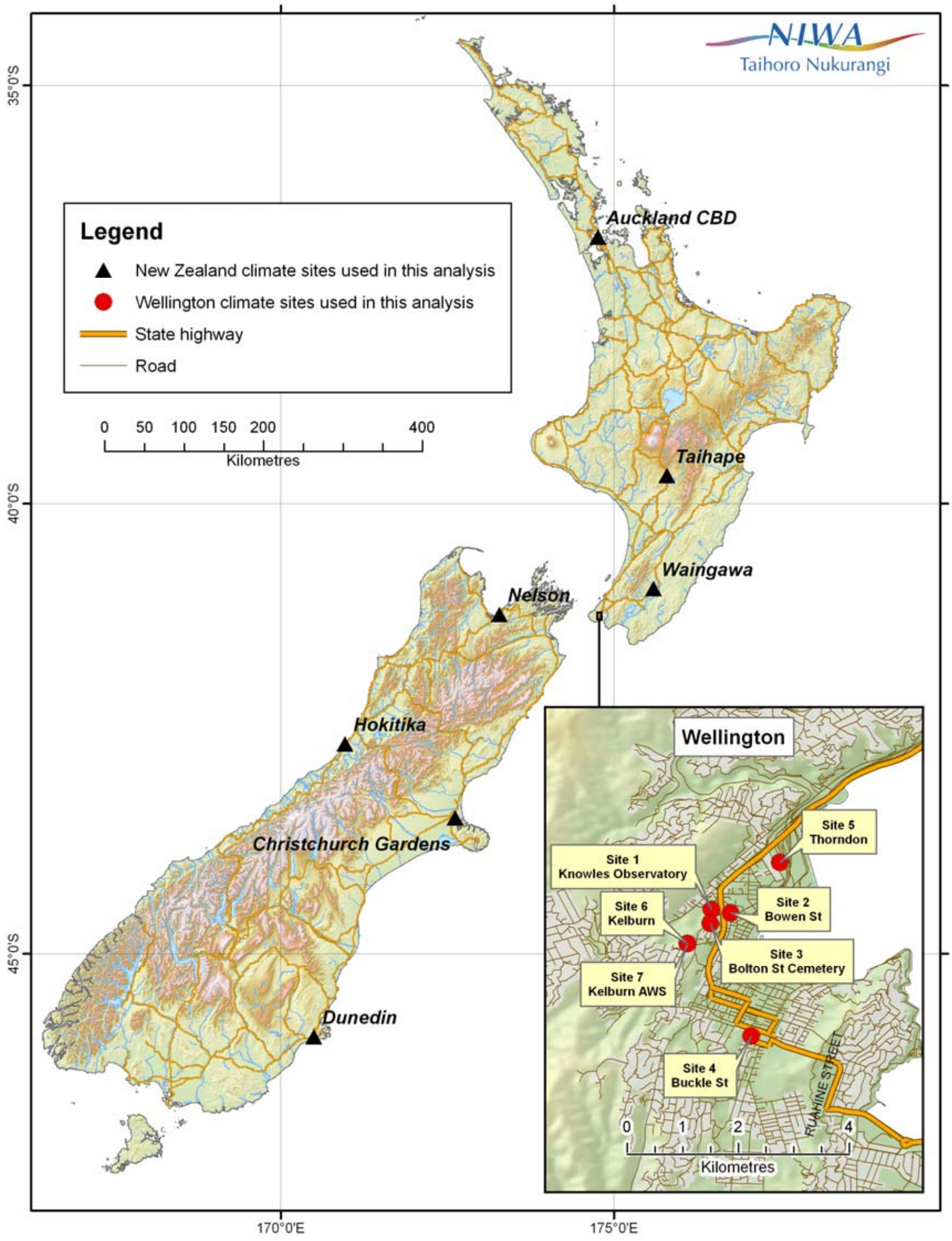

Figure 2: Map showing sites of temperature records referred to elsewhere within this document. The inset map locates the local Wellington sites.

Adjustment for Site Change in 2005

The first adjustment to calculate is that between the reference site (Kelburn, Site 6) and Kelburn AWS (Automatic Weather Station, Site 7 in Table 1, agent number 25354). Both these 'sites' are in exactly the same weather station grounds (the 'enclosure', Figure 1), located in the Wellington Botanic Gardens in the suburb of Kelburn at an elevation of 125 metres above sea level (m a.s.l.). The Kelburn AWS instrumentation was set up in late April 2004, and run in parallel with the manual instruments until August 2005. Kelburn AWS contributes temperatures to the composite temperature series for Wellington from September 2005 to the present day.

The previous Kelburn station (Site 6 in Table 1, agent number 3385) was located in the same enclosure as the Kelburn AWS in the Wellington Botanic Gardens. Observations of temperature first began at Kelburn (Site 6) in December 1927 and ceased at the beginning of September 2005. The Kelburn manual station (Site 6) provides temperatures for the composite Wellington series from January 1928 until August 2005.

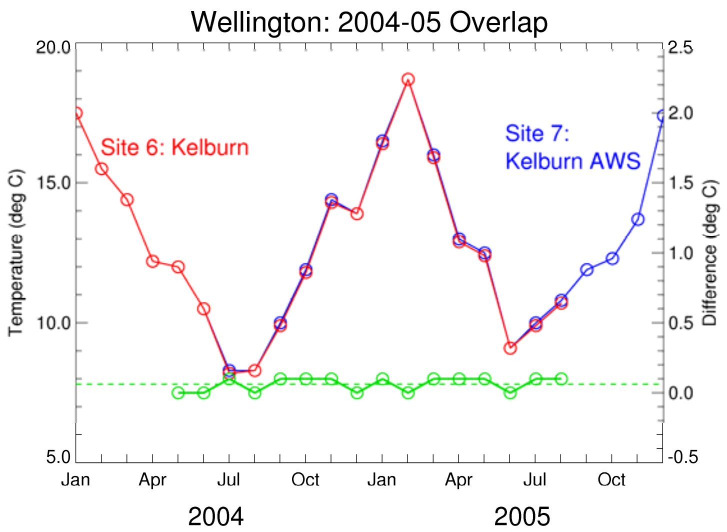

Figure 3: Monthly mean temperature series for Kelburn (Site 6, agent 3385, red line) and Kelburn AWS (Site 7, agent 25354, blue line) for 2004 and 2005. The monthly difference, Site 7 minus Site 6, is plotted by the solid green line, using the right-hand ordinate scale, and the average monthly difference is indicated by the dashed green line.

Monthly mean temperatures overlap at the Kelburn station (Site 6) and the Kelburn AWS (Site 7) for a total of 16 months between May 2004 and August 2005. This overlap allows us to directly compare temperatures at the two sites. We can then determine what adjustment may be necessary in order to make observations at Kelburn AWS (Site 7) consistent with those at Kelburn (Site 6). Figure 3 shows the overlapping monthly mean temperatures at Wellington Sites 6 and 7.

During the 16 months of the overlapping period, monthly mean temperatures at Kelburn AWS (Site 7) were very similar to those at Kelburn (Site 6), as one would expect. To two decimal places, the average difference between monthly temperatures at the two sites was +0.06 °C: that is, Kelburn AWS (Site 7) was 0.06 °C warmer than Kelburn (Site 6).

It seems reasonable to question whether an adjustment as small as this is required at all. During the 16-month overlapping period, monthly mean temperatures at Kelburn AWS (Site 7) were the same to one decimal place as Kelburn (Site 6) for 6 months, and 0.1 °C warmer than Kelburn (Site 6) during the other 10 months (not consecutive). This calculation over just a few months is not very precise, since monthly mean temperatures in the Climate Database are rounded to the nearest tenth of a degree. However, a calculation of the differences in the daily maximum and minimum temperatures produced exactly the same answer (to two decimal places): namely, the mean temperature at Kelburn AWS (Site 7) was 0.06 °C higher than at Kelburn (Site 6).

Therefore, temperatures at Kelburn AWS (Site 7) must be *decreased* by 0.06 °C to be consistent with the Wellington reference site of Kelburn (Site 6); this adjustment of -0.06 °C is shown in Table 1. In the February 2010 'Schedule of Adjustments', the adjustment for Kelburn AWS (Site 7) was 0.0 °C.

Kelburn Record 1928-2005

The temperature record for Kelburn (Site 6) has been incorporated into the Wellington composite series, without any adjustments over the period 1928 to 2005.

Careful consideration was given to a possible inhomogeneity around 1950. It is noted in the station history (Fouhy et al., 1992) that in July 1949 trees and bushes were cut back to improve exposure around the site. The same exercise was repeated in August 1959, and again in 1969. It appears likely that the 'screen' (the louvred box containing the thermometers) was changed at some point around 1950 from a small Stevenson screen to a modified-Stevenson or Bilham screen, but the date is not recorded.[6]

Salinger (1981) adjusted the earlier part of the Kelburn (Site 6) record, from 1928 to 1950, by -0.2 °C, saying that this was to compensate for some clearing of vegetation and the change in the type of thermometer screen. That is, the pre-1950 Kelburn temperatures were decreased by 0.2 °C, which increases the warming trend over the 20th century at the Wellington location. In the February 2010 'Schedule of Adjustments', which derive from Salinger et al. (1992), no adjustment was made to the early Kelburn (Site 6) record.

Comparisons were made between the Kelburn temperature record and measurements from a number of other sites about a supposed 1950 change-point. The evidence for an inhomogeneity at 1950 was not very convincing, and we decided against applying a correction to the Kelburn record at 1950.[7]

[6] Hessell (1980) says the screen change occurred in 1948, but we have been unable to find any original documentation.

[7] Site comparisons before and after 1950 gave the following (a negative change implying a decrease in temperatures at Kelburn after 1950): -0.01 °C (Appleby, near Nelson), -0.04 °C (Waingawa), -0.09 °C (Bagshot, northeast of Masterton), and -0.23 °C (Palmerston North). Thus, any correction would be

Adjustment for Site Change in 1928

From July 1912 until December 1927, the temperatures used in the composite temperature series for Wellington were observed at the Thorndon station (Site 5 in Table 1, agent number 3391). This station was established on Thorndon Esplanade at an elevation of 3 metres above sea level, in what are now the Wellington railway yards. Observations began at the Kelburn enclosure (Site 6) in December 1927, with the erection of the meteorological office in Kelburn. The Kelburn site is 122 m higher in altitude and about 2 km in distance from Thorndon Site 5 (Table 1 and Figure 2).

Observations at the Thorndon station ceased at the end of 1927, so measurements at Thorndon and Kelburn overlap only in December 1927. The monthly mean temperature at Thorndon (Site 5) in December 1927 was 14.7 °C, while at Kelburn (Site 6) it was 13.7 °C, a difference which is close to that which would be expected for sites with an elevation difference of 122 m.[8] However, a much longer period of comparison is required to reliably estimate the temperature offset between sites. It is therefore necessary to compare temperatures at Thorndon and Kelburn with other overlapping ('comparison') sites, to determine how temperatures differ between Wellington Sites 5 and 6. The preferred choices are nearby sites in the same climatic region. If such sites were not available (an issue in the earlier decades of the 20th century), then more distant sites need to be considered.

Figure 4 shows the correlation of mean temperature interannual differences at the Virtual Climate Station (VCS) grid point containing Kelburn (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).[9] Interannual temperature variations at Kelburn correlate well with those in the southern part of the North Island, including Masterton (+0.92), as well as Nelson (+0.93) in the northern part of the South Island.[10] Temperature variations at Kelburn also correlate well with those at Auckland (+0.88) and Christchurch (+0.89). So, temperature records from these more distant sites could also be used.

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small, with the evidence favouring a negative correction rather than a positive one, increasing the warming trend over the century. The F-test from the RHtests statistical package, applied to the raw appended-site temperature data, does not identify any inhomogeneity around 1950 (Australian Bureau of Meteorology, pers. comm.).

[8] Note that although the 'Monthly_Stats' table on the Climate Database reports these temperatures as monthly averages, there are actually 31 days contributing to the Thorndon average (1-31 December 1927) but only 29 days in the Kelburn average (3-31 December). If daily differences between Thorndon and Kelburn are calculated over just the 29 days in common, then over 3-31 December 1927 Thorndon was warmer than Kelburn by 1.2 °C (daily differences converted from Fahrenheit to Celsius, and rounded to one decimal place after averaging).

[9] 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).

[10] A correlation of +1.0 indicates perfect agreement; i.e., that the interannual temperature variations at two sites match perfectly (except for a constant offset and multiplicative factor).

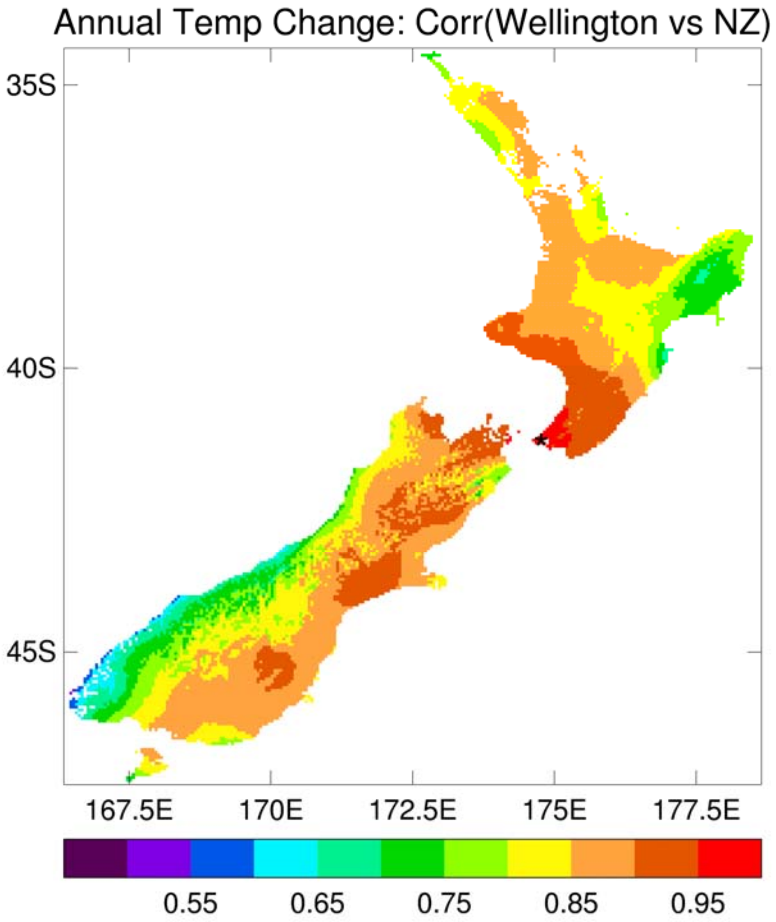

Figure 4: Map of correlation between interannual temperature changes at the grid-point nearest to Kelburn (Site 6, agent 3385, location marked by asterisk) in Wellington, 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

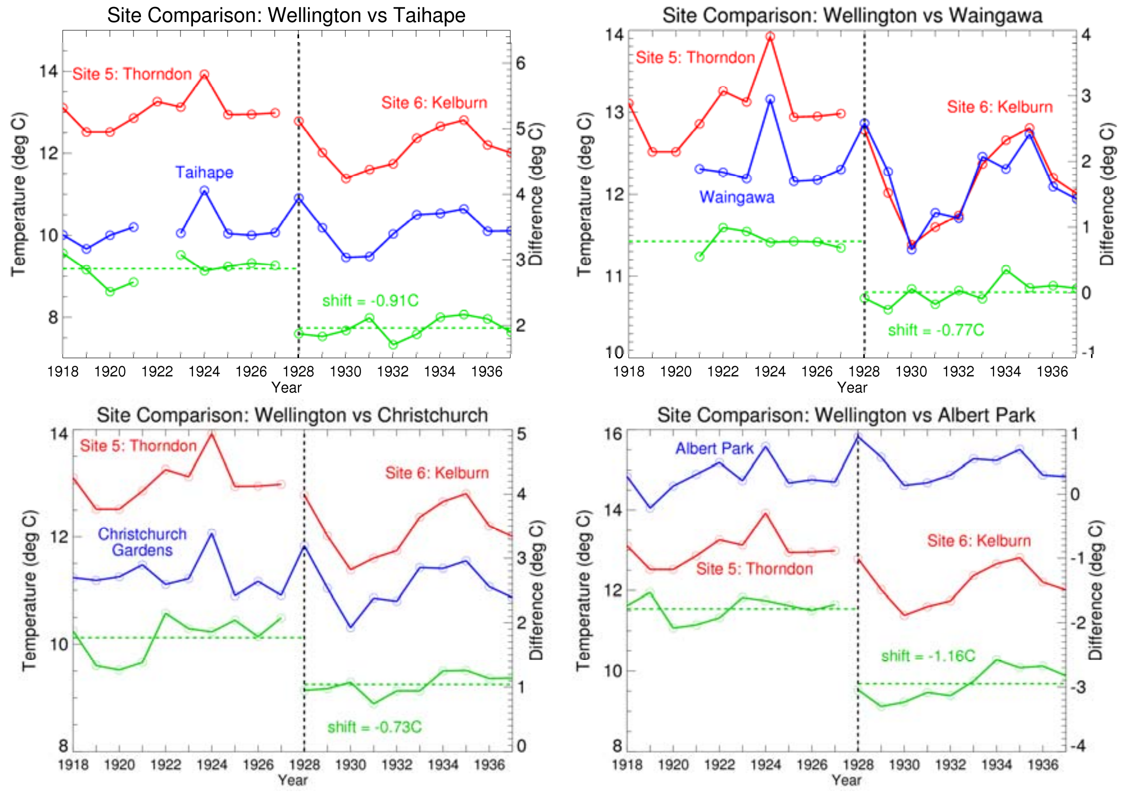

Figure 5: Annual mean temperature series at Thorndon (Site 5, agent 3391, red lines on the left half of each plot) and Kelburn (Site 6, agent 3385, red lines on the right half of each plot) compared with four other stations that overlap the Wellington site change: Taihape Hiwi (agent 3669, blue line in upper left plot), Waingawa (agent 2473, blue line in upper right plot), Christchurch Gardens (agent 4858, blue line in lower left plot), and Albert Park (agent 1427, blue line in lower right plot), from 1918 to 1937. The solid green line represents the difference in annual temperature (Thorndon/Kelburn minus the comparison station) using the right-hand ordinate scale. The horizontal green dashed line is the average difference before and after the site change. The year of the site change, 1928, is indicated by the vertical dashed line.

Figure 5 compares annual temperatures[11] at Thorndon and Kelburn with stations in Taihape, Waingawa (in Masterton), Christchurch and Auckland before and after the Wellington site change in 1928.[12] The drop in Wellington temperatures after the site change in 1928 is distinctly visible in Figure 5.

[11] Annual mean temperatures in this analysis have been calculated to several decimal places from the monthly mean temperatures in CliDB, in order to minimise round-off errors.

[12] The intention in these analyses is to compare temperatures over 10 years before and after the site change. This is not always possible since the record at the comparison site may not cover the whole of this period, or there may be information in the site history that points to other potential inhomogeneities in the record of the comparison site. The period of comparison between Thorndon and Waingawa (Figure 4, upper right plot) has been truncated due to the relocation of the Waingawa station in 1920.

The 'best' comparison stations are selected after inspection of their correlations with the target stations (Thorndon and Kelburn here), considering not just mean temperature but also maximum and minimum temperature correlations. Direct correlations between stations have been calculated using the first-difference series of annual temperatures over the period of comparison, excluding the year of the site change itself. This method prevents any discontinuity in the year of the site change from influencing the correlations (Aguilar et al. 2003).

Before the 1928 site change, Thorndon (Site 5) was on average 2.87 °C warmer than Taihape (Figure 5, upper left).[13] After the 1928 site change, Kelburn (Site 6) was on average 1.96 °C warmer than Taihape. Thus with reference to Taihape, the Kelburn site was 0.91 °C cooler than Thorndon.

We then repeat this process of comparison for the other stations in Figure 5. With reference to the Waingawa station in Masterton (Figure 5, upper right), Kelburn was 0.77 °C cooler than Thorndon. With reference to Christchurch Gardens (Figure 5, lower left), Kelburn was 0.73 °C cooler than Thorndon. Finally, with reference to Albert Park (Figure 5, lower right), Kelburn was 1.16 °C cooler than Thorndon.

This gives us four estimates of the difference between Thorndon and Kelburn: -0.91 °C, -0.77 °C, -0.73 °C and -1.16 °C, which gives an average offset of -0.89 °C.[14] Therefore, temperatures at Thorndon (Site 5) must be decreased by 0.89 °C in order to be consistent with Kelburn (Site 6), our reference site for the Wellington temperature series.

Given that the Thorndon to Kelburn adjustment is so large, it is important to estimate this correction as robustly as possible. There is quite a large spread from -0.73 °C to -1.16 °C based on these four sites. Annual temperatures at the Thorndon and Kelburn stations were also compared with another 13 stations, all having no known site relocations for at least five years before and after January 1928. The average difference between annual mean temperatures at Thorndon and Kelburn, with reference to all 17 comparison stations (including the four comparison stations in Figure 4), was -0.94 °C.

Thus, an offset of around -0.9 °C would seem to be robust, and the value of -0.89 °C we have adopted in Table 1 may even be slightly conservative. The adjustment calculated by Salinger et al. (1992), as given in the February 2010 'Schedule of Adjustments', was -0.8 °C. The Thorndon-to-Kelburn offset estimated even earlier by Salinger (1981) was -1.0 °C.[15] Additional analysis of the early Kelburn record using the RHtests software (presented in Appendix 3) identifies an offset that is very close to the -0.89 °C obtained in the present section.

[13] The maximum thermometer at Taihape was replaced in October 1921, but the new one proved to be defective below 6 °C, and was replaced on 14 June 1922 (Fouhy et al. 1992). Monthly mean temperatures from October 1921 to June 1922 were therefore not used in the comparison with Thorndon. The annual mean temperature at Taihape in 1921 was estimated from the January-September temperatures in 1921, using the local climatology; the annual mean temperature at Taihape was not estimated in 1922. For a description of the methodology used to estimate annual mean temperatures in years missing up to three months, please refer to Appendix 2 of the NIWA review document for Masterton: 'Creating a Composite Temperature Series for Masterton'.

[14] The estimated offsets from different comparison sites could be combined in some other way than a simple average. Typical approaches in the literature are to weight by correlation or by distance, or both (e.g., square of the correlation and inverse square of the distance).

[15] In Table W.N.6 (page C55 of Appendix C of Salinger, 1981), we find cumulative adjustments relative to the post-1950 Kelburn record of -0.2 °C for the 1928 to 1950 period (i.e., accounting for tree clearing and a screen change at 1950), and -1.2 °C for the 1913 to 1927 period of the Thorndon record. Thus, the relative change across 1928 is -1.0 °C.

Adjustment for Site Change in 1912

Observations began in Buckle Street (Site 4 in Table 1, agent number 3431) in Mount Cook, south Wellington, in June 1906. Observations ceased here at the end of July 1912, though the July 1912 return for Buckle Street is not recorded in CliDB. Observations began in Thorndon (Site 5) at the beginning of July 1912. Thus, there is only one overlapping month of observations at Buckle Street and Thorndon: July 1912.[16] This is an insufficient period to reliably estimate the mean temperature difference between the two sites. However, we can again compare temperatures at these two sites with observations at other stations, in order to determine any potential change in temperature associated with the change of site. Fewer climate stations were in operation in the earlier years of the 20th century, so it becomes necessary to compare the Wellington sites with more distant stations.[17]

Figure 6 compares temperatures at Buckle Street (Site 4) and Thorndon (Site 5) with stations in Auckland, Nelson and Christchurch from 1907 to 1922. This period spans the five whole years in which we have annual mean temperatures at Buckle Street (1907-1911), plus the ten whole years at Thorndon after the 1912 site change (1913-1922). The periods of comparison with Auckland and Nelson are truncated, due to relocations of those sites. In addition, five months of observations are missing from Nelson in 1919.

With reference to Albert Park (Figure 6, upper left), the Thorndon site was 0.26 °C warmer than Buckle Street. With reference to Nelson (Figure 6, upper right), Thorndon was 0.13 °C warmer than Buckle Street. And with reference to Christchurch Gardens (Figure 6, lower plot), Thorndon was 0.09 °C warmer than Buckle Street.

After averaging the three offsets (+0.26 °C, +0.13 °C and +0.09 °C), we conclude that Thorndon was 0.16 °C warmer than Buckle Street. Therefore, annual mean temperatures at Buckle Street should be increased by 0.16 °C to be consistent with those at Thorndon. The cumulative adjustment of Buckle Street relative to Kelburn (Site 6) is thus: -0.89 + 0.16 = -0.73 °C.

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[16] The mean monthly temperature recorded in the original meteorological return for Buckle Street in July 1912 is 47.4 °F, which is approximately 8.6 °C. The mean monthly temperature at Thorndon in July 1912, as recorded in CliDB, was 8.8 °C. Thus the Thorndon site was approximately 0.2 °C warmer than the Buckle Street site in July 1912.

[17] Of the comparison stations used for the 1928 site change in Figure 5, both Auckland and Christchurch are again suitable for comparison across the change from Buckle Street to Thorndon in 1912 (although there is only a short period at Auckland before the site move from Albert Park to the Princes Street Museum). The Waingawa station was moved in 1910, 1911 and 1912, while the temperature record at Taihape Hiwi begins in 1911, only a year before the Wellington site change in 1912. The Nelson site used in Figure 6 was one of the 17 sites considered at the 1928 change-point. It produced a shift of -1.20 °C between Thorndon and Kelburn, but appeared to have an odd cooling trend relative to Thorndon: thus, Nelson was not used in the final site selection that went into determining our adopted adjustment of -0.89 °C at 1928.

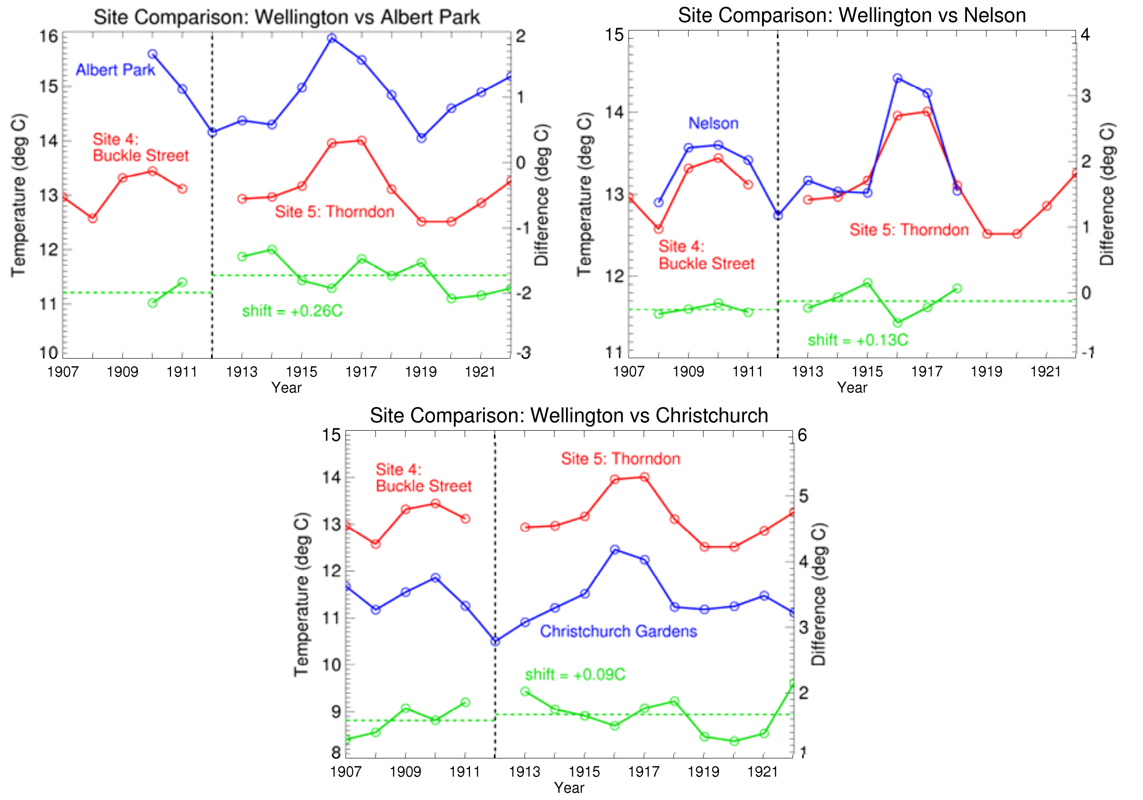

Figure 6: Comparisons of annual mean temperature series at Buckle Street (Site 4, agent 3431, red lines on the left part of each plot) and Thorndon (Site 5, agent 3391, red lines on the right part of each plot) with Albert Park in Auckland (agent 1427, blue line in upper left plot), Nelson (agent 4244, blue line in upper right plot) and Christchurch Gardens (agent 4858, blue line in lower plot) from 1907 to 1922. The solid green line represents the difference in annual temperature (Buckle Street/Thorndon minus the comparison station) using the right-hand ordinate scale. The horizontal green dashed line is the average difference before and after the site change. The year of the site change, 1912, is indicated by the vertical dashed line.

Adjustments for Site Changes in 1906 and Earlier

The Buckle Street (Site 4) observations began in June 1906. Immediately prior to that, observations had been taken at the Government Astronomical Observatory on a hill in the Bolton Street cemetery (Site 3 in Table 1, agent number 3390). These early temperature measurements have not been included in the revised composite series for Wellington. However, see Appendix 1 for a discussion of estimated adjustments for Bolton Street to Buckle Street (Site 3 to Site 4), and our reasoning for not including the Site 3 data in the revised temperature series. Appendix 2 discusses the earlier adjustments of Bowen Street to Bolton Street (Site 2 to Site 3), and Knowles Observatory to Bowen Street (Site 1 to Site 2).

Putting the Time Series Together

The revised temperature adjustments described above can be applied successively to the Wellington temperature records. The resultant annual time series from 1907 to 2009 is shown in Figure 7, with a comparison with the previous Wellington time series used by NIWA. A 100-year linear trend has been fitted to each series over the period from 1909 to 2009. The linear trend in the revised series is 0.86 (±0.30) °C /century, as compared to 0.79 (±0.30) °C /century for the trend calculated from the previous Wellington time series published in February 2010.[18]

Once the temperatures from the Wellington sites have been adjusted for consistency with Kelburn (Site 6), and then combined, we have a homogeneous temperature series for Wellington. However, simply appending the raw data from the Wellington records without correcting for known site changes would result in an inhomogeneous history of temperature, unsuitable for the analysis of long-term trends.

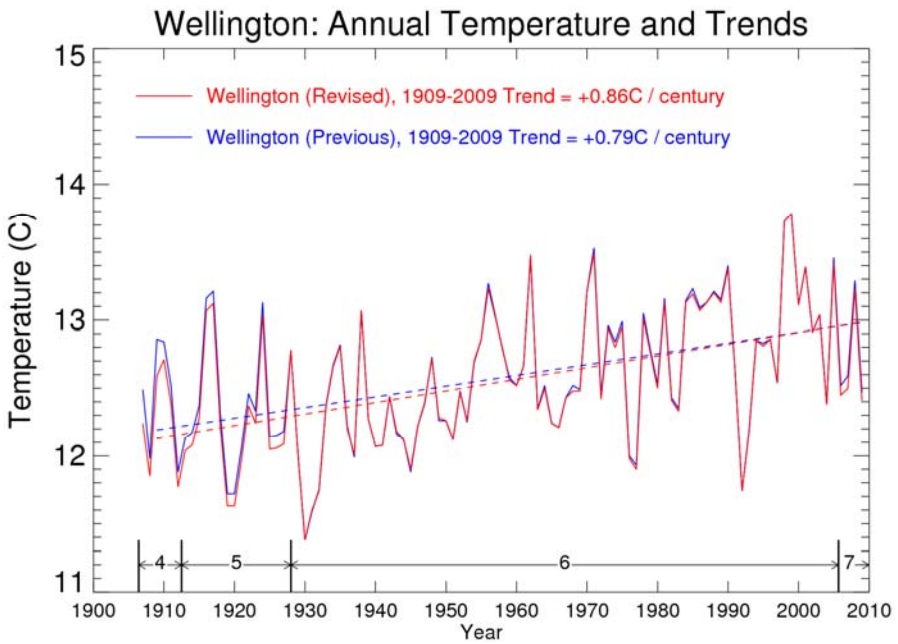

Figure 7: Comparison of the new series (red line) and previous NIWA series (blue line) of composite temperatures for Wellington from 1907 to 2009. The dashed lines indicate the fitted linear trends from 1909 to 2009. Labels near the bottom of the plot denote the Site numbers of Table 1. Vertical lines at the bottom of the plot mark the time periods over which each site contributes to the composite series, with the Sites numbered as in Table 1.

[18] 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 8 repeats the graph of the revised composite annual mean temperature series for Wellington, and compares the composite to the unadjusted raw multi-site temperatures. From 1928 to 2004 the two series are identical, since this period is covered by the Wellington reference site (Kelburn, Site 6) to which no adjustment is applied. The estimated adjustments are also shown in Figure 8. The adjustments are cumulative relative to Kelburn Site 6, and correspond to those in the final column of Table 1.

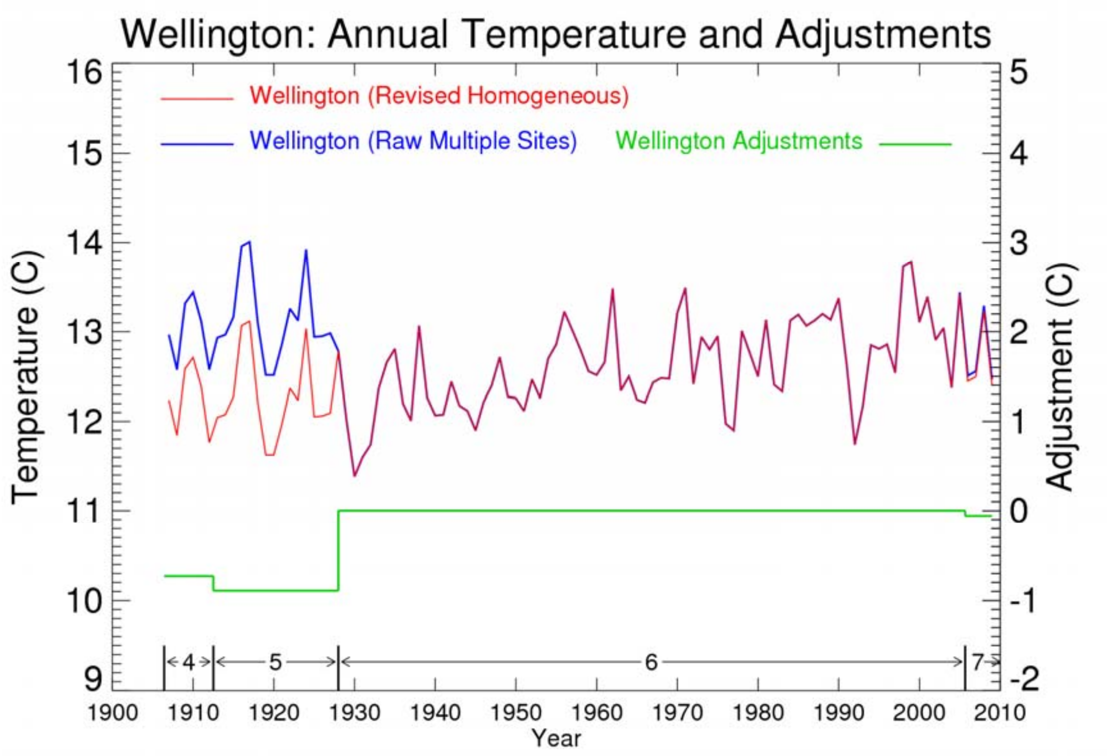

Figure 8: Comparison of new composite temperature series for Wellington from 1907 to 2009 (red line), with the raw multi-site series (Sites 4-7, blue line). The green line (using the right-hand axis) indicates the cumulative step adjustments to each site as shown at the bottom of the graph, and corresponds to the adjustments in the right-hand column of Table 1.

Further Information

Further technical information on different approaches to homogeneity adjustment of climate data can be found in the references below (Aguilar et al. 2003; Peterson et al. 1998; Rhoades and Salinger 1993).

Date: Document originally created 28 October 2010, and revised 13 December 2010 following review from the Australian Bureau of Meteorology.

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Appendix 1

Adjustment for Site Change in 1906

Observations of air temperature began at the Government Astronomical Observatory on a hill in the Bolton Street cemetery (Site 3 in Table 1, agent number 3390) in November 1869. Observations ceased here in June 1906, when the site was required at short notice for the grave of the Premier, Richard Seddon. The meteorological enclosure was therefore moved to Buckle Street (Site 4) at that time. In the meteorological return for June 1906, the observer noted that air temperatures at the Bolton Street cemetery and Buckle Street were "similar" during three days of simultaneous measurements. However, this is a very short period of time and the overlapping temperatures are not recorded. Once again we need to compare observations at the two Wellington sites to other overlapping stations in order to determine any potential change in temperature associated with the movement of the instruments.

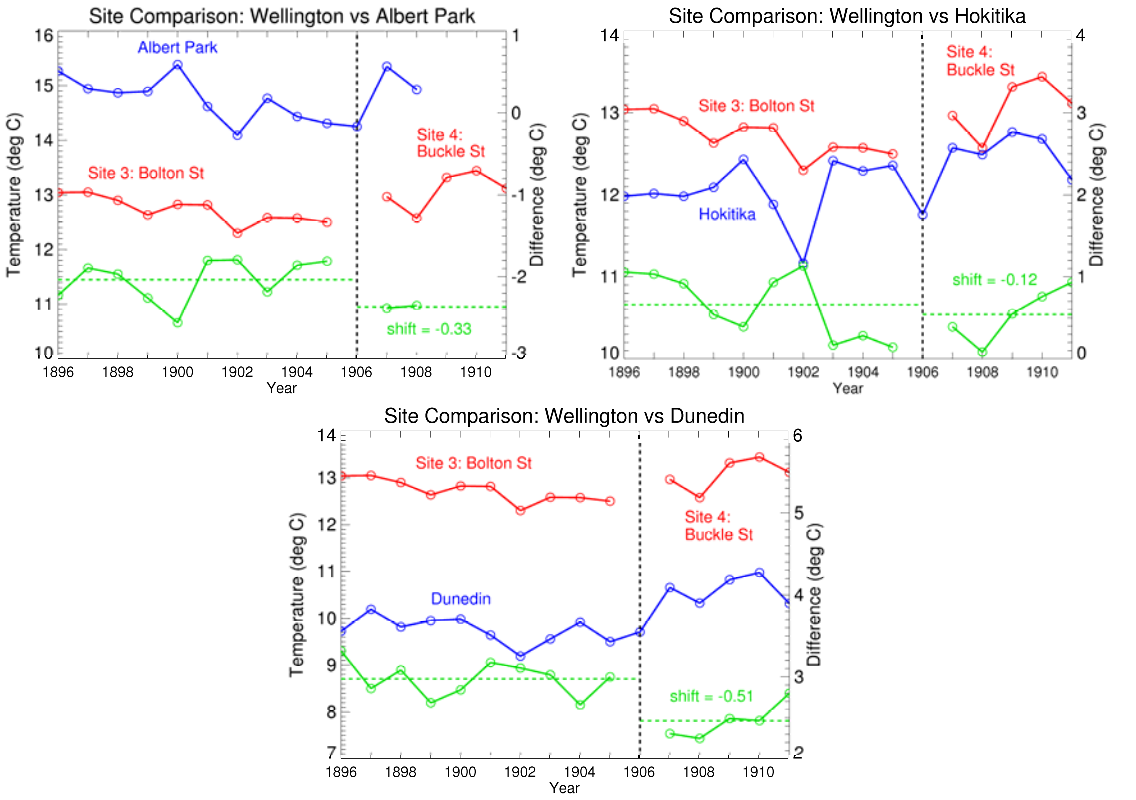

Figure A1.1: Comparisons of annual mean temperature series at the Bolton Street cemetery (Site 3, agent 3390, red lines on the left part of each plot) and Buckle Street (Site 4, agent 3431, red lines on the right part of each plot) with Albert Park in Auckland (agent 1427, blue line in upper left plot), Hokitika Town (agent 3907, blue line in upper right plot) and Leith Valley in Dunedin (agent 5380, blue line in lower plot), from 1896 to 1911. The solid green line represents the difference in annual temperature (Bolton Street/Buckle Street minus the comparison station) using the right-hand ordinate scale. The horizontal green dashed line is the average difference before and after the site change. The year of the site change, 1906, is indicated by the vertical dashed line.

Figure A1.1 compares annual temperatures at the Bolton Street cemetery and Buckle Street to stations in Albert Park in Auckland, Hokitika and Dunedin from 1896 to 1911.[19] This period spans the ten years at Bolton Street before the 1906 site change, 1896 to 1905, plus the five whole years for which we have annual mean temperatures at Buckle Street, 1907 to 1911.

Averaging the three offsets indicated in Figure A1.1 (-0.33 °C, -0.12 °C and -0.51 °C) suggests that Buckle Street was 0.32 °C colder than Bolton Street. Therefore, annual mean temperatures at Bolton Street should be decreased by 0.32 °C to be consistent with those at Buckle Street. The cumulative adjustment of Bolton Street relative to Kelburn (Site 6) is thus: -0.89 + 0.16 – 0.32 = -1.05 °C.

However, this cumulative adjustment of -1.05 °C has not been included in Table 1, and we have not extended the revised Wellington series back past the start of the Buckle Street record in June 1906. There are several reasons for this, and they all relate to the lack of confidence in the -0.32 °C adjustment above. First, there is inconsistency between previous attempts at determining the offset between Buckle and Bolton Streets. Salinger (1981) calculated an adjustment of -0.3 °C (in good agreement with our value above)[20], but Salinger et al. (1992) determined the offset to +0.1 °C (i.e., in the opposite direction).

Furthermore, if the offset is indeed negative and as large as -0.3 °C, this makes Buckle Street the warmest of the Wellington CBD Sites 3 through 5. This is difficult to justify given that Bolton Street had the highest altitude of all three sites. And finally, the very limited options for selecting comparison sites has caused us to use Hokitika in Figure A1.1 even though we know the measurements there were erroneously high.[19] If the Hokitika station is ignored, the average offset from the remaining two stations is even more extreme at -0.42 °C, and compounds the problems discussed above.

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[19] Monthly mean temperatures are missing from Leith Valley in Dunedin in September 1900 and August 1909. Annual mean temperatures at Leith Valley in 1900 and 1909 have therefore been estimated from the eleven existent monthly mean temperatures in each of these years, using the 1886-1913 climatology at Leith Valley. The Hokitika temperatures are recognised as being too warm during the 1894-1912 period, but could be used if we assume that they are uniformly warm throughout the overlap comparison period of Figure 6, and the temperatures pre- and post-1912 are not used together in the same comparison.

[20] Salinger (1981) used the same 3 comparison sites as in our Figure A1.1, plus Lincoln. Unfortunately, there are considerable homogeneity issues associated with the early Lincoln record (see NIWA review document for Lincoln: ‘Creating a Composite Temperature Series for Lincoln’).

Appendix 2

Adjustments for Sites Prior to 1870

In 1862, observations began at the Knowles Observatory (Site 1 in Table 1, agent number 3383), midway between the shore of Wellington Harbour and the base of the Tinakori Range. From November 1868 to October 1869, temperatures were observed at Bowen Street (Site 2 in Table 1, agent number 3389) in the grounds of the old Museum. In November 1869, the meteorological instruments were moved again, this time to the Bolton Street cemetery (Site 3).

Very few stations are available for comparison around the time of these early site changes in Wellington. Comparisons to stations in Nelson, Hokitika, Christchurch and Dunedin do not indicate a consistent change in annual mean temperature associated with the shift from the Knowles Observatory (Site 1) to subsequent sites. Again, due to the uncertainty associated with the early observations, no additional adjustment has been estimated for these site changes, and no revised adjustments for Wellington Sites 1 and 2 have included in Table 1. In the February 2010 ‘Schedule of Adjustments’, the adjustments for Wellington Sites 1 and 2 were both set to -0.5 °C; that is, no correction relative to the 1869 to 1906 Bolton Street temperature record.

Appendix 3

Example: Application of RHtests Software to the 1928 Site Change

Statistical methods can be used to detect mean shifts in temperature within a time series, with or without prior knowledge of site changes. One such method is the penalised maximal *t* test (Wang *et al.*, 2007). The penalised maximal *t* test (PMT) moves through a time series, checking the data before and after each value in the time series. The PMT can also be applied to a series of temperature observations with reference to comparison stations. In this case, the PMT identifies a 'change-point' in the temperature series at the time of the maximum shift in mean temperatures with reference to the comparison stations.

An example of the application of the PMT to the Wellington temperature series is presented in this Appendix.[21] First, the unadjusted monthly mean temperatures at Thorndon (Site 5) and Kelburn (Site 6) from January 1921 to September 1942 were appended to one another; the break between the two stations in this series was December 1927/January 1928, which is when the composite Wellington temperature series changes from the Thorndon record to the Kelburn record. The penalised maximal *t* test was applied to this monthly series, with reference to averaged monthly temperatures at Taihape (agent 3669), Waingawa (agent 2473) and Nelson (agent 4244) from January 1921 to September 1942.[22] The test was performed over the longest period possible for which a homogeneous series could be constructed from the comparison stations, given the relocations of the Nelson station in December 1920 and the Waingawa station in October 1942.

Two mean shifts in the 1921-1942 Wellington temperature series were initially detected by the PMT: a statistically significant decrease of 1.10 °C in December 1927; and an increase of 0.21 °C in September 1933 which "may or may not be statistically significant".[23] Since the composite Wellington series actually changes from Thorndon to Kelburn in January 1928, the date of the first change-point was changed to January 1928. A reapplication of the PMT then diagnosed a statistically significant decrease in mean temperature of 1.09 °C in January 1928, and an increase of 0.22 °C in September 1933 which "may or may not be statistically significant". Figure A3.1

[21] The RHtestsV3 data homogenisation software was used to perform the penalised maximal *t* test (http://cccma.seos.uvic.ca/ETCCDMI/software.shtml).

[22] The monthly series of averaged Taihape, Waingawa and Nelson temperatures did not contain data from October 1921 to June 1922, due to a defective maximum thermometer at Taihape during this period. Note that in Figure 5 describing the 1928 adjustment, stations Albert Park and Christchurch Gardens are used in place of Nelson.

[23] The statistical significance of mean shifts in temperature, at a nominal confidence level, is also calculated by the RHtests software. The nominal confidence level of the RHtest was set to its default value of 95%. The test statistic used is not the well-known Student's t-test (in spite of the name of the test), and the software calculates a confidence interval on the 95th percentile. If the statistic is below the lower bound on the 95th percentile, then the change is considered "not significant"; if above the upper bound it is considered "statistically significant"; if the statistic lies between the estimated bounds, then the phrase "may or may not be statistically significant" is used, and the analyst is given the choice of accepting the change-point as significant or not. If this second change-point (of +0.21 °C in September 1933) is not accepted, then the software recalculates a new estimate of the first change-point which will be close to the sum of the two previous values (i.e., -1.10 +0.21 = -0.89 °C).

shows the differences between monthly mean temperatures at the Wellington sites and the averaged monthly temperatures at the comparison sites from January 1921 to September 1942.

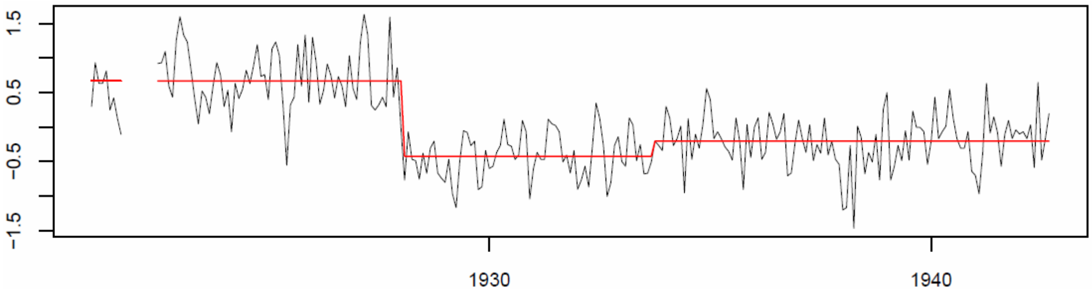

Figure A3.1: Monthly mean temperatures observed at Thorndon (Site 5) and Kelburn (Site 6) minus averages of monthly mean temperatures observed at Taihape, Waingawa and Nelson from January 1921 to September 1942 (black line). The y-axis represents the difference in monthly mean temperature in degrees Celsius (°C); the x-axis represents time. The red line indicates the average monthly temperature difference between the Wellington stations and the comparison stations, including the statistically-diagnosed mean shifts in 1928 and 1933, as described in the text.

The Kelburn site was reasonably open in 1928, but by 1949 trees and shrubs in the vicinity of the enclosure were providing too much shelter. This growth was removed in July 1949. It is possible that by 1933 vegetation was affecting the exposure of the Kelburn station, but no sudden and significant site change in 1933 is documented in the station history published by Fouhy *et al.* (1992). On the other hand, it is also recognised that two close inhomogeneities flagged by RHtests may be indicative of one change only. The combined inhomogeneities (-1.09 °C + 0.22 °C) sum to -0.87 °C, which is very similar to the result of -0.89 °C reported in Table 1.

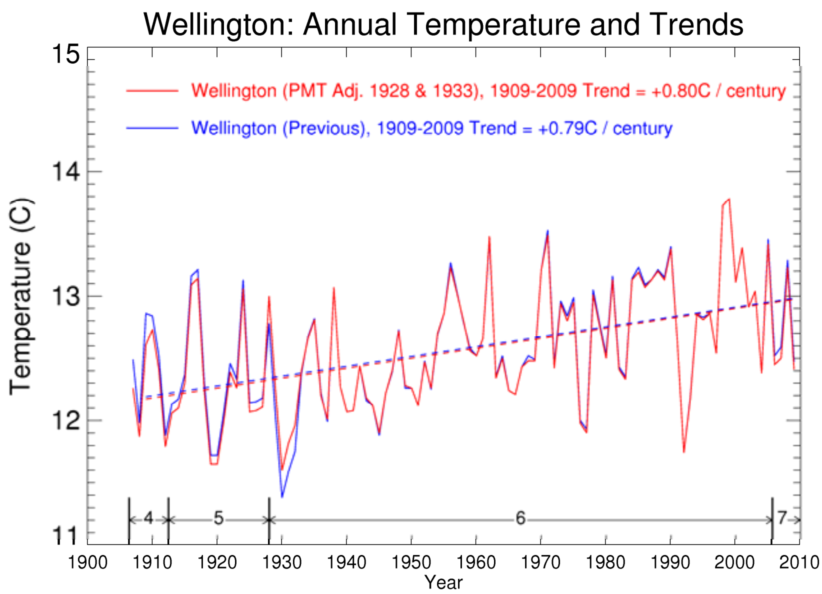

Figure A3.2: Composite series of annual mean air temperatures for Wellington (red line) from 1900 to 2009. The adjustments in 1928 and 1933 were diagnosed by the penalised maximal *t* test, as described in the text. The blue line shows the previous NIWA composite series for Wellington. The dashed lines show the fitted linear trends from 1909 to 2009. Wellington site labels from Table 1 are displayed at the bottom of the plot.

To investigate the effect of the statistically-detected mean shifts upon the overall temperature trend for Wellington, the adjustments based on the 1928 and 1933 mean shifts diagnosed by the PMT were applied to the Wellington temperature series, in addition to the adjustments for the Wellington site changes in 1912 and 2005 that are described earlier in this document. The resultant annual mean temperature series is shown in Figure 11. The 100-year linear trend fitted from 1909 to 2009 is +0.80 °C/century, which is 0.06 °C/century less than the fitted trend of the revised series (0.86 °C /century) shown in Figure 7.

Since the date of the second change-point, September 1933, was not directly supported by information in the Kelburn station history, and the temperature shift was within the 95% uncertainty range, it was removed. The penalised maximal *t* test was then reapplied (Figure A3.3), and the step shift at January 1928 was calculated to be -0.96 °C. This is close to the same temperature shift previously diagnosed via the analysis of annual mean temperatures in the section 'Adjustment for Site Change in 1928'.[24]

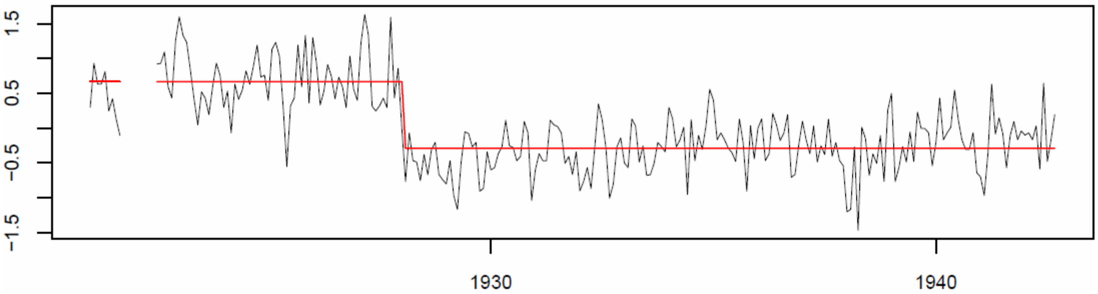

Figure A3.3: Monthly mean temperatures observed at Thorndon (Site 5) and Kelburn (Site 6) minus averages of monthly mean temperatures observed at Taihape, Waingawa and Nelson from January 1921 to September 1942 (black line). The y-axis represents the difference in monthly mean temperature in degrees Celsius (°C); the x-axis represents time. The red line indicates the average monthly temperature difference between the Wellington stations and the comparison stations after the removal of the 1933 change-point, as described in the text.

This example illustrates how statistical methods can be used to independently identify mean shifts in a temperature series. Further research will determine adjustments to monthly maximum and minimum temperatures separately. The statistical tests will also be applied systematically to the newly derived homogeneous temperature series to see if there are other change-points not already accounted for.

[24] If the same RHtests stations were used in the analysis of Figure 7 (i.e., Nelson in place of Auckland and Christchurch), then exactly the same adjustment of -0.96 °C is found in the earlier analysis.

Creating a Composite Temperature Series for Nelson

December 2010

Figure 1: Climate station G13222, Nelson Aero, looking north (2007, NIWA). Note that this site, although still called Nelson Aero, is situated beside Whakatu Drive (State Highway 6); it was moved off the airport grounds in mid-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.

This present document revisits and describes in greater detail the process by which a composite station series has been developed for Nelson. The primary purpose is to demonstrate in an intuitive way how to estimate adjustments to temperature records 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., RHtests, Wang *et al.*, 2007) to identify other change-points in the data.

Table 1: Information about Nelson 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 record;
(Column 4) altitude of site in metres above sea level;
(Column 5) previous period of record (as of February 2010) for which the site contributed to the composite time series used by NIWA;
(Column 6) previous temperature adjustment (with respect to Appleby, Site 4), taken from the February 2010 'Schedule of Adjustments', and further discussed in the appendices;
(Column 7) new period of record for which the site contributes to the composite time series; and
(Column 8) revised temperature adjustment to be applied (with respect to Nelson Aero, Site 7), as discussed in the text.

Site Label	Site Name (Agent Number)	Location (Full Period of Record)	Height (m a.s.l.)	Previous Period	Previous Temp. Adjust. (°C)	Revised Period	Revised Temp. Adjust. (°C)
Site 1	Nelson (4244)	Nelson City (Jul 1862 to Dec 1880)	6	Jul 1862 to Dec 1880	-0.6	Not Used	-0.42[2]
Site 2	Nelson (4244)	Nile St East, Nelson City (Oct 1907 to Nov 1920)	10	Oct 1907 to Nov 1920	-0.9	Oct 1907 to Nov 1920	-1.05
Site 3	Nelson (4244)	Cawthron Institute, Nelson City (Dec 1920 to Dec 1951)	7	Dec 1920 to Dec 1931	-0.1	Dec 1920 to Dec 1931	-0.17
Site 4	Appleby (4239)	Appleby, DSIR station west of Nelson (Jan 1932 to Nov 1996)	17	Jan 1932 to Nov 1996	**0.0**	Jan 1932 to Nov 1996	-0.02
Site 5	Appleby EWS (12755)	Appleby, HortResearch station, about 10 km west of Nelson airport (Oct 1996 to May 2000)	17	Dec 1996 to May 2000	+0.2	Not Used	N/A
Site 6	Nelson Aero (4241)	Nelson airport (Apr 1943 to May 1997)	2	Not Used	N/A	Dec 1996 to May 1997	+0.31
Site 7	Nelson Aero (4241)	Whakatu Drive (SH6), about 2 km east of Nelson airport (Jun 1997 to present)	2	Jun 2000 to Mar 2001	+0.2	Jun 1997 to present	**0.00**[3]
Site 8	Appleby 2 EWS (21937)	Appleby, Seifried Estate (Apr 2001 to present)	18	Apr 2001 to present	+1.0	Not Used	N/A

[2] We have included the estimated adjustment of Site 1 in this Table for ease of comparison with previous estimates (column 6). The correction is derived in the Appendix. We do not, however, have high confidence in the adjustments estimated for very early temperature data, and so have "not used" (column 7) these early adjusted temperatures in the revised NIWA temperature series for Nelson.

[3] The zero adjustments in bold in columns 6 and 8 mark the reference stations to which temperatures from all other stations are adjusted. The previous Nelson composite series was adjusted relative to Appleby (Site 4), whereas the revised Nelson composite series is referenced to Nelson Aero (Site 7).

Calculation of Adjustments

Table 1 summarises the information about the local sites used to develop the composite temperature series for the Nelson location. The adjustments in use as at February 2010 (labelled 'Previous Temperature Adjustment') are based on Sites 1-5, then Sites 7 and 8. The new adjustments derived in this document (labelled 'Revised Temperature Adjustment') are based on Sites 2-4, and then Sites 6 and 7. The previous adjustments were calculated to one decimal place, whereas the revised adjustments are specified to two decimal places.[4]

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 was made not to include temperatures prior to 1900. In the case of Nelson, the natural starting point for the revised series is October 1907, given the break in the Nelson observations over the period January 1881 to September 1907.

Table 1 lists eight different sites, although one of these (listed as Site 5) involves automation of the observations and is not a change in the physical location. The 'previous' NIWA temperature series for Nelson (i.e., corresponding to the adjustments published in February 2010) was based on Sites 1 to 5 plus Sites 7 and 8. As seen in Table 1, short periods of record from three different sites were used after the closure of the long-running Appleby manual station (Site 4) in November 1996. This is not the optimal approach, but was simply how the series evolved operationally with the closing of sites outside of NIWA's control.

The 'revised' Nelson temperature series uses Sites 2 to 4, and then Sites 6 and 7. Both Sites 6 and 7 are identified as Nelson Aero (agent 4241) in the NIWA Climate Database, although the station was actually moved off the airport grounds in June 1997. Apart from the desire to have as few stations as possible contributing to the composite Nelson series, two other factors are relevant to the decision to replace the Appleby automatic sites in the revised temperature series:

- Appleby 2 EWS (Site 8) has a rather different climate to Appleby (Site 4) or Appleby EWS (Site 5), having a significantly lower minimum temperature (by about 2 °C on average). Furthermore, Site 8 showed clearly anomalous rapid warming between 2007 and 2009, making the site unsuitable for long-term monitoring;[5]
- Nelson Aero temperature observations had been missing from the Climate Database over the period July 1994 to May 1997, but were located during the process of this revision exercise.

[4] Calculation to two decimal places has been done to minimise the accumulation of round-off errors. This should not be interpreted as an indication of the accuracy of the adjustment. Air temperatures are recorded to the nearest 0.1 °C on the NIWA Climate Database.

[5] Site photographs suggest that Appleby 2 EWS is in a 'frost hollow'. NIWA climate scientists update the 'seven-station' series monthly, and had noticed the unusual behaviour at Appleby 2 EWS after 2007 – the Nelson location often had a very different monthly anomaly to the other six locations. An estimated anomaly from Nelson Aero was being used from late-2009 in place of the suspect data from Appleby.

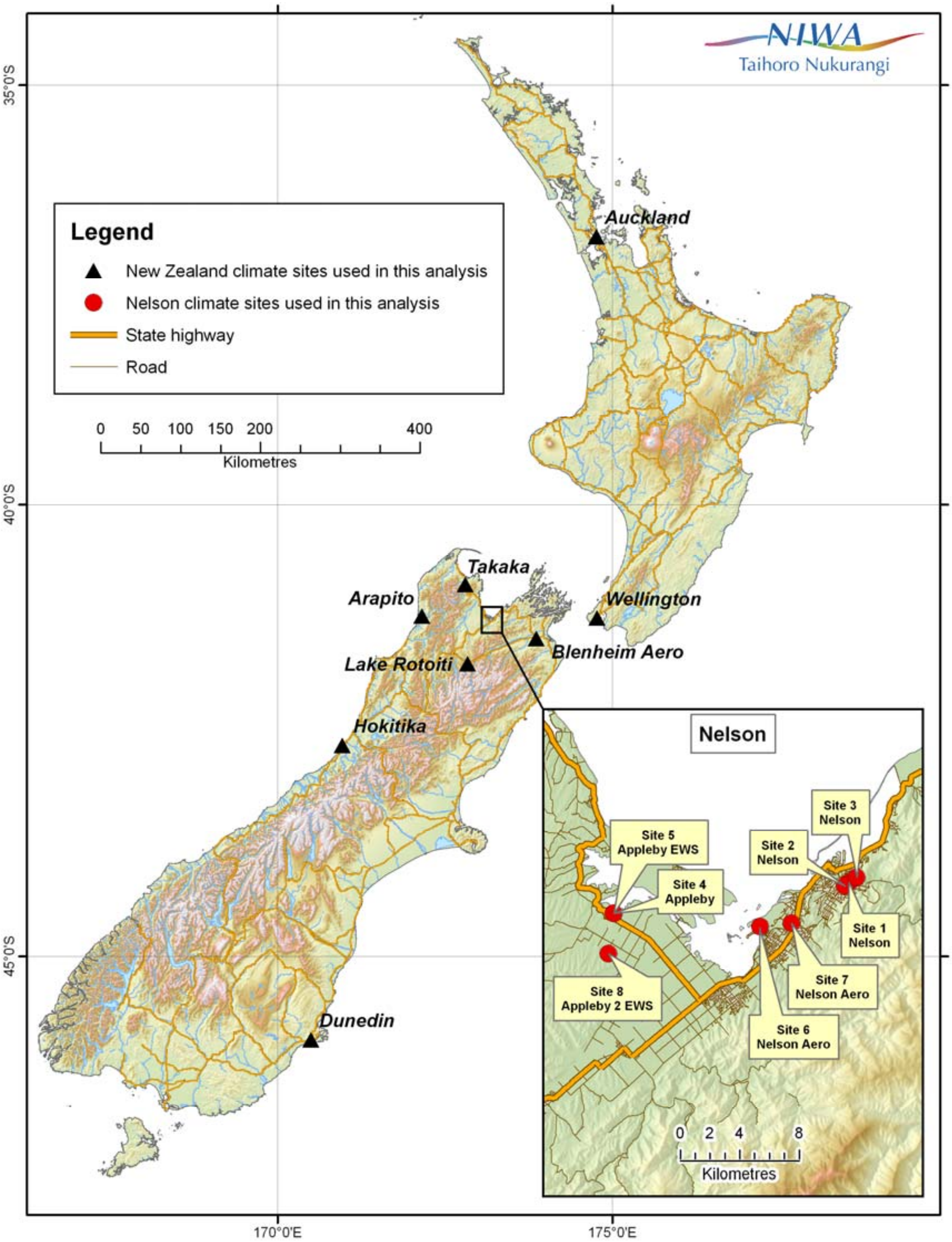

Figure 2: Map showing sites of temperature records referred to elsewhere within this document. The inset map locates the local Nelson sites.

The first factor was a strong argument in favour of not using Appleby 2 EWS data; the second allowed Nelson Aero data to be used continuously from December 1996 onwards, albeit with a site change in mid-1997.

These changes to the Nelson sites make it rather complicated to describe and explain the adjustments in both the 'previous' and 'revised' temperature series. The approach adopted here is to derive the adjustments to the new (revised) series in the main text, and describe the previous adjustments in the appendices.

It is common practice to adjust all the historical measurements to be consistent with the current open site (Aguilar *et al.*, 2003). For the revised temperature series, the current site of Nelson Aero is used as the 'reference' station, and all earlier sites adjusted relative to it. For the 'previous' temperature series, the adjustments shown in Table 1 are given relative to the manual Appleby station (Site 4) for consistency with what was done in practice.

Adjustment for Site Change in 1997

The temperature data from the Nelson Aero currently open site (Site 7, Figures 1 and 2) are adopted without change into the Nelson series. The first adjustment to consider is therefore that at June 1997 when the Nelson Aero station (Site 6) was moved about 2 km away from the airport to nearby Whakatu Drive (Site 7, the current open site). This station is not rural but has a fairly open exposure, and is situated in a small greenbelt set back from a highway.

Nelson Aero is generally an excellent site with a record extending back to April 1943. At the time of the Site 4 closure though, Nelson Aero had also closed temporarily, with the Climate Database record for the Nelson Aero site ending June 1994. This station was re-opened in June 1997 outside the airport grounds on Whakatu Drive (State Highway 6) opposite a Mitre 10 carpark (and along from the World of Wearable Art Museum in Quarantine Road). Although Nelson Aero was officially closed during July 1994 to May 1997, the observer on site had nevertheless continued to record the daily temperatures and provide them to the Nelson newspaper[6].

There is no overlap in the temperature observations between the Nelson Aero Sites 6 and 7. It is therefore necessary to make comparisons, before and after the 1997 site change, with other climate sites that respond similarly to climatic variations as do the Nelson Aero sites.

Figure 3 shows the correlation of mean temperature interannual differences at the Virtual Climate Station (VCS) grid point containing Nelson (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] Interannual temperature variations at Nelson

[6] The observer was also servicing the MetService Nelson AWS (agent 4271) at the time. Nelson Aero (agent 4241) temperatures for July 1994 to May 1997 were quality controlled and added to the NIWA National Climate Database tables in August 2010. These Nelson Aero measurements were not available to the Database at the time Appleby (Site 4) closed.
[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

Aero correlate strongly with those in the Motueka River valley and western Marlborough, the correlation typically being over +0.95.[8] Temperature variations at Appleby also correlate well with those in Auckland (+0.91), Wellington (+0.93), Masterton (+0.93), Lincoln (+0.92), and even Dunedin (+0.83). So if necessary, these more distant sites could be used.

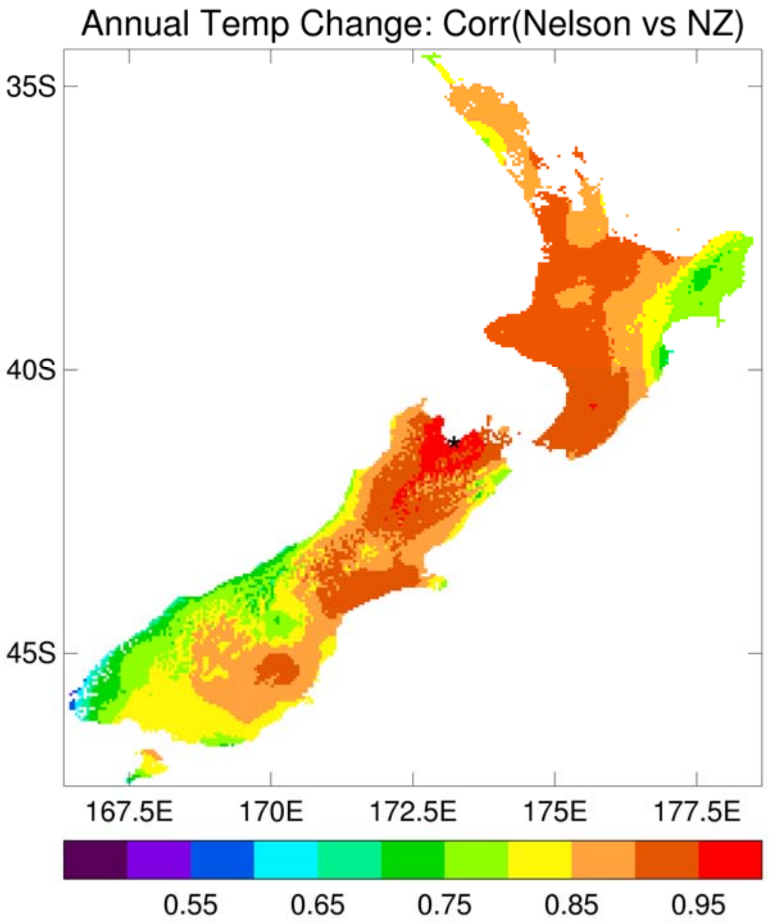

Figure 3: Map of correlation between interannual temperature changes at the grid-point nearest to Nelson Aero (Site 6, agent 4241, location marked by asterisk), 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

Figure 3 is a good guide to where we might find other climate sites that have a similar temperature response to that at Nelson. In practice, these 'comparison' sites are selected on a number of criteria:

- The comparison site obviously has to be operating for a reasonable period both before and after the site change that is being examined, and must not have a site change itself within this period;
- Inspection of the site history should not raise any concerns about the quality of the site observations;

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 correlation of +1.0 indicates perfect agreement; i.e., that the interannual temperature variations at two sites match perfectly (except for a constant offset and multiplicative factor).

- Interannual correlations[9] are calculated between the reference site (e.g., Nelson Aero) and a selected comparison site (e.g., Blenheim Aero, see Figure 2) for up to 10 years before and after the reference site change. This is done for maximum and minimum temperatures as well as for mean temperatures. We select comparison stations with the highest correlations;
- Adjustments for the site change are calculated with respect to each comparison station, and we look for consistency across the set of comparison sites eventually selected.

The intention in these analyses is therefore to compare temperatures over 10 years before and after the site change. This is not always possible since the record at the comparison site may not cover the full 21 year period, or there may be site history information that points to other potential inhomogeneities in the comparison site record.

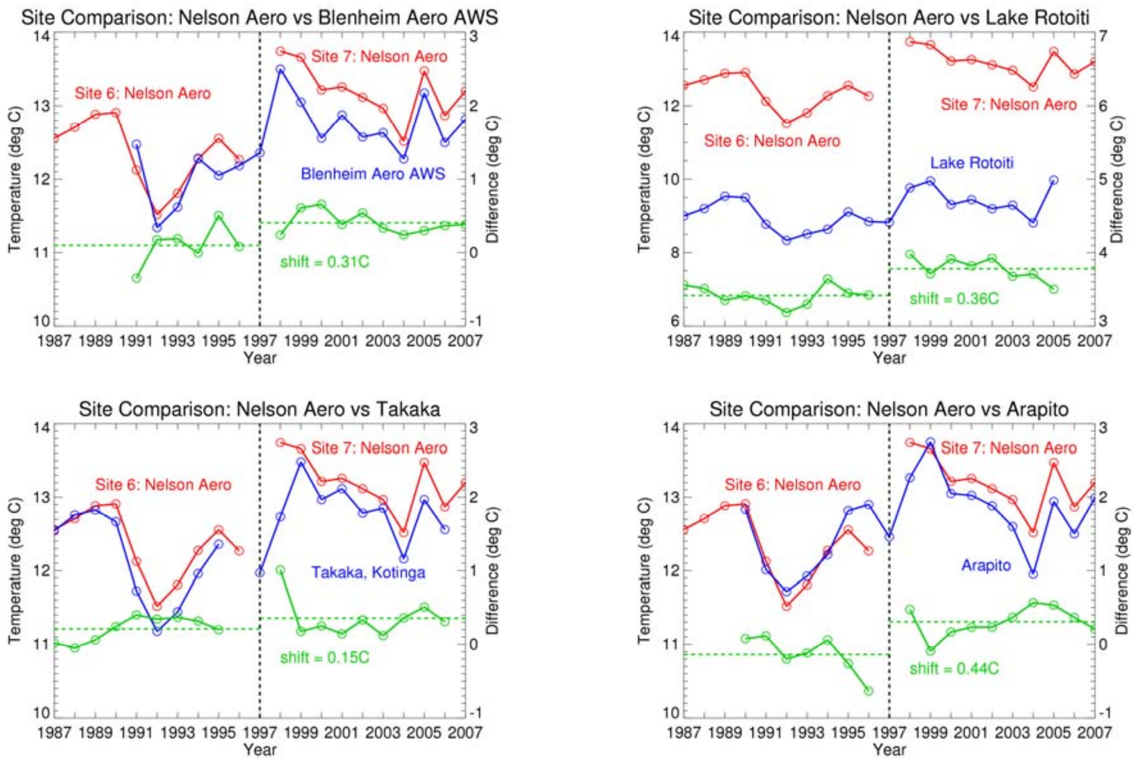

Figure 4: Annual mean temperatures at Nelson Aero (Site 6, red line on the left half of each plot) and the re-located Nelson Aero (Site 7, red line on the right half of each plot), compared with temperatures at four other stations that overlap the Nelson Aero site move: Blenheim Aero AWS (agent 4326), Lake Rotoiti (agent 3892), Takaka Kotinga 2 (agent 3789) and Arapito (agent 3846). The solid blue line shows the temperatures at these comparison stations. The solid green line represents the difference (Site 6/7 minus the comparison station) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The year of the site change, 1997, is indicated by the vertical dashed line.

Figure 4 shows annual temperatures before and after the Site 6/Site 7 change-over, comparing the Nelson Aero sites with four comparison stations (refer to Figure 2):

[9] Correlations are used to assess how well the year to year variations at a comparison site match those at the Nelson sites in question (and therefore if it is a ‘good’ comparison site). Correlations are calculated using the first-difference series of annual temperatures, excluding the year of the site change itself. This method prevents any discontinuity at the site-change year from influencing the correlations (Aguilar *et al.*, 2003).

Blenheim Aero AWS (agent 4326)[10], Lake Rotoiti (agent 3892), Takaka (agent 3789) and Arapito (agent 3846). These stations are between 60 and 90 km from Nelson, and share the characteristic with Nelson Aero that they are somewhat sheltered from south-westerly winds but are exposed to northerlies.

Before the 1997 site change, Nelson Aero (Site 6) was 0.10 °C warmer than Blenheim Aero, but after the site change the new Nelson Aero site (Site 7) was 0.41 °C warmer than Blenheim Aero. Thus, the new Nelson Aero Site 7 was 0.31 °C warmer than the earlier Nelson Aero Site 6, according to the comparison with Blenheim Aero. Examining each comparison site in turn, the Site 6 to Site 7 move caused measured temperatures to be higher by 0.36 °C (with respect to Lake Rotoiti), 0.15 °C (Takaka) and 0.44 °C (Arapito).

Thus, we have four estimates of the difference between Nelson Aero Site 6 and Nelson Aero Site 7: +0.31 °C, +0.36 °C, +0.15 °C, and +0.44 °C. The average is +0.31 °C, with Nelson Aero Site 7 being warmer than Nelson Aero Site 6. Thus, an adjustment of +0.31 °C needs to be made to the Nelson Aero Site 6 temperatures to bring them into line with the current open site (Site 7). This adjustment has been inserted into Table 1 (final column) against Site 6. The value is positive, meaning that the raw Site 6 temperatures must be *increased* by this amount to make them homogeneous with the current open site.

Adjustment for Site Change in 1996

We continue to work back in time from the current open site, and now need to consider the effect of the change from Site 4 (Appleby) to Site 6 (Nelson Aero). Appleby is located 13 km west of Nelson city and about 10 km west of the airport (Figure 2). The surrounding land is undulating, rising to the Moutere Hills to the south. The climate station was at the DSIR (later HortResearch) Fruit and Trees Research Station, with the instruments sited on a grassed knoll.

Nelson Aero (Site 6) is used in Table 1 to fill a 6-month gap, December 1996 to May 1997, between Site 4 and Site 8. There is however a long overlap between Nelson Aero (Site 6) and Appleby (Site 4), 1943-1996, which we can use to estimate the site correction. Figure 5 is a plot of just the 10 years 1986-1995 immediately prior to the closure of Appleby; there is a fairly constant difference between the two sites, with Nelson Aero being 0.33 °C cooler than Appleby.

Therefore, relative to Nelson Aero (Site 6), the Appleby temperatures should be reduced by 0.33 °C. The cumulative adjustment for Appleby (Site 4) relative to the current open site (Nelson Aero, Site 7) is thus: -0.33 +0.31 = -0.02 °C. So it turns out that Appleby (Site 4) and the current Nelson Aero site (Site 7) have virtually no difference, on average, in their annual mean temperatures. This makes the adjustments in Table 1 easier to follow, since it doesn't make any significant difference whether

[10] In the NIWA Climate Database, the two acronyms AWS (Automatic Weather Station) and EWS (Electronic Weather Station) are both 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.

we adjust the other Nelson sites with respect to Appleby (Site 4) or the current Nelson Aero (Site 7).

Figure 6 provides further support for the equivalence of annual mean temperatures Appleby and the current Nelson Aero (Site 7). The plot shows that the annual mean temperature difference between Blenheim Aero and Appleby over 1991-1995 is essentially the same as between Blenheim Aero and Nelson Aero (Site 7) over 1998-2007.[11]

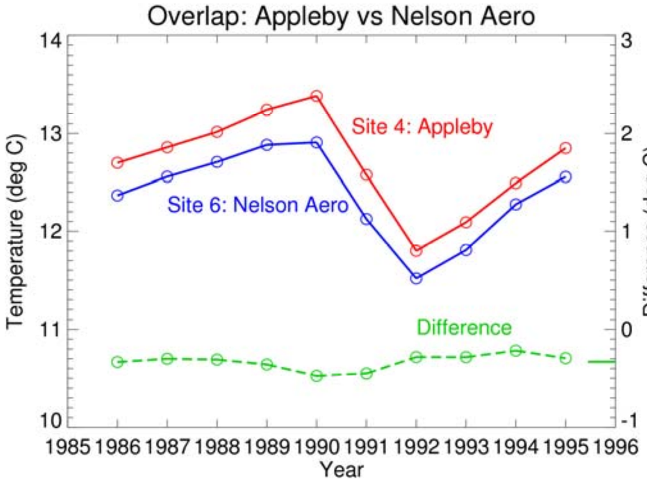

Figure 5: Annual mean temperatures at Appleby (Site 4, red line) and at Nelson Aero (Site 6, blue line). The difference, Site 6 minus Site 4, is plotted by the green dashed line, using the right-hand ordinate scale, and the mean annual difference over 1986-1995 is given by the short green solid line on the right side of the plot.

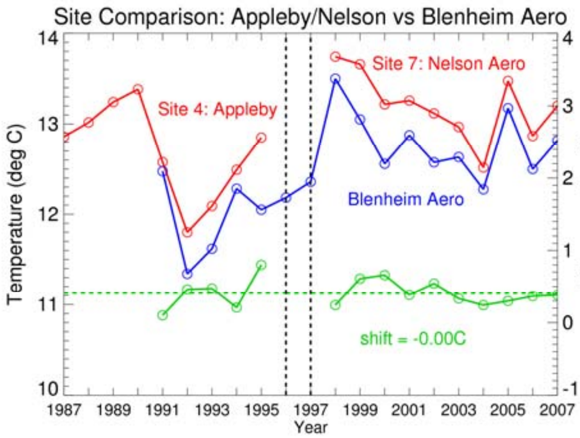

Figure 6: Annual mean temperatures at Appleby (Site 4, red line on the left half of the plot) and Nelson Aero (Site 7, red line on the right half of the plot), compared with temperatures at Blenheim Aero AWS (blue line). The solid green line represents the difference (Site 4/7 minus Blenheim) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The years of the site changes, 1996 (for Appleby) and 1997 (for Nelson Aero), are indicated by the vertical dashed lines.

[11] The small difference between the two calculations (i.e., -0.02 °C and 0.00 °C) arises because different periods of data are used.

Adjustment for Site Change in 1932

The Appleby station (Site 4 in Table 1, and described earlier) was opened in December 1931. Prior to 1932, the composite temperature series uses the Nelson City measurements from Cawthron Institute (agent 4244, Site 3). The Cawthron Institute was situated in northwest Nelson city, partly on a hill and partly on the flat. The meteorological station was in an open enclosure on the flat with a wire netting fence. The elevation was 7 m with a good exposure. The station (Nelson Site 3) operated between December 1920 and December 1951. There is thus a 20-year overlap with Appleby (Site 4).

Figure 7 shows the first 10 years of overlapping records at Appleby and Cawthron, following the opening of the Appleby site. Over this period, the two sites were in close agreement, with Appleby averaging 0.15 °C cooler than Nelson Cawthron.

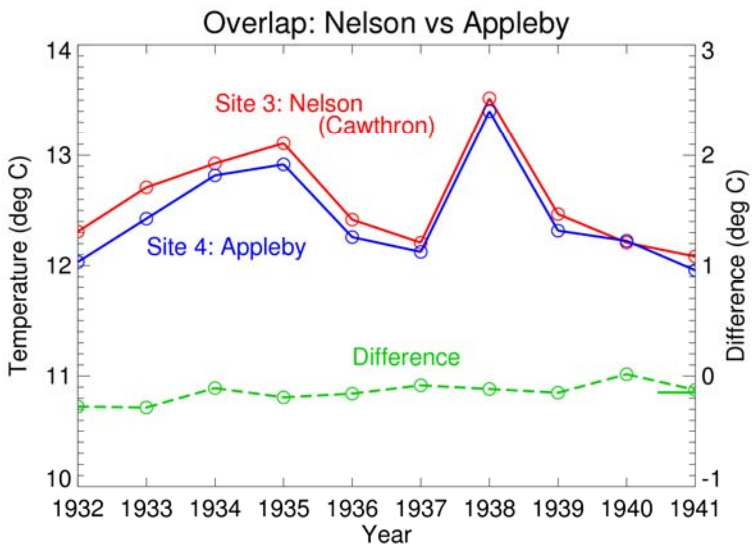

Figure 7: Annual mean temperatures at Nelson Cawthron Institute (Site 3, red line) and at Appleby (Site 4, blue line), for the decade following the opening of the Appleby station in January 1932. The difference, Site 4 minus Site 3, is plotted by the green dashed line, using the right-hand ordinate scale, and the mean annual difference over 1932-1941 is given by the short green solid line on the right side of the plot.

The difference line in Figure 7 has a small upward slope, suggesting that there might be some differential warming at Nelson City relative to Appleby. The Cawthron record continues for a further 10 years to 1951, and over the 1942-1951 period, the temperatures are clearly diverging. For 1932-1941 (as in Figure 7), Cawthron was 0.15 °C warmer than Appleby; over 1942-1946 it was 0.16 °C warmer (very similar), but over 1947-1951 Cawthron was 0.32°C warmer, suggesting the possibility of an urban influence affecting the City site in the late 1940s.

Owing to concerns that any non-climatic warming at Cawthron could affect the estimated site adjustment, we have also calculated site comparisons. Figure 8 shows annual temperatures before and after the Site 3/Site 4 change-over, comparing the Nelson sites with three comparison stations: Auckland, Albert Park (agent 1427), Dunedin Botanical Gardens (agent 5375) and Hokitika Town (agent 3907). The comparison sites used previously (Figure 4) were not operating in 1932, so much more distant sites had to be considered instead.[12]

In this comparison, we ignore the Cawthron temperatures after 1931. Comparing the Cawthron and Appleby temperatures with the comparison site over 1921-1931 and 1932-1941, respectively, we find Appleby is consistently colder than Cawthron. The offsets are: -0.11 °C (with respect to Albert Park), -0.12 °C (Dunedin) and -0.22 °C (Hokitika). These average to -0.15 °C, the same as found previously from the direct Appleby-Cawthron overlap in Figure 7.[13]

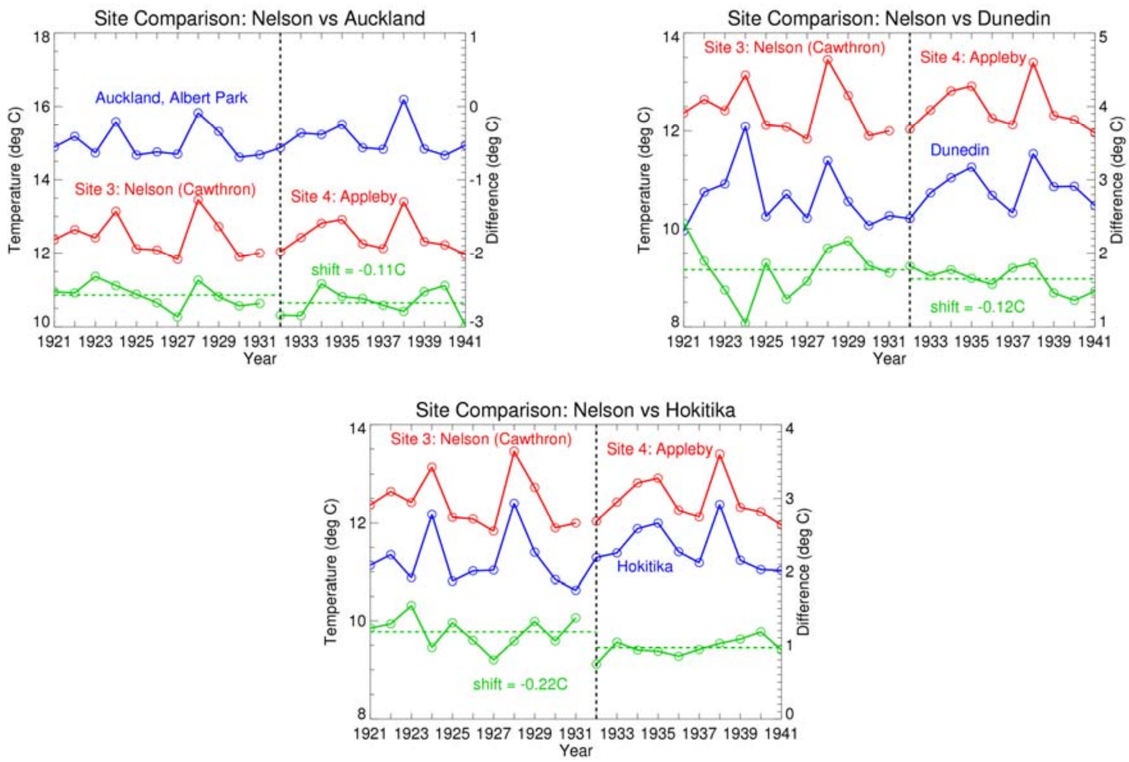

Figure 8: Annual mean temperatures at Nelson Cawthron Institute (Site 3, red line on the left half of each plot) and at Appleby near Nelson (Site 4, red line on the right half of each plot), compared with temperatures at three other stations that overlap the 1931/32 site change: Auckland Albert Park (agent 1427), Dunedin Botanical Gardens (agent 5375), and Hokitika Town (agent 3907). The solid blue line shows the temperatures at these comparison stations. The solid green line represents the difference (Site 3/4 minus the comparison station) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The year of the site change, 1932, is indicated by the vertical dashed line.

[12] We also considered Wellington Kelburn (agent 3385) and Waingawa Essex Street (agent 2473). However, Kelburn measurements began in 1928 so there are only 4 years for comparison with Cawthron; Waingawa had poorer interannual correlations (less than +0.8 for maximum and minimum temperatures) and the estimated adjustments for both mean and minimum temperatures were rather different to those of the other 4 sites. Thus, neither Wellington nor Waingawa (Masterton) were included in the final comparison.

[13] The fact that the two calculations agree exactly to 2 decimal places is of course rather fortuitous. If a period of only 10 years prior to the site change was used (i.e., 1922-1931), then the average offset over the 3 comparison sites of Figure 8 changes to -0.13 °C. If the additional two comparison sites mentioned in the footnote above (Wellington and Masterton) are included, the average offset is -0.16 °C. The close agreement of all these figures gives us confidence in the robustness of the 1932 adjustment.

The cumulative adjustment of Cawthron relative to Nelson Aero Site 7 is thus: +0.31 -0.33 -0.15 = -0.17 °C. This adjustment has been inserted into Table 1 (final column) against Site 3. Note that the Cawthron data are not used after 1931, thereby avoiding the apparently anomalous 1940s temperature trend noted there.

Adjustment for Site Change in 1920

The meteorological station at Cawthron Institute (Nelson Site 3) operated between December 1920 and December 1951. There is no overlap with the earlier Nelson City site in Nile Street (Site 2)[14], which closed in November 1920.

In 1920, there were a lot fewer climate stations operating than in recent history, and this limits the options for comparing the Site 2/3 temperature discontinuity. Figure 9 shows comparisons with four other long-term sites: Auckland Albert Park (agent 1427), Dunedin Botanical Gardens (agent 5375), Wellington Thorndon (agent 3391), and Hokitika Town (agent 3907). Three of these sites are common to the 1932 comparison (Figure 8), and they are all referred to elsewhere in the documents on the "seven-station" temperature series. The records from these comparison sites were truncated where necessary: for example, at Hokitika, data prior to 1913 were excluded because of the warm bias during the period 1894-1912.

Before the 1920 site change, comparisons were made over the six years 1913-1918 with Nelson Nile Street (Site 2). There are 5 months of missing data at Nile Street in the middle of 1919, which excludes this year from consideration. With respect to Auckland Albert Park, Nelson Nile Street was 1.54 °C colder, whereas Nelson Cawthron was 2.56 °C colder. With respect to Dunedin Botanical Gardens, Nelson Nile Street was 2.53 °C warmer, whereas Nelson Cawthron was 1.78 °C warmer. With respect to Wellington Thorndon, Nelson Nile Street was 0.13 °C warmer, whereas Nelson Cawthron was 0.78 °C colder. With respect to Hokitika, Nelson Nile Street was 2.02 °C warmer, whereas Nelson Cawthron was 1.16 °C warmer.

Thus, the comparisons show that the new Nelson site at Cawthron was consistently colder than the previous Nile Street site, by: -1.02 °C (Auckland), -0.75 °C (Dunedin), -0.91 °C (Wellington), and -0.86 °C (Hokitika). The average offset between Nile Street and Cawthron is -0.88 °C[15]. Therefore, just as Cawthron was warmer than Appleby (Site 4) by 0.15 °C, so Nile Street was warmer again than Cawthron by a further 0.88 °C. The cumulative adjustment of Nile Street relative to Nelson Aero Site 7 is thus: +0.31 -0.33 -0.15 -0.88 = -1.05 °C. This adjustment has been inserted into Table 1 (final column) against Site 2.

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[14] According to 1932 historical notes by Dr Edward Kidson, then Director of the New Zealand Meteorological Service, the Nile Street location was "considered in Nelson to be a warm one, being sheltered from the southwest and sufficiently high not to be so subject to frost as places further north."

[15] The estimated offsets from different comparison sites could be combined in some other way than a simple average. Typical approaches in the literature are to weight by correlation or by distance, or both. In this instance, an alternative weighting would produce a very similar answer to a simple average. The two sites physically closest to Nelson are Wellington and Hokitika, whose individual offsets straddle the -0.88 °C average. These two sites also have the highest correlation on interannual differences in annual mean temperature (both +0.95), with lower correlations for the distant sites: +0.91 with Auckland, and +0.87 with Dunedin over the periods of record shown in Figure 8.

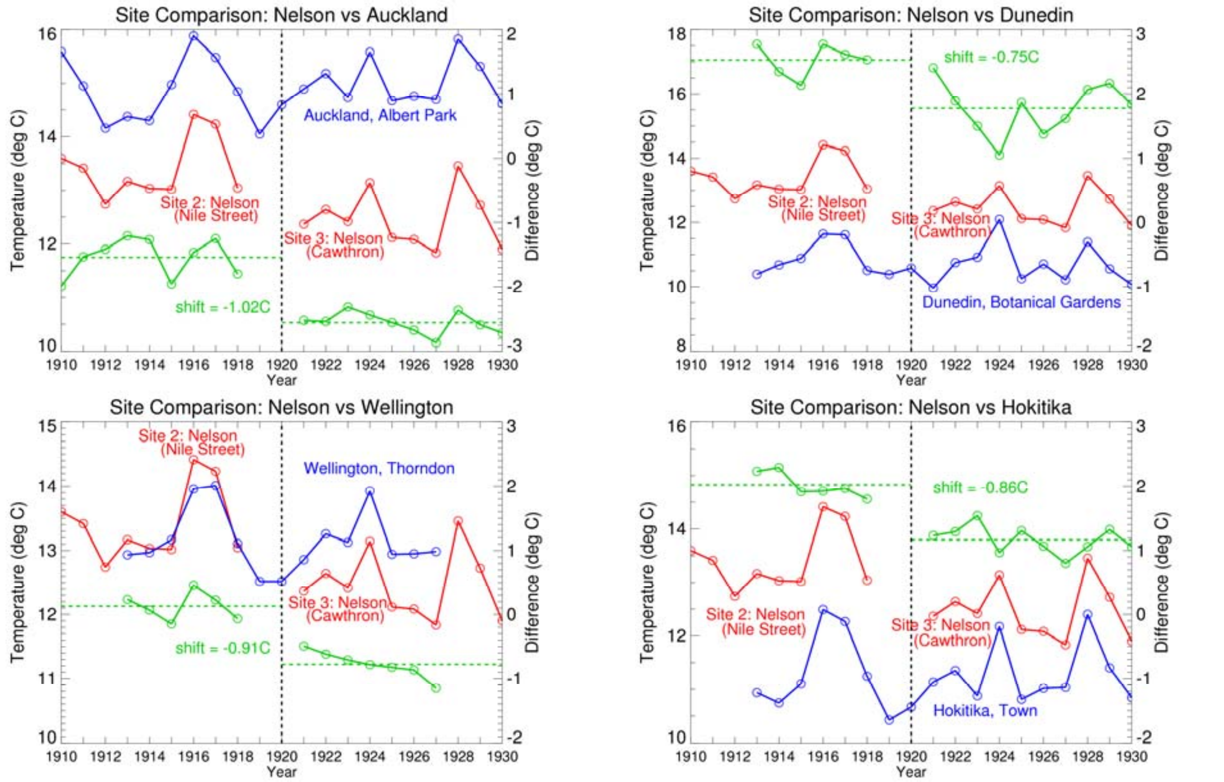

Figure 9: Annual mean temperatures at Nelson Nile Street (Site 2, red line on the left half of each plot) and Nelson Cawthron Institute (Site 3, red line on the right half of each plot) compared with temperatures at four other stations that overlap the Nelson site change: Auckland Albert Park (agent 1427), Dunedin Botanical Gardens (agent 5375), Wellington Thorndon (agent 3391), and Hokitika Town (agent 3907). The solid blue line shows the temperatures at these comparison stations. The solid green line represents the difference, Nelson minus the comparison station, using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The year of the site change, 1920, is indicated by the vertical dashed line.

The adjustment for the Nile Street to Cawthron site change is the final one considered in the revised Nelson composite series. Adjustments for additional sites used in the previous Nelson composite series, but not used in this revised series, are re-derived in Appendix 1.

Putting the Time Series Together

The various adjustments described above can be applied successively to the Nelson temperature records. The resulting final time series from 1908 to 2009 is shown in Figure 10, including a comparison with the previous Nelson time series used by NIWA.[16] A linear trend has been fitted to each series over the period 1909 to 2009. Expressed in units of degrees per century, the linear trend in the revised series is 0.76 (±0.30) °C /century, as compared with 0.81 (±0.30) °C /century for the trend calculated from the previous Nelson time series published in February 2010.[17]

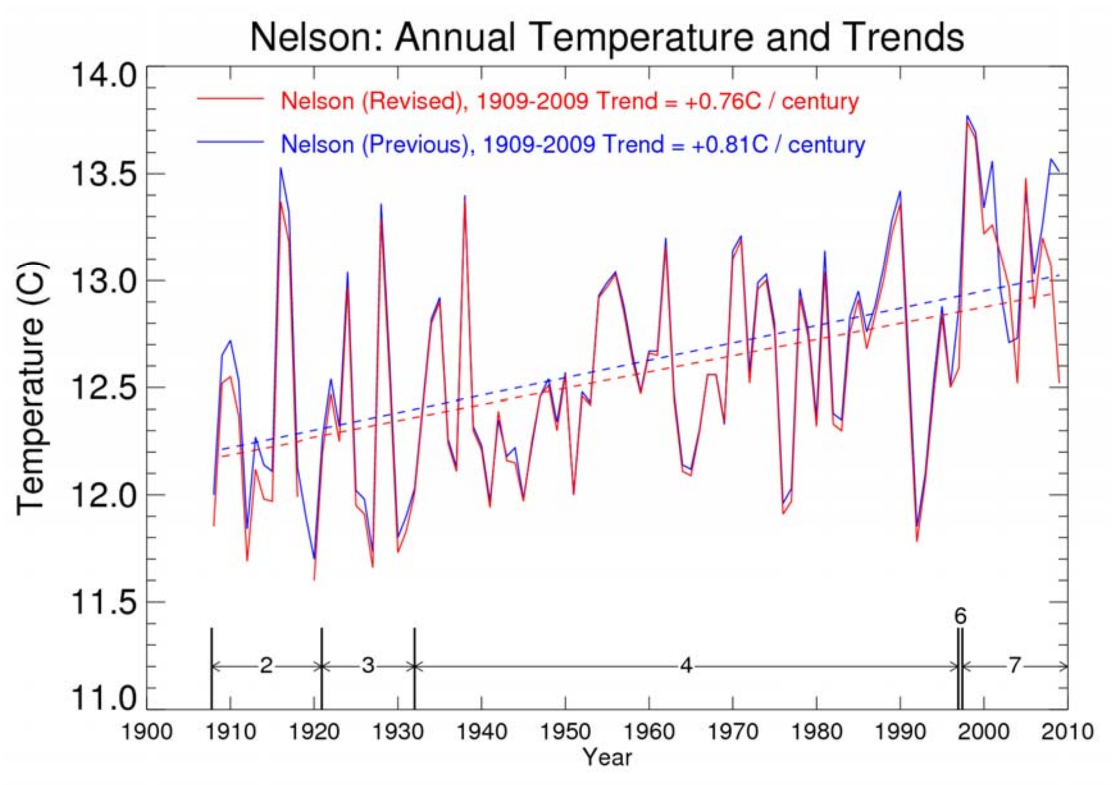

Figure 10: Comparison of revised series (red line) and previous NIWA series (blue line) of composite temperatures for Nelson from 1908 to 2009. The dashed lines indicate the fitted linear trend over the period 1909-2009. Labels near the bottom of the plot denote the site numbers of Table 1. Vertical lines at the bottom of the plot mark the time periods over which each site contributes to the composite series, with the sites numbered as in Table 1. Note the divergence between the red and blue lines in the last two years, owing to the erroneous Appleby 2 EWS values in the previous time series. This has only a small effect on the 100-year trend.

[16] In the revised composite temperature series for Nelson shown in Figure 10, annual mean temperatures in years containing up to three missing months have been estimated from the composite 1971-2000 climatology for Nelson. The methodology for these estimates is described in Appendix 2 of the Masterton document.

[17] The uncertainty here (±0.30 °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.

There is minimal change in the 100-year trend between the previous Nelson series (as posted on the NIWA website in February 2010) and the revised one using the adjustments derived in this document.

Figure 11 repeats the graph of the revised composite annual mean temperature series for Nelson, but now compares the composite with the unadjusted raw multi-site temperatures. The two series are identical from 1998 onwards, since this period is covered by the Nelson reference site (Nelson Aero, Site 7) for which no adjustment is applied. The estimated adjustments are also shown in Figure 11. The adjustments are cumulative relative to Nelson Aero Site 8, and correspond to those in the final column of Table 1.

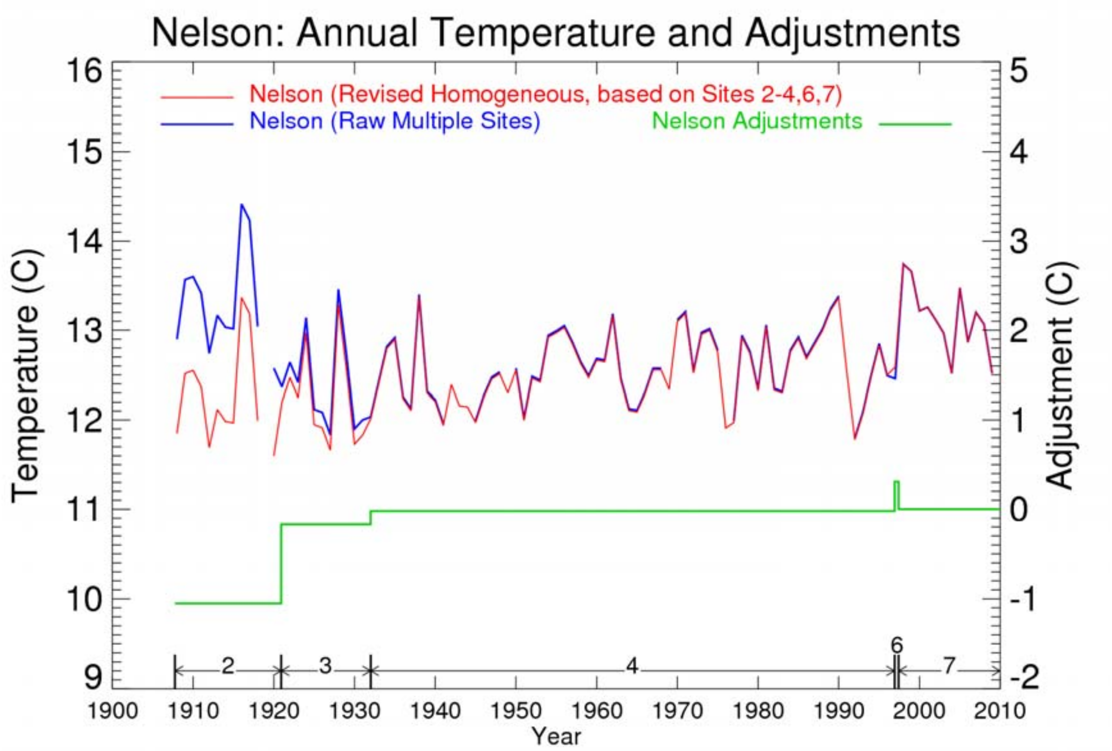

Figure 11: Comparison of revised composite temperature series for Nelson (red line), and the raw multi-site series (blue line), 1908 to 2009. The green line (using right-hand axis) indicates the cumulative step adjustments to each site as shown at the bottom of the graph. The site numbers and periods of record correspond to those listed in Table 1.

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).

Date: Document originally created 29 October 2010, and revised 13 December 2010 following review from the Australian Bureau of Meteorology.

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Appendix 1

Revisiting the 'Previous' Temperature Adjustments

Table A1.1 is an abbreviated version of Table 1, and summarises the adjustments based on the 'previous' set of Nelson stations, labelled Sites 1 through 5, then 7 and 8. A comparison is provided between the adjustments in use as at February 2010 (labelled 'Previous Temperature Adjustment'), and new ones derived in this document (labelled 'Revised Temperature Adjustment'). Some of the adjustments have already been discussed in the main text; the others will be described in this appendix.

Table A1.1: Information about Nelson climate observations:
(Column 1) the site label used in the text;
(Column 2) the site name, and (in parentheses) the 'agent number' used by NIWA Climate Database (CliDB) to identify the station;
(Column 3) period of record for which the site contributed to the composite time series used by NIWA (as of February 2010) ;
(Column 4) previous temperature adjustment, taken from the February 2010 'Schedule of Adjustments'; and
(Column 5) revised temperature adjustment to be applied (with respect to Appleby, Site 4), as discussed in the appendix.

Site Label	Site Name (Agent Number)	Period of Record of Contributing Site Data	Previous Temperature Adjustment (°C)	Revised Temperature Adjustment (°C)
Site 1	Nelson City (4244)	Jul 1862 to Dec 1880	-0.6	-0.40
Site 2	Nelson City, Nile St East (4244)	Oct 1907 to Nov 1920	-0.9	-1.03
Site 3	Nelson City, Cawthron Institute (4244)	Dec 1920 to Dec 1931	-0.1	-0.15
Site 4	Appleby (4239)	Jan 1932 to Nov 1996	**0.0**	**0.00**
Site 5	Appleby EWS (12755)	Dec 1996 to May 2000	+0.2	+0.14
Site 7	Nelson Aero (Whakatu Drive) (4241)	Jun 2000 to Mar 2001	+0.2	+0.02
Site 8	Appleby 2 EWS (21937)	Apr 2001 to Dec 2007	+1.0	+1.03
		Jan 2008 to present	+1.0	???[18]

The previous adjustments were relative to Appleby (Site 4) as the reference site, so we will use the same convention here. The following sections go through each site change in turn, first working forward from Appleby's closure in 1996 to the present, and then working backwards prior to the start of Appleby in 1932. Table A1.1 uses the same site numbering as in Table 1. Note in particular that Site 6 (Nelson Aero, when it was actually at the airport) is not used in this series.

[18] A spurious warming is evident in the observations after 2007. See discussion in text.

Adjustment for Site 4 to Site 5 Change in 1996

Two automated Appleby sites (Table A1.1) were previously used to build the Nelson temperature series. The manual observation station (Site 4) was closed 12 December 1996, and replaced by an automatic station on the same site (Appleby EWS, Site 5). Appleby EWS, which had a 2-month overlap (October-November 1996) with Site 4[19], remained in operation until June 2000. Measurement of Appleby temperatures was taken over in April 2001 by a new station (Appleby 2 EWS, Site 8), situated 2.5 km south of the previous Site 5 within the Seifried Estate vineyard. There is thus a 10-month gap, June 2000 to March 2001, between Site 5 and Site 8 in Table A1.1, which is filled using a temperature record from Nelson Aero (Site 7). The Nelson Aero record extends back to April 1943. In June 1997, the station was moved off the airport grounds, as discussed in the main text.

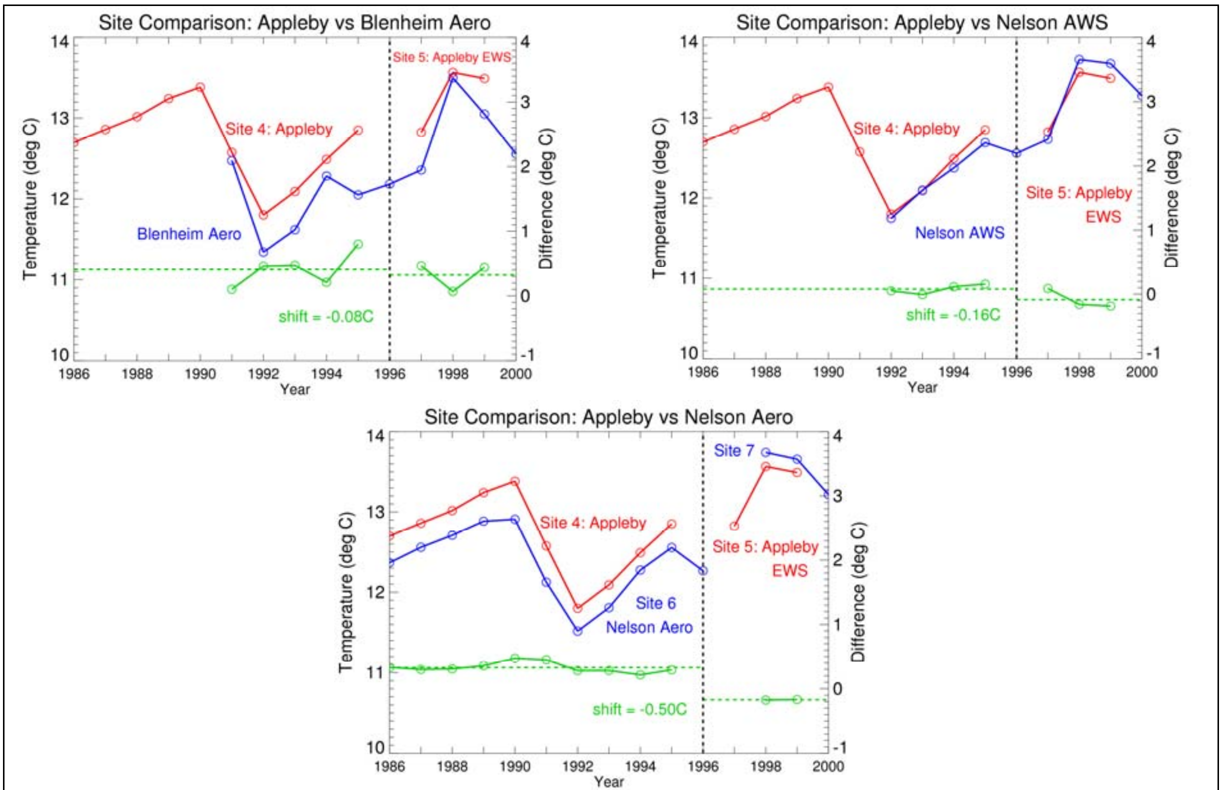

Figure A1.1: Annual mean temperatures at Appleby (Site 4, red line on the left half of each plot) and Appleby EWS (Site 5, red line on the right half of each plot) compared with temperatures at three other stations that overlap the Appleby site change: Blenheim Aero AWS (agent 4326), Nelson AWS (agent 4271), and Nelson Aero (agent 4241). The solid blue line shows the temperatures at these comparison stations. The solid green line represents the difference (Site 4/5 minus the comparison station) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The year of the site change, 1996, is indicated by the vertical dashed line. The lower plot uses the raw data from Nelson Aero (both Sites 6 and 7) without adjustment, with the year of the site change (1997) removed.

[19] Appleby EWS was colder than Appleby by 0.1 °C in October 1996, and warmer by 0.1 °C in November 1996.

Figure A1.1 shows annual temperatures before and after the Site 4/Site 5 changeover, comparing the Appleby sites with three comparison stations: Blenheim Aero AWS (agent 4326), Nelson AWS (agent 4271) and Nelson Aero (agent 4241). Unfortunately, Appleby EWS has only three complete years over which to make a comparison. Before the 1996 site change, Appleby (Site 4) was 0.40 °C warmer than Blenheim Aero and 0.08 °C warmer than Nelson AWS. After the site change, Appleby EWS (Site 5) was 0.32 °C warmer than Blenheim Aero and 0.08 °C cooler than Nelson AWS. Thus, the new Appleby EWS Site 5 was 0.08 °C cooler than Appleby Site 4 according to the comparison with Blenheim Aero and, 0.16 °C cooler according to the comparison with Nelson AWS.

The comparison of the Appleby sites with Nelson Aero is complicated by the fact that Nelson Aero had a site change itself in mid-1997. Thus, in Figure A1.1 (lower plot), the year 1997 has been removed from the Nelson Aero data. According to Figure A1.1, Appleby EWS is 0.50 °C cooler than Site 4. However, part of this difference is due to the re-location of the Nelson Aero station in mid-1997 Site 6 to Site 7. From analysis presented above, we know that the new Nelson Aero site from June 1997 was 0.31 °C warmer than the old one on the airport. Allowing for this difference implies that the new Appleby EWS site was only 0.19 °C cooler than the previous site.

Thus, we have three estimates of the difference between Appleby Site 4 and Appleby Site 5: -0.08 °C, -0.16 °C, and -0.19 °C. The average is -0.14 °C, with Appleby Site 5 being cooler than Appleby Site 4. Thus, an adjustment of +0.14 °C needs to be added to Appleby Site 5 to bring it into line with Site 4. This adjustment has been inserted into Table 2 (final column) against Site 5.

Following Figure 3, more distant comparison sites were also considered to help estimate the Site 4/5 change in mean annual temperature. Sites were selected according to how good their correlations were with Appleby, considering maximum and minimum temperature as well as mean temperature. In this instance, more distant sites had rather poorer correlations and so were not used[20].

Adjustment for Site 5 to Site 7 Change in 2000

Nelson Aero (Site 7) is used in Table A1.1 to fill a 10-month gap, June 2000 to March 2001, between Site 5 and Site 8. This adjustment has already been calculated in the main text. The adjustment of Nelson Aero back to the Appleby manual record is thus +0.02 °C, and this has been entered into Table 2 against Site 7. Note that there is a considerable discrepancy between the previous and revised adjustments for this site. We believe an error was made previously when updating the Salinger et al (1992) adjustments, probably due to overlooking the site move off the airport grounds.

[20] All the more distant sites examined had around +0.8 correlation or lower for at least one of Mean, Maximum and Minimum temperature correlations over the period in question (Figure 4). The indicated adjustments tended to be slightly positive with respect to the more distant sites: +0.02 °C (Tauranga Aero AWS, agent 1615), +0.05 °C (Wellington Kelburn, agent 3385), +0.07 °C (Auckland Aero, agent 1962). These were in conflict with the adjustments calculated from the nearby sites and were disregarded.

Adjustment for Site 7 to Site 8 Change in 2001

Appleby 2 EWS (Site 8) took over from Nelson Aero (Site 7) in April 2001 (Table A1.1). Nelson Aero continued in operation, so a direct temperature comparison can be made for the overlap from 2002 onwards (Figure A1.2). For the first 6 years of the overlap, 2002 to 2007, there is a relatively constant difference between the two sites: the new Appleby 2 EWS site is, on average, 1.01 °C colder than Nelson Aero, and therefore 1.03 °C colder than Appleby Site 4. This is consistent with the February 2010 ‘Schedule of Adjustments’. The large difference in mean temperature between Appleby 2 EWS and other Nelson region sites is due primarily to very low minimum temperatures recorded at Appleby 2 EWS. Over 2002-2007, its annual minimum averaged 2.37 °C colder than that of Nelson Aero. It could be said that Site 8 is in a ‘frost hollow’, and site photographs show there are banks at higher elevation on three sides of the meteorological enclosure.

Figure A1.2 (left-hand panel) shows a rapid warming trend in the most recent two years at Appleby 2 EWS, 2008-2009, possibly due to growth of trees or maturing of grape vines. The conclusion that it is Appleby 2 EWS and not Nelson Aero that has changed in the last two years is confirmed by a comparison of Nelson Aero with Blenheim Aero AWS (right-hand panel of Figure A1.2).

Thus, if the Appleby 2 EWS was to be used for 2008 and 2009, a different adjustment would need to be applied. This recent trend at Appleby 2 EWS does not give a lot of confidence in the last few years of the ‘previous’ Nelson composite record.

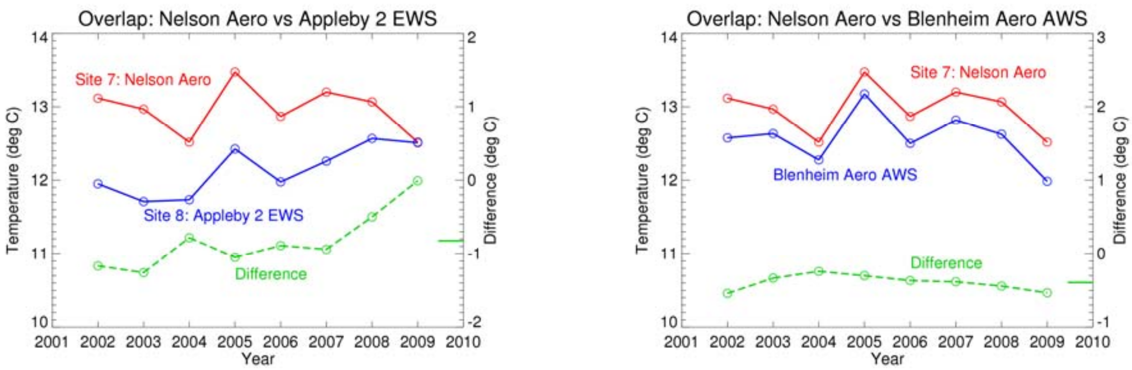

Figure A1.2: Annual mean temperature at Nelson Aero (Site 6, red line), compared with temperatures at two other sites: Appleby 2 EWS (Site 7, blue line) and Nelson AWS (agent 5271, blue line). The difference, ‘other site’ minus Nelson Aero, is plotted by the green dashed line, using the right-hand ordinate scale, and the mean annual difference over 2002-2009 is given by the short green solid line on the right side of the plot.

Adjustments for Site Changes 3 to 4 in 1932, and 2 to 3 in 1920

The adjustments for these site changes have been worked out in the main text: Site 3 (Cawthron) is 0.15°C warmer than Site 4 (Appleby), and Site 2 (Nile St) is a further 0.88°C warmer than Site 3 (Cawthron). These corrections have been accumulated relative to the reference site of Appleby (Site 4), and entered into Table A1.1.

Adjustment for Site 1 to Site 2 Change between 1880 and 1907

According to documented information on climate station histories (Fouhy et al., 1992), observations of air temperature at Nelson began as early as 1844. Sir James Hector, Director of the New Zealand Meteorological Service (and its forerunner[21]) 1867-1903, considered that there was a great improvement in the quality of the observations after 1863. In 1867, the observatory (station G13231) was situated in the centre of town at an elevation of 5.5m. The site was near the present Nelson Institute and the government buildings. NZ Meteorological Service staff notes on file say the temperatures would probably have been too high, as at most of the early stations, because of defects in the type of shelter used. The station was closed at the end of 1880, as happened to a number of other climatological stations at that time.

In 1905 daily observations recommenced at the Vicarage, Nile Street, but these were not considered sufficiently reliable until October 1907. The site elevation was 10 m and it was considered a “warm” site, being sheltered from the southwest and high enough to escape frosts. There were too many large trees for free exposure. In December 1920, the station was taken over by the Cawthron Institute.

In the NIWA Climate Database, there are records of Nelson temperature for the period 1864-1880, with a few months of observations in 1862 also. Then there is a large gap in observations until resumption in October 1907. In order to relate Nelson temperatures pre-1881 with those post-1907, there is only one feasible comparison site, Auckland Albert Park (agent 1427), there being too many site changes occurring in Wellington and Dunedin.

[21] In 1879, there were two meteorological organizations in New Zealand: the Meteorological Department with its climatological stations under Sir James Hector, and the Weather Signal Department under Commander R.A. Edwin in the Marine Department (de Lisle, 1986). Hector proposed to the Colonial Secretary (Sydney) that cost savings could be achieved by combining the two organizations into one, and at the same time reducing the number of first-class climatological stations from 12 to just 3 (Auckland, Wellington, and Dunedin). This duly occurred at the end of 1880.

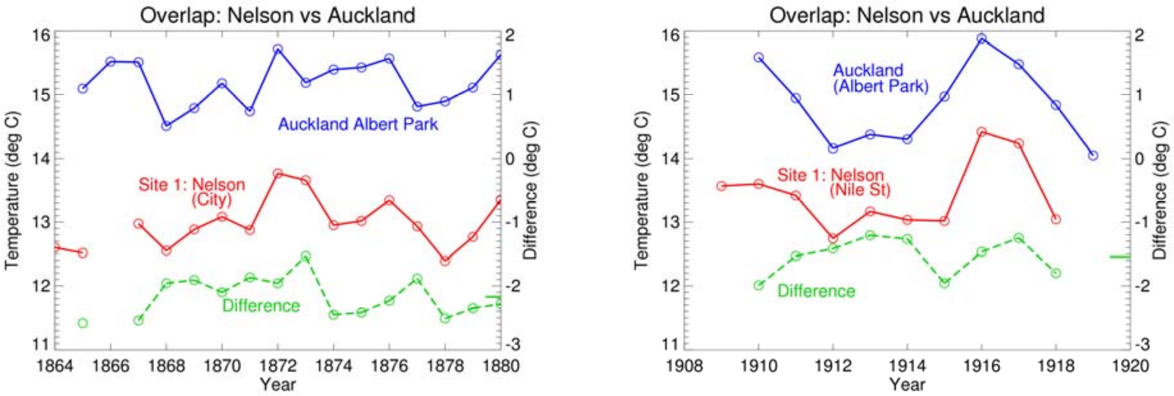

Figure A1.3: Annual mean temperature at Nelson Site 1 (red line on left plot) 1862-1880, and Nelson Site 2 (red line on right half plot) 1909-1918, compared with temperatures at Auckland Albert Park (agent 1427, blue line) over the same periods. The dashed green line represents the difference, Nelson minus Auckland, using the right-hand ordinate scale, and the mean annual difference over the period plotted is given by the short green solid line on the right side of each plot.

Figure A1.3 shows graphs of Nelson annual temperature up to 1880 (left panel) and following the move to Nile Street in 1907 (right panel).

In the earliest period of record, 1865-1880, Nelson City (agent 4244) averaged 2.17°C colder than Auckland. In the early 20th century, 1910-1918, Nelson was 1.54°C colder than Auckland. The location of the 'Auckland' site had itself changed twice in this period: from the Domain to the Museum in 1883, and from the Museum to Albert Park in 1909. However, the estimated temperature adjustments indicate no change in annual mean temperature between the pre-1880 site (Auckland Domain) and the post-1909 site (Auckland Albert Park).[22]

These temperature comparisons imply that the pre-1881 Nelson City site was colder than Nile Street by 0.63 °C. Applying this change to Site 1, its adjustment relative to Appleby Site 4 would be: -0.15 -0.88 +0.63 = -0.40 °C. This means the early Nelson City site was 0.4 °C warmer than Appleby Site 4, and its temperature measurements would need to be adjusted downwards by this amount to match the micro-climate that Appleby would have been experiencing at that time.

Owing to the greater uncertainty in early temperature measurements, we have not included this period of record in the revised composite temperature series for Nelson. However, the adjustment has been included in Table 1 and Table A1.1 for ease of comparison with the Salinger *et al.* (1992) estimate. Note that the offset of +0.6 °C between Sites 1 and 2 (with Site 2 warmer) is rather different to the previous offset of +0.3 °C (Column 6 of Table 1, as determined by Salinger *et al.*, 1992), another indication of uncertainties in the early measurements.

[22] The February 2010 Schedule of Adjustments, based on Salinger et al (1992), suggested a small change of 0.1 °C at September 1868 and thereafter no further adjustment until 1951. The revised adjustments (see Auckland document) suggest that the pre-1883 Auckland site in the Domain is equivalent to the post-1909 site in Albert Park. During 1883-1909, when there is no Nelson for comparison purposes, the intermediate Auckland Museum site was warmer by 0.1 °C.

Putting the Time Series Together using the 'Previous' Adjustments

The various adjustments described above can be applied successively to the Nelson temperature records. The resulting final time series from 1908 to 2007 is shown in Figure A1.4, including a comparison to the previous Nelson time series used by NIWA. Note that in this case we have truncated both series at 2007, so that the erroneous Appleby 2 EWS values in 2008 and 2009 do not influence the trend. This figure parallels Figure 10, but using our revised adjustments based on the earlier set of Nelson stations.

The revised 1909-2007 trend for the Nelson region is +0.80 °C/century, which is similar to the +0.75°C/century trend calculated from the seven-station time series published in February 2010. Note also the difference between the 'Previous' trend calculated here for the period 1909-2007, with that in Figure 10 for the 1909-2009 period. The difference is due to the erroneously high values in 2008 and 2009 at Appleby 2 EWS. The replacement of the Appleby automatic sites (Sites 5 and 8) by the Nelson Aero sites (Sites 6 and 7), as discussed in the main text, avoids this problem.

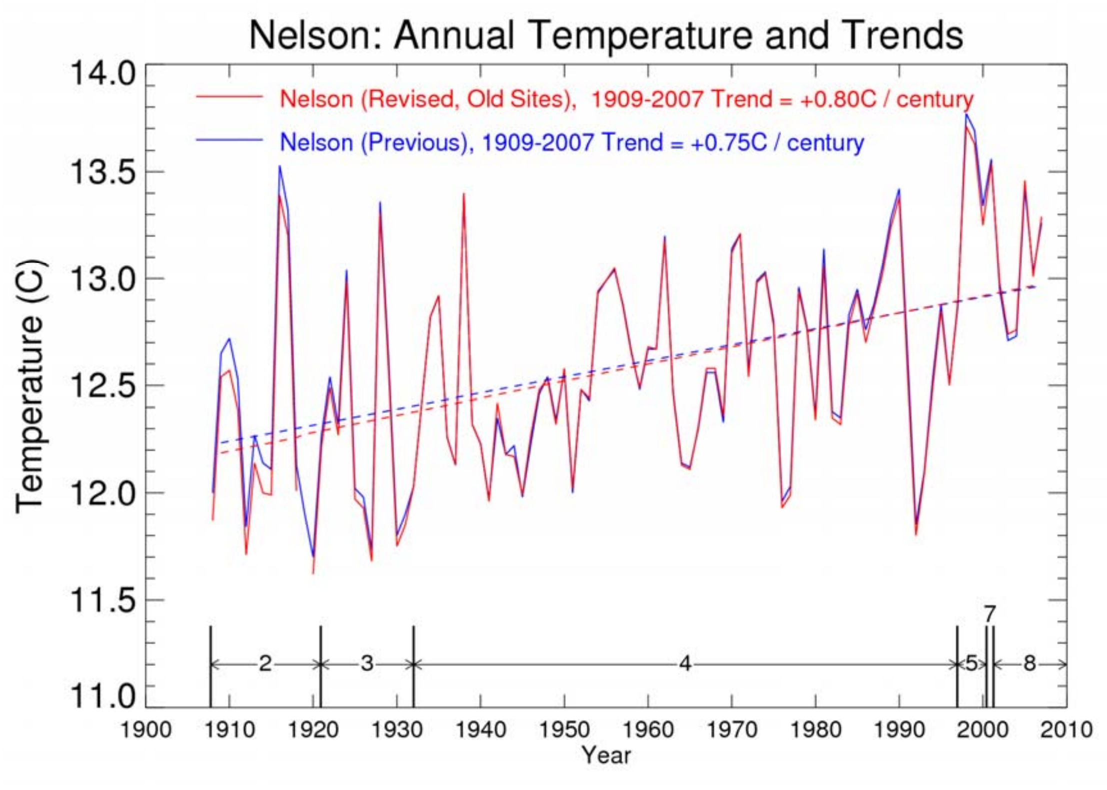

Figure A1.4: Comparison of revised series (red line) and previous NIWA series (blue line) of composite temperatures for Nelson from 1908 to 2007. The dashed lines indicate the fitted linear trend over the period 1909-2007. Labels near the bottom of the plot denote the Site numbers of Table 1. Vertical lines at the bottom of the plot mark the time periods over which each site contributes to the composite series, with the Sites numbered as in Table A1.1.

Figure A1.5 repeats the graph of the revised composite annual mean temperature series for Nelson, and compares the composite with the unadjusted raw multi-site temperatures. For the period 1932-1996 the two series are identical, since this period is covered by the Nelson reference site (Appleby, Site 4) for which no adjustment is applied. The estimated adjustments are also shown in Figure A1.5. The adjustments are cumulative relative to Appleby Site 4, and correspond to those in the final column of Table A1.1. Note that again the series have been truncated at the year 2007.

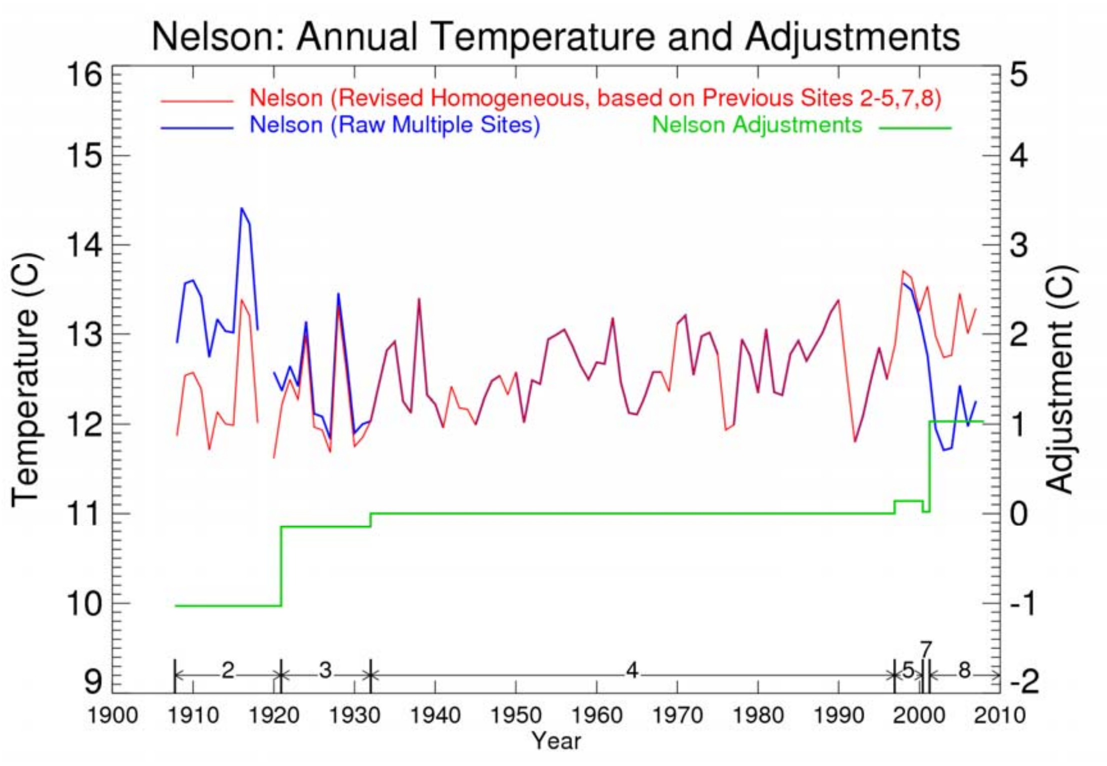

Figure A1.5: Comparison of revised composite temperature series for Nelson from 1908 to 2007 (red line), based on the previous site selection, with the raw multi-site series (blue line). The green line (using right-hand axis) indicates the cumulative step adjustments to each site as shown at the bottom of the graph. The site numbers and periods of record correspond to those listed in Table A1.1.

Creating a Composite Temperature Series for Hokitika

December 2010

Figure 1: Looking south towards the Hokitika Aero climate station (agent number 3909) in 1982.

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 Hokitika. The primary purpose is to demonstrate in an intuitive way how to estimate adjustments to temperature records 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., RHtests, Wang *et al.*, 2007) to identify other change-points in the data.

Table 1: Information about Hokitika climate observations:
(Column 1) the site label used in the text;
(Column 2) the site name, and (in parentheses) the 'agent number' used by 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 period of record (as of February 2010) 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 of record for which the site contributes to the composite time series; and
(Column 8) revised temperature adjustment to be applied (with respect to Hokitika Aero, Site 3), 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	Hokitika Town (3907)	Fitzherbert Street, Hokitika (Jan 1866 to Dec 1880, Jan 1894 to Jan 1946)	2	Jan 1894 to Aug 1912	−1.3	Jan 1900 to Aug 1912	−1.57
				Sep 1912 to Jul 1943	−0.3	Sep 1912 to Oct 1928	−0.36
						Nov 1928 to Dec 1944	−0.34
Site 2	Hokitika Southside (37939)[3]	Old Hokitika Airport (Aug 1943 to Dec 1964)	13	Aug 1943 to Dec 1964	+0.3	Jan 1945 to Dec 1963	+0.34
Site 3	Hokitika Aero (3909)	Hokitika Airport (Nov 1963 to present)	39	Jan 1965 to present	0	Jan 1964 to Oct 1967	+0.05
						Nov 1967 to present	**0.00**

Calculation of Adjustments

Table 1 summarises the information about the local sites used to develop the composite temperature series for the Hokitika 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

[2] Because of lower confidence in early temperature measurements the revised temperature series is not constructed prior to 1900. 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] Hokitika Southside (37939) data were originally stored in CliDB under agent number 3907, along with the data from the earlier Hokitika Town site. A separate agent number was assigned early in 2010, after the publication of earlier version of the present document.

place, whereas the revised adjustments are specified to two decimal places. Table 1 lists three different sites as contributing to the composite Hokitika temperature series and at the first site there was a discontinuity in the record in 1912. In addition, there were two minor site changes so in total there are five change points to be considered. The temperature record must be closely examined before and after the change-dates, in order to identify potential biases.

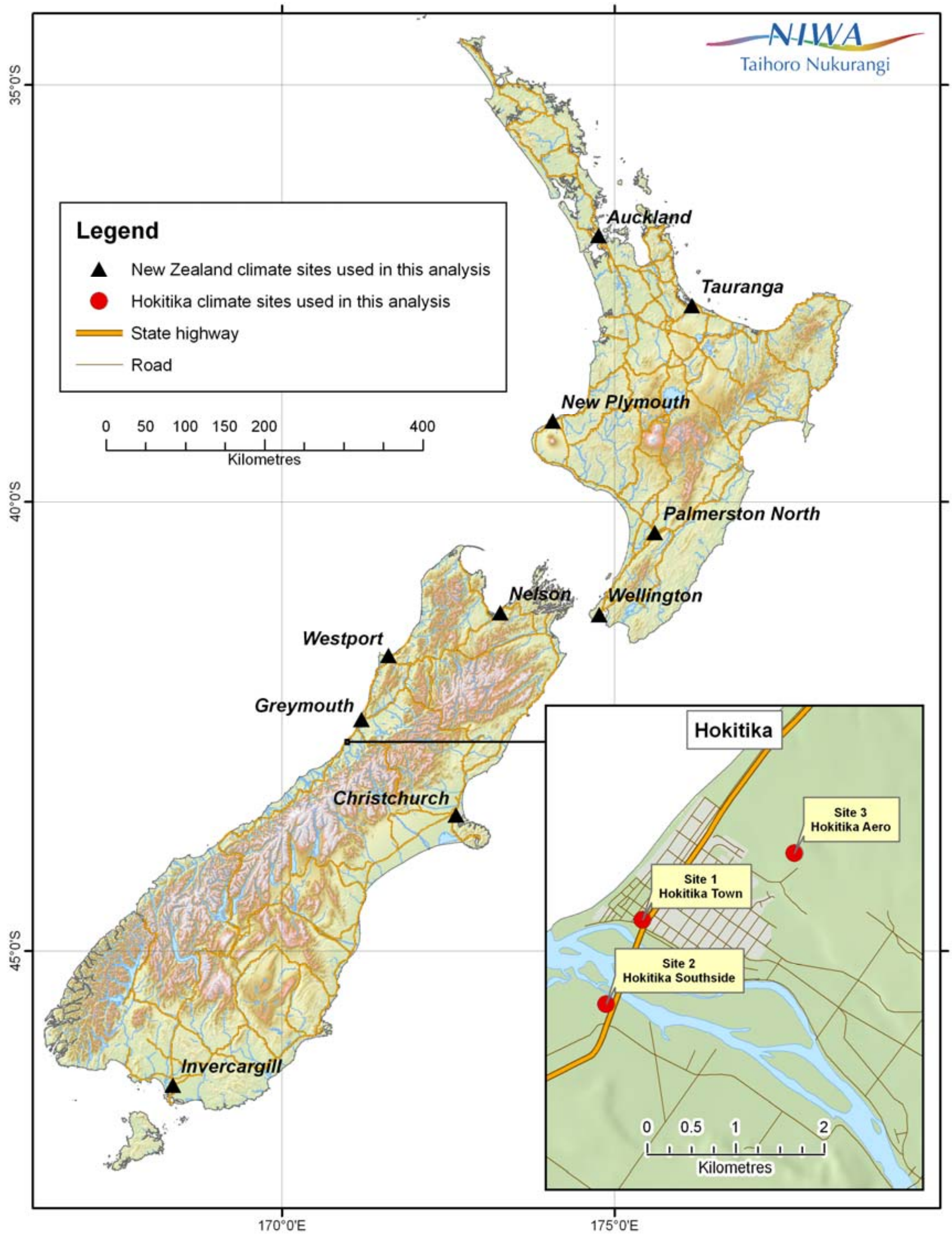

Figure 2: Map showing sites of temperature records referred to in this document. The inset map locates the Hokitika sites.

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 was 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 Hokitika, there was an instrumentation change in 1912, correcting temperatures that were previously too high. 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. Furthermore, although it is quite clear from the site documentation and the data themselves that there was a significant bias in the measurements before the change, the specific reason for the bias is not clear, and the possibility that it varied with time cannot be ruled out. So the revised Hokitika annual temperature time series is constructed from 1900, but the values before 1913 must be considered somewhat unreliable.

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 Hokitika, where the reference site is Hokitika Aero (Figure 1), labelled Site 3 in Table 1. Figure 2 provides a map locating the Hokitika sites of Table 1, and also the more distant sites discussed in the subsequent text.

The sites contributing to the Hokitika 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 Changes in 1964 and 1967

We will work backwards in time from the current open site: Hokitika Aero (Site 3). This instrument enclosure is some 200 m NW of the Hokitika Airport terminal area, surrounded by low scrub (Figure 1 and Figure 2). Hokitika Aero opened in November 1963, replacing the Hokitika Southside site at the old airport, south of Hokitika River (Site 2). There was an overlap period of 14 months (Nov 1963 to Dec 1964) during which both sites operated. However, there is the complication that the Hokitika Aero instruments were initially installed in a temporary enclosure west of the terminal area and were moved to the present location in October 1967. Below we shall use three different approaches to estimate the separate and combined effects of the move from Hokitika Southside to Hokitika Aero and the site change at Hokitika Aero.

The 14-month overlap period between Site 2 and the temporary enclosure at Site 3 allows a straightforward calculation of the temperature difference, although ideally one would like an overlap period of two years or more (Della-Marta *et al.*, 2004). The difference (Figure 3) is reasonably steady from month to month (standard deviation = 0.23 °C) and has a mean value of 0.29 °C (Site 3 temporary enclosure minus Site 2).

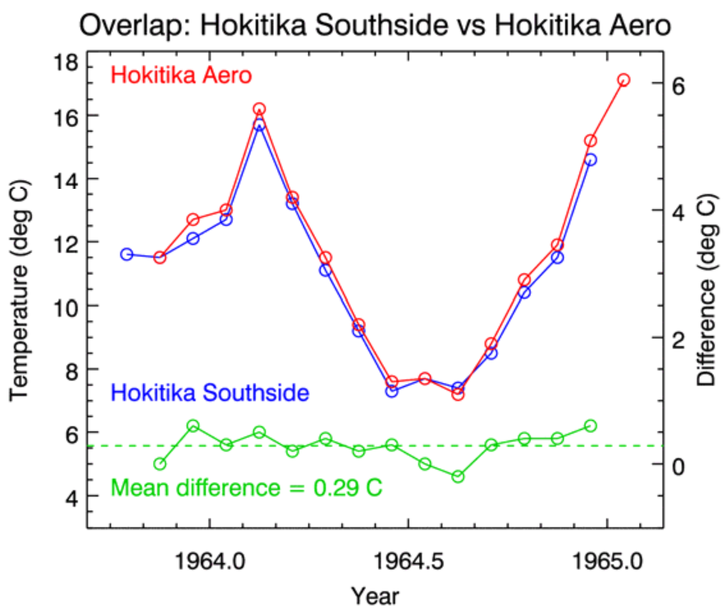

Figure 3: Monthly mean temperature series for Hokitika Southside (Site 2, blue line) and Hokitika Aero (Site 3, red line) during their overlap period. The monthly difference, Site 3 minus Site 2, is indicated by the solid green line, using the right-hand ordinate scale, and the mean monthly difference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

The overlap period did not encompass the 1967 site change, therefore the only way to objectively estimate the effect of that change is by comparing the measurements with those at other climate stations. 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 evidence of a site change or instrumentation change at the comparison station or (less ideally) a good estimate for the effect of that change;
- 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.

As background information for the selection of comparison stations, Figure 4 shows the correlation of mean temperature interannual differences at the Virtual Climate Station (VCS) grid cell containing Hokitika Aero (Site 3) with interannual differences at all other locations on the VCS grid from 1972 until 2008 (i.e., 1972-73 difference, 1973-74, … , 2007-08)[4]. This map gives a good indication of the locations at which

[4] 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).

temperatures are likely to be highly correlated with the sites comprising the Hokitika composite series.

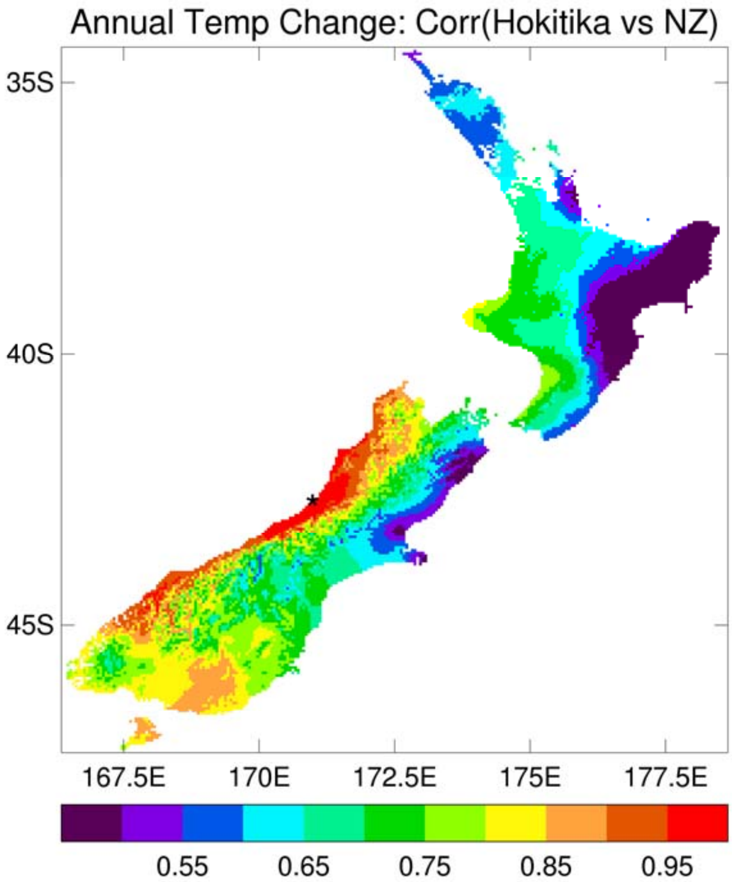

Figure 4: Map of correlation between interannual temperature changes at the Hokitika Aero grid-point (Site 5, location marked by asterisk), 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

Not surprisingly, interannual temperature variations at Hokitika correlate highly with those in the Westland region as a whole, the correlation coefficient typically being over 0.90. The correlation is above 0.80 in Southland and remains at or above 0.70 in a band extending through Nelson and on the west coast of the North Island. It is lower (~ 0.5) on the east coasts of both the North and South Island.

To isolate the effect of the 1967 change, we form a composite Hokitika temperature series, with Hokitika Southside data up to 1963 and Hokitika Aero data from 1964, the former adjusted by +0.29 °C to allow for the difference between the two stations, as estimated from the overlap (Figure 3). This series is then compared (Figure 5) with the temperature records at four stations: Invercargill Aero (5814)[5], Appleby (4239), Wellington Kelburn (3385) and Palmerston North (3238). They are all at least 200 km distant from Hokitika and the first-difference correlation coefficients shown in Figure 4 are ~ 0.7–0.8. The closer, more highly correlated stations of Greymouth Aero (3950) and Westport Aero (3810) were also considered, but in both cases there was evidence of an inhomogeneity affecting their data around 1965 (Appendix 3).

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

The comparison period was 1957–1977, excluding the change year, 1967. The closeness of the match between each comparison station and the Hokitika 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 stations used here, the correlations were 0.63, 0.78, 0.70 and 0.80, respectively.

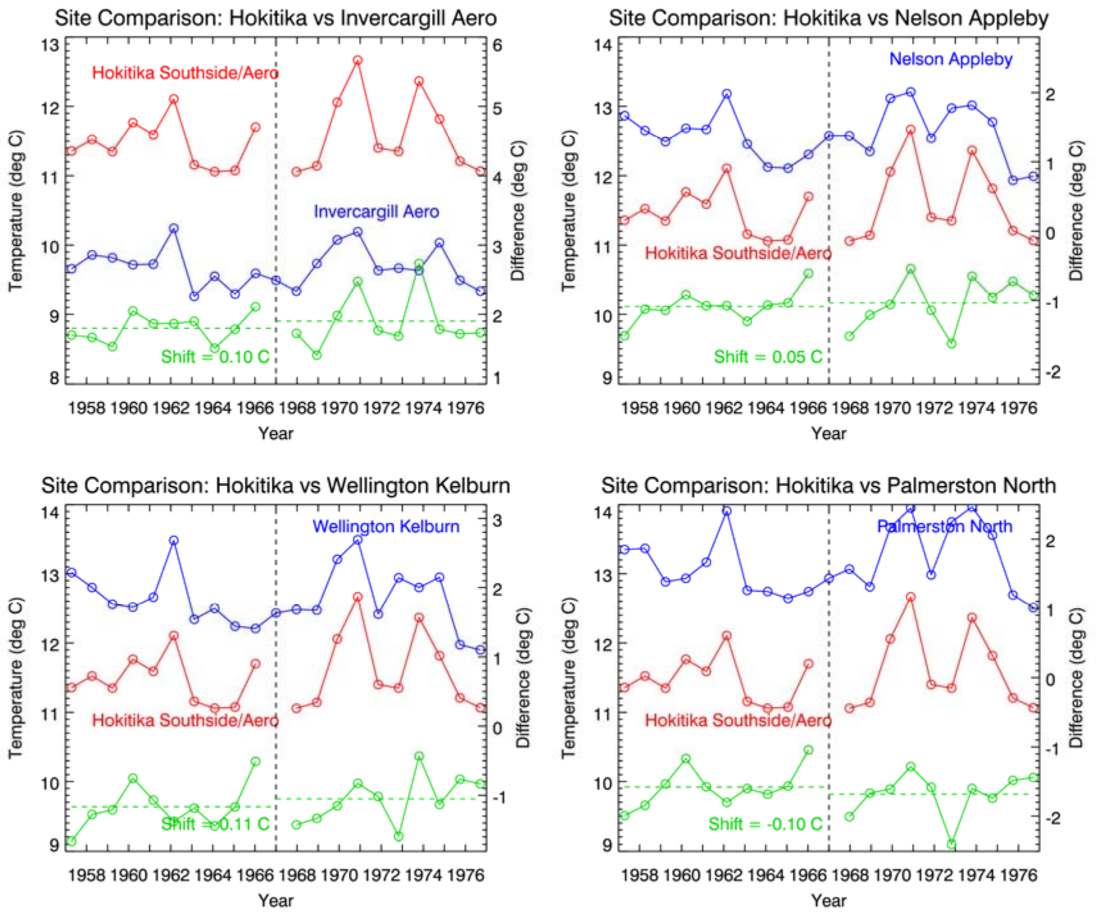

Figure 5: A composite annual-mean temperature series at Hokitika Southside/Aero before and after the site change in 1967, compared with Invercargill Aero, Appleby, Wellington Kelburn and Palmerston North. The procedure for compositing Hokitika Southside and Hokitika Aero data is described in the text. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Hokitika minus comparison station) using the right-hand ordinate scale. The year of the site change, 1967, is indicated by a vertical dashed line. The mean differences for the periods before and after the change are indicated by dashed green lines.

The temperature change at 1967 is estimated relative to each comparison station in turn. Before the change, the Hokitika series was on average 1.80 °C warmer than Invercargill Aero. After the change, the Hokitika series was on average 1.90 °C warmer than Invercargill Aero. Therefore, the comparison with Invercargill Aero results in the estimate that Hokitika Aero temperatures warmed by 0.10 °C with the 1967 site change.

A similar procedure was followed for the other three comparison sites. The comparison with Appleby results in the estimate that Hokitika Aero was 0.05 °C warmer after the site change than before. The comparison with Wellington Kelburn results in the estimate that Hokitika Aero was 0.11 °C cooler after the site change than before. The comparison with Palmerston North results in the estimate that Hokitika Aero was 0.10 °C cooler after the site change than before.

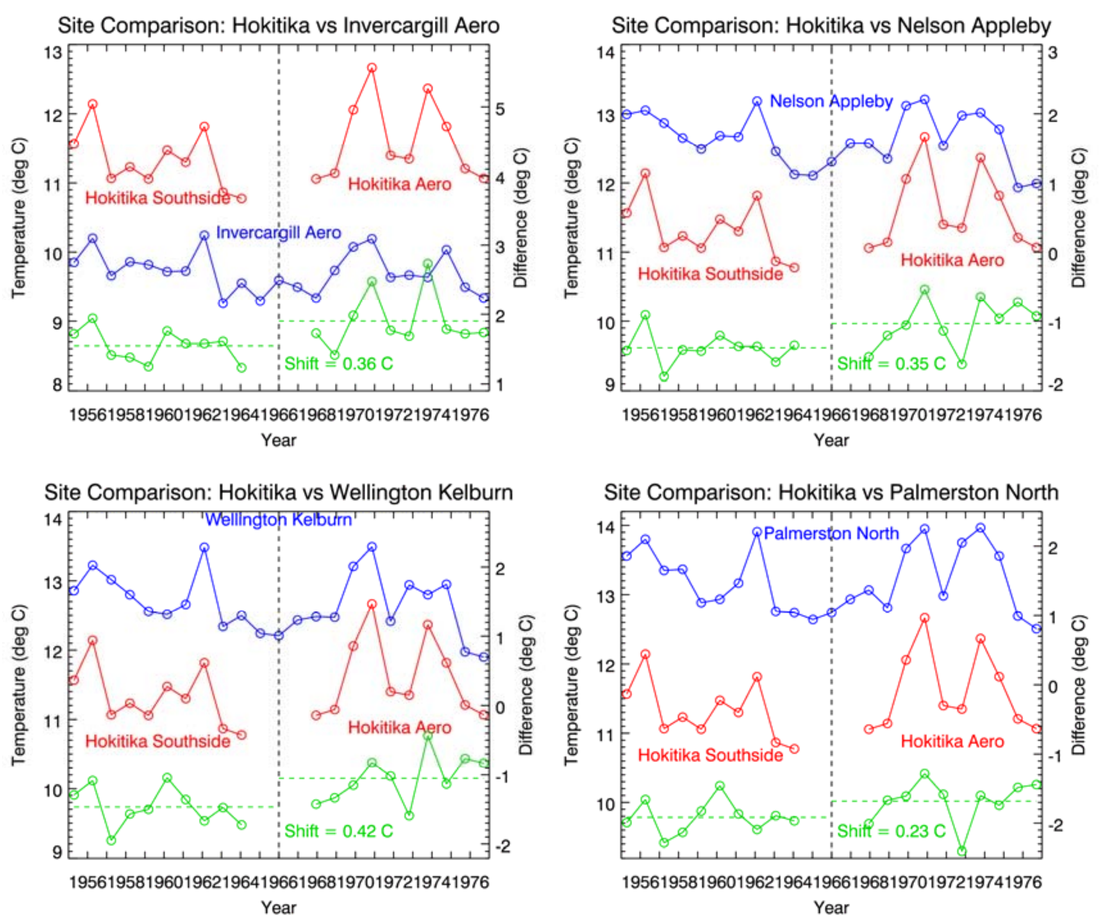

Figure 6: Annual-mean temperature series at Hokitika Southside and at Hokitika Aero after the site change in 1967, compared with Invercargill Aero, Appleby, Wellington Kelburn and Palmerston North. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Hokitika minus comparison station) using the right-hand ordinate scale. The mean differences for the periods before and after the change are indicated by dashed green lines.

An average of the four differences (0.10 °C, 0.05 °C, 0.11 °C and −0.10 °C), gives the estimate that Hokitika Aero after the 1967 site change was 0.04 °C warmer than before the site change.

As an alternative approach, Figure 6 presents a set of comparisons with the same four stations to determine the difference between the Hokitika Aero permanent enclosure and Hokitika Southside, omitting the Hokitika Aero data from 1964 to 1967. The resulting estimates are 0.36 °C (Invercargill Aero), 0.35 °C (Appleby), 0.42 °C (Wellington Kelburn) and 0.23 °C (Palmerston North). The average of all four is 0.34 °C.

Synthesising these estimates, the move from Hokitika Southside to the Hokitika Aero temporary enclosure resulted in a warming of 0.29 °C, and there was a further warming of 0.05 °C with the move to the present enclosure in October 1967. The latter change is very small and could be approximated as zero. However we retain it because it is associated with a documented site change. Thus, the adjustment required for Hokitika Aero temperatures before October 1967 to make them homogeneous with the reference period at Hokitika Aero is +0.05 °C and the adjustment required for temperatures at Hokitika Southside is + 0.05 + 0.29 = 0.34 °C. The latter is the same, to one decimal place, as the +0.3 °C applied to this station in the previous series.

Adjustment for Site Change in 1945

Hokitika Southside (Site 2) opened in August 1943 at what was then the airport on the south side of Hokitika River, approximately 1.1 km from the previous climate station on the edge of Hokitika town (Site 1). However, for some reason a new station number was not initiated at the time. Thus, when the climate data were digitised in the late 1960s, there was only the one station number and only one set of data was transferred to the computerized archive. This situation has recently been corrected and the Hokitika CliDB site has been split into two—Hokitika Town (3907) and Hokitika Southside (37939)—with data from an overlap period between August 1943 and January 1946 re-entered from paper and assigned to the correct station[6]. Of course, all original measurements from both sites are still held in paper form in the NIWA climate archives.

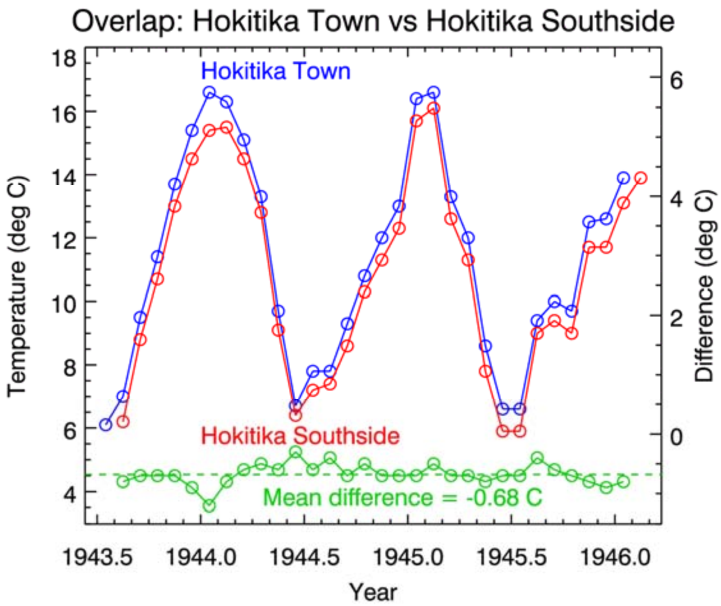

Figure 7: Monthly mean temperature series for Hokitika Town (Site 1, blue line) and Hokitika Southside (Site 2, red line) during their overlap period. The monthly difference, Site 2 minus Site 1, is indicated by the solid green line, using the right-hand ordinate scale, and the mean monthly difference is indicated by the dashed green line.

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[6] In the process of checking the records, an error was discovered in the CliDB Hokitika (agent number 3907) temperatures for 1945. The actual sequence of temperatures in the database (now corrected) was as follows: Site 1 up to Jul-1943; Site 2 for Aug-1943 to Dec-1944; Site 1 for Jan-1945 to Dec-1945; Site 2 from Jan-1946. Note that the previous Hokitika composite temperature series does *not* suffer from this problem – the sequencing of the site data used in calculating that was correct.

The 30-month overlap period should allow an accurate estimate of the effect of the shift (Figure 7). The difference is reasonably steady from month to month (standard deviation = 0.17 °C) and has a mean value of −0.68 °C (Site 2 minus Site 1).

As a check, the effect of the site change has also been estimated by comparison with other stations (Figure 8). The stations were Westport Aero (3810), Appleby (4239), Wellington Kelburn (3385) and New Plymouth (2276). The comparison period was 1935–1954, with the change taken between 1944 and 1945, and the first-difference correlations were 0.97, 0.83, 0.80 and 0.84, respectively.

The estimates resulting from the comparison are −0.44 °C (Westport Aero), −0.54 °C (Appleby), −0.54 °C (Wellington Kelburn) and −0.55 °C (New Plymouth). The average of all four is −0.52 °C, which is smaller (less negative) than the overlap estimate by 0.16 °C.

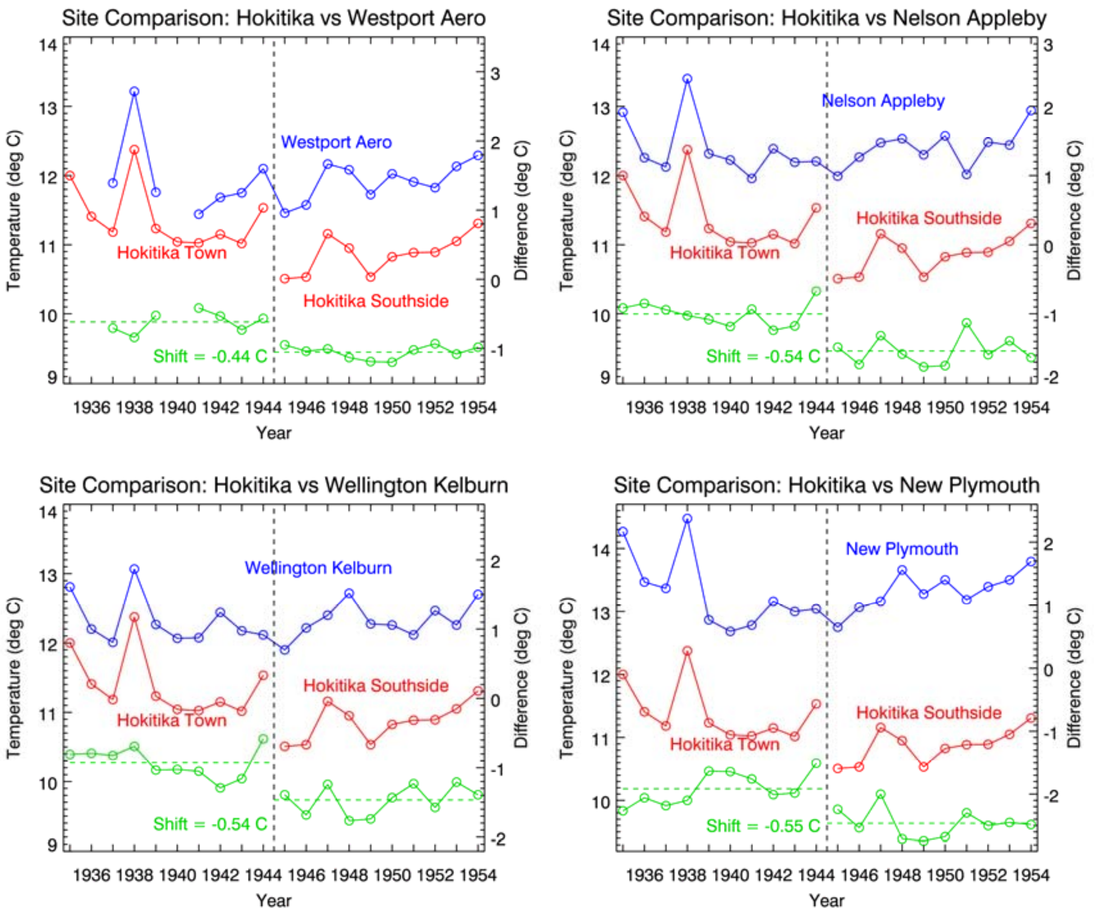

Figure 8: Annual-mean temperature series at Hokitika Town and at Hokitika Southside, compared with Westport Aero, Appleby, Wellington Kelburn and New Plymouth. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Hokitika minus comparison station) using the right-hand ordinate scale. The mean differences for the periods before and after the site change are indicated by dashed green lines.

So the comparison method and the overlap method both indicate that Hokitika Southside is substantially cooler than Hokitika Town, but the former suggests a smaller difference than the latter, by ~ 0.2 °C. We have decided to adopt the estimate from the overlap method, on the grounds that an overlap between two nearby stations should provide a more direct estimate of the difference between them than a comparison involving more distant stations.

The final adjustment of temperatures at Hokitika Town (Site 1) to make them homogeneous with Hokitika Aero (Site 3) is + 0.05 + 0.29 − 0.68 = −0.34 °C. This agrees to one decimal place with the −0.3 °C applied to this station in the previous series.

Adjustment for Site Change in 1928

It is noted in the Hokitika station history (Appendix 2; see also *Fouhy et al.*, 1992) that the original enclosure was only 2.1 × 2.7 m and was enlarged to 15 × 12 m in October 1928. Such a change to the physical surroundings of the thermometer screen has the potential to affect temperature readings. The effect on the mean temperature has been estimated by comparison with other climate stations.

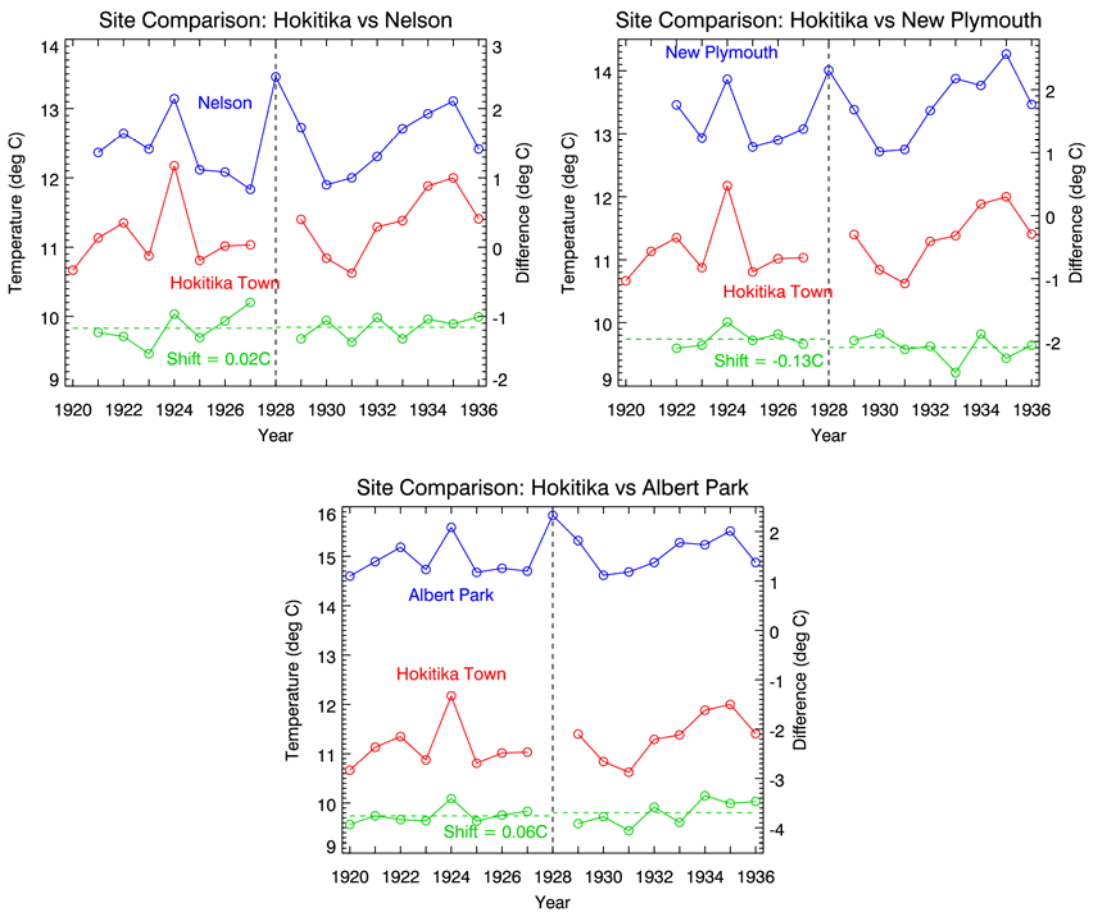

Figure 9: Annual-mean temperature series at Hokitika Town (Site 1) before and after the enclosure enlargement in 1928, compared with Nelson, New Plymouth and Albert Park. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Hokitika Town minus comparison station) using the right-hand ordinate scale. The year of the change, 1928, is indicated by a vertical dashed line. The mean differences for the periods before and after the change are indicated by dashed green lines.

The stations selected for the 1928 comparison were Nelson (4244), New Plymouth (2276) and Albert Park, Auckland (1427). They are all (but particularly New Plymouth and Albert Park) distant from Hokitika and the first-difference correlation coefficients shown in Figure 4 are ~ 0.7–0.8. The comparison period was from 1920 to 1936, i.e., eight years before and after the change year of 1928. The Nelson data for 1920 was omitted because it was affected by a site change[7].

The comparison is shown in Figure 9. The estimates are 0.02 °C (Nelson), −0.13 °C (New Plymouth), and 0.06 °C (Albert Park) and the average is −0.02 °C. The final adjustment of Hokitika Town temperatures before the enclosure change to make them homogeneous with the reference period at Hokitika Aero (Site 3) is + 0.05 + 0.29 − 0.02 − 0.68 = −0.36 °C.

Adjustment for Site Change in 1912

The station history (Appendix 2) records that the maximum temperatures were believed to be about 3 °F too high before August 1912, at which time new thermometers and a new screen were installed. Again, there was no overlap between measurements with the different thermometer/screen combinations, but the effect of the change can be estimated by comparisons with other climate stations. Salinger (1981) compared the Hokitika data with four sites: Nelson, Christchurch, Lincoln, and Dunedin. The average inter-site differences between 1894–1911 and 1913–1945 were calculated, and Salinger concluded that Hokitika maximum temperatures cooled by 1.7 °C after 1912 (which agrees with the estimate that they were 3 °F too high beforehand) and that minimum temperatures cooled by 0.5 °C. Thus the mean temperatures cooled after 1912 by 1.1 °C.

Here we repeat the comparison, but with our own choice of comparison stations and for a shorter period, more in line with the other comparisons in this and other documents. The comparison period was from 1904 to 1920, i.e., eight years before and after the change year of 1912. For changes occurring as long ago as 1912, the selection of comparison stations is severely constrained by the lack of high-quality, homogeneous records. The stations selected were Christchurch Gardens (4858), Nelson (4244) and Albert Park, Auckland (1427)[8]. The first-difference correlations were 0.82, 0.95 and 0.87, respectively.

Figure 10 compares annual temperatures at Hokitika Town with those at the comparison stations. From the comparison with Christchurch Gardens, we estimate that the temperature difference associated with the change was −1.30 °C. From the comparisons with Nelson and Albert Park, we estimate differences of −1.17 °C and −1.15 °C, respectively. After averaging the three differences, we estimate that the difference in mean temperature associated with the change was −1.21 °C. The estimated differences in maximum and minimum temperatures are −1.97 °C and −0.42 °C, respectively. These are reasonably close to Salinger's (1981) estimates of −1.1 °C (mean), −1.7 °C (maximum) and −0.5 °C (minimum).

[7] See "Creating a Composite Temperature Series for Nelson".

[8] The Albert Park measurement site was shifted in 1909 from the Auckland Museum to Albert Park. According to the Auckland document ("Creating a Composite Temperature Series for Auckland", Appendix 4) the new site was 0.09 °C cooler than the old site. Therefore, for the present work, temperatures before 1909 have been shifted by −0.09 °C to correct for the site change.

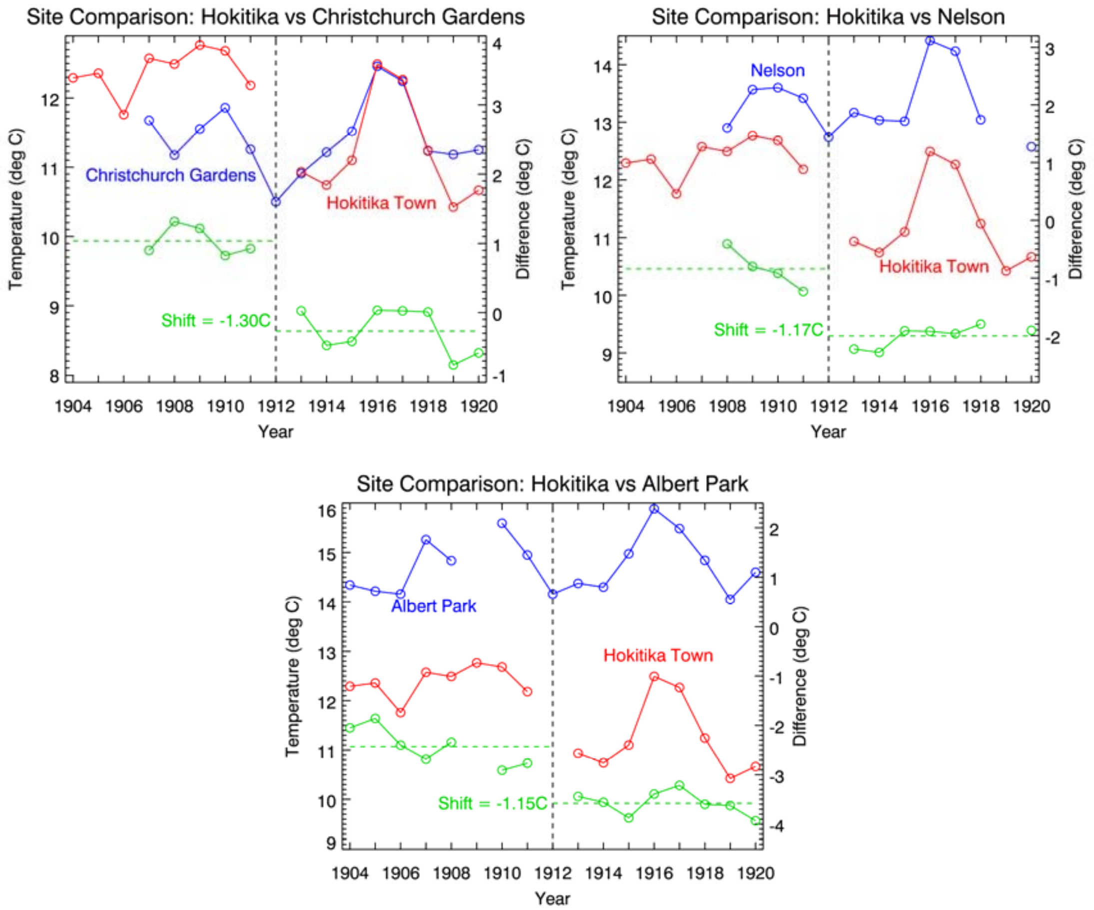

Figure 10: Annual-mean temperature series at Hokitika Town before and after the instrumentation change in 1912, compared with Christchurch Gardens, Nelson and Albert Park. See footnotes in the text for information about adjustments applied to Albert Park. The solid blue line in each plot represents the temperature at the comparison station and the solid green line represents the difference (Hokitika minus each comparison station) using the right-hand ordinate scale. The year of the site change, 1912, 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 Site 1 before the 1912 instrumentation change consistent with the reference period at Hokitika Aero (Site 3) is therefore: + 0.05 + 0.29 − 0.68 − 0.02 − 1.21 = −1.57 °C.

Putting the Time Series Together

The various adjustments described above can be applied successively to the Hokitika temperature records. The resultant annual time series from 1900 to 2009 is shown in Figure 11, with a comparison to the previous Hokitika 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 1.11 (±0.36) °C/century, as compared to 1.07 (±0.36) °C/century for the trend calculated from the seven-station time series published in February 2010.[9]

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 instrument problems before August 1912. However for completeness we have also calculated the trends for the period 1909–2009: the values are 1.14 (±0.35) °C/century for the revised series and 1.07 (±0.35) °C/century for the previous series.

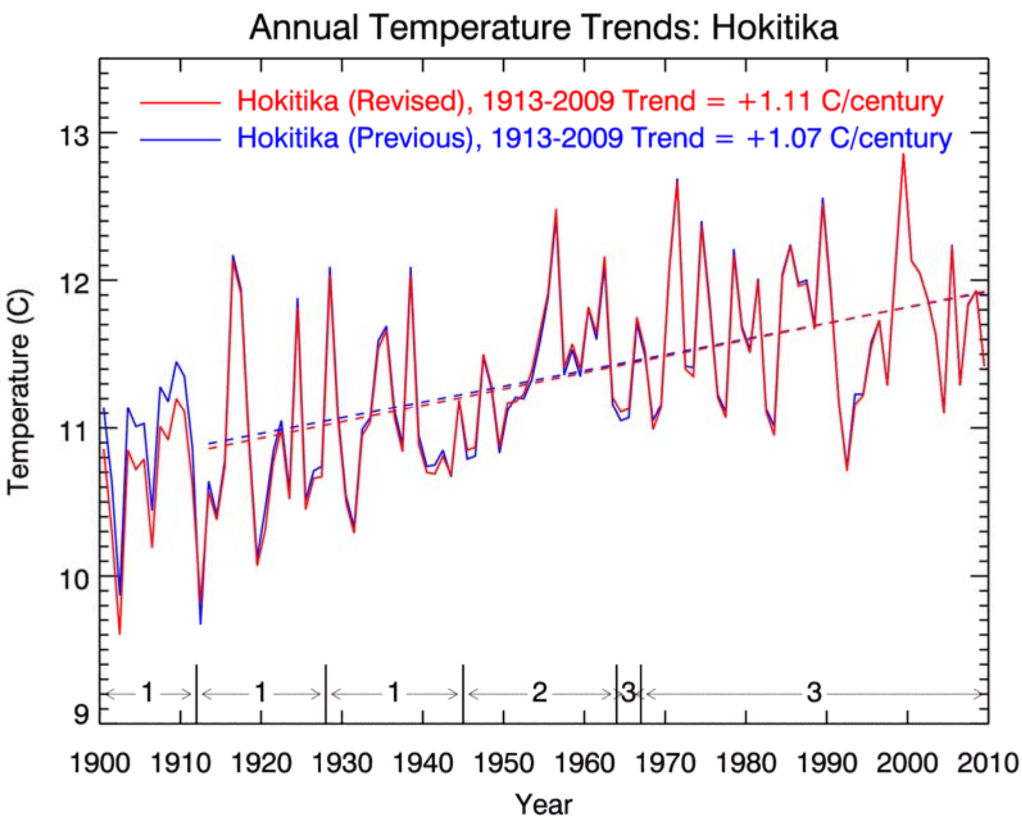

Figure 11: Comparison of the revised composite series of annual mean air temperatures for Hokitika (red line) with the previous NIWA Hokitika series (blue line) from 1900 to 2009. The dashed lines show the fitted linear trends from 1913 to 2009. Site labels from Table 1 are displayed at the bottom of the plot.

[9] The uncertainty here (±0.36 °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.

Once the temperatures from the Hokitika sites have been adjusted for consistency with Hokitika Aero (Site 3), and then combined, we have a series dating back to 1900. However, simply appending the raw data from the Hokitika records without correcting for known site changes would result in an inhomogeneous history of temperature, unsuitable for the analysis of long-term trends.

Figure 12 repeats the graph of the revised composite annual mean temperature series for Hokitika, and compares the composite with the unadjusted raw multi-site temperatures. For the period 1968–2009 the two series are identical, since this period is covered by the reference site for which no adjustment is applied. The cumulative adjustments relative to the reference site are also shown in Figure 12, and correspond to those in the final column of Table 1.

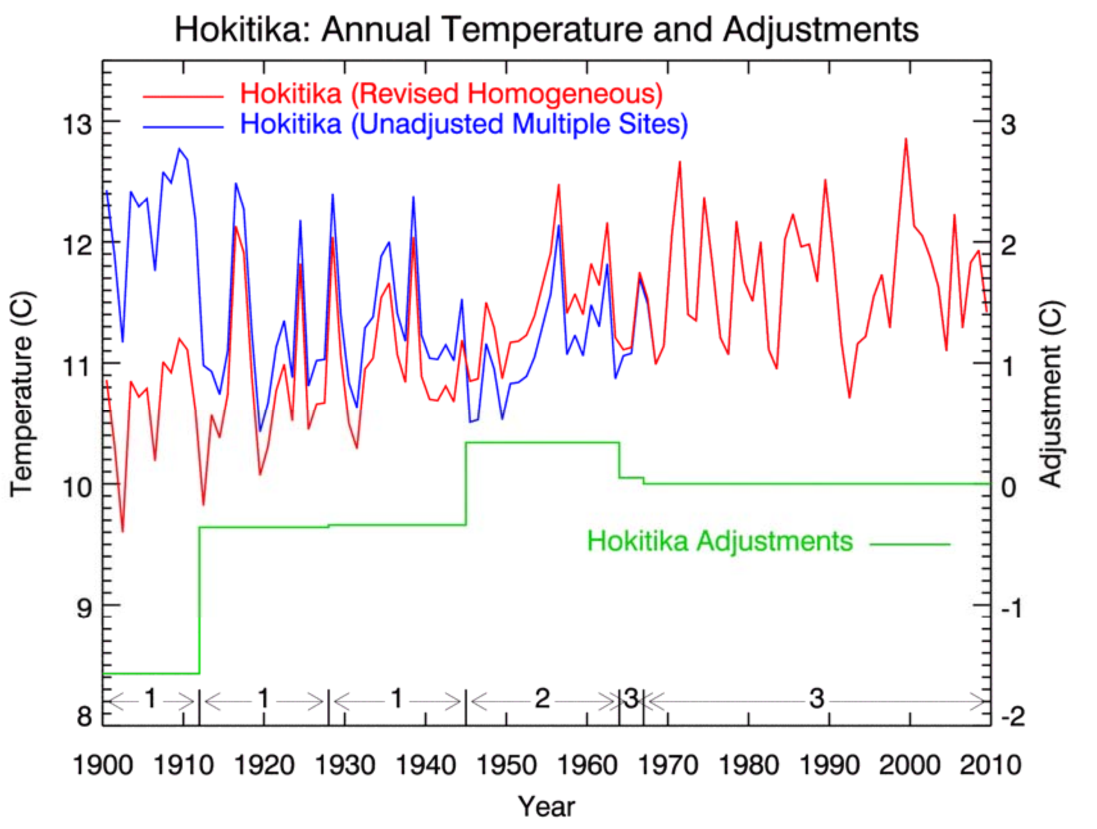

Figure 12: Comparison of the revised composite temperature series for Hokitika (red line), with an unadjusted composite series (blue line) from 1900 to 2009. Numbers near the bottom of the plot denote the site labels of Table 1, with vertical lines marking the time periods over which each site contributes to the composite series. The green line (using right-hand ordinate scale) indicates the adjustment for each period.

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).

Date: A review of the Hokitika adjustments was posted on the NIWA website in February 2010. This current document, created 15 December 2010, updates that earlier version following the same methodology and formatting as for the other 6 station review documents.

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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 Hokitika series. 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.

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

Hokitika composite series

Hokitika Southside, 1951 (July); Hokitika Aero, 1968 (May).

1945 site change, comparison stations

Wesport Aero (3810): 1937 (January, February).

Appleby (4239): 1942 (June); 1943 (June); 1944 (April); 1949 (August).

Appendix 2

Station History

Notes on the early Hokitika climate record from the station history file, as made by Dr Edward Kidson, Director of the New Zealand Meteorological Service 1927–1939.

Notes on the Climatological Station at Hokitika.

The station was established in February 1866 although there had been some observations of a less organized nature previously. Mr. Rochfort, the first Observer reported that,-

> "The Observatory is 11 feet 3 inches above mean sea level. The rain gauge is 30 feet above the surface of the ground, or about 37 feet above mean sea level. There is a second rain gauge on the ground. Taking a north-east direction, the land gradually rises by steps till, at the distance of a mile from the station, it attains the height of about 100 feet. The station is 19 chains east of the sea, and 7 chains north of the Hokitika River. There are no hills near it with the exception of the terrace, 100 feet high, to the north-east."

The station appears to have been throughout in an open space behind the Government buildings but to have been moved to several different parts of this enclosure. There is, for instance, reference to a move in April 1869. In the beginning, the principal rain gauge appears to have been on the roof of a building. A square gauge was used. The rainfall record from from 1866 to 1880 is, therefore, probably subject to some error. Observations were made at 9 a.m. in February 1866, at 10 a.m. from March 1866 till December 1867, and thereafter at 9.30 a.m. until February 1907. Apparently the time was changed to 9 a.m. in March 1907 or possibly at the beginning of the year.

The mercury barometer was apparently housed in a small building near the meteorological station, and was for the most part of the time subject to extreme temperature changes. Observations were discontinued in 1880. When observations were recommenced in 1894 it was presumably with the same instruments and on the same site as in 1880. By this time the gauge would be circular in pattern and on the ground. The station was inspected in September 1912 and a new screen and thermometers were provided. It was then found that the enclosure was too small. From 1894 to this time, the maximum thermometer was apparently reading about 3°F. too high. The observations of wind direction are different from those at other periods, and apparently some method other than that of observing the local surface wind must have been adopted. The amount of cloud, also, was evidently recorded much too low during this period. The humidity values are too low, probably owing chiefly to the error in the maximum dry thermometer. From 1918 to 1920, also, the humidity data are unreliable, presumably due to errors in the wet-bulb thermometers.

In 1912 a new Fortin barometer was taken to the Harbour Board Office for the daily weather reports. The old barometer at the station was becoming worn out, and from April 1913 the barometer readings made at the Harbour Board (to hundredths of an inch only) were used. The height was assumed to be the same as that at the Meteorological station (12 feet.) In October 1920, the barometer was transferred from the Harbour Board Office to a building in the grounds near the Meteorological station (apparently the position of the old barometer.) Its altitude was 12 feet. It was subject to a similar range of temperature to what it would have experienced in the open air.

In August 1925, the barometer was removed to Mr. Chesney's Office, the altitude being 30 feet. Apparehtly it was affected in some way by the move since the readings have been high since then.

Although the enclosure for the instruments was presumably enlarged in 1912, it was found by Mr. Pemberton in January 1928 to be only 9 ft. x 7 ft. and surrounded by a fence 3 feet high. It was enlarged to 40 ft. x 50 ft. later on in that year.

In January 1928 ordinary wet and dry bulb thermometers were substituted for the maximum and minimum wet bulbs. and a new Kew Pattern Barometer in January 1931.

The observers have all been Government servants and, except in the case of Mr. Fleming (1917-1919) members, apparently, of the Lands and Survey Department.

Further details will be found on the sheet of mean pressure readings.

E.K.

23rd May, 1930.

Appendix 3

Hokitika versus Other Stations

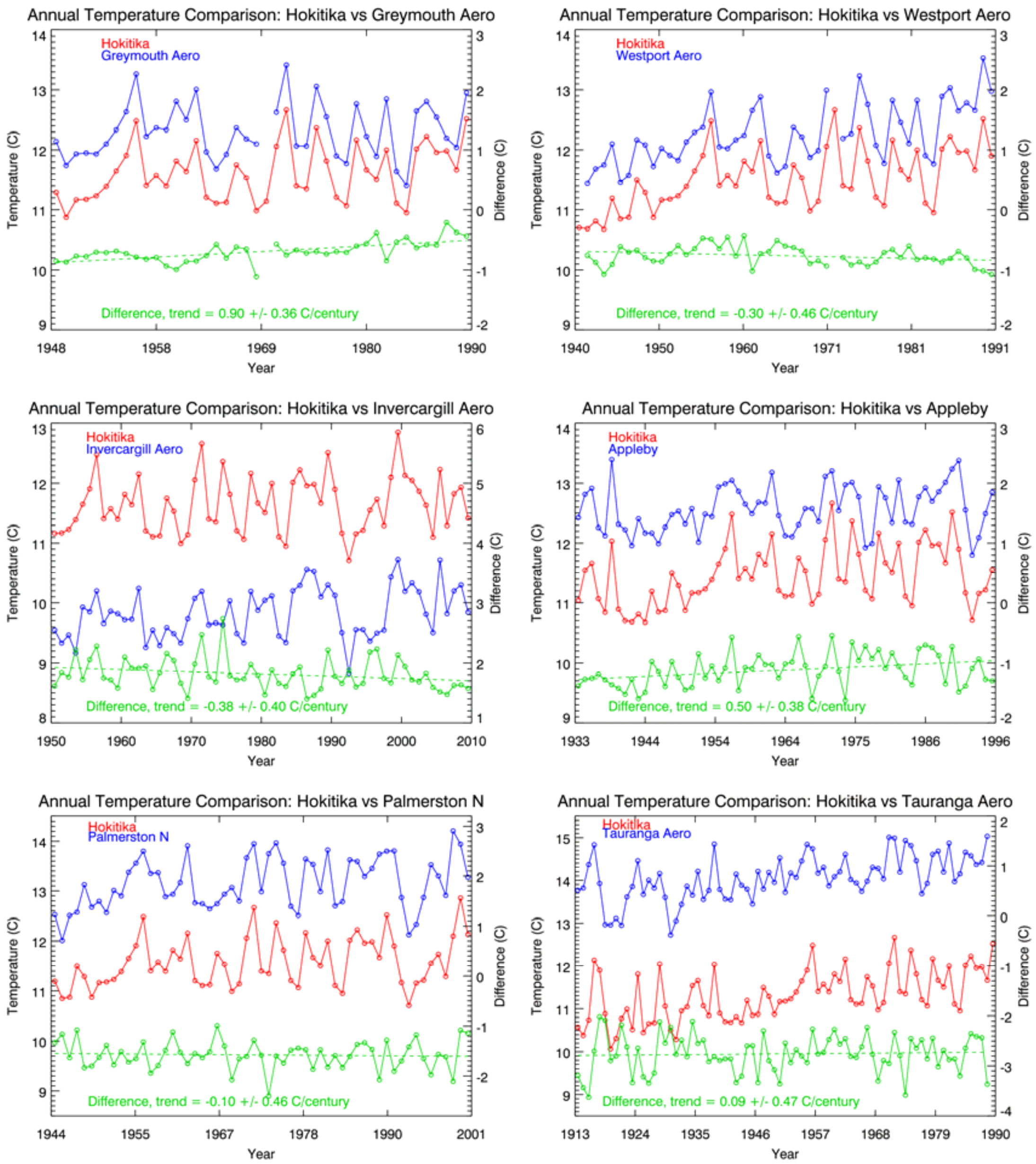

Figure A3.1: Comparison of the revised composite temperature series for Hokitika (red line), with time series of annual mean temperature (blue line) at other stations: Greymouth Aero, Westport Aero, Invercargill Aero, Appleby, Palmerston North and Tauranga Aero. The solid green line represents the difference (Hokitika 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[10].

It is reasonable to ask whether other, comparable stations show a similar trend to Hokitika. Figure A3.1 shows the revised Hokitika composite temperature series

[10] 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).

compared with temperature series from several other climate stations in Westland and further afield. The stations have been 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.

The Greymouth Aero (3950) and Westport Aero (3810) stations are both situated on the Westland coastal plain (Figure 2). The name “Aero” indicates an airport station, but the Greymouth Aero station moved away from the airport in 1991, at which point the time series shown here is terminated. The difference time series (Hokitika minus Greymouth) shows a positive trend of +0.90 ± 0.36 °C/century, implying that Hokitika has warmed relative to Greymouth Aero over the period shown. However for Westport Aero there is a smaller, statistically insignificant negative trend in the difference, of −0.30 ± 0.46 °C/century. The large (~ 1 °C/century) range of trends encompassing Westport Aero, Hokitika and Greymouth Aero is surprising as all three locations appear to be similar climatically, and interannual fluctuations in temperature track each other very closely (Figure 4). The site history on CliDB for the Greymouth and Westport stations shows no entries for the first 30–40 years, but a search through the paper records revealed a site change at Greymouth Aero in December 1965. Comparisons of temperature difference with other stations suggest very little change in mean temperatures at Greymouth Aero as a result of that site change, but a warming of a few tenths of a degree at about the same time at Westport Aero. Clearly, a more careful examination of the metadata and data for these two stations is required before firm conclusions can be drawn about the trends relative to Hokitika.

Looking further afield, Hokitika warmed significantly relative to Appleby (4239, 0.50 ± 0.38 °C/century over 62 years), cooled relative to Invercargill Aero (5814, −0.38 ± 0.40 °C/century over 60 years), and had no significant change relative to Palmerston North (3238, −0.10 ± 0.46 °C/century over 55 years). The longest period comparison shown here is with Tauranga Aero (1615) over 76 years from 1913 to 1988; it shows a statistically insignificant difference in the trend (0.09 ± 0.47 °C/century). The differences in the trend amongst these stations probably involve various climatic differences, and possibly some non-climatic effects, such as changes in station exposure. However the trend in the Hokitika composite time series is within the range of variation observed at other New Zealand stations.

Creating a Composite Temperature Series for Lincoln

December 2010

Figure 1: Looking southwest toward the enclosure of Lincoln Broadfield EWS (Electronic Weather Station, agent number 17603) in February 2000.

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.

This present document revisits and describes in greater detail the process by which a composite station series has been developed for Lincoln. The primary purpose is to demonstrate in an intuitive way how to estimate adjustments to temperature records 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., RHtests, Wang *et al.*, 2007) to identify other change-points in the data. An application of statistical methods is presented in this document, in the section 'Adjustments for the first Lincoln station'.

Table 1: Information about Lincoln 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 record;
(Column 4) altitude of site in metres above sea level;
(Column 5) previous period of record (as of February 2010) for which the site contributed to the composite time series used by NIWA;
(Column 6) previous temperature adjustment (with respect to Lincoln Broadfield EDL, Site 4), taken from the February 2010 'Schedule of Adjustments',
(Column 7) new period of record for which the site contributes to the composite time series;
(Column 8) revised temperature adjustment to be applied (with respect to Lincoln Broadfield EWS, Site 5), as discussed in the text.

Site Label	Site Name (Agent Number)	Location[2] (Full Period of Record)	Height (m a.s.l.)	Previous Period	Previous Temp. Adjust. (°C)	Revised Period	Revised Temp. Adjust. (°C)
Site 1	Lincoln (4881)	On the side of a field, 200 metres south of the main college buildings. (Jan 1881 to Dec 1943)	11	Jan 1881 to Dec 1904	−0.5	Not Used	N/A
				Jan 1905 to Jun 1915	−1.0	Jan 1905 to Nov 1915	−0.97
				Jul 1915 to May 1929	−0.8	Dec 1915 to Oct 1923	−0.45
						Nov 1923 to Dec 1925	−1.02
				Jun 1929 to Dec 1943	−0.3	Jan 1926 to Dec 1943	−0.41
Site 2	Lincoln (4881)	In a field north of Lincoln College buildings. (Jan 1944 to Apr 1964)[3]	11	Jan 1944 to Apr 1964	+0.4	Jan 1944 to Apr 1964	+0.22
Site 3	Lincoln (4881)	Research farm block, 500 metres west of Lincoln College. (May 1964 to Dec 1975)[4]	11	May 1964[5] to Dec 1975	+0.2	May 1964 to Dec 1975	−0.10
Site 4	Lincoln (4881)	Open paddock, 200 m north of Site 3. (Jul 1975 to Dec 1987)[6]	11	Jan 1976 to May 1987	0.0	Jan 1976 to May 1987	+0.02
Site 5	Lincoln Broadfield EDL (4882)	Open paddock, 2 km northwest of Lincoln township. (Jun 1987 to May 2000)	12	Jun 1987 to Dec 1999	0.0	Jun 1987 To Dec 1999	0.00
Site 6	Lincoln Broadfield EWS (17603)	Open paddock, 200 m northeast of Site 5. (Jul 1999 to present)	18	Jan 2000 to present	0.0	Jan 2000 to present	**0.00**

[2] Information about the locations of the Lincoln stations was obtained from Fouhy *et al.* (1992),

Calculation of Adjustments

Table 1 summarises the information about the local sites used to develop the composite temperature series for the Lincoln 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 1 decimal place, whereas the revised adjustments are specified to 2 decimal places.[7] Table 1 lists the 6 different sites that contribute to the revised composite Lincoln temperature series. Thus, there are at least 5 change-points, and the temperature record must be closely examined before and after the change-dates, in order to identify potential biases. The first Lincoln station (Site 1 in Table 1, agent number 4881) was subject to changes in exposure, so additional adjustments need to be applied to Site 1. These additional adjustments are based on statistically-diagnosed change-points.

The previous composite Lincoln series used by NIWA also included temperatures observed in Christchurch from 1864 to 1880. 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 was made <u>not</u> to include temperatures prior to 1900. Furthermore, if there was a site change or a potential discontinuity in observed temperatures around 1910 for which an adjustment could not be accurately estimated, then the time series was truncated at that point. In the case of Lincoln, the revised series begins at Lincoln Site 1 in 1905.

Due to the necessity for additional adjustments to the early Lincoln record, future research will investigate the suitability of temperatures observed at Christchurch Gardens prior to 1944 for the composite Lincoln series. However, this would represent a significant change to the composite Lincoln series and will require careful consideration. Lincoln has the advantage of a more rural location than Christchurch Gardens, which is located in the centre of Christchurch. The current revised Lincoln series also has the merit of geographical consistency, in that all the Lincoln sites are within 3 km of one another.

Salinger (1981), CliDB, and notes and sketches in the Lincoln station history.

[3] Additional meteorological returns from Lincoln Site 2 in November and December 1943 are not recorded in CliDB.

[4] Additional meteorological returns from Lincoln Site 3 in January, February, April and May 1976 are not recorded in CliDB. The return for February 1976 contains only 13 days of observations.

[5] The record of agent number 4881 changes from Lincoln Site 3 to Lincoln Site 4 in May 1964, rather than the date of March 1965 indicated in the February 2010 'Schedule of Adjustments'.

[6] Observations at Lincoln Site 4 from January 1976 to December 1987 are recorded in CliDB under agent number 4881. Observations at Lincoln Site 4 from July 1975 to August 1978 are recorded in CliDB under agent number 4883. The record of agent number 4883 is therefore a duplicate of the record of agent number 4881 from January 1976 to August 1978.

[7] Calculation to 2 decimal places has been done to minimise the accumulation of round-off errors. This should not be interpreted as an indication of the accuracy of the adjustment. Air temperatures are recorded to the nearest 0.1 °C in the NIWA Climate Database.

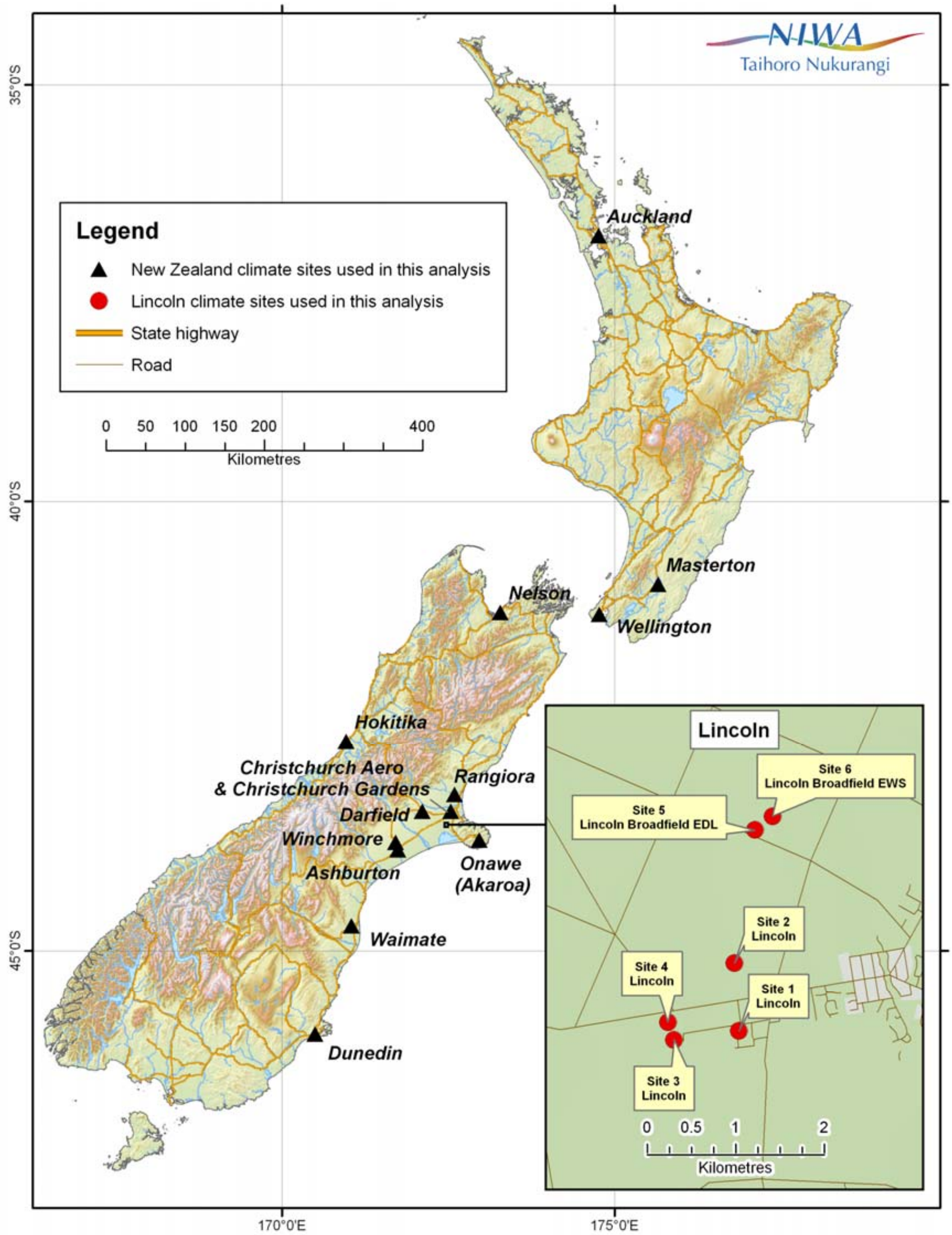

Figure 2: Map showing sites of temperature records referred to within this document. The inset map locates the local Lincoln sites.

It is common practice to adjust all the historical measurements to be consistent with the current open site (Aguilar *et al.*, 2003). Therefore, measurements will be adjusted for consistency with Lincoln Broadfield EWS (Electronic Weather Station), which is labelled Site 6 in Table 1 and shown in Figure 1.[8] Figure 2 provides a map locating the local Lincoln sites of Table 1, and also a number of the more distant comparison sites discussed in the subsequent text.

Site Change in 2000

We will work backwards in time from the current open site: Lincoln Broadfield EWS (Site 6 in Table 1, agent 17603, Figures 1 and 2). This station is located in an open paddock, approximately 2 km northwest of Lincoln township. The surrounding area is flat, fertile farm land. Lincoln Broadfield EWS first opened in late June 1999 and monthly mean temperatures are available in the NIWA Climate Database (CliDB) from July 1999 onward. Lincoln Broadfield EWS contributes temperatures to the composite temperature series for Lincoln from January 2000 to the present day.

From June 1987 until December 1999, the composite Lincoln temperatures are provided by the Lincoln Broadfield EDL (Environmental Data Logger) station (Site 5 in Table 1, agent 4882, Figure 2). Lincoln Broadfield EDL was also located in open farm land with good exposure, approximately 200 m southwest of the current site, Lincoln Broadfield EWS. Lincoln Broadfield EDL closed in early May 2000.

During the period of overlapping observations at Lincoln Broadfield EWS (Site 6) and Lincoln Broadfield EDL (Site 5) from July 1999 to April 2000, the average difference between monthly mean air temperatures at the two stations was +0.26 °C: that is, Site 6 was 0.26 °C warmer than Site 5. However, a longer period of comparison is required to reliably estimate the temperature difference between the two sites. It is therefore necessary to compare the Lincoln temperatures with other overlapping sites, to determine how temperatures differ between Lincoln Sites 5 and 6. The preferred choices are nearby sites in the same climatic region. If such sites were not available (an issue in the 19th century and earlier decades of the 20th century), then more distant sites need to be considered.

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).

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[8] The final adjusted temperature series should therefore be thought of as representing historical temperatures at Lincoln Broadfield EWS from 1905 onwards. We could easily choose to adjust the temperature records to a different site. This would make no difference to the trend or variability, which is what we are trying to work out. However, the absolute temperatures would change; for example, they would be higher for a warmer reference site, but would still retain the same trend in time.

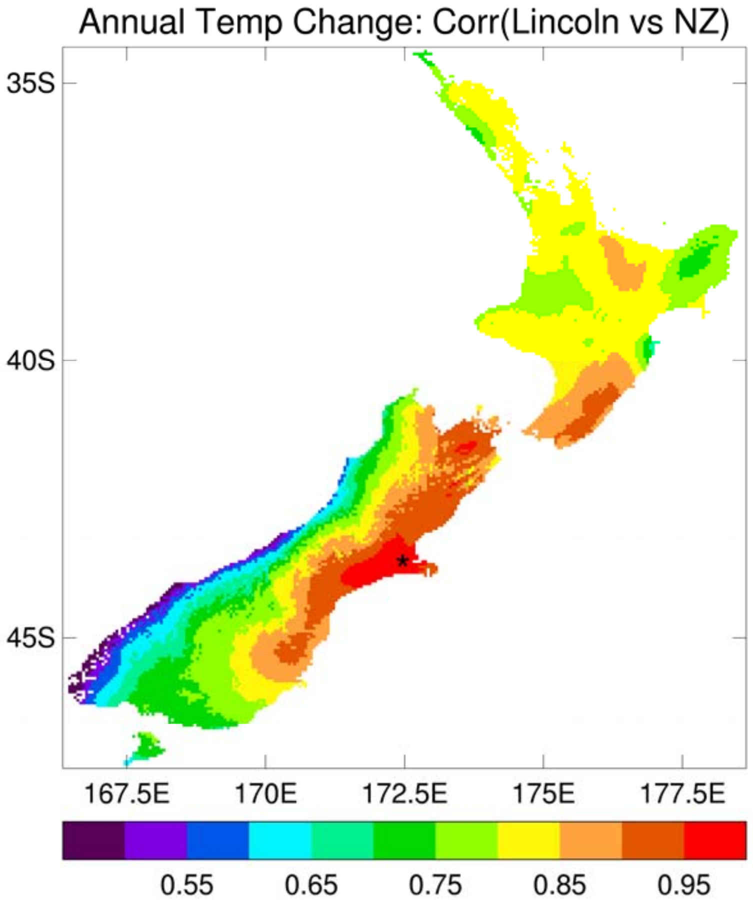

Figure 3: Map of correlation between interannual temperature changes at the grid-point nearest to Lincoln Broadfield EWS (Site 6, agent 17603, location marked by an asterisk), for 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

Figure 3 shows the correlation of mean temperature interannual differences at the VCS grid-point containing Lincoln Broadfield EWS (Site 6) with interannual differences at all other locations on the VCS grid from 1972 until 2008 (that is, the 1972-73 difference, 1973-74, …, 2007-08). Annual temperature variations at Lincoln correlate strongly with those in the rest of the Canterbury Plains; the correlation is typically over +0.90.[9] Observations at Lincoln can be compared with those at a number of other stations in central Canterbury for much of the 20th century. Interannual temperature variations at Lincoln also correlate well with those at Nelson (+0.92), Masterton (+0.90), Wellington (+0.89), and Dunedin (+0.83), so if necessary, temperature records at these more distant sites could be used.

[9] Acorrelation of +1.0 indicates perfect agreement; i.e., that the interannual temperature variations at two sites match perfectly (except for a constant offset and multiplicative factor).

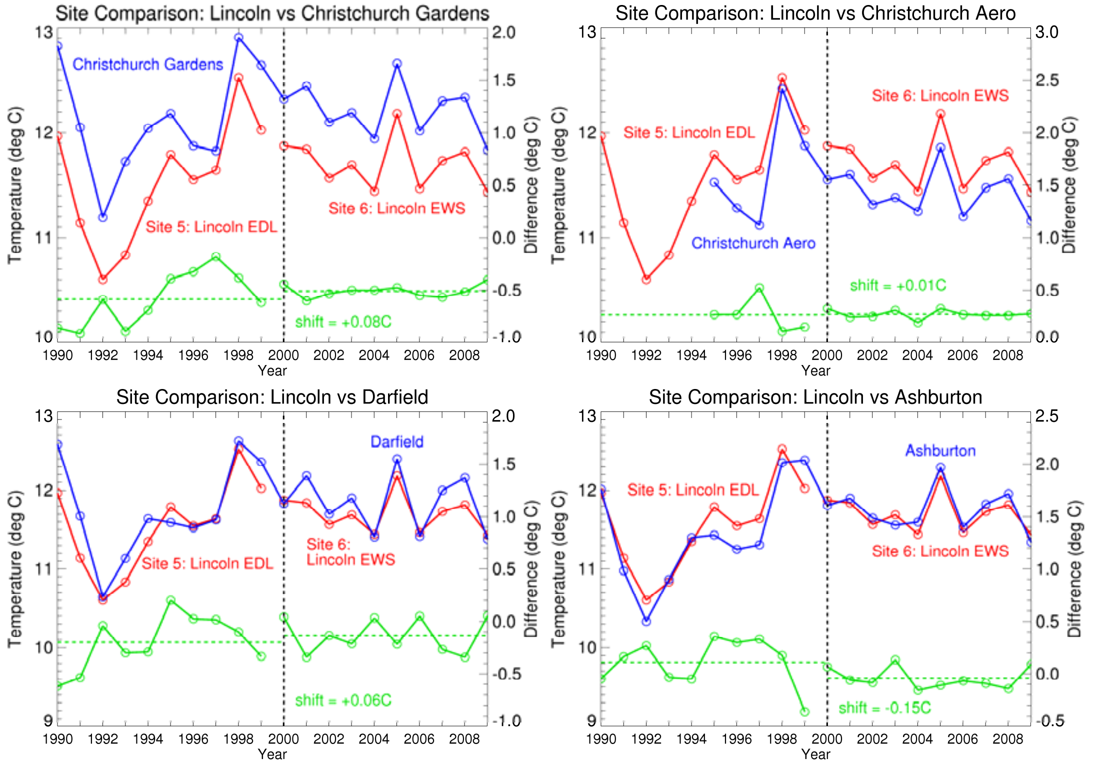

Figure 4: Annual mean temperatures at Lincoln Broadfield EDL (Site 5, agent 4882, red line on the left half of each plot) and Lincoln Broadfield EWS (Site 6, agent 17603, red line on the right half of each plot) compared with 4 other stations that overlap the Lincoln site change: Christchurch Gardens (agent 4858), Christchurch Aero (agent 4843), Darfield (agent 4836) and Ashburton Council (agent 4778). The solid blue line shows the temperatures at these comparison stations (Christchurch Gardens, Christchurch Aero, Darfield and Ashburton Council). The solid green line represents the difference (Lincoln Site 5/6 minus the comparison station) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The year of the site change, 2000, is indicated by the vertical dashed line.

Figure 4 compares annual temperatures[10] at Lincoln Broadfield EDL and Lincoln Broadfield EWS with 4 nearby stations: Christchurch Gardens, Christchurch Aero, Darfield and Ashburton Council.[11] The annual temperature differences (solid green lines in Figure 4) between Lincoln and these 4 nearby stations become more consistent after the change to Lincoln Broadfield EWS in 2000. Lincoln Broadfield EDL was on average 0.58 °C cooler than Christchurch Gardens before the 2000 site change, and Lincoln Broadfield EWS was on average 0.50 °C cooler than Christchurch Gardens after the 2000 site change (Figure 4, upper left). Thus with reference to Christchurch Gardens, Lincoln Broadfield EWS was 0.08 °C warmer

[10] Annual mean temperatures in years missing up to 3 months' data have been estimated from the existent monthly mean temperatures at each station, using the local climatology at that station. Appendix 3 contains a table of the years in which annual mean temperatures have been estimated at stations in this analysis.

[11] The intention in these analyses is to compare temperatures during the 10 years before and after the site change. This is not always possible since the record at the comparison site may not cover the whole of this period, or there may be information in the site history that points to other potential inhomogeneities in the record of the comparison site. The period of comparison between Lincoln Broadfield EDL and Christchurch Aero has been truncated due to the automation of the Christchurch Aero station in 1994.

than Lincoln Broadfield EDL.

We then repeat this process of comparison for the other 3 stations in Figure 4. With reference to Christchurch Aero (Figure 4, upper right), Lincoln Broadfield EWS was 0.01 °C warmer than Lincoln Broadfield EDL. With reference to Darfield (Figure 4, lower left), Lincoln Broadfield EWS was 0.06 °C warmer than Lincoln Broadfield EDL. Finally, with reference to Ashburton Council (Figure 4, lower right), Lincoln Broadfield EWS was 0.15 °C cooler than Lincoln Broadfield EDL.

Thus we have 4 estimates of the difference between Lincoln Broadfield EWS and Lincoln Broadfield EDL: +0.08 °C, +0.01 °C, +0.06 °C and −0.15 °C. The average estimated difference between Lincoln Broadfield EWS and Lincoln Broadfield EDL is 0.00 °C.[12] The final adjustment required to make temperatures at Lincoln Broadfield EDL (Site 5) consistent with those at Lincoln Broadfield EWS (Site 6) is thus 0.00 °C, that is, no adjustment is necessary.

This example shows how a comparison over a longer period can lead to a somewhat different adjustment to a short-term overlap. The ±10 year inter-comparison about 1999/2000, averaged over 4 comparison sites, suggested no systematic difference in annual mean temperature between Sites 5 and 6. However, it was noted previously that the 10-month overlap, July 1999 to April 2000, suggested Site 6 was warmer than Site 5 by 0.26 °C. The difference line between Lincoln and the comparison sites (Figure 4) is noticeably more erratic for the EDL (Site 5) than for the EWS (Site 6), and it may be that the Lincoln Broadfield EDL gauge (Site 5) was reading too cold in 1999.

[12] The estimated differences from different comparison sites could be combined in some other way than a simple average. Typical approaches in the literature are to weight by correlation or by distance, or both (e.g., square of the correlation and inverse square of the distance). We have employed a simple average here. In this analysis, correlations have been calculated using the first-difference series of annual temperatures. When calculating the correlations between stations across a known site change, the year of the site change is excluded from the correlation. This method prevents any discontinuity in the year of the site change from influencing the correlations (Aguilar *et al.*, 2003). For the site change at Lincoln in 2000, weighting by correlation would result in a small positive adjustment being applied to Lincoln Broadfield EDL. This is because the correlation between interannual differences at Lincoln and Ashburton (+0.91) during the period of comparison is slightly lower than the correlations between Lincoln and the other stations in Figure 4 (Christchurch Gardens: +0.94; Christchurch Aero: +0.96; Darfield: +0.92). Weighting by distance would also result in a small positive adjustment to Lincoln Broadfield EDL, since the Ashburton station is further away from Lincoln than each of the other 3 comparison stations in Figure 4.

Site Change in 1987

The Lincoln station (Site 4 in Table 1, agent 4881, Figure 2) was established in July 1975 and provides observations for the composite Lincoln temperature series from January 1976 to May 1987. Lincoln Site 4 was located in a well-exposed area, west of Lincoln College and approximately 2 km south-southwest of Lincoln Broadfield EDL (Site 5). Lincoln Site 4 closed at the end of 1987, so monthly mean temperatures at Lincoln Site 4 and Lincoln Broadfield EDL overlap for a period of only 7 months.[13] Once again, a longer period of comparison is required to reliably estimate the difference between the two sites. We must therefore compare temperatures at the Lincoln stations with observations at other overlapping stations, before and after the site change at Lincoln in 1987.

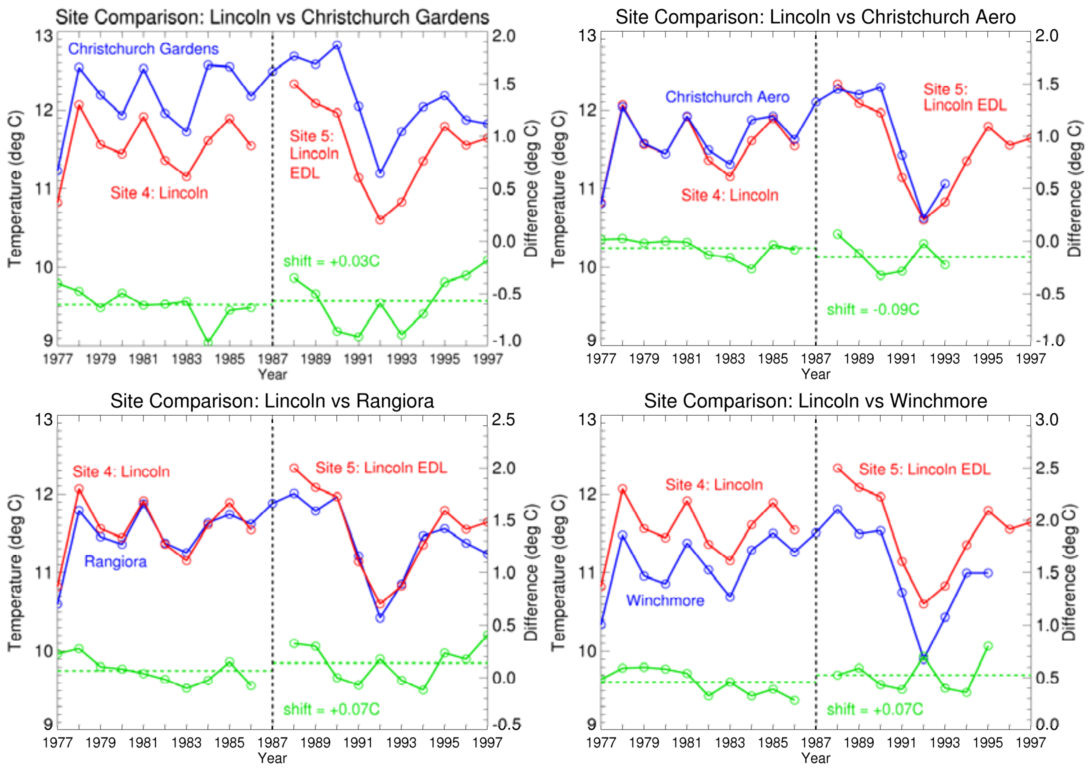

Figure 5: Annual mean temperatures at Lincoln (Site 4, agent 4881, red line on the left half of each plot) and Lincoln Broadfield EDL (Site 5, agent 4882, red line on the right half of each plot) compared with 4 other stations that overlap the Lincoln site change: Christchurch Gardens (agent 4858), Christchurch Aero (agent 4843), Rangiora (agent 4827) and Winchmore EWS (agent 4764). The solid blue line shows the temperatures at these comparison stations. The solid green line represents the difference (Lincoln Site 4/5 minus the comparison station) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The year of the site change, 1987, is indicated by the vertical dashed line.

[13] During the 7 months of overlapping observations at Lincoln Broadfield EDL (Site 5) and Lincoln Site 4 from June to December 1987, the average monthly difference between Lincoln Broadfield EDL and Lincoln Site 4 was -0.03 °C: that is, Lincoln Broadfield EDL was 0.03 °C cooler than Lincoln Site 4.

Figure 5 compares annual temperatures at Lincoln Site 4 and Lincoln Broadfield EDL with 4 nearby stations: Christchurch Gardens, Christchurch Aero, Rangiora and Winchmore EWS.[14] With reference to Christchurch Gardens (Figure 5, upper left), Lincoln Broadfield EDL was 0.03 °C warmer than Lincoln Site 4. With reference to Christchurch Aero (Figure 5, upper right), Lincoln Broadfield EDL was 0.09 °C cooler than Lincoln Site 4. With reference to Rangiora (Figure 5, lower left), Lincoln Broadfield EDL was 0.07 °C warmer than Lincoln Site 4. Finally, with reference to Winchmore (Figure 5, lower right), Lincoln Broadfield EDL was 0.07 °C warmer than Lincoln Site 4.

Thus we have 4 estimates of the difference between Lincoln Broadfield EDL and Lincoln Site 4: +0.03 °C, −0.09 °C, +0.07 °C and +0.07 °C. The average estimated difference is +0.02 °C, with Lincoln Broadfield EDL being warmer than Lincoln Site 4. Temperatures at Lincoln Site 4 therefore should be *increased* by 0.02 °C for consistency with both Lincoln Broadfield EDL and our reference site for the composite Lincoln series, Lincoln Broadfield EWS (Site 6).[15]

Adjustment for Site Change in 1976

From May 1964 to December 1975, temperatures for the composite Lincoln series were recorded in the Lincoln research farm block (Site 3 in Table 1, agent 4881, Figure 2). This station was established west of Lincoln College and 200 metres south of Lincoln Site 4, with readings recorded in CliDB from May 1964 to December 1975. The overlapping period between the research farm block and Lincoln Site 4 is again too short to allow us to reliably estimate the temperature difference between the two stations.[16] We must therefore again compare their records with other overlapping sites, to determine how temperatures differ between Lincoln Sites 3 and 4.

Figure 6 compares annual temperatures at the research farm block and Lincoln Site 4 with stations in Christchurch, Ashburton, Rangiora and Winchmore. With reference to Christchurch Gardens (Figure 6, upper left), Lincoln Site 4 was 0.14 °C cooler than the research farm block. With reference to Ashburton Council (Figure 6, upper right), Lincoln Site 4 was 0.06 °C cooler than the research farm block. With reference to Rangiora (Figure 6, lower left), Lincoln Site 4 was 0.06 °C cooler than the research farm block. And finally, with reference to Winchmore EWS (Figure 6, lower right), Lincoln Site 4 was 0.21 °C cooler than the research farm block.

Thus we have 4 estimates of the difference between Lincoln Site 4 and the research farm block: −0.14 °C, −0.06 °C, −0.06 °C and −0.21 °C. The average estimated difference is −0.12 °C, with Lincoln Site 4 being cooler than the research farm block. Temperatures at the research farm block therefore must be decreased by 0.12 °C for

[14] The period of comparison between Lincoln Broadfield EDL and Winchmore EWS has been truncated due to the automation of the Winchmore station in 1996.

[15] This trivially small adjustment could be set to zero. However, even though the estimated adjustment is almost zero, it has a non-zero uncertainty associated with it, which should be retained for a full assessment of uncertainties in the final trend.

[16] During the 5 months of overlapping temperatures at Lincoln Site 4 and the research farm block (Site 3) that are recorded in CliDB (August to December 1975) , the average monthly difference between the two stations was +0.04 °C: that is, Lincoln Site 4 was 0.04 °C warmer than the research farm block.

consistency with Lincoln Site 4. The cumulative adjustment of the research farm block (Site 3) relative to Lincoln Broadfield EWS (Site 6) is thus: 0.00 + 0.02 − 0.12 = −0.10 °C.

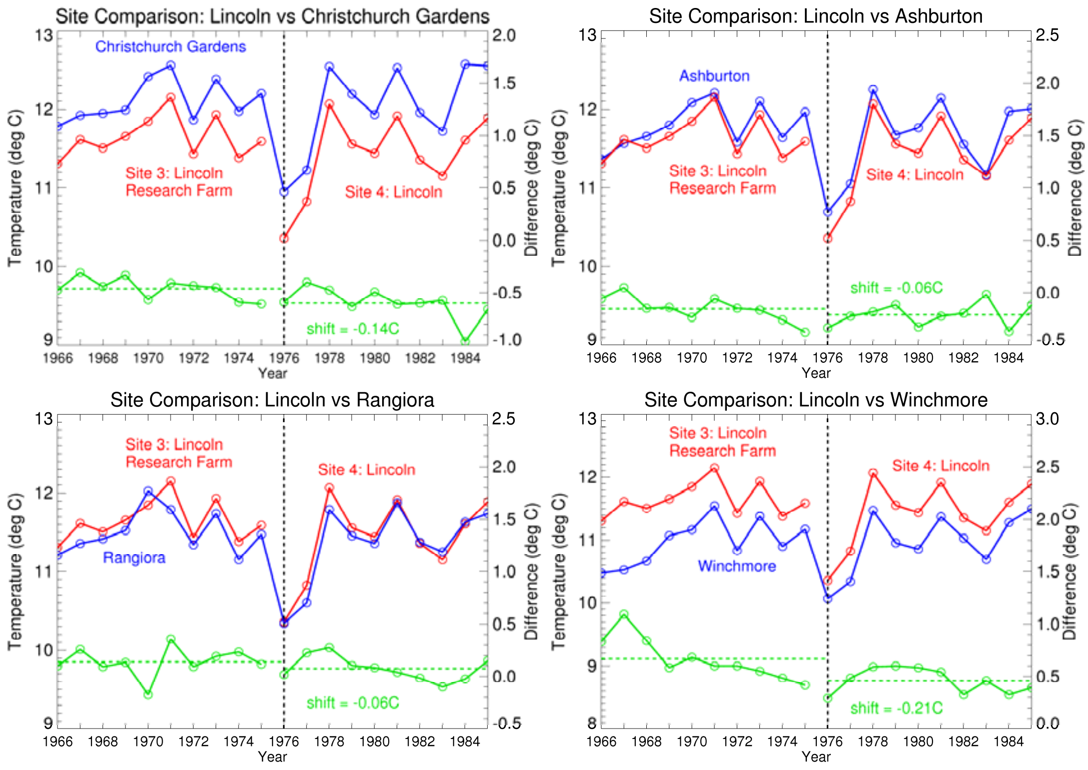

Figure 6: Annual mean temperatures at the Lincoln research farm block (Site 3, agent 4881, red line on the left half of each plot) and Lincoln (Site 4, agent 4881, red line on the right half of each plot) compared with 4 other stations that overlap the Lincoln site change: Christchurch Gardens (agent 4858), Ashburton Council (agent 4778), Rangiora (agent 4827) and Winchmore EWS (agent 4764). The solid blue line shows the temperatures at these comparison stations. The solid green line represents the difference (Lincoln Site 3/4 minus the comparison station) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The year of the site change, 1976, is indicated by the vertical dashed line.

It should be noted that Salinger *et al.* (1992) applied a different adjustment of +0.2 °C to temperatures at the research farm block. An additional 3 monthly returns (January, April and May 1976) from the research farm block are not recorded in CliDB. If these 3 additional returns are included in calculations, then there is an 8-month overlap (August to December 1975, plus January, April and May 1976) between the research farm block and Lincoln Site 4. During these 8 overlapping months, Lincoln Site 4 was on average 0.18 °C (0.2 °C to 1 decimal place) warmer than the research farm block. Salinger *et al.* (1992) may have calculated a +0.2 °C adjustment to the research farm block based on this 8-month overlap between the two sites. However, with reference to the 4 comparison stations in Figure 6, the monthly mean temperatures observed at the research farm block in April and May 1976 appear to be erroneously low.[17]

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[17] In April 1976, the temperature difference between the research farm block and the 4 comparison stations in Figure 6 (Christchurch Gardens, Ashburton Council, Rangiora and Winchmore EWS) was 7.7 standard deviations below its mean difference in April months from 1966 to 1975. In May 1976, the temperature difference between the research farm block and the 4 comparison stations was 2.7 standard

Adjustment for Site Change in 1964

From January 1944 to April 1964, the composite Lincoln series is provided by the Lincoln station (Site 2 in Table 1, agent 4881, Figure 2). Lincoln Site 2 was located in a field north of the Lincoln College buildings. This site was established in October 1943 and closed in early May 1964. Observations were made in parallel at Lincoln Site 2 and the research farm block for almost a year, but again a longer period of comparison is necessary to reliably calculate an adjustment.[18] Figure 7 compares annual temperatures at Lincoln Site 2 and the Lincoln research farm block[19] with Christchurch Gardens, Christchurch Aero, Darfield and Ashburton.

With reference to Christchurch Gardens (Figure 7, upper left), the research farm block was 0.28 °C warmer than Lincoln Site 2. With reference to Christchurch Aero (Figure 7, upper right), the research farm block was 0.31 °C warmer than Lincoln Site 2. With reference to Darfield (Figure 7, lower left), the research farm block was 0.37 °C warmer than Lincoln Site 2. Finally, with reference to Ashburton Council (Figure 7, lower right), the research farm block was 0.32 °C warmer than Lincoln Site 2.

Thus we have 4 very consistent estimates of the difference between the research farm block and Lincoln Site 2: +0.28 °C, +0.31 °C, +0.37 °C and +0.32 °C. The average is +0.32 °C, with the research farm block being warmer than Lincoln Site 2. Temperatures at Lincoln Site 2 therefore must be increased by 0.32 °C for consistency with the research farm block. The cumulative adjustment of Lincoln Site 2 relative to Lincoln Broadfield EWS (Site 6) is thus: 0.00 + 0.02 − 0.12 + 0.32 = +0.22 °C.

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deviations below its mean difference in May months from 1966 to 1975. These erroneous values in early 1976 from Site 3 are not used in the revised composite time series for Lincoln.

[18] Correspondence attached to the Lincoln meteorological return of April 1964 mentions the parallel observation of temperatures at Lincoln Site 2 and the research farm block (Site 3) during a period of 'almost a year'. Daily maximum temperatures at Lincoln Site 2 and the research farm block are noted to be about the same, while daily minimum temperatures at the research farm block are noted to be around 1 °F (approximately 0.56 °C) warmer than those at Lincoln Site 2. This implies that mean temperatures (the average of the daily maximum and daily minimum) at the research farm block were around 0.28 °C (half of 0.56 °C) warmer than those at Lincoln Site 2 over this period.

[19] The minimum thermometer at the Lincoln research farm block (Site 3) was reading 1.1 °C too low between August 1964 and January 1965 (Fouhy *et al.*, 1992). This caused mean temperatures at the research farm block over this period to be 0.55 °C too low. Therefore, for the present analysis, from August 1964 to January 1965, minimum temperatures at the research farm block have been increased by 1.1 °C and mean temperatures have been increased by 0.55 °C. Note that these corrections of +1.1 °C and +0.55 °C are only estimates based on expert judgement, and we cannot be sure of the precise value of the error. The original values as recorded are the values returned by a CliDB enquiry. For the calculation of the difference between Lincoln Sites 2 and 3, the corrections have been applied only to the month of January 1965, since the year of the site change at Lincoln, 1964, has been excluded from the site comparisons shown in Figure 7.

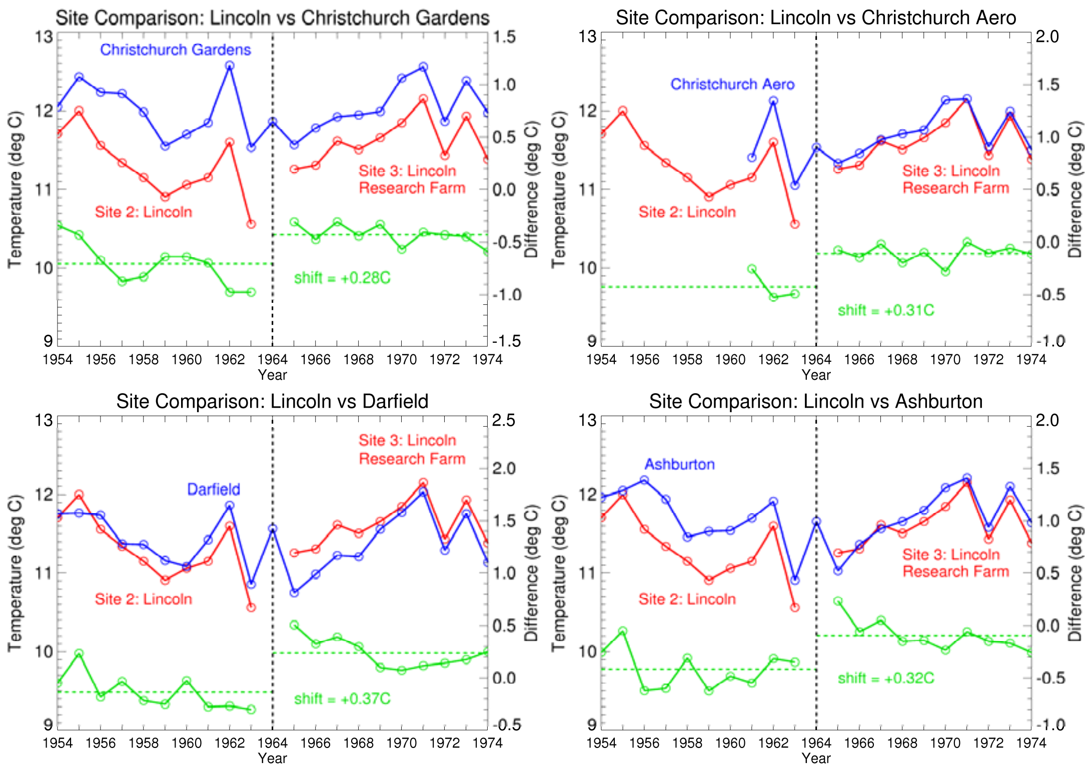

Figure 7: Annual mean temperatures at Lincoln (Site 2, agent 4881, red line on the left half of each plot) and the Lincoln research farm block (Site 3, agent 4881, red line on the right half of each plot) compared with 4 other stations that overlap the Lincoln site change: Christchurch Gardens (agent 4858), Christchurch Aero (agent 4843), Darfield (agent 4836) and Ashburton Council (agent 4778), The solid blue line shows the temperatures at these comparison stations. The solid green line represents the difference (Lincoln Site 2/3 minus the comparison station) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The year of the site change, 1964, is indicated by the vertical dashed line.

Adjustment for Site Change in 1944

The first Lincoln station (Site 1 in Table 1, agent 4881, Figure 2) was established in January 1881. This station provides temperatures for the revised composite series for Lincoln from January 1905 until December 1943. Lincoln Site 1 was located in a small enclosure on the side of a field, 200 metres south of the main college buildings. A note on file dated May 1889 suggested that the director of the college was putting the Lincoln station in another location. However, the record sheet in 1935 describes the enclosure as being situated 200 metres south of the main college buildings, on the side of a long, level field: that is, no change of location (Fouhy *et al.*, 1992).

Readings ceased at Lincoln Site 1 at the end of December 1943. Observations at Lincoln Sites 1 and 2 overlapped for only two months[20], so again we must analyse any potential difference in temperature via comparison to other sites. Figure 8 compares annual temperatures at Lincoln Sites 1 and 2 with stations in Christchurch, Ashburton, Onawe (on Banks Peninsula) and Waimate.[21]

With reference to Christchurch Gardens (Figure 8, upper left), Lincoln Site 2 was 0.81 °C cooler than Lincoln Site 1.[22] With reference to Ashburton Council (Figure 8, upper right), Lincoln Site 2 was 0.61 °C cooler than Lincoln Site 1. With reference to Onawe (Figure 8, lower left), Lincoln Site 2 was 0.50 °C cooler than Lincoln Site 1. Finally, with reference to Waimate (Figure 8, lower right), Lincoln Site 2 was 0.58 °C cooler than Lincoln Site 1.

Thus we have 4 estimates of the difference between Lincoln Sites 2 and 1: −0.81 °C, −0.61 °C, −0.50 °C and −0.58 °C. The average is −0.63 °C, with Lincoln Site 2 being cooler than Lincoln Site 1. Temperatures at Lincoln Site 1 therefore need to be decreased by 0.63 °C to bring them into line with Site 2. The cumulative adjustment required to make observations at Lincoln Site 1 consistent with those at Lincoln Broadfield EWS (Site 6) is thus: 0.00 + 0.02 − 0.12 + 0.32 − 0.63 = −0.41 °C.

[20] In the original meteorological returns in November and December of 1943, monthly mean air temperature at Lincoln Site 2 was on average 0.58 °C cooler than Lincoln Site 1.

[21] The periods of comparison with Ashburton and Waimate have been truncated due to relocations of those sites. 6 months of temperatures are missing from the Waimate record in 1948, so an estimate of the annual mean temperature at Waimate is not possible in that year. The CliDB record of annual mean temperatures at Onawe begins in 1938.

[22] The Lincoln station history contains handwritten monthly summaries of temperatures observed at the Lincoln sites from 1881 to 1970. In these summaries, the mean temperature of Lincoln Site 2 is noted to be approximately 1.5 °F (i.e. around 0.8 °C) cooler than that of Lincoln Site 1. The origin of this estimated difference appears to be a comparison of Lincoln Sites 1 and 2 to Christchurch Gardens from 1939 to 1950, since the handwritten calculations of this comparison are present within the Lincoln station history.

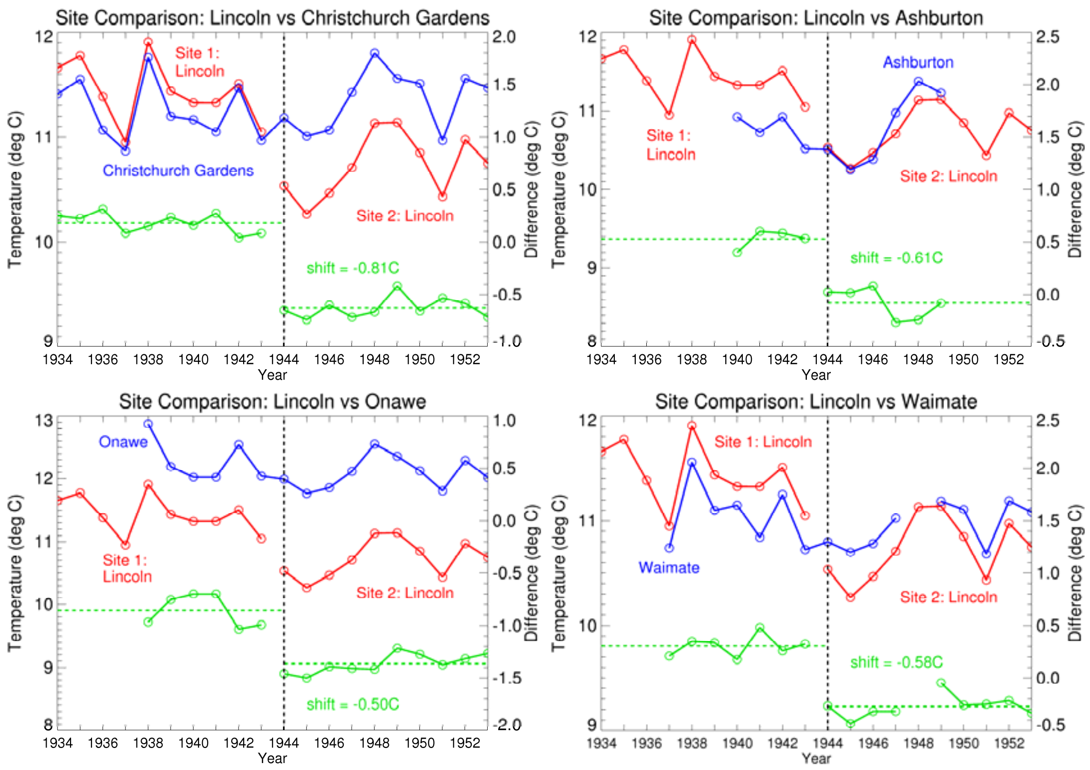

Figure 8: Annual mean temperatures at Lincoln (Site 1, agent 4881, red line on the left half of each plot) and Lincoln (Site 2, agent 4881, red line on the right half of each plot) compared with 4 other stations that overlap the Lincoln site change: Christchurch Gardens (agent 4858), Ashburton Council (agent 4778), Onawe Duvauchelle Bay (agent 4928) and Waimate (agent 5102). The solid blue line shows the temperatures at these comparison stations. The solid green line represents the difference (Lincoln Site 1/2 minus the comparison station) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after the site change. The year of the site change, 1944, is indicated by the vertical dashed line.

Adjustments for the first Lincoln station

The enclosure of Lincoln Site 1 was well exposed when the station was first established in 1881, but the land around Lincoln College was subsequently developed and shelter belts were planted right up to the edge of the enclosure (Fouhy *et al.*, 1992). Discontinuities are evident in the early Lincoln temperature record; these are noted in the Lincoln station history (see Appendix 2) and by Salinger (1981).[23] Figure 9 compares annual mean temperatures at Lincoln Site 1 with those at Christchurch Gardens, approximately 18 km to the northeast of the Lincoln station, from the beginning of the Christchurch Gardens record in 1905 until 1943. The station history for Christchurch Gardens records no sudden changes over this time.

[23] One or two monthly mean temperatures are missing from the record of Lincoln Site 1 in each of 17 years between 1881 and 1943 (see Appendix 3). Additionally, the monthly minimum temperature at Lincoln in January 1918 is, by comparison with other stations, anomalously low by several degrees Celsius. This monthly anomaly is not documented in the Lincoln station history and has been removed from the present analysis. Due to the amount of missing data and the fluctuations in the observed temperatures, the early record of Lincoln Site 1 should be treated with caution. Salinger (1981) noted that the Lincoln record prior to 1927 'should be used with caution for climatic change work'.

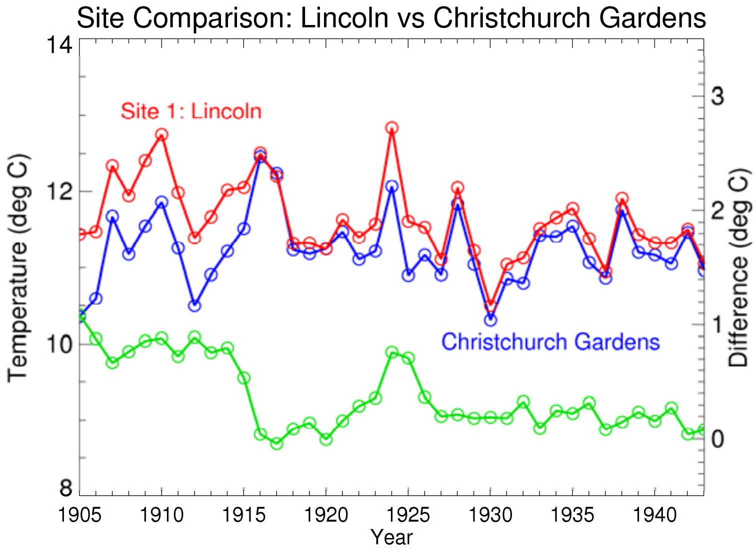

Figure 9: Annual mean temperatures at Lincoln Site 1 (agent 4881, red line) compared with Christchurch Gardens (agent 4858, blue line) from 1905 to 1943. The green line represents the difference (Lincoln minus Christchurch Gardens) using the right-hand ordinate scale.

With respect to Christchurch Gardens, one can see a marked fall in temperatures at Lincoln around 1915 and 1916, and additional variations around 1922 and 1927. The planting of shelter belts and the development of the land surrounding the college may have created artificial shifts in the Lincoln temperature record. The exact dates of these changes in exposure are not documented in the Lincoln station history. However, statistical methods can detect sudden mean shifts within a climatic time series, with or without prior knowledge of changes to the recording site.

One such statistical method is the penalised maximal *t* test (Wang *et al.*, 2007), which can be applied to a series of temperature observations with reference to well-correlated temperatures recorded at other stations. The penalised maximal *t* test (PMT) moves through a time series, checking the data before and after each value in the time series. A 'change-point' is identified in the temperature series at the time of the maximum shift in mean temperatures with reference to the comparison stations. The PMT tends to identify change-points more accurately within longer time series, so the comparison stations should ideally have overlapping observations and no significant site changes over a relatively long period.

The PMT was therefore applied to monthly mean temperatures at Lincoln Site 1 over a period of just under 30 years, with reference to two other stations[24] with no known relocations during that time: Christchurch Gardens (agent 4858) and Dunedin

[24] From 1913 to 1942, the correlation coefficients of interannual differences in mean temperatures, calculated between Lincoln and each of the comparison stations, were: Christchurch Gardens [+0.95]; Dunedin Botanical Gardens [+0.94]. In order to calculate the correlations, annual temperatures in years missing up to 3 months were estimated from the local climatology at each station (see Appendix 3).

Botanical Gardens[25] (agent 5375). The period of comparison was from January 1913 to November 1942, during which time the monthly temperatures at Christchurch and Dunedin were combined into a simple average. The period of comparison between Lincoln and these other stations was made as long as possible, given that observations began at the Dunedin Botanical Gardens in January 1913 and ceased in November 1942.

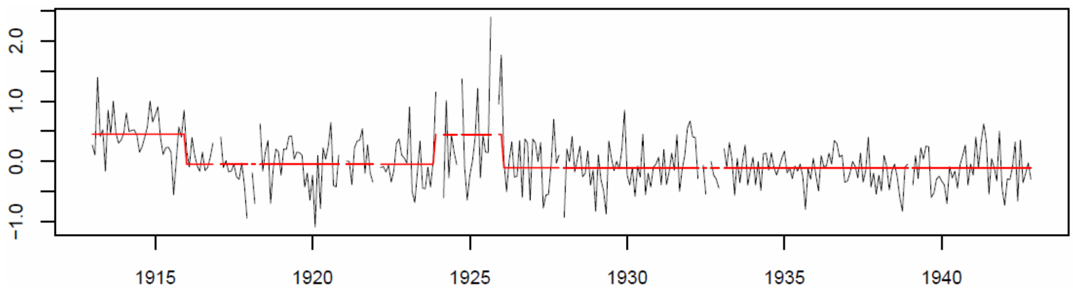

Figure 10: Monthly mean temperatures at Lincoln (Site 1, agent 4881) minus monthly averages of mean temperatures at Christchurch Gardens (agent 4858) and Dunedin Botanical Gardens (agent 5375) from January 1913 to November 1942 (black line), as discussed in the text. The y-axis represents the monthly difference in temperature in degrees Celsius (°C); the x-axis represents time. The red line indicates the mean monthly temperature difference between Lincoln and the comparison stations. The shifts in the mean temperature difference have been statistically detected by the penalised maximal *t* test, as described in the text.

Between January 1926 and November 1942, the PMT did not detect any significant changes in the mean air temperatures at Lincoln Site 1, with reference to the averaged temperatures at Christchurch Gardens and Dunedin Botanical Gardens (Figure 10). Temperatures at Lincoln appear to be fairly consistent with respect to the comparison stations over this period. Therefore no additional revised adjustment has been applied to the mean temperature at Lincoln Site 1 from January 1926 to November 1942.

The PMT detected a −0.61 °C mean shift in temperature at Lincoln in January 1926 (Figure 10), which was statistically significant.[26] From the available information in the station history, it is reasonable to assume that this shift was caused by an artificial change to the exposure of the first Lincoln station. Since we have an estimated artificial shift in mean temperature of −0.61 °C in January 1926, we must therefore *decrease* the mean temperature at Lincoln Site 1 prior to January 1926 by 0.61 °C, for consistency with the Site 1 record from January 1926 to December 1943.

[25] Maximum and mean temperatures at Dunedin Botanical Gardens were in error for a period in 1921 (Fouhy *et al.*, 1992). Monthly maximum and mean temperatures at Dunedin Botanical Gardens from April to August 1921 have therefore been excluded from the present analysis.
[26] The statistical significance of mean shifts in temperature, at a nominal confidence level, is calculated by the RHtests software (Wang *et al.*, 2007), which was used to perform the penalised maximal *t* test. The nominal confidence level of the RHtest was set to its default value of 95%.

Table 2: Revised cumulative adjustments to mean temperatures at Lincoln Site 1 (agent 4881), for consistency with the Lincoln reference site: Lincoln Broadfield EWS (Site 6, agent 17603).

Period	Cumulative Sum of Adjustments (°C)	Cumulative Adjustment (°C)
Jan 1926 to Dec 1943	0.00 + 0.02 − 0.12 + 0.32 − 0.63	−0.41
Nov 1923 to Dec 1925	0.00 + 0.02 − 0.12 + 0.32 − 0.63 – 0.61	−1.02
Dec 1915 to Oct 1923	0.00 + 0.02 − 0.12 + 0.32 − 0.63 – 0.61 + 0.57	−0.45
Jan 1905 to Nov 1915	0.00 + 0.02 − 0.12 + 0.32 − 0.63 – 0.61 + 0.57 − 0.52	−0.97

We then repeat this process for the estimated artificial shifts detected at Lincoln in November 1923 (+0.57 °C) and December 1915 (−0.52 °C), both of which were statistically significant and can also be seen in Figure 10. Table 2 presents the revised cumulative adjustments to mean temperatures at Lincoln Site 1, based on the estimated artificial shifts in the mean temperatures detected by the penalised maximal *t* test.[27] The revised Lincoln series begins in January 1905; the reasoning for this is discussed in Appendix 1.

[27] Note that the revised adjustments to the early record of the first Lincoln station are based on periods which are bounded by statistically-detected breakpoints in the record. These periods are different to those used by Salinger *et al.* (1992), as shown in Table 1, but are more similar to those used by Salinger (1981).

Putting the Time Series Together

The revised adjustments described above can be applied successively to the Lincoln temperature records. The time series from 1905 to 2009 is shown in Figure 11, including a comparison to the previous Lincoln time series used by NIWA. A linear trend has been fitted to each series. Expressed in units of degrees per century, the linear trend in the revised series is 0.83 (±0.30) °C /century, as compared with 0.99 (±0.32) °C /century for the trend calculated from the seven-station time series published in February 2010.[28]

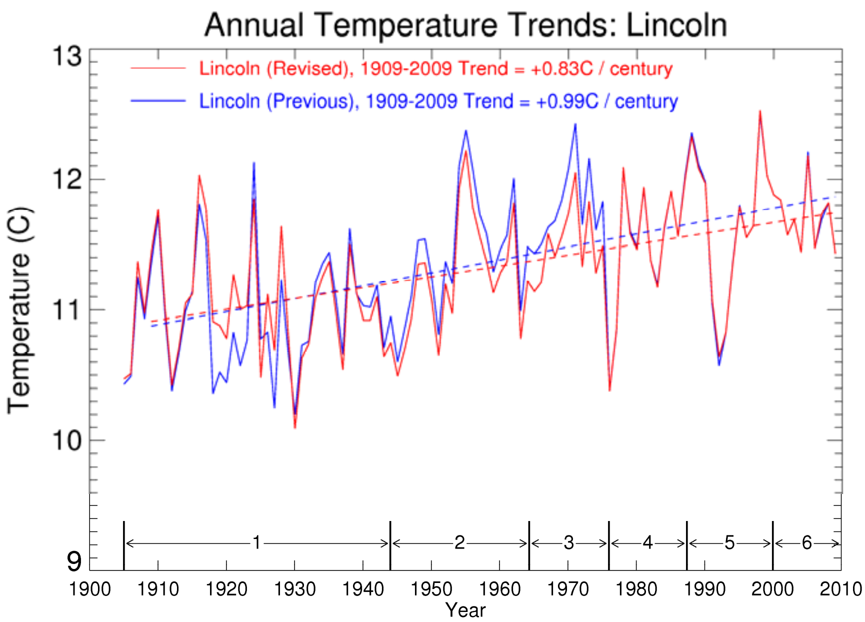

Figure 11: Comparison of the revised series (red line) and the previous NIWA series (blue line) of composite temperatures for Lincoln from 1905 to 2009. The dashed lines indicate the fitted linear trends from 1909 to 2009. Labels near the bottom of the plot denote the site numbers of Table 1. Vertical lines at the bottom of the plot mark the time periods over which each site contributes to the composite series, with the sites numbered as in Table 1.

Once the temperatures from the Lincoln sites have been adjusted for consistency with Lincoln Broadfield EWS (Site 6), and then combined, we have a series dating back to 1905. However, simply appending the raw data from the Lincoln records without correcting for known site changes would result in an inhomogeneous history of temperature, unsuitable for the analysis of long-term trends.

Figure 12 repeats the graph of the revised composite series of annual mean temperatures for Lincoln, and compares the composite with the unadjusted raw multi-site temperatures. From 1988 to 2009 the two series are identical, since this period is

[28] The uncertainty here (±0.30 °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.

covered by Lincoln Broadfield EWS (Site 6, the Lincoln reference site) and Lincoln Broadfield EDL (Site 5), to which no adjustment is applied. The estimated adjustments are also shown in Figure 12. The adjustments are cumulative relative to Lincoln Broadfield EWS, and correspond to those in the final column of Table 1.

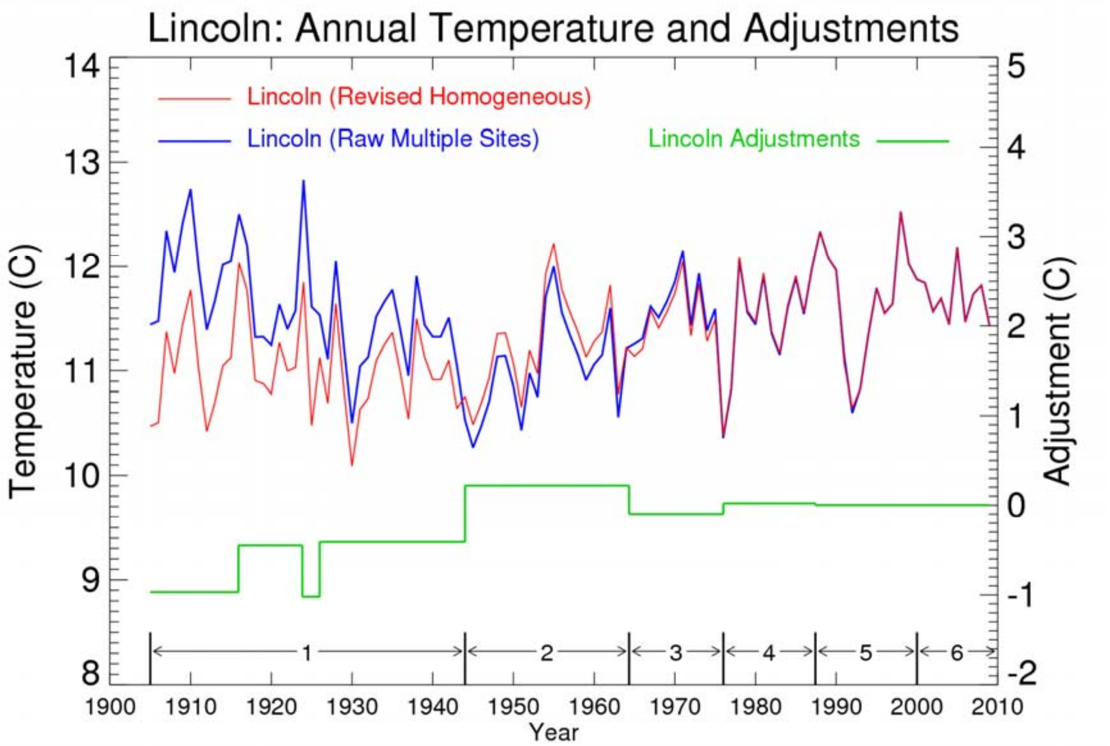

Figure 12: Comparison of revised composite temperature series for Lincoln from 1905 to 2009 (red line), with the raw multi-site series (Sites 1-6, blue line). The green line (using the right-hand axis) indicates the cumulative step adjustments to each site as shown at the bottom of the graph, and corresponds to the revised adjustments in the right-hand column of Table 1.

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).

Date: Document originally created 29 October 2010, and revised 13 December 2010 following review from the Australian Bureau of Meteorology.

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Appendix 1: Potential Discontinuity in 1905

In this appendix, we will examine the discontinuity in 1905 that is mentioned in the note on the Lincoln station history (this note is presented in Appendix 2). Few stations are available for comparison during the early record of the first Lincoln station. The Lincoln record cannot be compared with temperatures recorded at the Magnetic Observatory in the Christchurch Gardens prior to January 1905, as this is when observations began at the Magnetic Observatory. Figure A1.1 compares annual mean temperatures at Lincoln Site 1 with 4 other stations: Leith Valley in Dunedin, Hokitika Town, Bolton Street Cemetery in Wellington, and Albert Park in Auckland.[29]

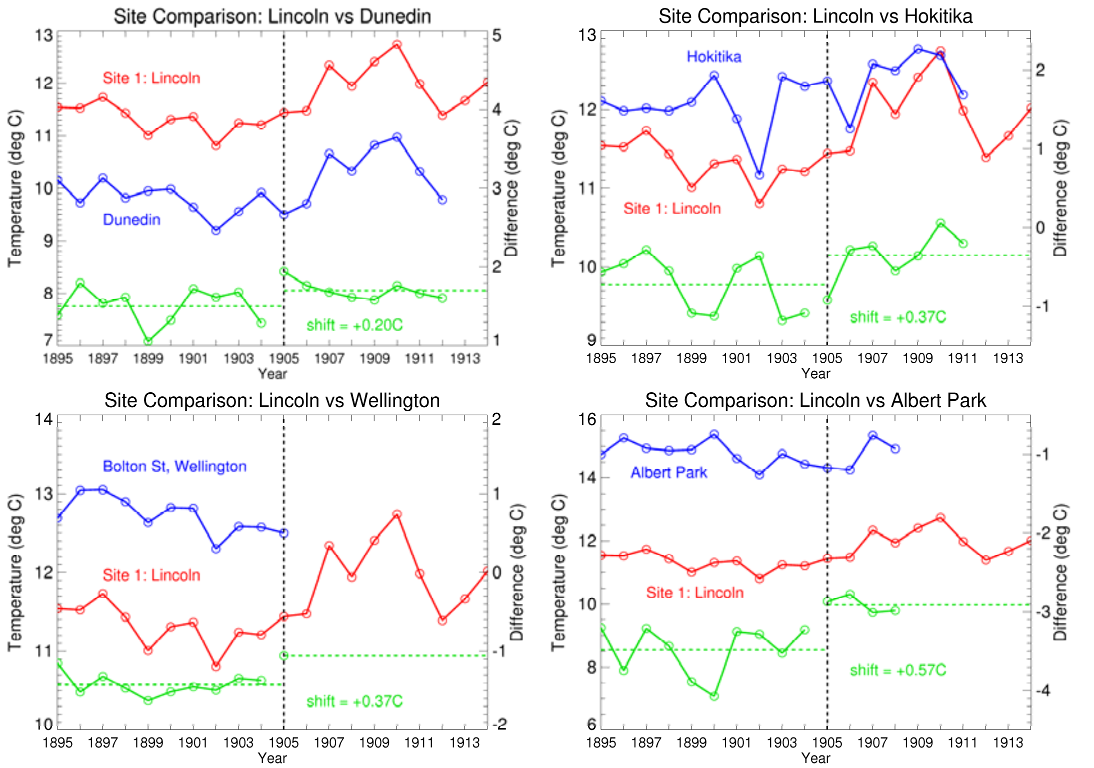

Figure A1.1: Annual mean temperatures at Lincoln (Site 1, agent 4881, red line) compared with 4 other stations that overlap the potential discontinuity in 1905: Dunedin Leith Valley (agent 5380), Hokitika Town (agent 3907), Bolton Street Cemetery in Wellington (agent 3390), and Albert Park in Auckland (agent 1427). The solid blue line shows the temperatures at these comparison stations. The solid green line represents the difference (Lincoln Site 1 minus the comparison station) using the right-hand ordinate scale. The horizontal dashed green line is the average difference before and after January 1905. The year of the potential discontinuity, 1905, is indicated by the vertical dashed line.

[29] The periods of comparison between Lincoln Site 1 and Leith Valley in Dunedin, Bolton Street Cemetery in Wellington and Albert Park in Auckland have been truncated due to relocations of each these comparison stations. The Hokitika temperatures are recognised as being too warm during the 1894-1912 period, but could be used if we assume that they are uniformly warm throughout the overlapping comparison period of Figure A1.1, and the temperatures pre- and post-1912 are not used together in the same comparison. Note too that Hokitika has a poorer correlation with Lincoln than many other locations (+0.60 for period shown in Fig. 3), but the choices of comparison sites become rather limited by 1905.

Annual mean temperatures at Lincoln do rise after 1905 with reference to the other stations in Figure A1.1, particularly with respect to Albert Park in Auckland. However, the year of the discontinuity is not distinctly visible in the annual difference series (green lines) in Figure A1.1. The identification of any artificial temperature shift is hampered by interrupted records and poorer correlations between stations in the 19^{th} century and very early 20^{th} century. The penalised maximal *t* test has therefore not been used to diagnose artificial temperature shifts in the very early Lincoln record. In the absence of more proximate and strongly correlated stations, or more precise information in the station history, it is difficult to confidently calculate an adjustment for an artificial temperature shift at Lincoln in 1905. Thus the revised composite series for Lincoln begins in January 1905, before which time temperatures observed at Lincoln cannot be compared with those observed at a near neighbour.

Appendix 2: Note on the Lincoln College Records

Note on the Lincoln College Records from the station history file (agent 4881, network number H32461).

Note on the Lincoln College Records.

Comparison of the annual mean temperatures at Lincoln College with those at the Christchurch Magnetic Observatory indicate discontinuities in 1916, 1922, and 1927. It is known that there has been no sudden change at the Magnetic Observatory so that there is little doubt that the discontinuities were due to changes in the exposure at Lincoln College. This is confirmed by comparison with Dunedin and Wellington, which indicate discontinuities at 1905, 1916, 1922 and about 1927. In the early years the Lincoln temperature may have been about normal for the locality. From 1905 to 1915 it appears to have been high and from 1916 to 1921 low. From 1922 to 1926 it was high again while subsequent to that the value has probably been fairly normal.

On the 19th May, 1899, Mr. J.W. Mellor, the then observer, noted that the "Director of this College is putting station in another situation", so that there might have been several changes.

The station was established in 1881. The instrument returns of 1913 give the following list of instruments: Barometer - aneroid barometer and barograph; Robinson anemometer, Jordan sunshine recorder, rain gauge, solar maximum thermometer, grass minimum thermometer, maximum dry bulb, minimum dry bulb; maximum wet bulb, minimum wet bulb, dry and wet bulb thermometers; most of these instruments had been in use for 30 years. A new Campbell Stokes sunshine recorder was taken there by Mr. Bates in May, 1915. He stated that everything was in good order but recommended that the anemometer be moved to a more open situation as the trees in the vicinity had grown considerably during the past few years.

Mr. Bates again inspected the station in 1920.

Dr. Kidson inspected the station in August, 1927. The anemometer pole was not vertical. The muslin on the wet bulb was old and dirty. The pans used for holding the water were too large and filled to overflowing, and the presence of so much water would affect the temperature readings. The grass minimum thermometer was surrounded by a fairly high wire netting screen. The enclosure should be enlarged, and the pine trees in the vicinity should be topped. The enclosure was rather small and did not allow for proper exposure of the rain gauge. The 1" and 9" earth thermometers were exposed in the side of a trench which was at times partly filled with water.

Mr. A. Thomson inspected the station on the 6th June, 1929. "The plot had recently been enlarged and fenced in and the tops of nearby shrubs were cut off to about 4 ft. above the level of the ground the exposure of the instruments was tolerably good."

Mr. Simmers inspected the station on the 29th July, 1933. "The enclosure was sheltered by pine trees which would considerably affect the rain gauge and sunshine recorder. The enclosure should be enlarged by 20 ft. The barometer was cleaned and tested and found to be unreliable." The grass minimum thermometers have been frequently broken.

27/9/38

The station was inspected by P/O Lancaster on the 9th December, 1942; the grass in the enclosure was rather long and the mast supporting the anemometer and sunshine recorder was unsteady. The anemometer required oiling. The wet bulb reservoir was apparently the same as Dr. Kidson mentioned in his report in 1927 (August). The observer was not particularly interested and the week-end observations were made by anyone available. A location for a new site was in progress. F/Lt. Ewing inspected the station on 30th August, 1943, found the proposed location to be an excellent open one, and was 40 chains northward of the former site; the wind run from the anemometer would show a marked increase. A new Bilham screen, sheathed thermometers, 4", 8" 1ft. and 3ft. earth thermometers; new copper rain gauge were eventually installed towards the end of October, 1943 with the assistance of the Met. personnel from Wigram. The College Beck Fortin barometer No. 39 was exchanged for a M.O. re-conditioned Hicks Fortin barometer No. 1477. Two months' overlap of readings were made and the observations discontinued at the old site on 1/1/44.

When the station was inspected by the Met. Officer from Wigram in June, 1944, he found the new enclosure in excellent order.

29/6/44

Appendix 3: Estimation of Missing Data

Annual mean temperatures in years missing up to 3 months of data have been estimated from the existent monthly mean temperatures at each station, using the local climatology at that station. Table A3.1 lists the years in which annual mean temperatures have been estimated at stations used in this analysis. For a description of the methodology used to estimate annual mean temperatures, please refer to Appendix 2 of the NIWA review document for Masterton: 'Creating a Composite Temperature Series for Masterton'.

Note that in the present analysis of the Lincoln record, annual mean temperatures estimated in years prior to 1934 have been either plotted in figures or used to calculate correlations, but have not been used to calculate the revised adjustments to the Lincoln record. The revised adjustments to the early Lincoln record were calculated from mean shifts detected by the RHtests software, using monthly mean temperatures.

For the revised composite Lincoln series, annual mean temperatures in years missing up to 3 months of data have been estimated from the composite 1971-2000 climatology for Lincoln.

Table A3.1: Years in which annual mean temperatures have been estimated at stations used in this analysis. The number of monthly mean temperatures missing from each year is shown in parentheses in the 3rd column.

Station Name	Agent Number	Years (Number of Missing Months)
Ashburton Council	4778	1954 (1), 1956 (1), 1958 (1), 1982 (1), 1990 (1), 2001 (1), 2004 (1)
Christchurch Gardens	4858	1905 (1), 1906 (1), 1980 (1), 1981 (1), 1983 (1), 1984 (1)
Darfield	4836	2003 (1), 2009 (1)
Dunedin Botanical Gardens	5375	1942 (1)
Dunedin, Leith Valley	5380	1895 (1), 1900 (1), 1909 (1), 1912 (1)
Lincoln	4881	1884 (1), 1885 (1), 1887 (1), 1899 (1), 1900 (1), 1916 (1), 1917 (1), 1918[23] (1), 1920 (1), 1921 (1), 1922 (2), 1924 (2), 1925 (2), 1927 (1), 1932 (2), 1933 (1), 1939 (1), 1965 (1), 1967 (2), 1970 (1)
Lincoln Broadfield EDL	4882	1991(1), 1992 (2)
Rangiora	4827	1979 (1), 1981 (1), 1989 (1), 1997 (2)
Waimate	5102	1949 (1)
Wellington, Bolton Street Cemetery	3390	1895 (1)

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 <u>not</u> 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).

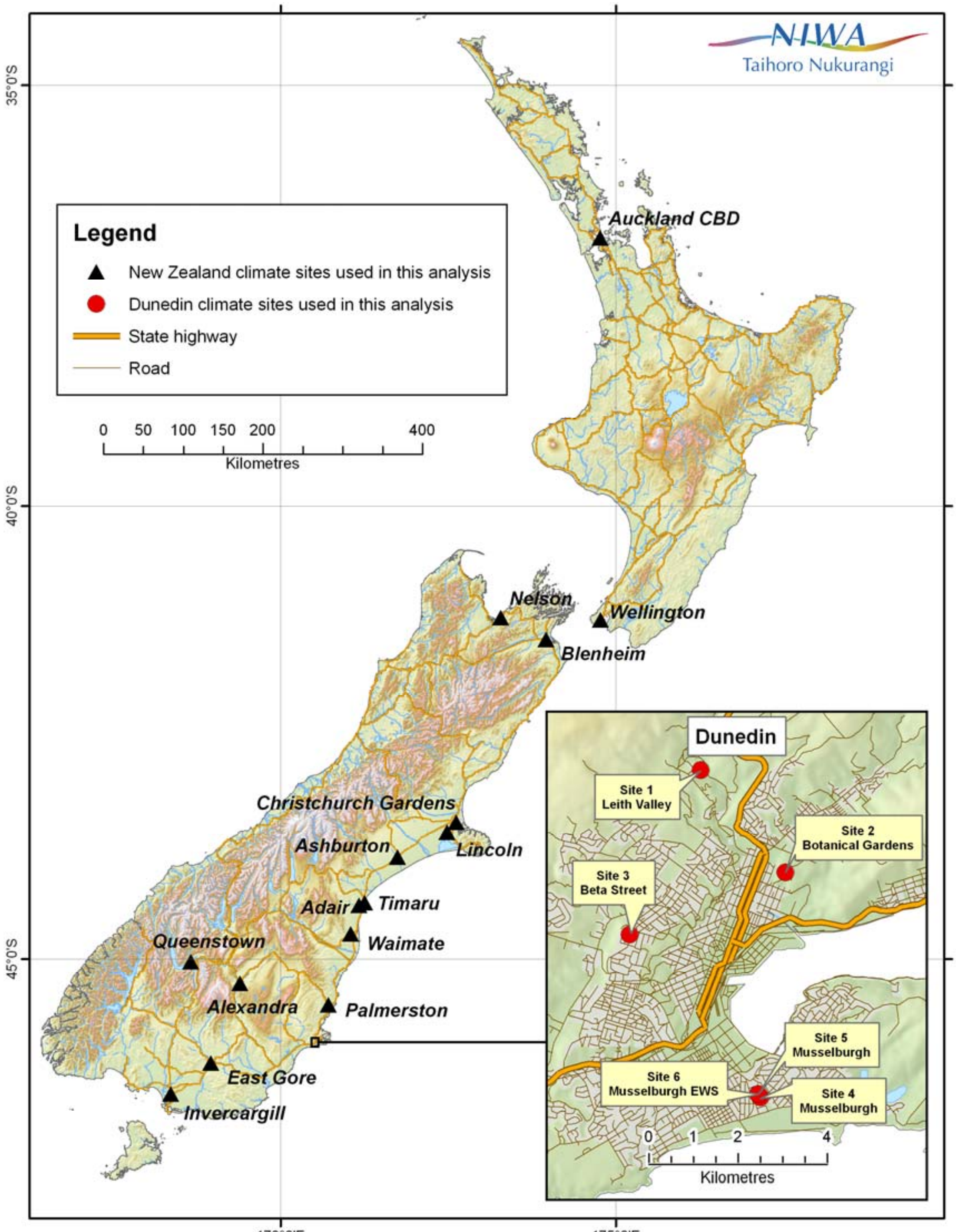

Figure 2: Map showing sites of temperature records referred to in this document. The inset map locates the Dunedin sites.

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.

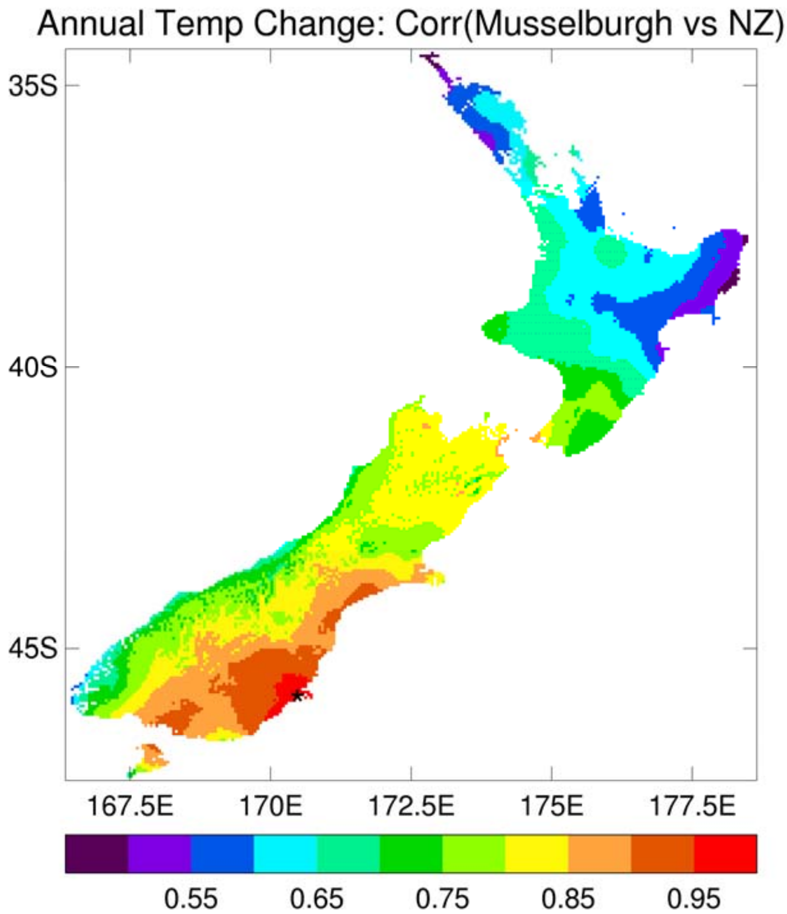

Figure 3: Map of correlation between interannual temperature changes at the Musselburgh EWS grid-point (Site 6, location marked by asterisk) near Dunedin, 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

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

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[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.

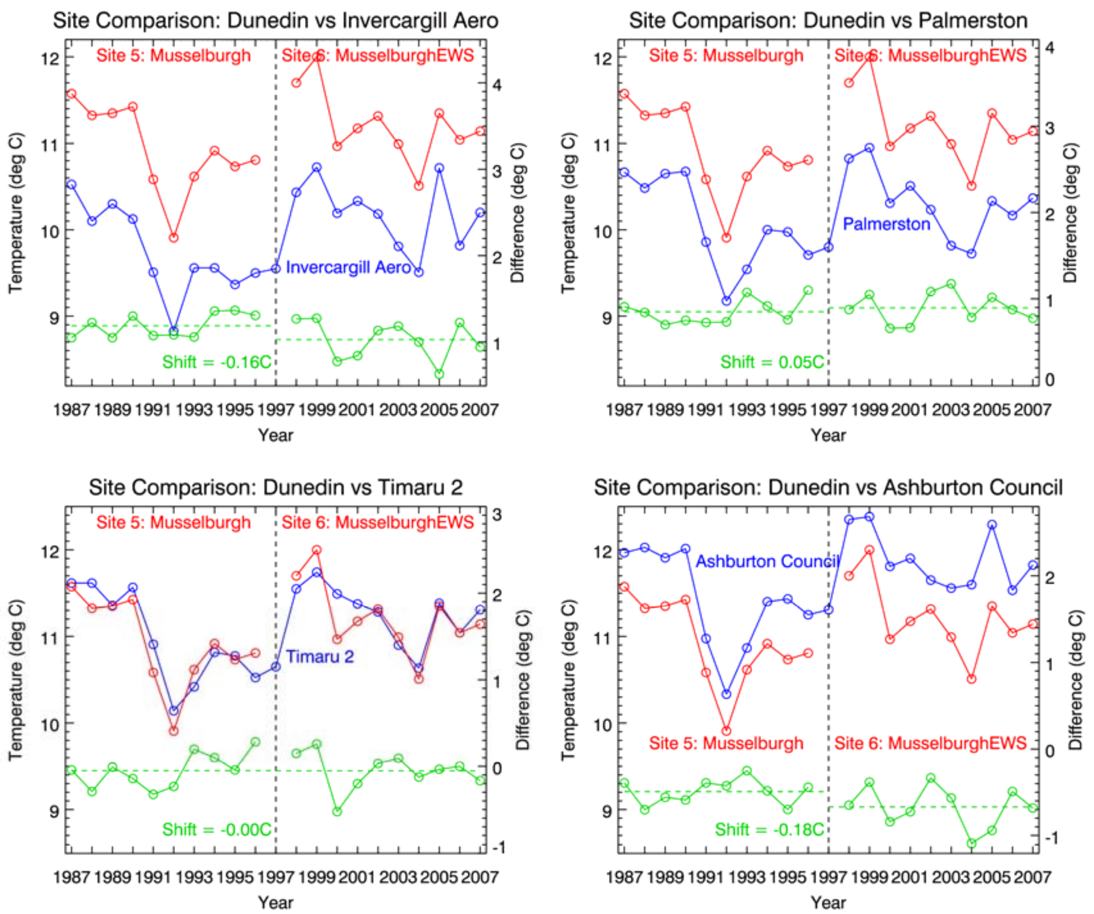

Figure 4: Annual mean temperature series at Musselburgh (Site 5, red line on the left of each plot) and Musselburgh EWS (Site 6, red line on the right of each plot) compared with several stations: Invercargill Aero, Palmerston, Timaru 2, and Ashburton Council. The solid blue line in each plot represents 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.

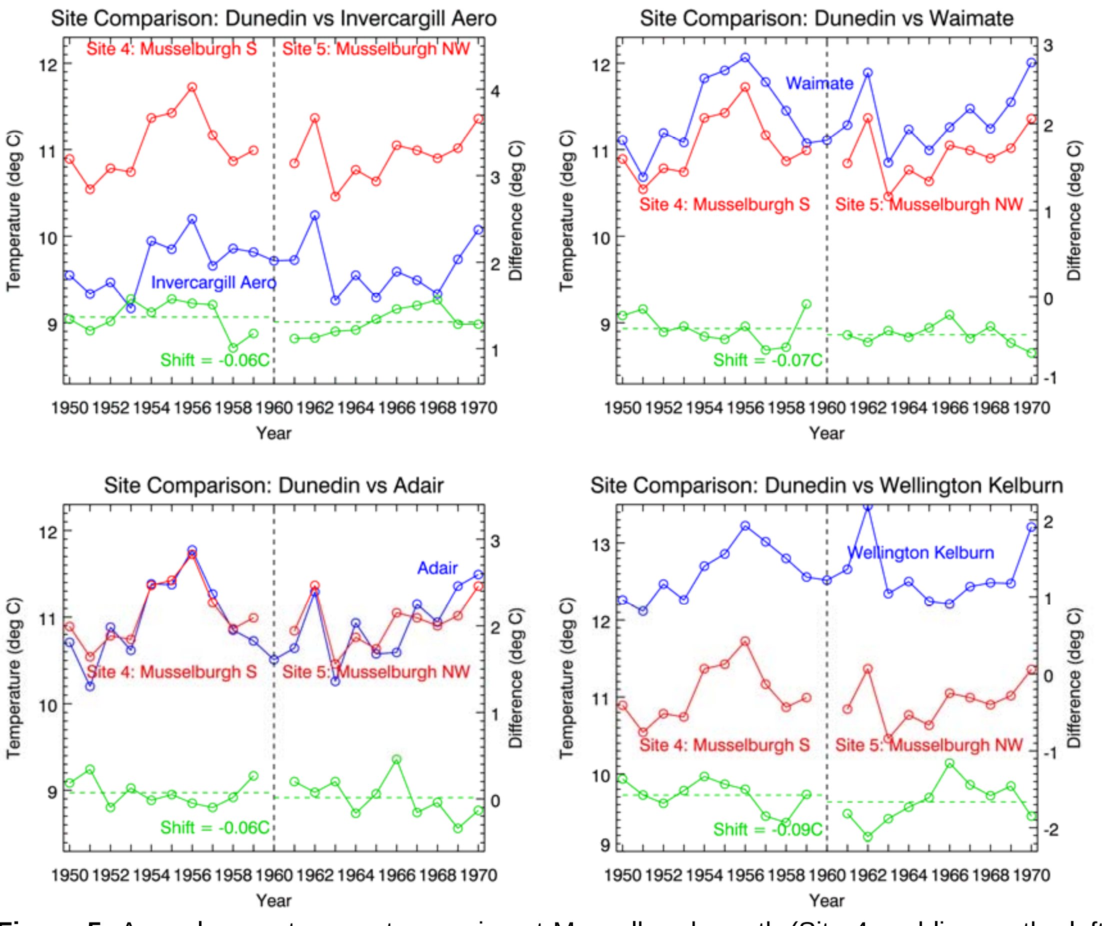

Figure 5: Annual-mean temperature series at Musselburgh south (Site 4, red line on the left of each plot) and Musselburgh northwest (Site 5, red line on the right of each plot) compared with Invercargill Aero, Waimate, Adair and Wellington Kelburn. The solid blue line in each plot represents the temperature 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.

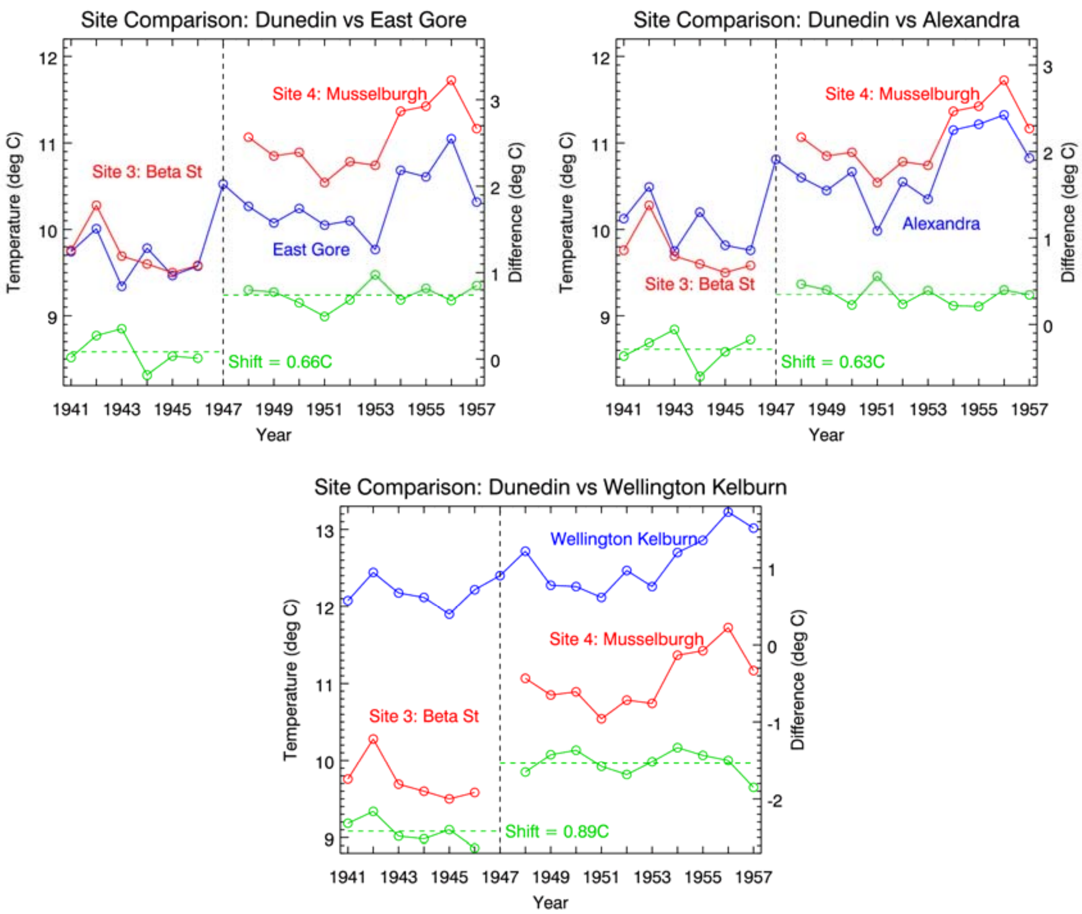

Figure 6: Annual-mean temperature series at Dunedin Beta Street (Site 3, red line on the left of each plot) and Musselburgh (Site 4, red line on the right of each plot) compared with East Gore, Alexandra and Wellington Kelburn. The solid blue line in each plot represents the temperature at the comparison 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.

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[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.

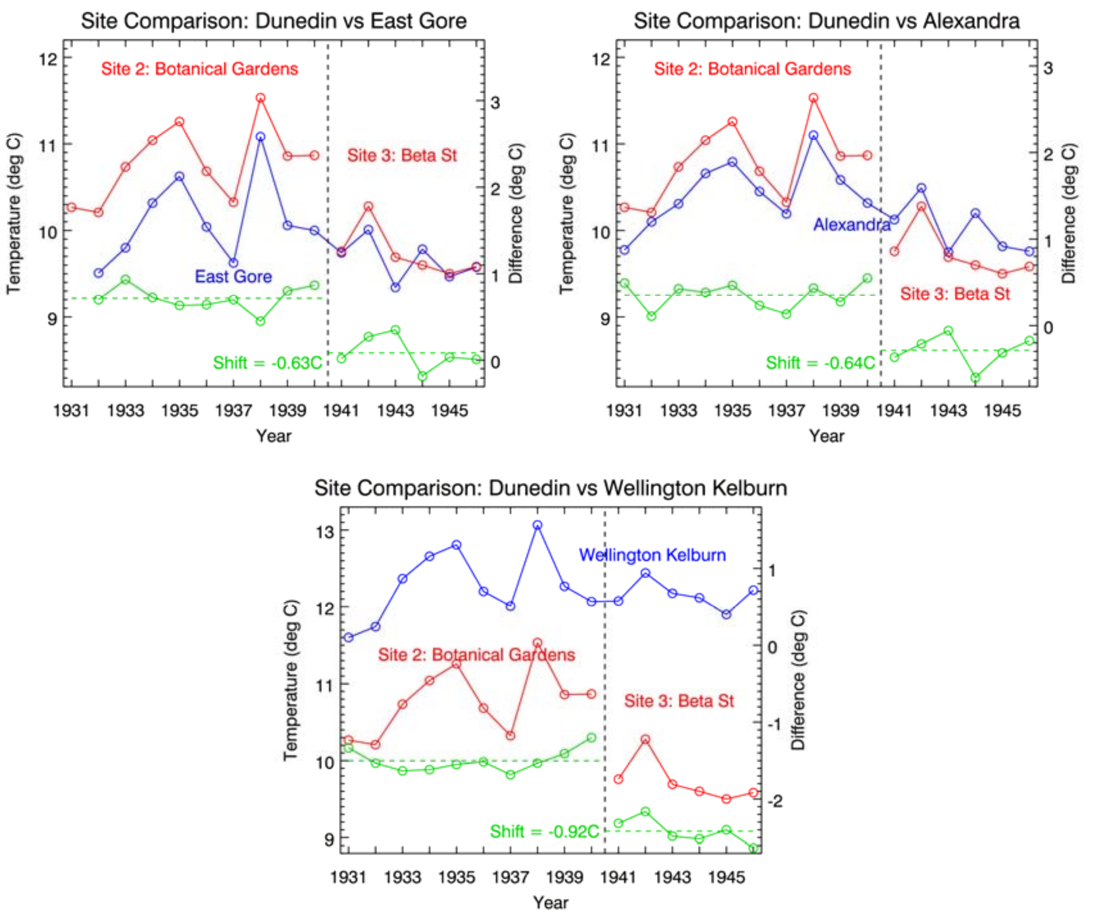

Figure 7: Annual-mean temperature series at Dunedin Botanical Gardens (Site 2, red line on the left of each plot) and Beta Street (Site 3, red line on the right of each plot) compared with East Gore, Alexandra and Wellington Kelburn. The solid blue line in each plot represents the temperature at the 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.

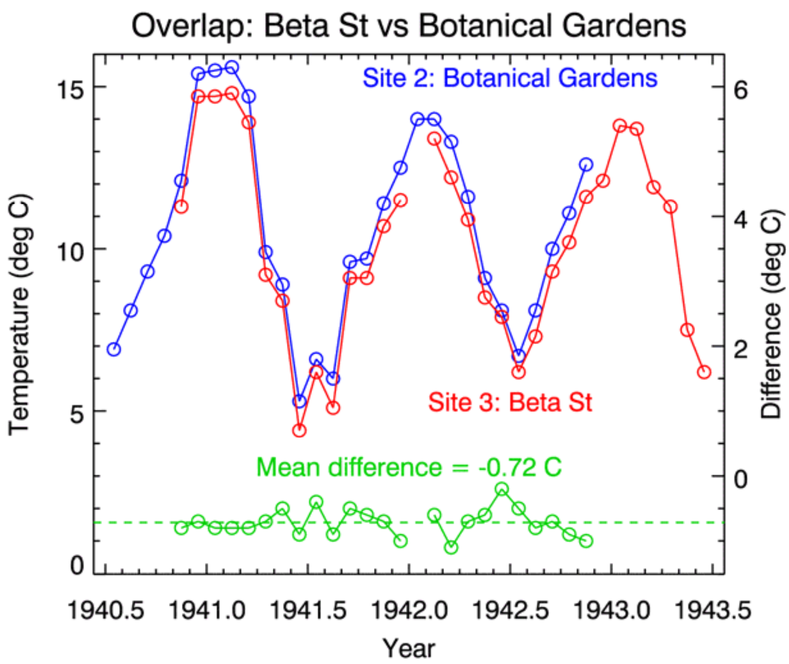

Figure 8: Monthly mean temperature series for Dunedin Botanical Gardens (Site 2, blue line) and Dunedin Beta Street (Site 3, red line) during their overlap period. The monthly difference, Site 3 minus Site 2, is indicated by the solid green line, using the right-hand ordinate scale, and the mean monthly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

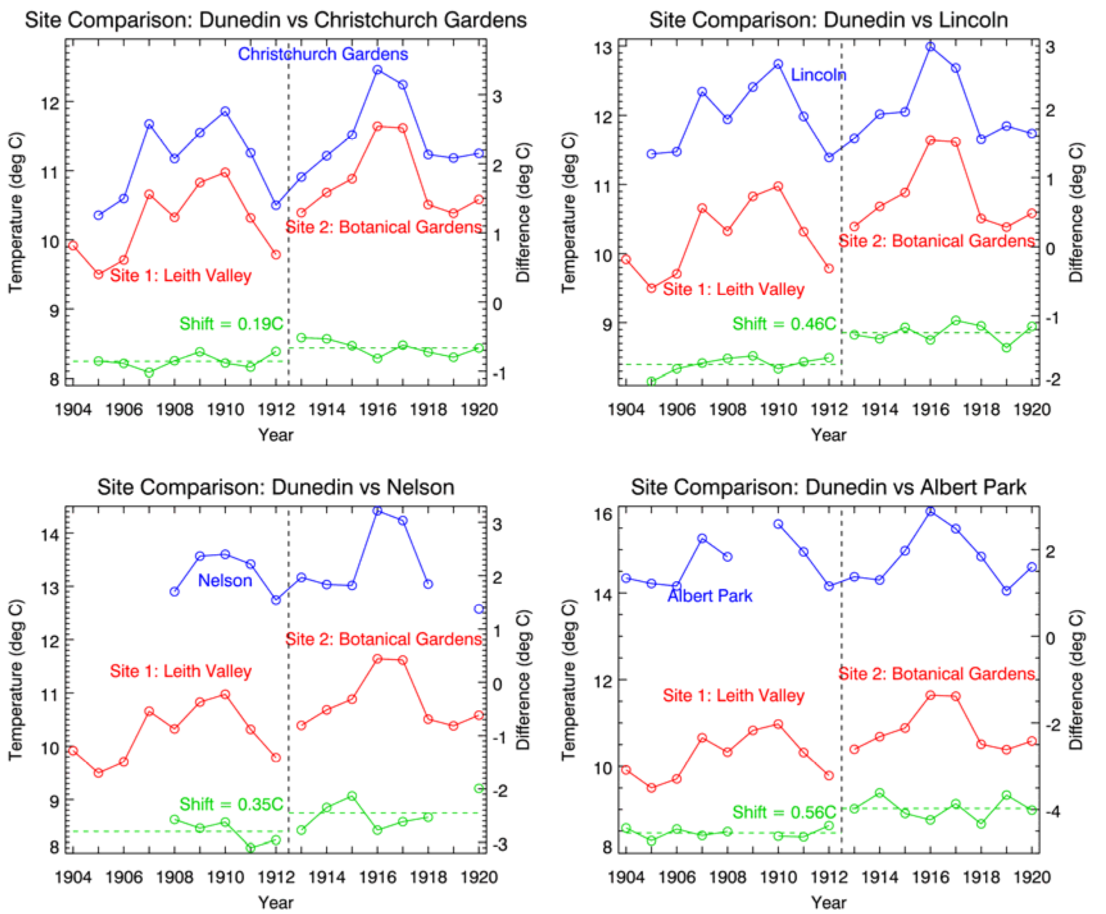

Figure 9: Annual-mean temperature series at Leith Valley (Site 1, red line on the left of each plot) and Dunedin Botanical Gardens (Site 2, red line on the right of each plot) compared with Christchurch Gardens, Lincoln, Nelson and Albert Park. See footnotes in the text for information about adjustments 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.

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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.

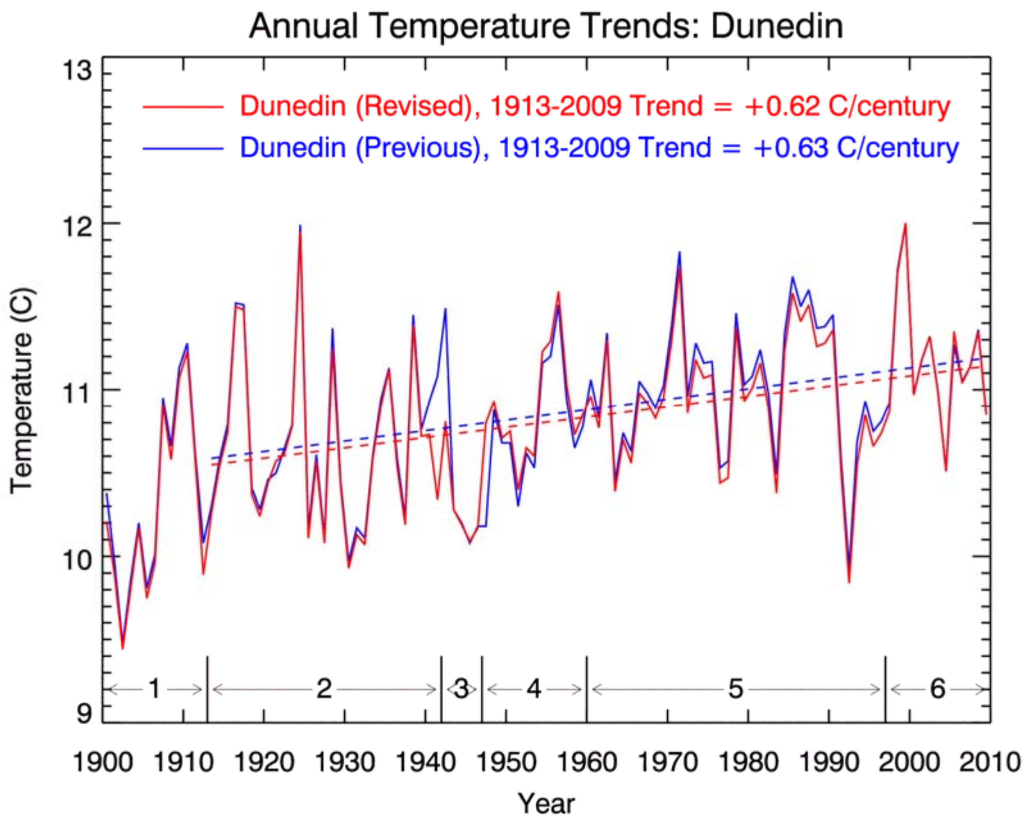

Figure 10: Comparison of the revised composite series of annual mean air temperatures for Dunedin (red line) to the previous NIWA Dunedin series (blue line) from 1900 to 2009. The dashed lines show the fitted linear trends from 1909 to 2009. Dunedin site labels from Table 1 are displayed at the bottom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

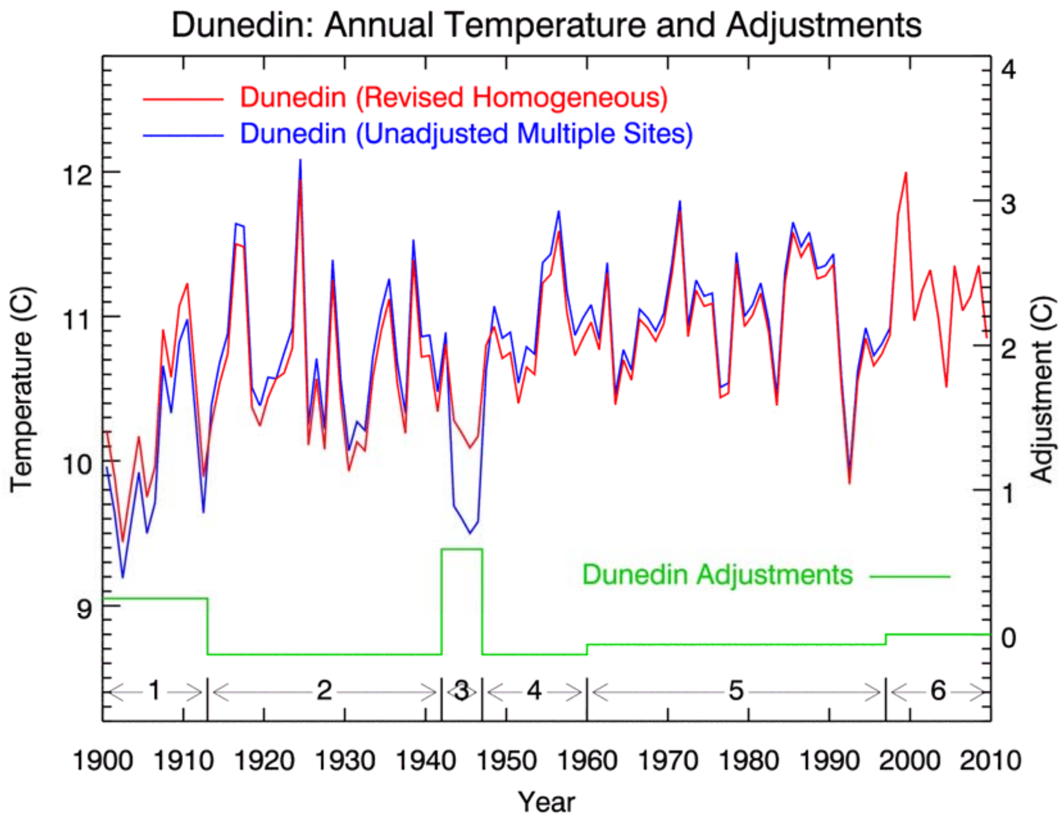

Figure 11: Comparison of the revised composite temperature series for Dunedin (red line), with an unadjusted composite series (blue line) from 1900 to 2009. Numbers near the bottom of the plot denote the site labels of Table 1, with vertical lines marking the time periods over which each site contributes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

Date: Document originally created 29 October 2010, and revised 13 December 2010 following review from the Australian Bureau of Meteorology.

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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.

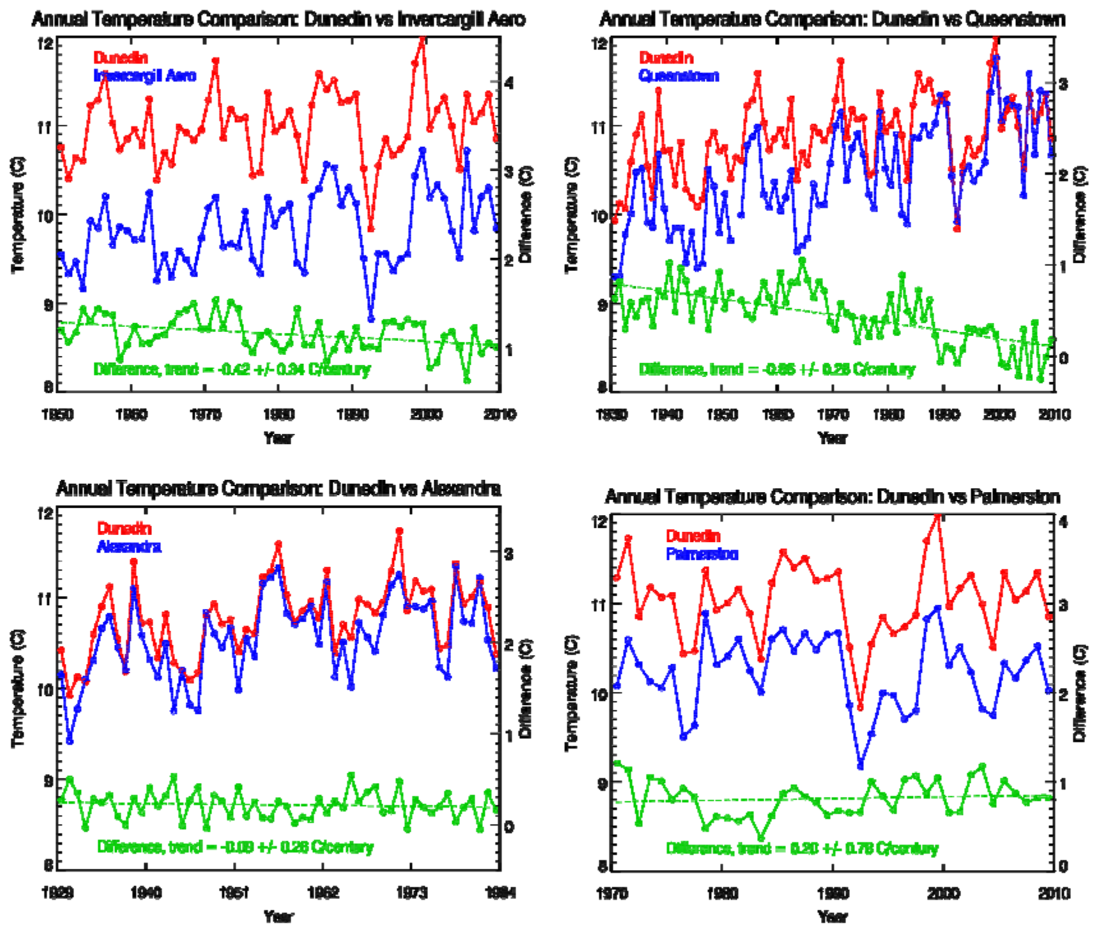

Figure A2.1: Comparison of the revised composite temperature series for Dunedin (red line), with time series of annual mean temperature (blue line) at stations in the southern half of the South Island: Invercargill Aero, Queenstown, Alexandra and Palmerston. The solid green line represents the difference (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.