# 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 not 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.

[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 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 in the Wellington CBD, but still retain the same trend in time.

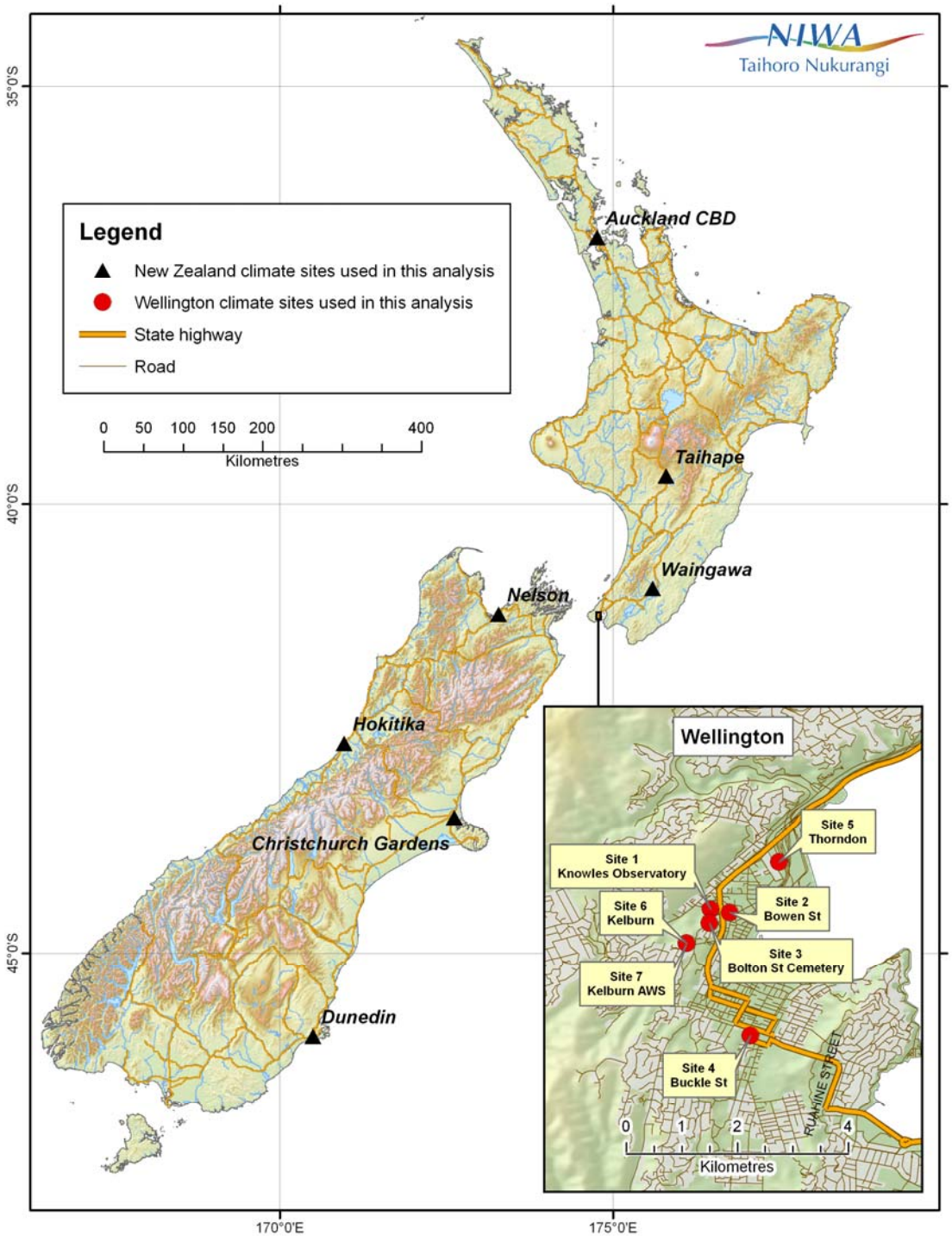


**Figure 2:** Map showing sites of temperature records referred to elsewhere within this document. The inset map locates the local Wellington sites.

### *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.

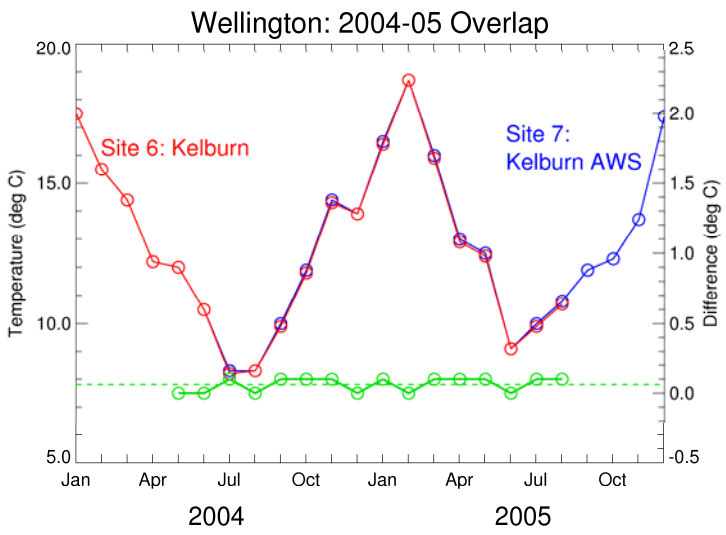


**Figure 3:** Monthly mean temperature series for Kelburn (Site 6, agent 3385, red line) and Kelburn AWS (Site 7, agent 25354, blue line) for 2004 and 2005. The monthly difference, Site 7 minus Site 6, is plotted by the solid green line, using the right-hand ordinate scale, and the average monthly difference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

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[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).

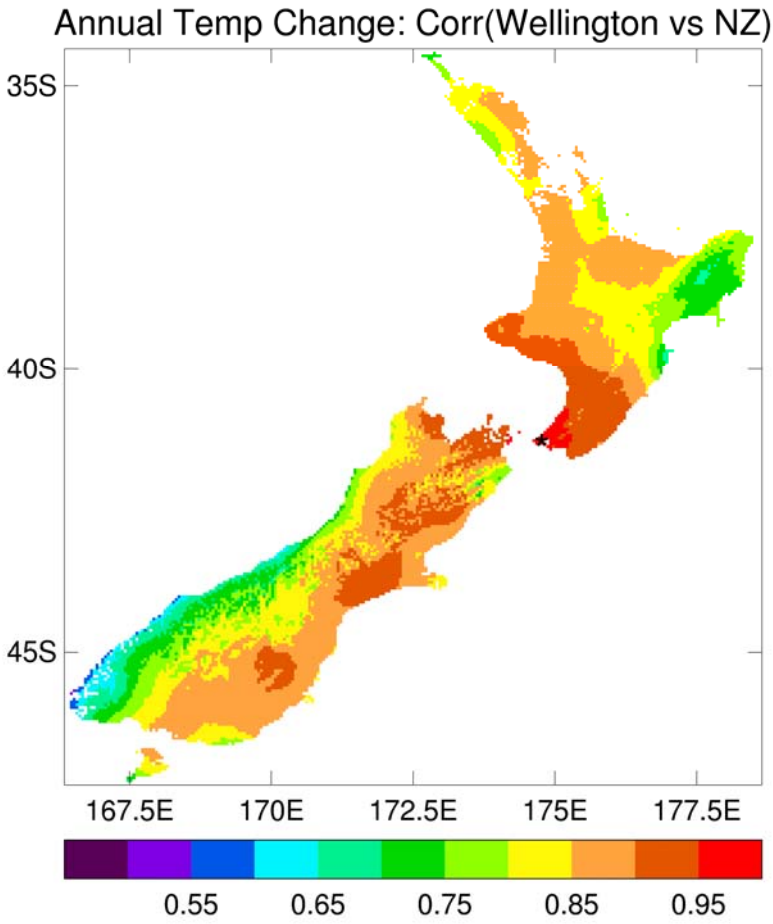


**Figure 4:** Map of correlation between interannual temperature changes at the grid-point nearest to Kelburn (Site 6, agent 3385, location marked by asterisk) in Wellington, 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

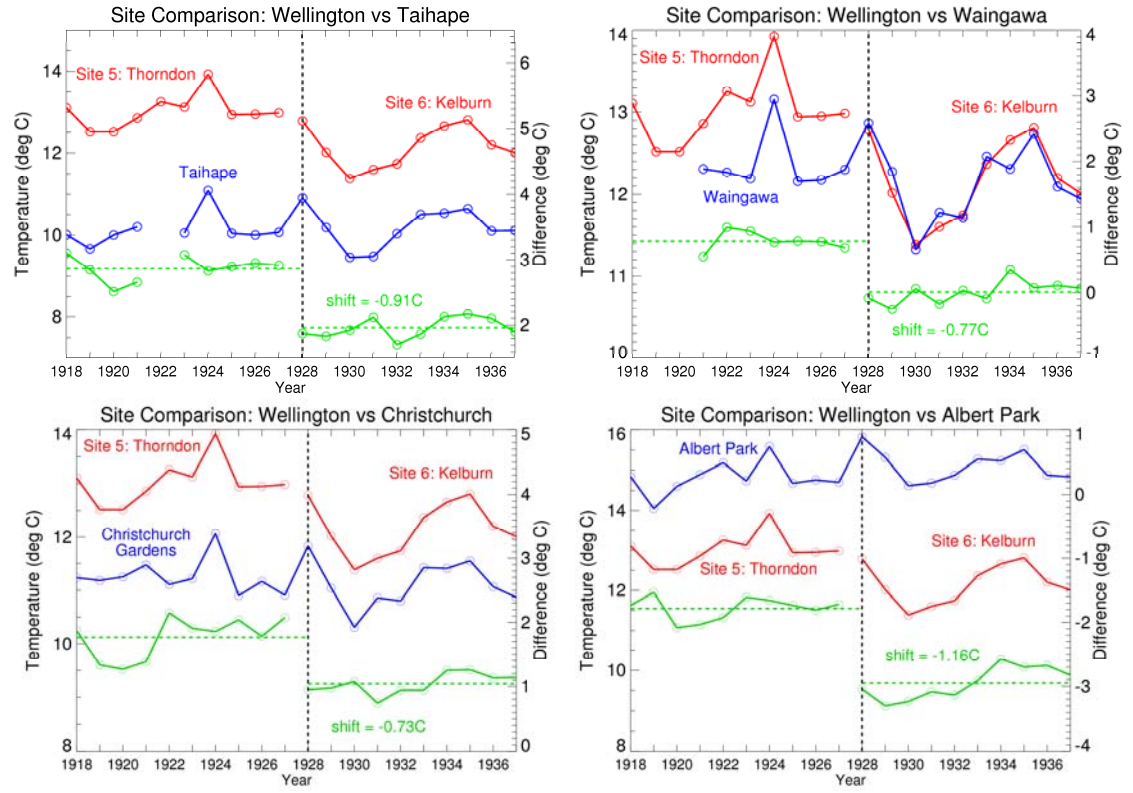


**Figure 5:** Annual mean temperature series at Thorndon (Site 5, agent 3391, red lines on the left half of each plot) and Kelburn (Site 6, agent 3385, red lines on the right half of each plot) compared with four other stations that overlap the Wellington site change: Taihape Hiwi (agent 3669, blue line 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.

[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.

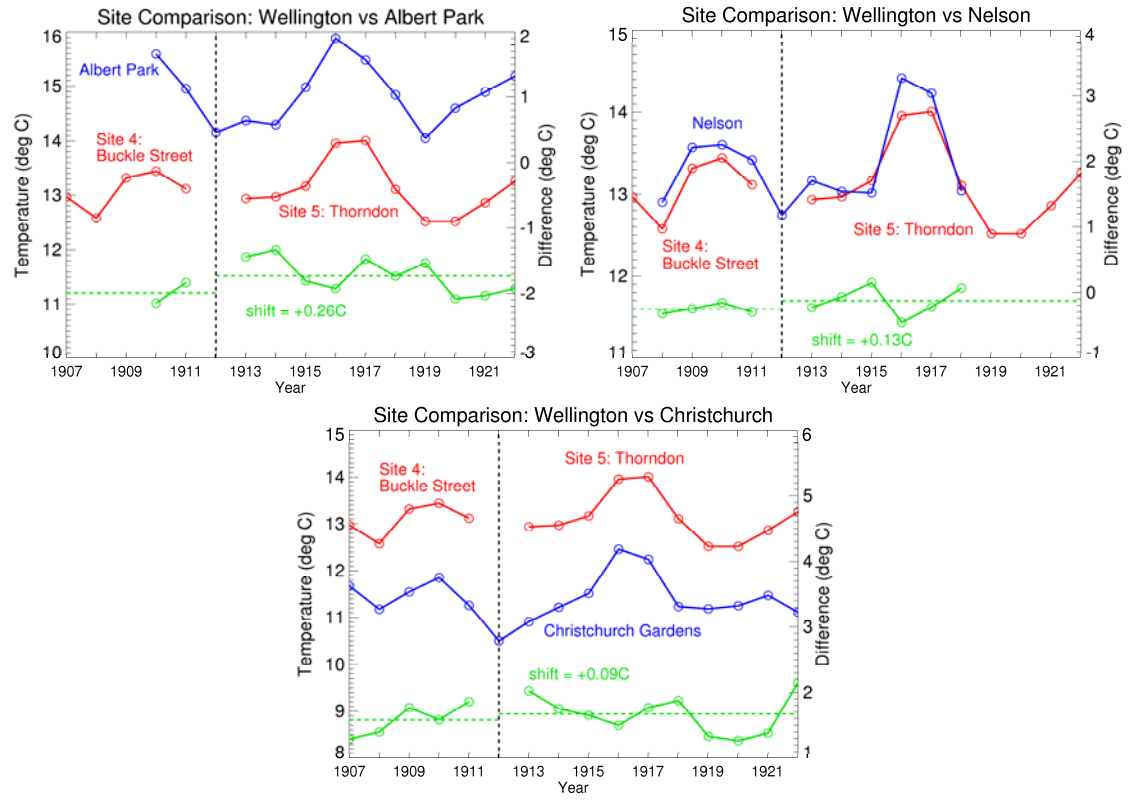


**Figure 6:** Comparisons of annual mean temperature series at Buckle Street (Site 4, agent 3431, red lines on the left part of each plot) and Thorndon (Site 5, agent 3391, red lines on the right part of each plot) with Albert Park in Auckland (agent 1427, blue line in upper left plot), Nelson (agent 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.

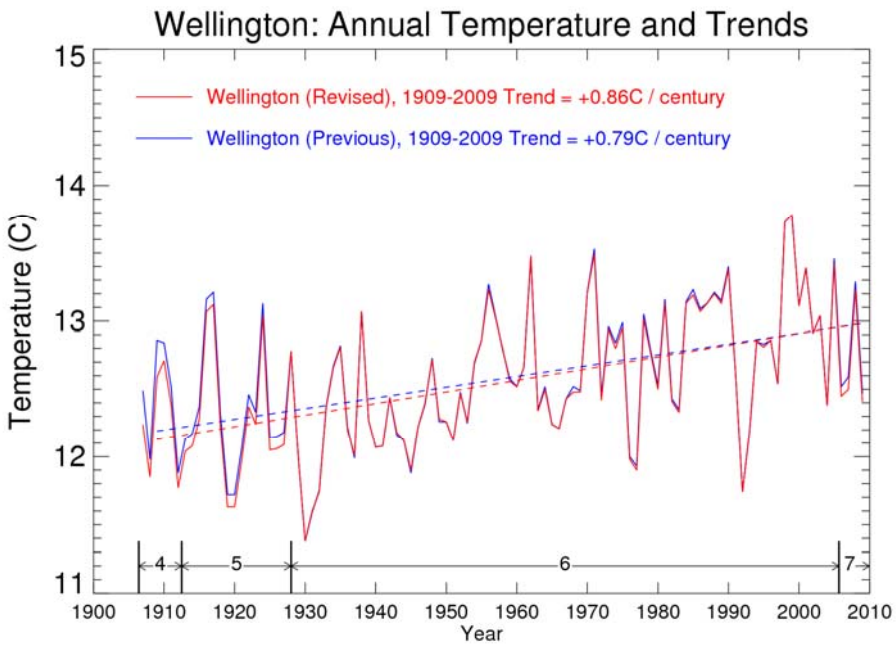


**Figure 7:** Comparison of the new series (red line) and previous NIWA series (blue line) of composite temperatures for Wellington from 1907 to 2009. The dashed lines indicate the fitted linear trends from 1909 to 2009. Labels near the bottom of the plot denote the Site numbers of Table 1. Vertical 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.

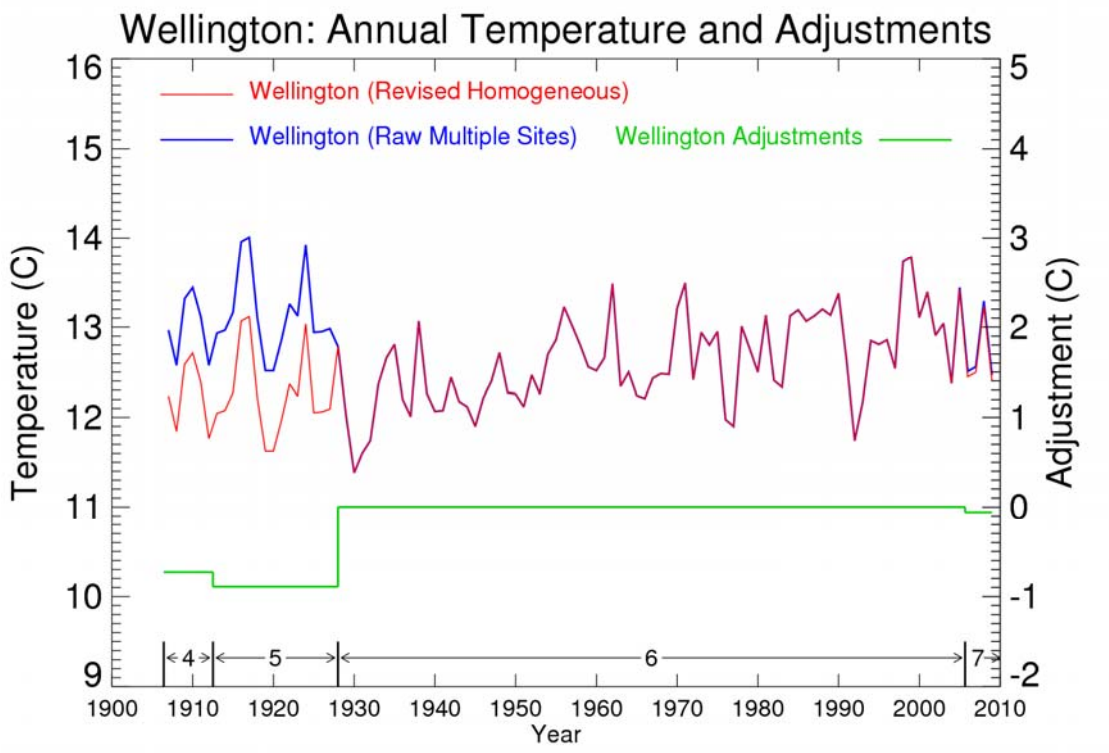


**Figure 8:** Comparison of new composite temperature series for Wellington from 1907 to 2009 (red line), with the raw multi-site series (Sites 4-7, blue line). The green line (using the right-hand axis) indicates the cumulative step adjustments to each site as shown at the bottom of the graph, and corresponds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

**References:**


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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.

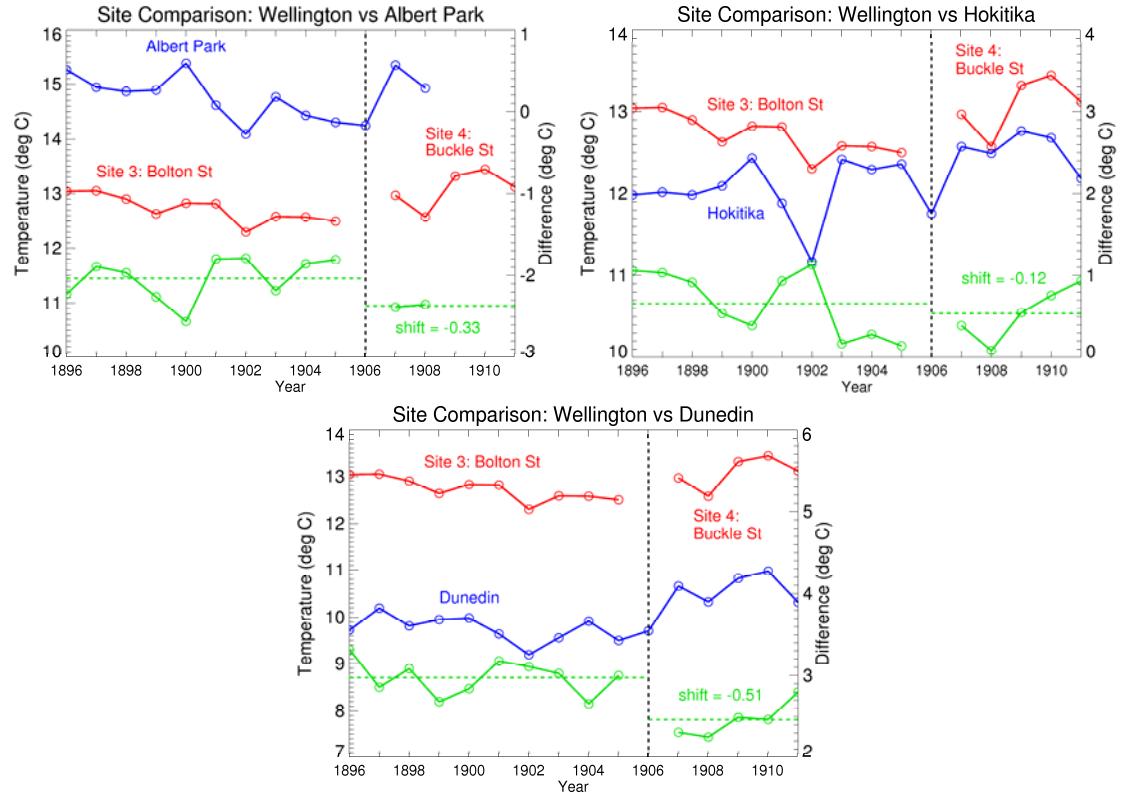


**Figure A1.1:** Comparisons of annual mean temperature series at the Bolton Street cemetery (Site 3, agent 3390, red lines on the left part of each plot) and Buckle Street (Site 4, agent 3431, red lines on the right part of each plot) with Albert Park in Auckland (agent 1427, blue line in upper left 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.

[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 95$^{th}$ percentile. If the statistic is below the lower bound on the 95$^{th}$ 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.

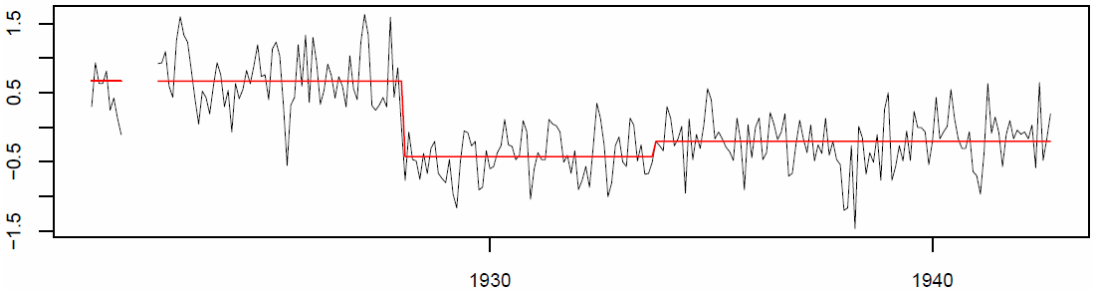


**Figure A3.1:** Monthly mean temperatures observed at Thorndon (Site 5) and Kelburn (Site 6) minus averages of monthly mean temperatures observed at Taihape, Waingawa and Nelson from January 1921 to September 1942 (black line). The y-axis represents the difference in monthly mean temperature in degrees 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.

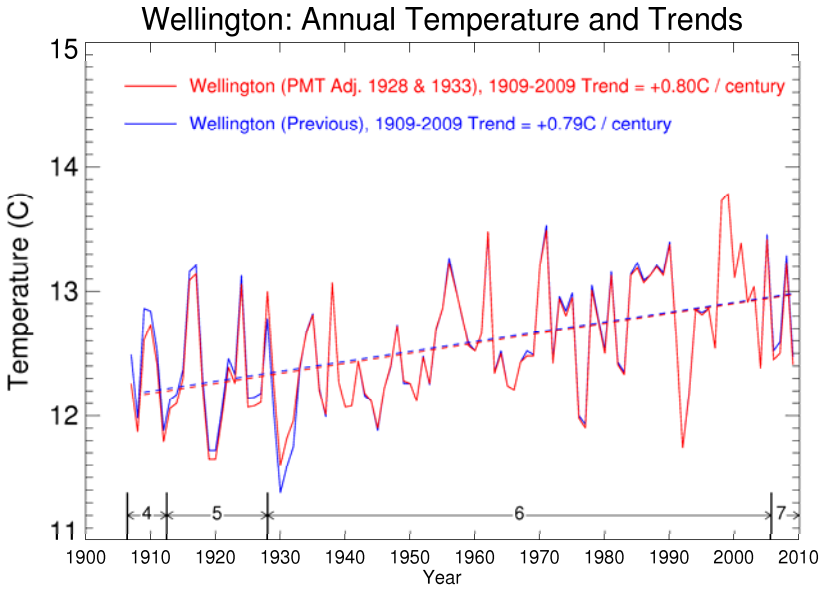


**Figure A3.2:** Composite series of annual mean air temperatures for Wellington (red line) from 1900 to 2009. The adjustments in 1928 and 1933 were diagnosed by the penalised maximal *t* test, as described in the text. The blue line shows the previous NIWA composite series for Wellington. The dashed 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]

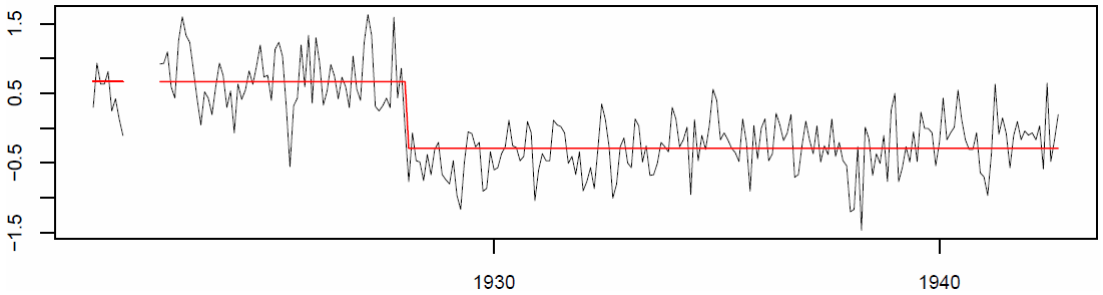


**Figure A3.3:** Monthly mean temperatures observed at Thorndon (Site 5) and Kelburn (Site 6) minus averages of monthly mean temperatures observed at Taihape, Waingawa and Nelson from January 1921 to September 1942 (black line). The y-axis represents the difference in monthly mean temperature in degrees 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.