Creating a Composite Temperature Series for Masterton

December 2010

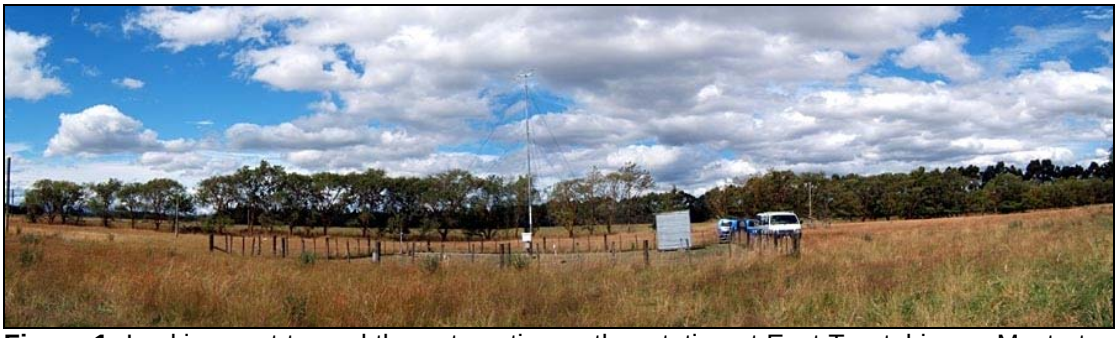

Figure 1: Looking east toward the automatic weather station at East Taratahi near Masterton (agent number 2612) in 2007.

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 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 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 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 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 all 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.

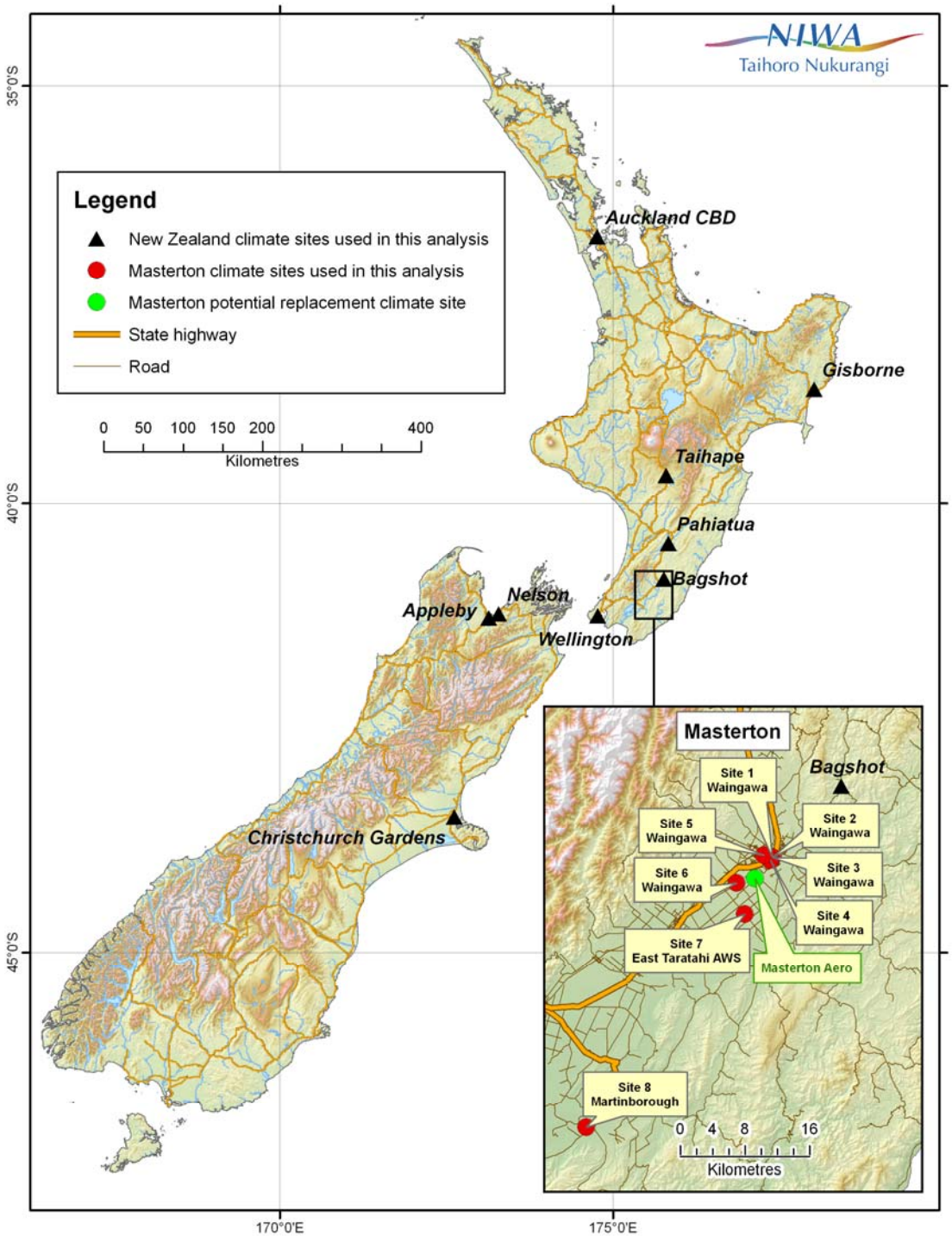

Figure 2: Map showing sites of temperature records referred to elsewhere within this document. The inset map locates the local Masterton sites.

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]

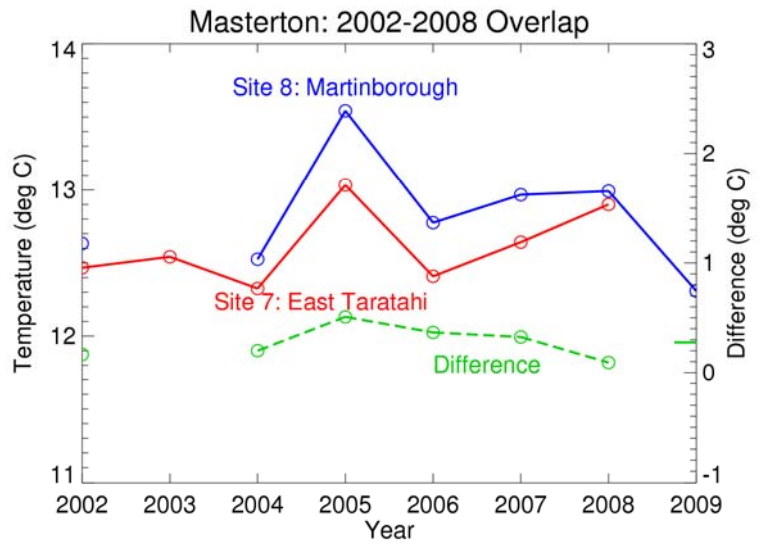

Figure 3: Annual mean temperature series for East Taratahi AWS (Site 7, agent 2612, red line), and Martinborough EWS (Site 8, agent 21938, blue line), from 2002 to 2009. The annual difference, Site 8 minus Site 7, is plotted by the green dashed line, using the right-hand ordinate scale, and the mean 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.

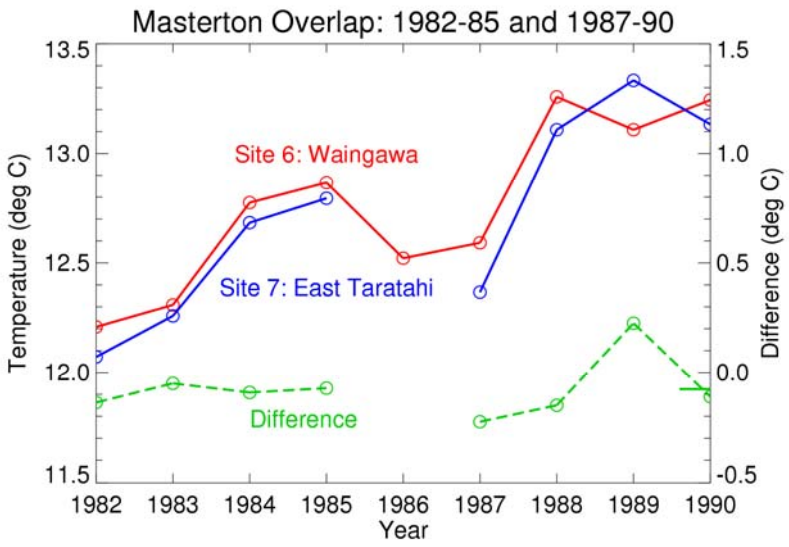

Figure 4: Annual mean temperature series for Waingawa (Site 6, agent 2473, blue line) and East Taratahi AWS (Site 7, agent 2612, red line) from 1982 to 1990. The annual difference, Site 7 minus Site 6, during overlapping years is plotted by the green dashed line, using the right-hand ordinate scale,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

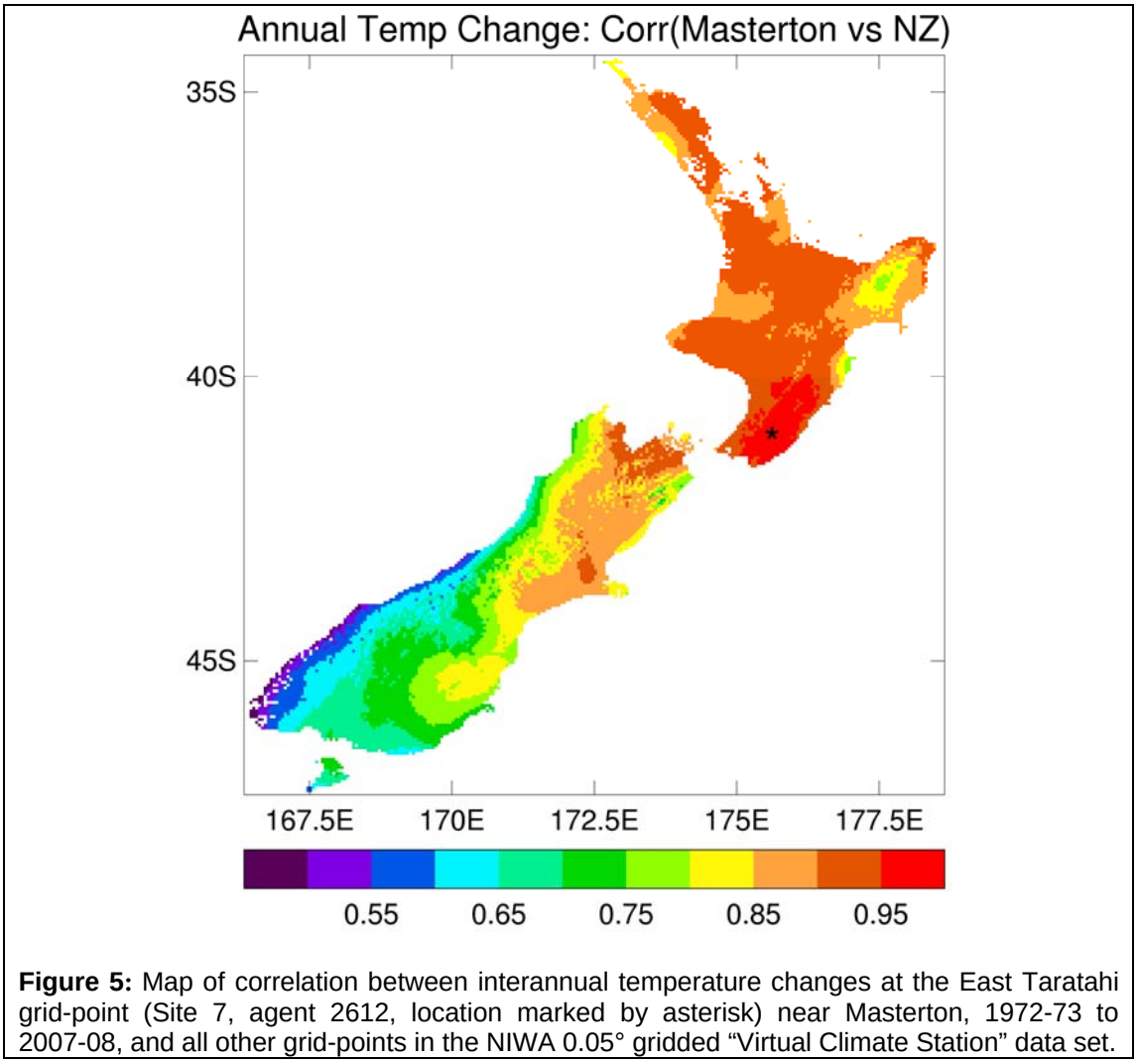

Figure 5: Map of correlation between interannual temperature changes at the East Taratahi grid-point (Site 7, agent 2612, location marked by asterisk) near Masterton, 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

[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 cooler 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.

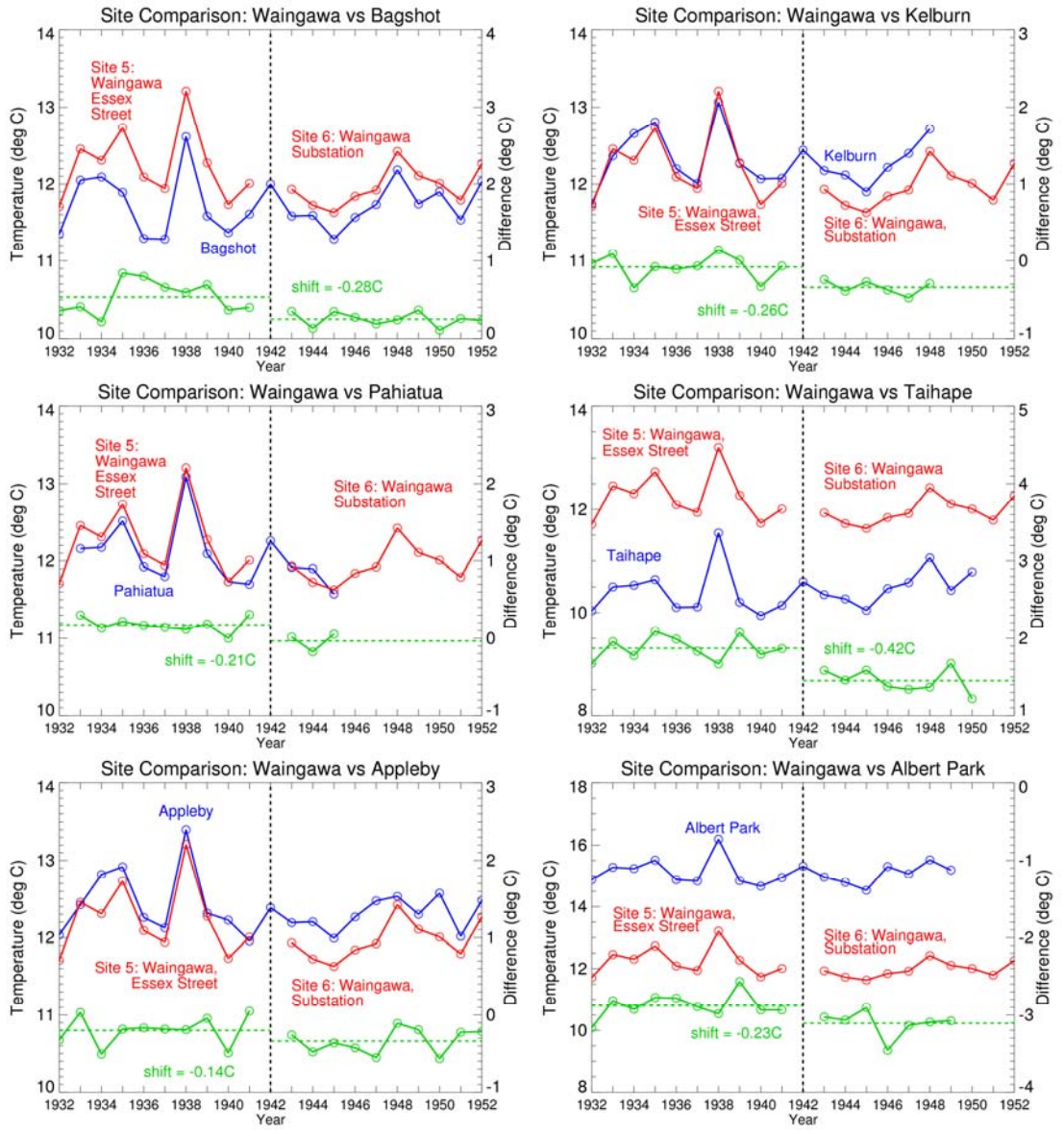

Figure 6: Comparisons of annual mean temperature series at Essex Street (Site 5, agent 2473, red lines on the left of each plot) and Waingawa substation (Site 6, agent 2473, red lines on the right of each plot) with Bagshot Station (agent 2446, blue line in upper left plot), Wellington Kelburn (agent 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'.

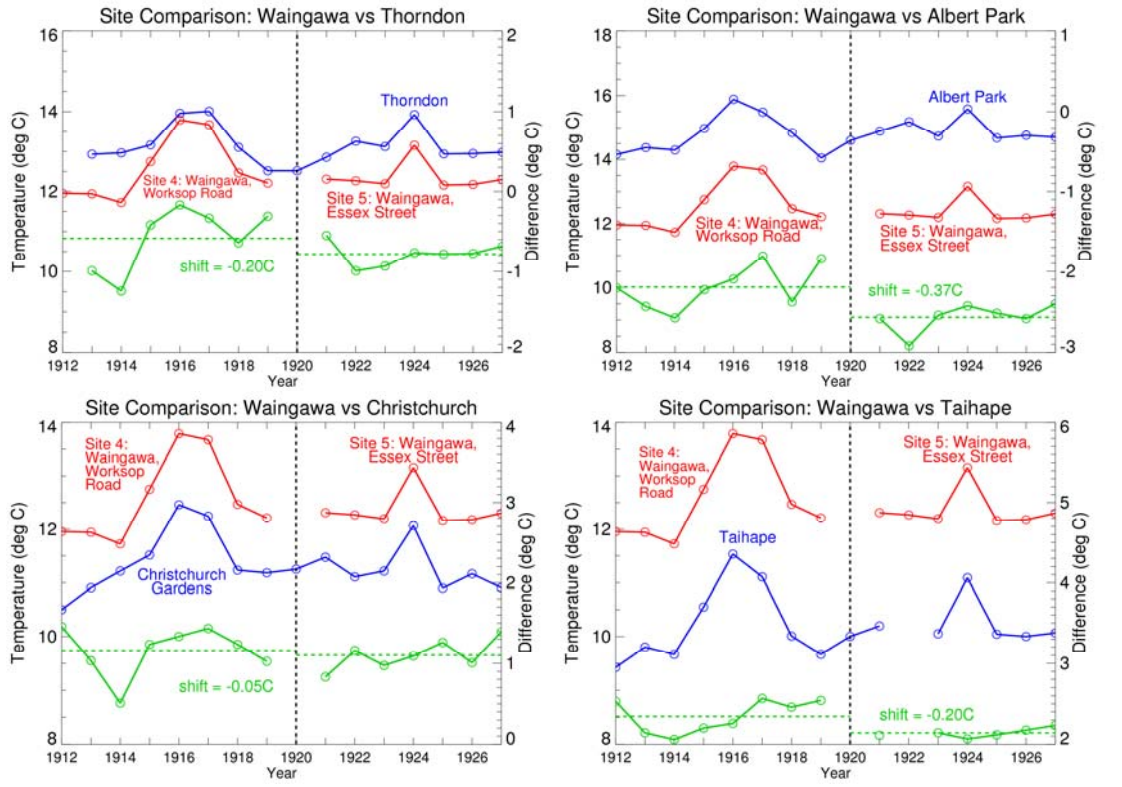

Figure 7: Comparisons of annual mean temperature series at Waingawa Worksop Road (Site 4, agent 2473, red lines on the left of each plot) and Waingawa Essex Street (Site 5, agent 2473, red lines on the right of each plot) with Thorndon (agent 3391, blue line in upper left plot), Albert Park (agent 1427, 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.

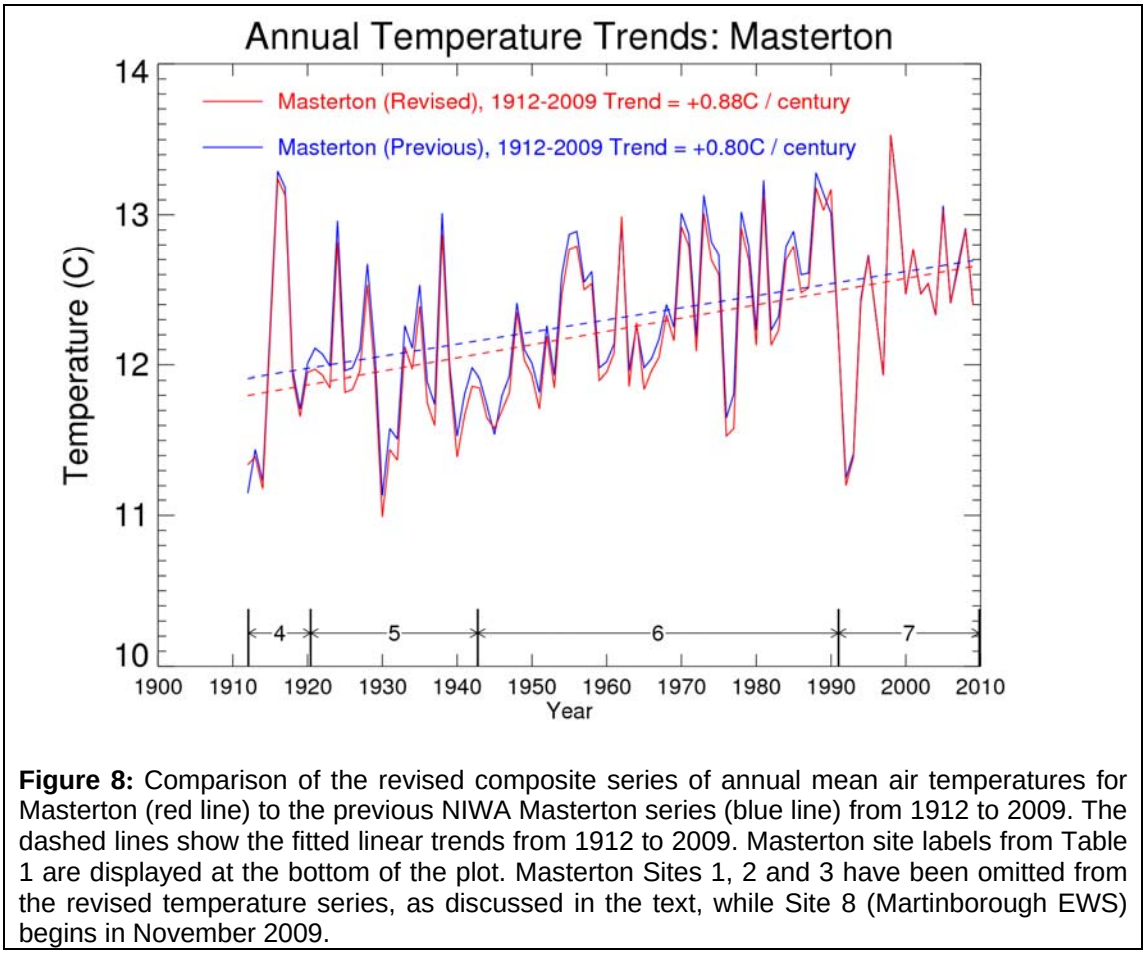

Figure 8: Comparison of the revised composite series of annual mean air temperatures for Masterton (red line) to the previous NIWA Masterton series (blue line) from 1912 to 2009. The dashed lines show the fitted linear trends from 1912 to 2009. Masterton site labels from Table 1 are displayed at the 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.

[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.

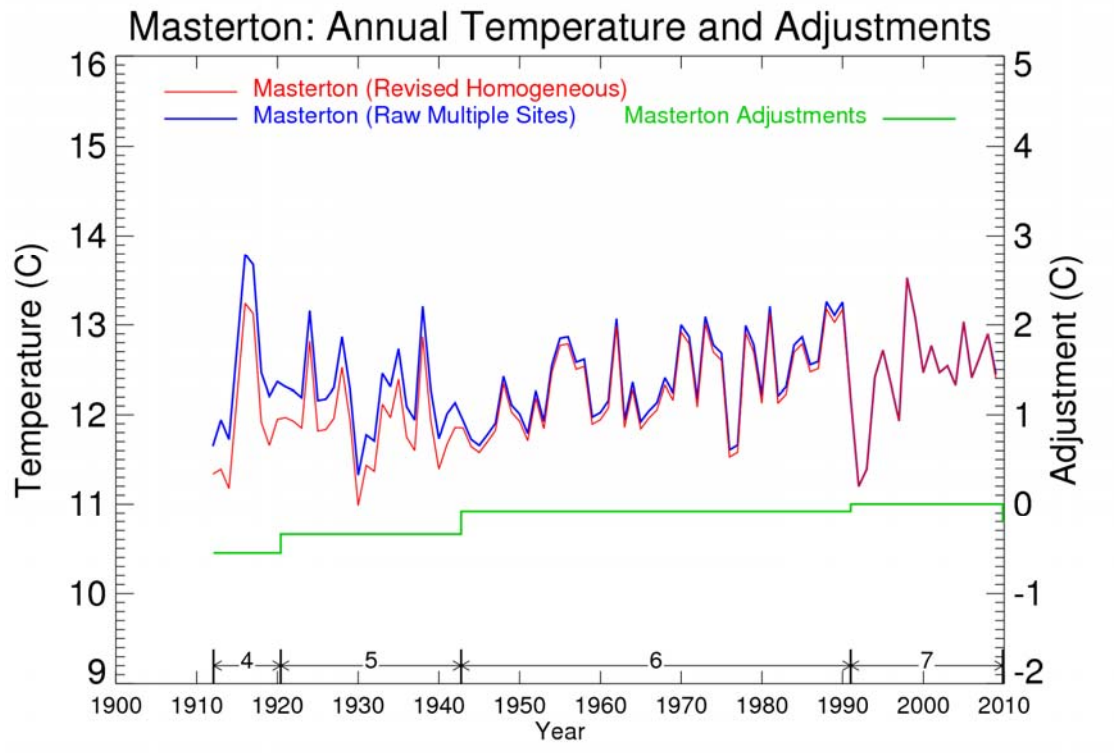

Figure 9: Comparison of new composite temperature series for Masterton from 1912 to 2009 (red line), with the raw multi-site series (Sites 4-7, blue line). The green line (using right-hand axis) indicates the cumulative step adjustments to each site as shown at the bottom of the graph, and corresponds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

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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.

[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.

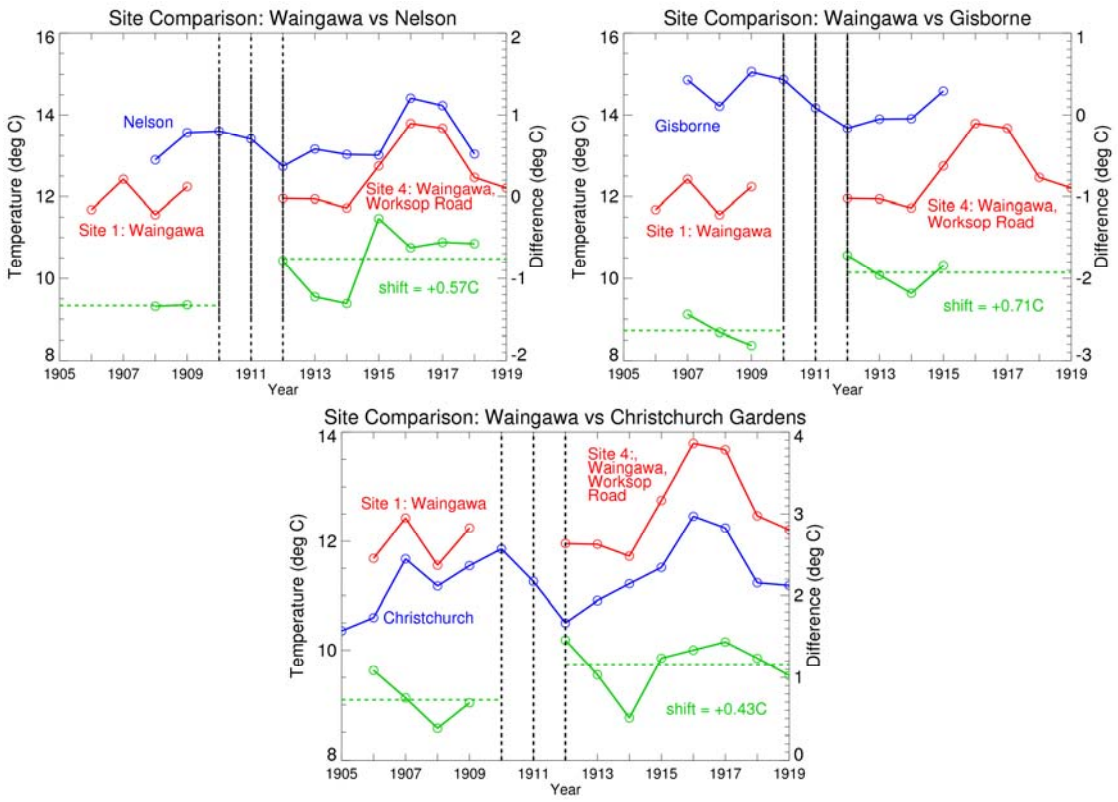

Figure A1.1: Comparisons of annual mean temperature series at Masterton Site 1 (Waingawa, agent 2473, red lines on the left of each plot) and Masterton Site 4 (Waingawa, Worksop Road, agent 2473, red lines on the right of each plot) with Nelson (agent 4244, blue line in upper left plot), Gisborne Aero (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.