

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 not 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.

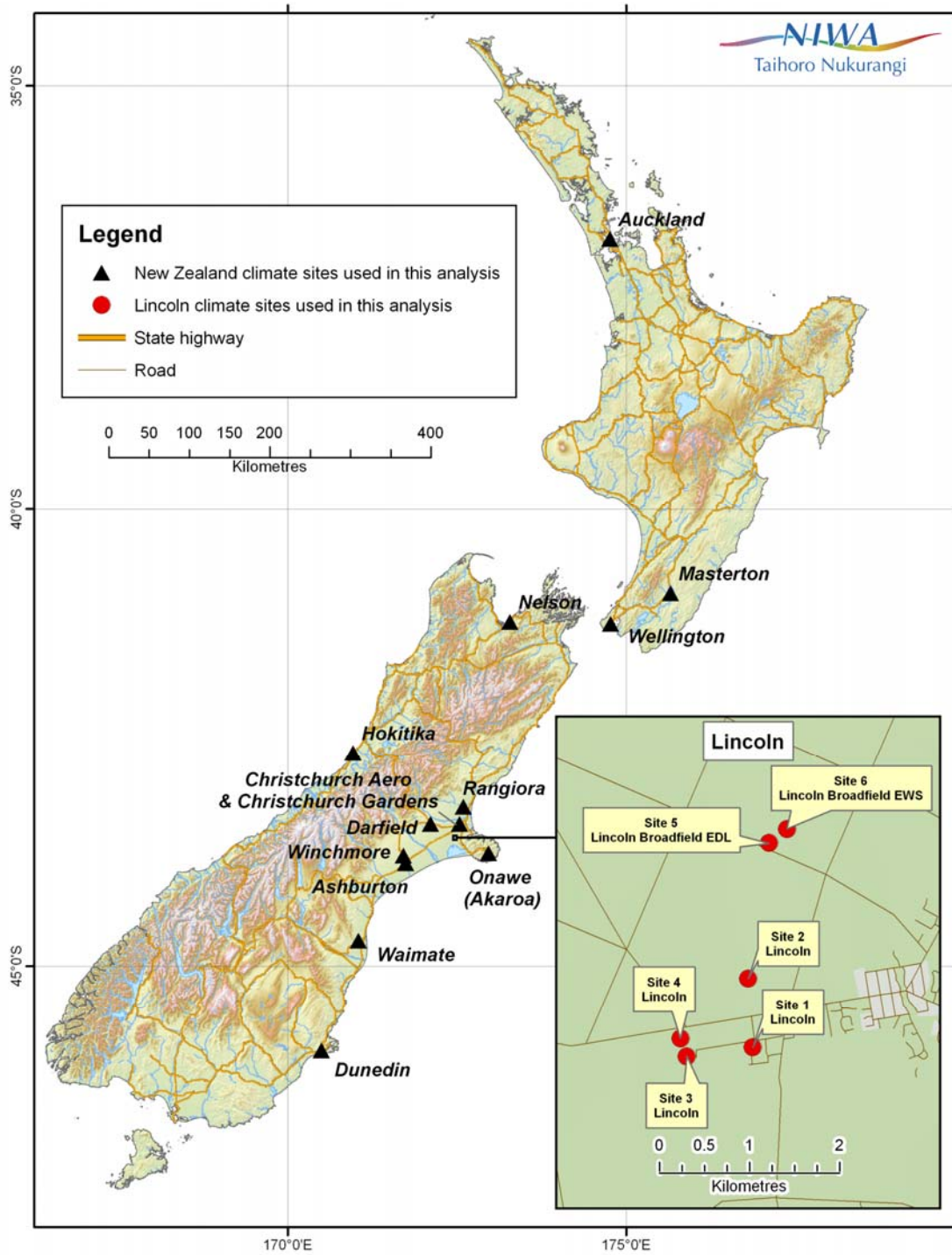


Figure 2: Map showing sites of temperature records referred to within this document. The inset map locates the local Lincoln sites.

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).

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.

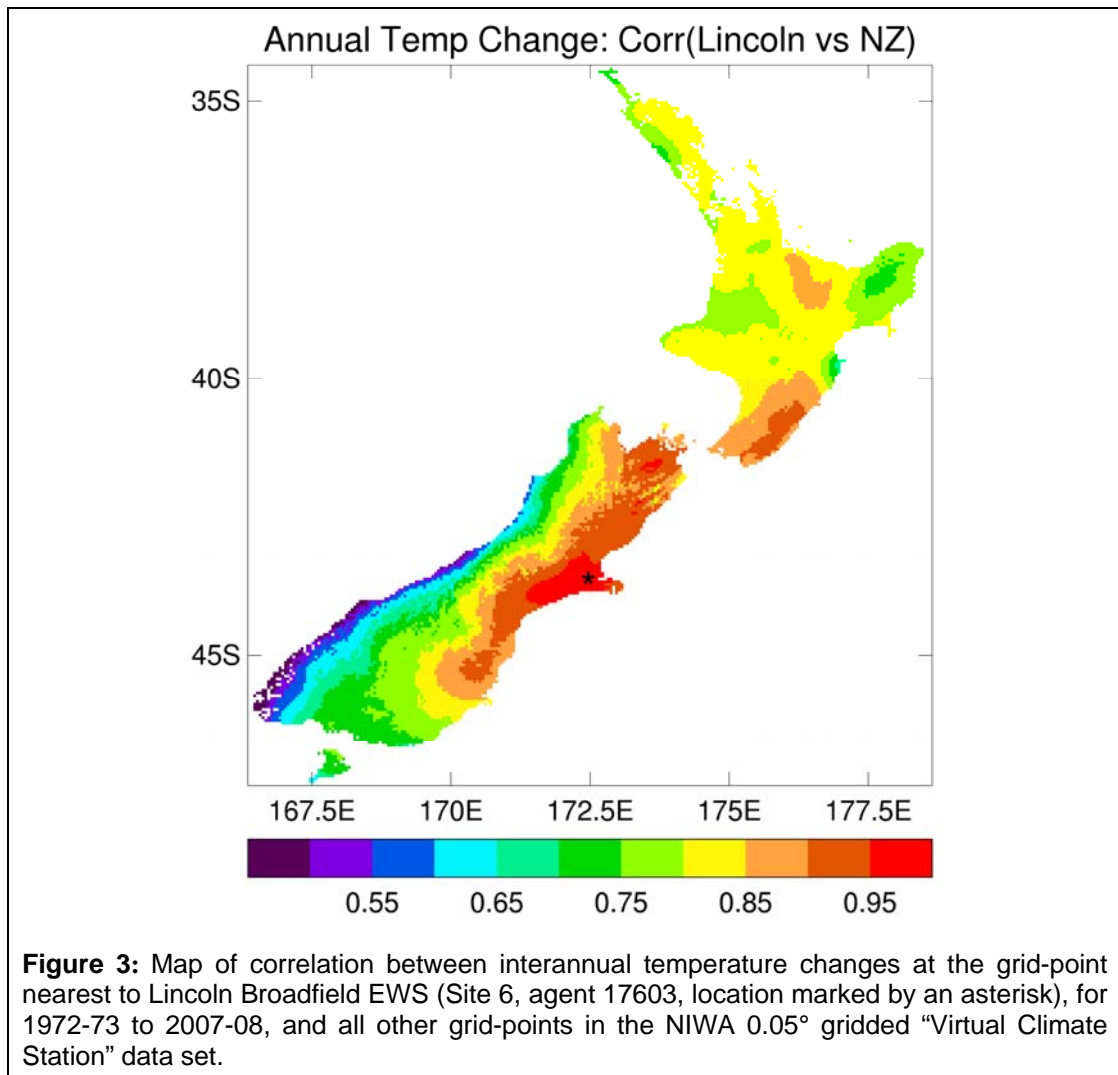


Figure 3 shows the correlation of mean temperature interannual differences at the VCS grid-point containing Lincoln Broadfield EWS (Site 6) with interannual differences at all other locations on the VCS grid from 1972 until 2008 (that is, the 1972-73 difference, 1973-74, ..., 2007-08). Annual temperature 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 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).

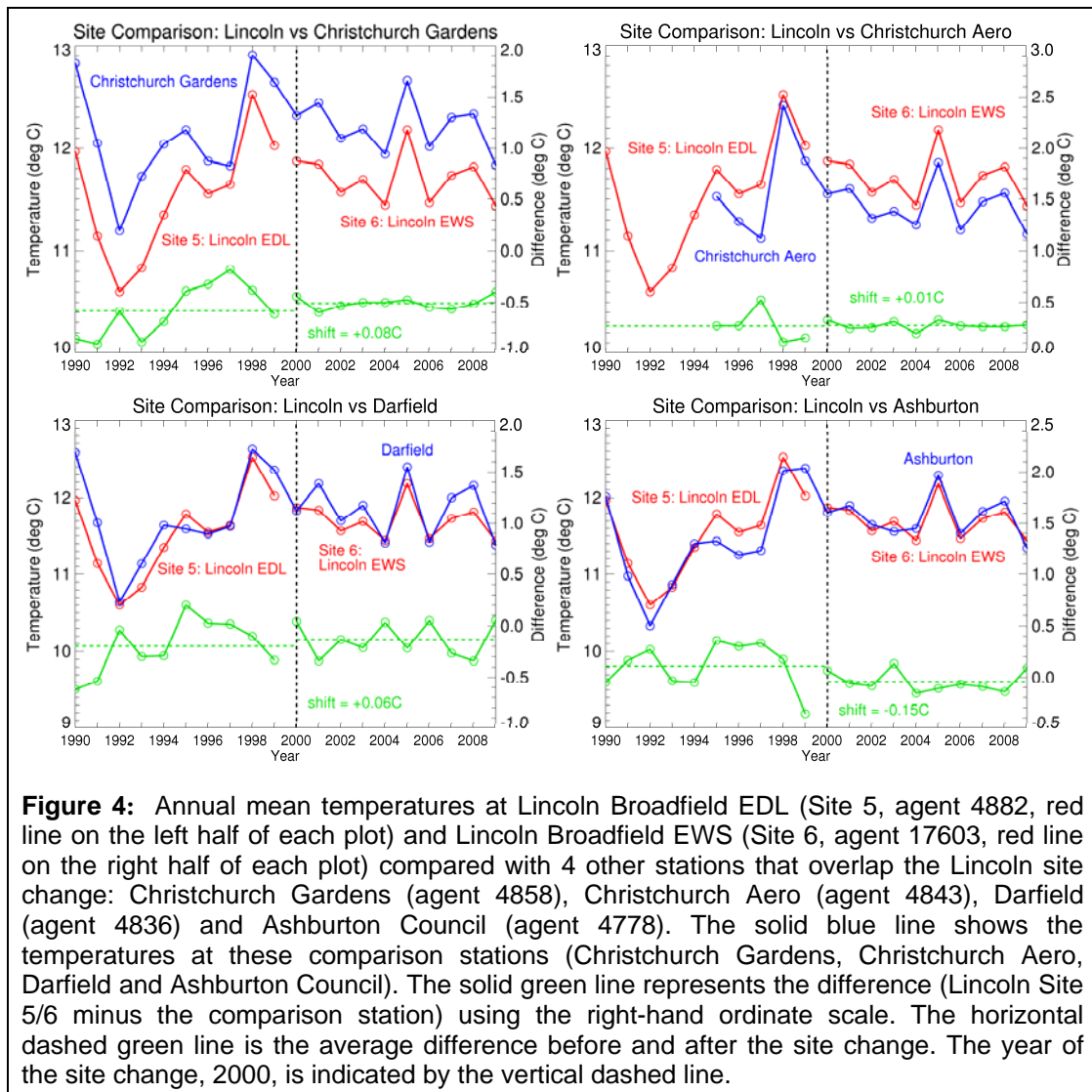


Figure 4: Annual mean temperatures at Lincoln Broadfield EDL (Site 5, agent 4882, red line on the left half of each plot) and Lincoln Broadfield EWS (Site 6, agent 17603, red line on the right half of each plot) compared with 4 other stations that overlap the Lincoln site change: Christchurch Gardens (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 temperatures¹⁰ 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.

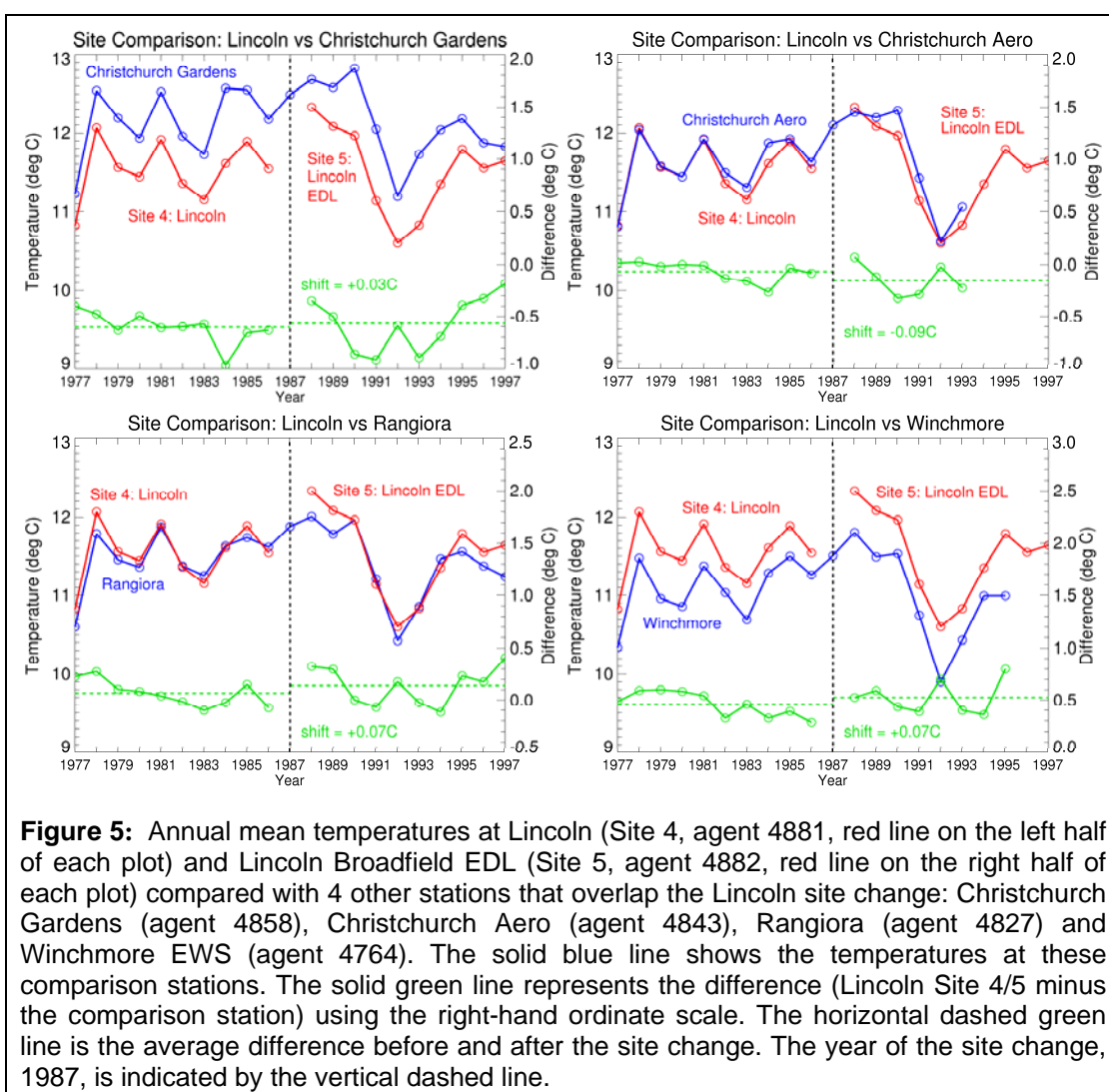
Thus we have 4 estimates of the difference between Lincoln Broadfield EWS and Lincoln Broadfield EDL: +0.08 °C, +0.01 °C, +0.06 °C and -0.15 °C. The average estimated difference between Lincoln Broadfield EWS and Lincoln Broadfield EDL is 0.00 °C.¹² The final adjustment required to make temperatures 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.



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 $-0.03\text{ }^{\circ}\text{C}$: that is, Lincoln Broadfield EDL was $0.03\text{ }^{\circ}\text{C}$ 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.

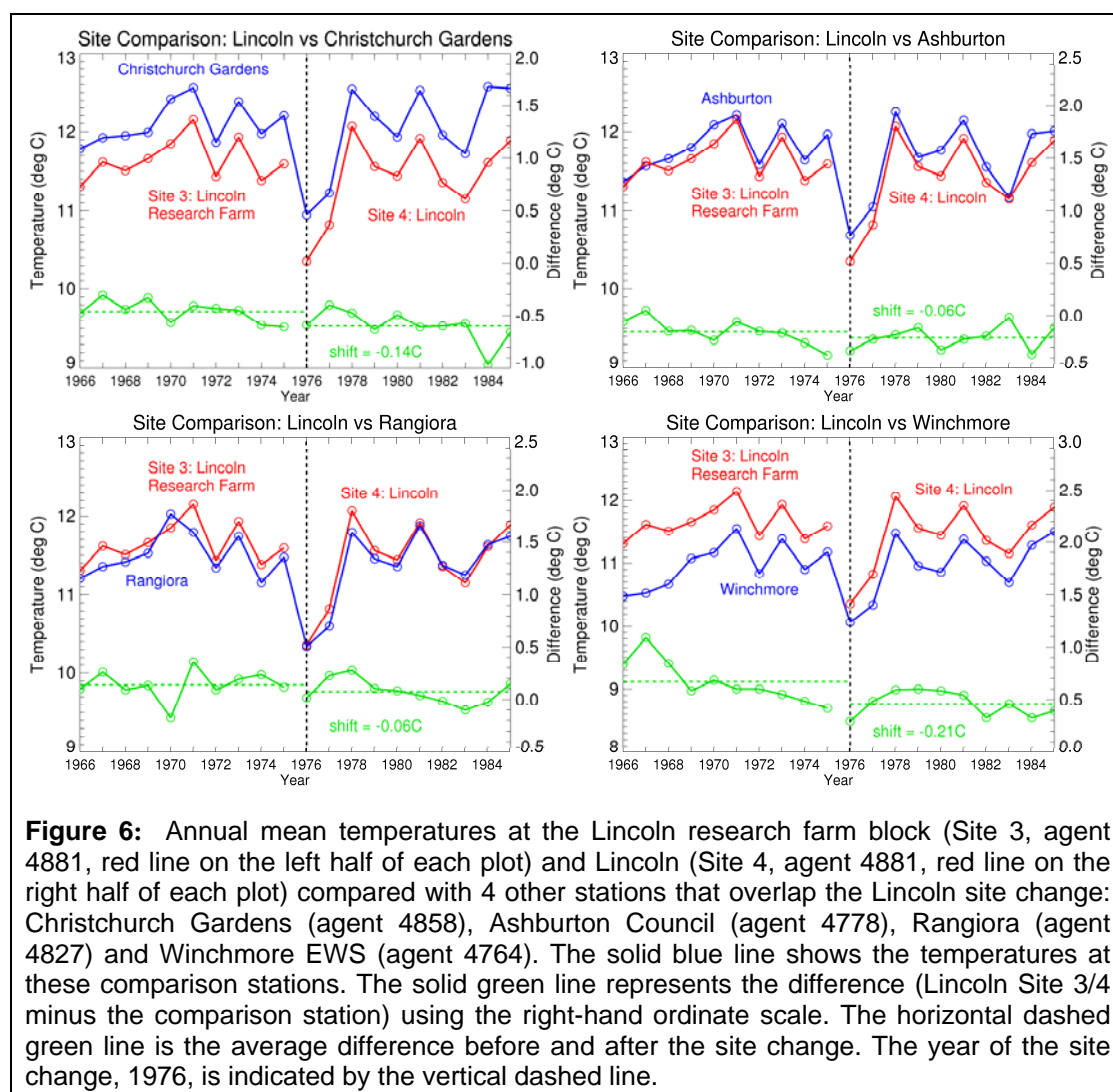
Thus we have 4 estimates of the difference between Lincoln Site 4 and the research farm block: -0.14 °C, -0.06 °C, -0.06 °C and -0.21 °C. The average estimated difference is -0.12 °C, with Lincoln Site 4 being cooler than the research farm block. Temperatures at the research farm block therefore must 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: $0.00 + 0.02 - 0.12 = -0.10\text{ }^{\circ}\text{C}$.



It should be noted that Salinger *et al.* (1992) applied a different adjustment of $+0.2\text{ }^{\circ}\text{C}$ 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 $0.18\text{ }^{\circ}\text{C}$ ($0.2\text{ }^{\circ}\text{C}$ to 1 decimal place) warmer than the research farm block. Salinger *et al.* (1992) may have calculated a $+0.2\text{ }^{\circ}\text{C}$ 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

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 block¹⁹ with Christchurch Gardens, Christchurch Aero, Darfield and Ashburton.

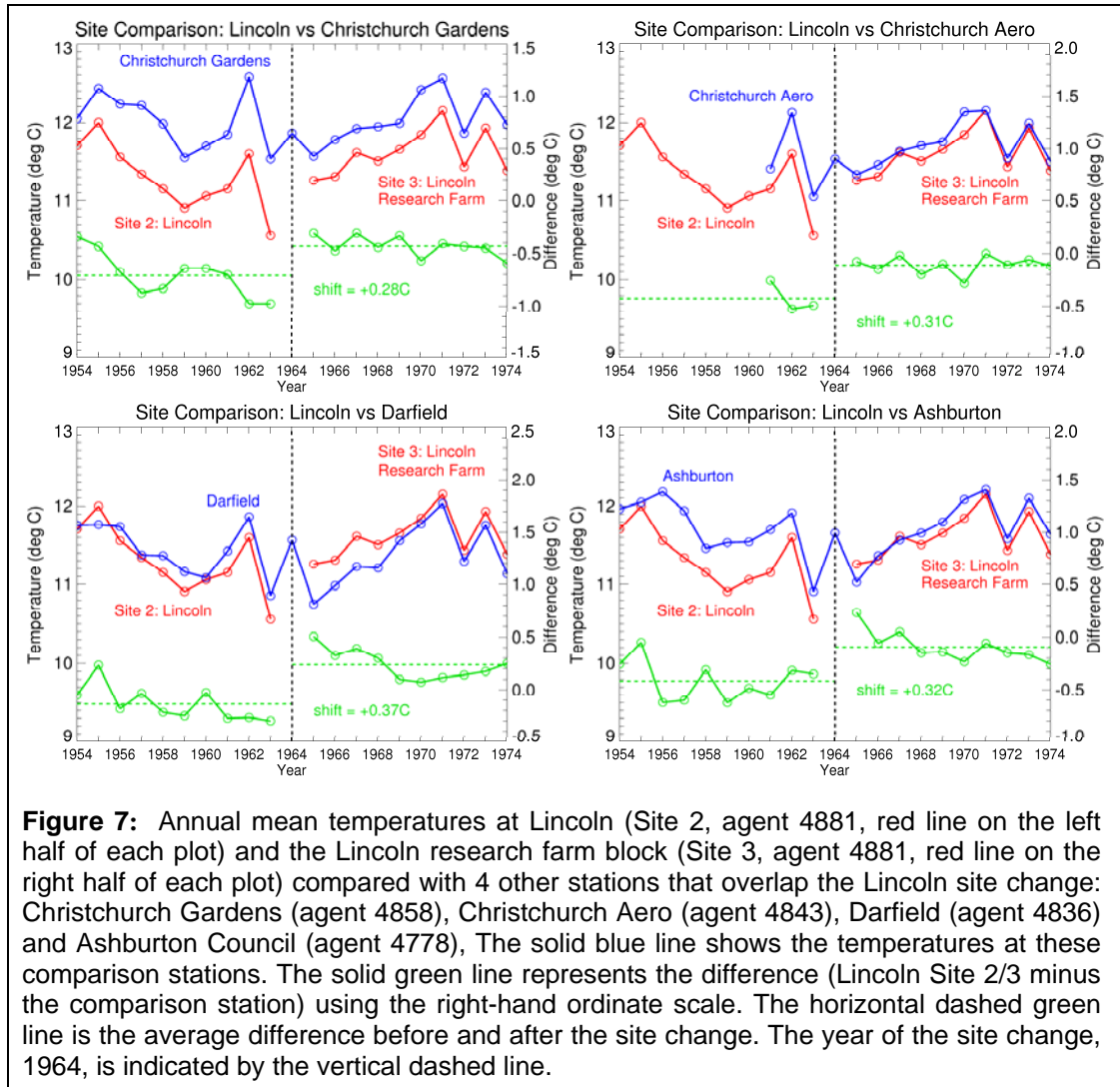
With reference to Christchurch Gardens (Figure 7, upper left), the research farm block was 0.28 °C warmer than Lincoln Site 2. With reference to Christchurch Aero (Figure 7, upper right), the research farm block was 0.31 °C warmer than Lincoln Site 2. With reference to Darfield (Figure 7, lower left),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

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.



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 months²⁰, 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

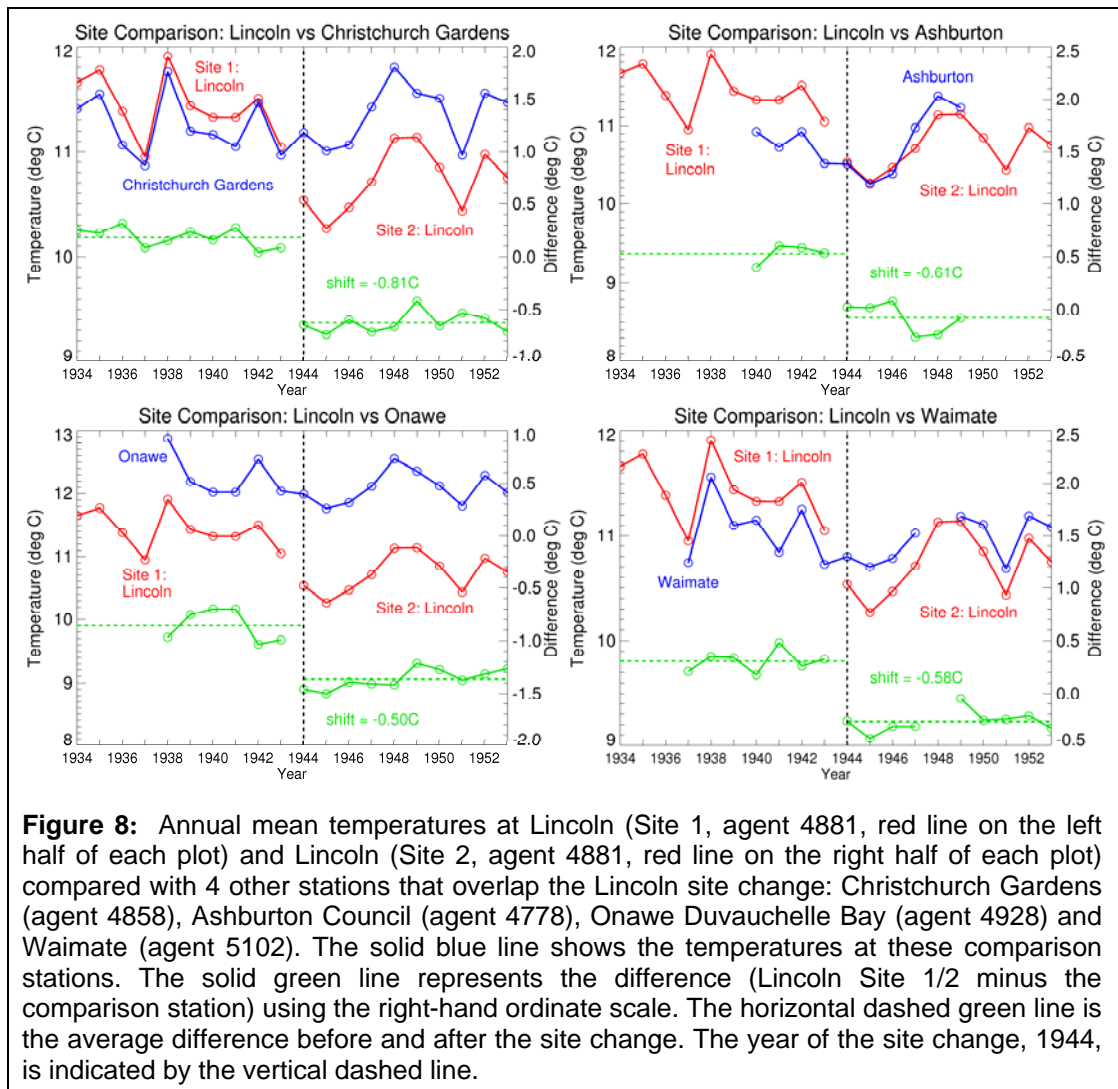
With reference to Christchurch Gardens (Figure 8, upper left), Lincoln Site 2 was 0.81 °C cooler than Lincoln Site 1.²² With reference to Ashburton Council (Figure 8, upper right), Lincoln Site 2 was 0.61 °C cooler than Lincoln Site 1. With reference to Onawe (Figure 8, lower left), Lincoln Site 2 was 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.

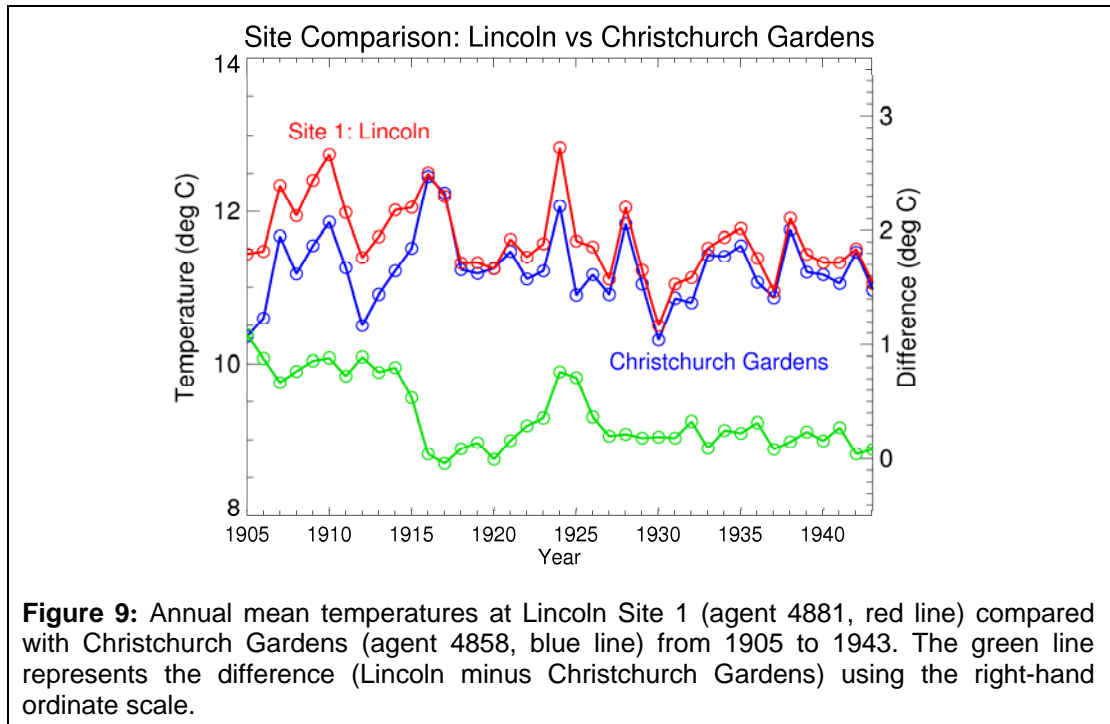
²² The Lincoln station history contains handwritten monthly summaries of temperatures observed at the Lincoln sites from 1881 to 1970. In these summaries, the mean temperature of Lincoln Site 2 is noted to be approximately 1.5 °F (i.e. around 0.8 °C) cooler than that of Lincoln Site 1. The origin of 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.



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'.



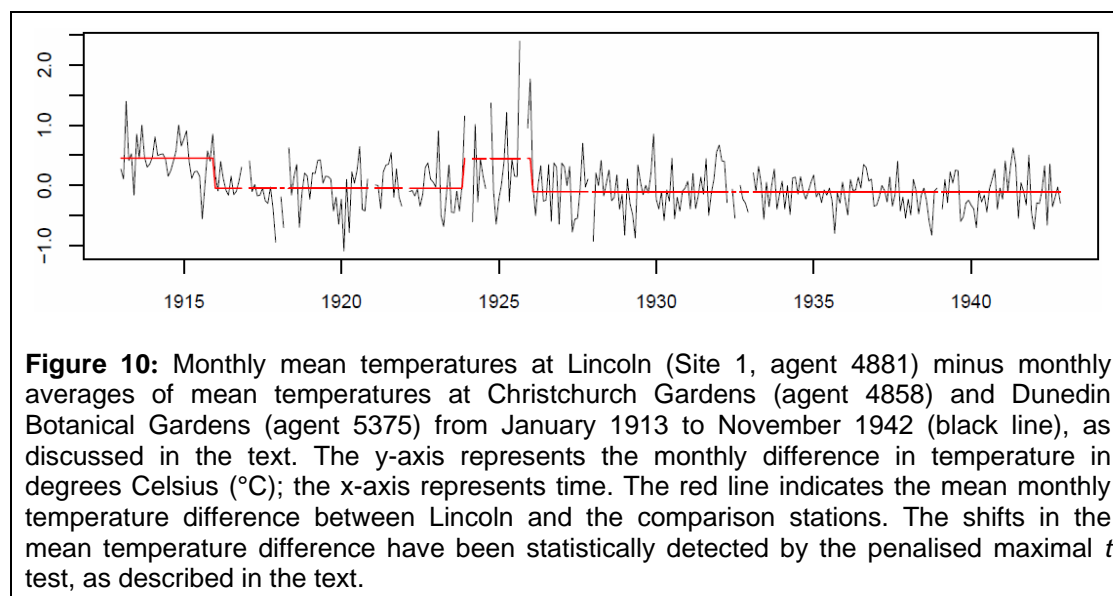
With respect to Christchurch Gardens, one can see a marked fall in temperatures at Lincoln around 1915 and 1916, and additional variations around 1922 and 1927. The planting of shelter belts and the development of the land surrounding the college may have created artificial shifts in the Lincoln temperature 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 stations²⁴ 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 Gardens²⁵ (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.



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).

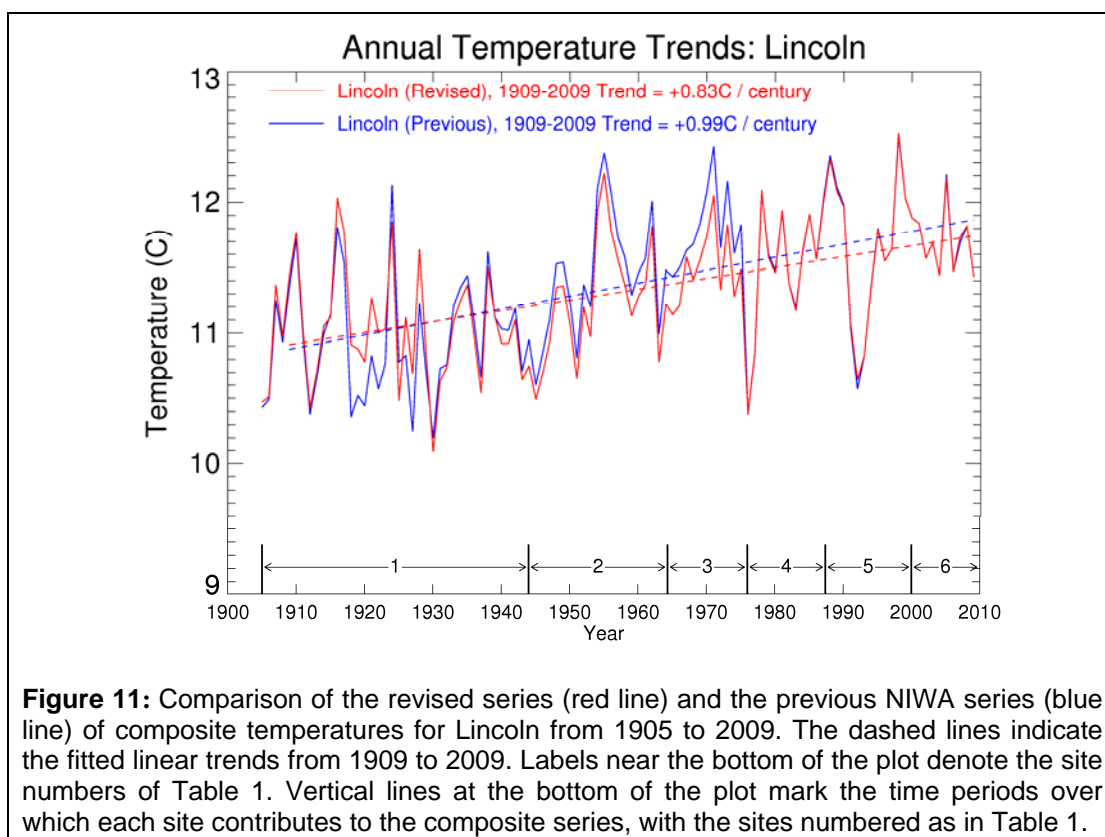
Period	Cumulative Sum of Adjustments (°C)	Cumulative Adjustment (°C)
Jan 1926 to Dec 1943	$0.00 + 0.02 - 0.12 + 0.32 - 0.63$	-0.41
Nov 1923 to Dec 1925	$0.00 + 0.02 - 0.12 + 0.32 - 0.63 - 0.61$	-1.02
Dec 1915 to Oct 1923	$0.00 + 0.02 - 0.12 + 0.32 - 0.63 - 0.61 + 0.57$	-0.45
Jan 1905 to Nov 1915	$0.00 + 0.02 - 0.12 + 0.32 - 0.63 - 0.61 + 0.57 - 0.52$	-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 $0.83 (\pm 0.30) \text{ }^\circ\text{C} / \text{century}$, as compared with $0.99 (\pm 0.32) \text{ }^\circ\text{C} / \text{century}$ for the trend calculated from the seven-station time series published in February 2010.²⁸

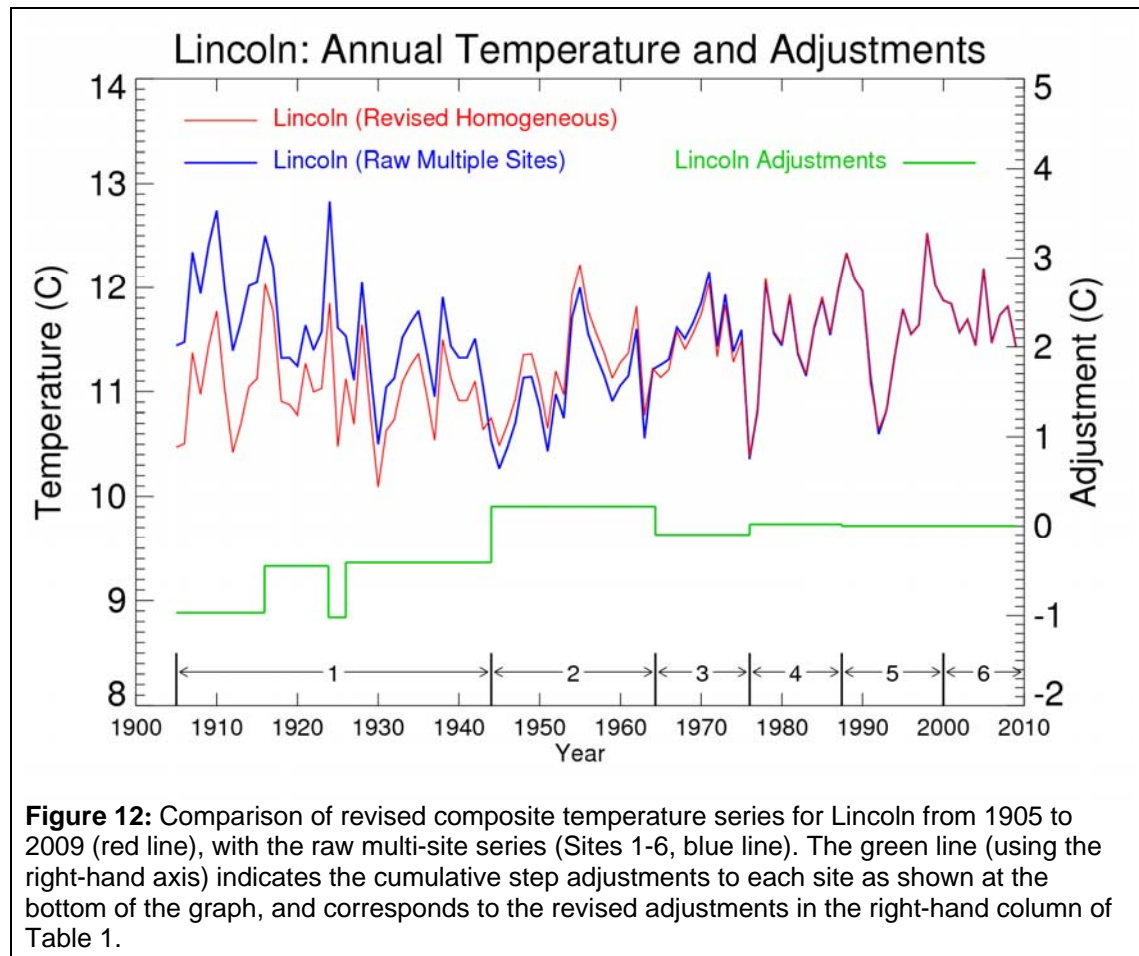


Once the temperatures from the Lincoln sites have been adjusted for consistency with Lincoln Broadfield EWS (Site 6), and then combined, we have a series dating back to 1905. However, simply appending the raw data from the Lincoln records without correcting for known site changes would result in an inhomogeneous 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 ($\pm 0.30 \text{ }^\circ\text{C}$) 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.



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).

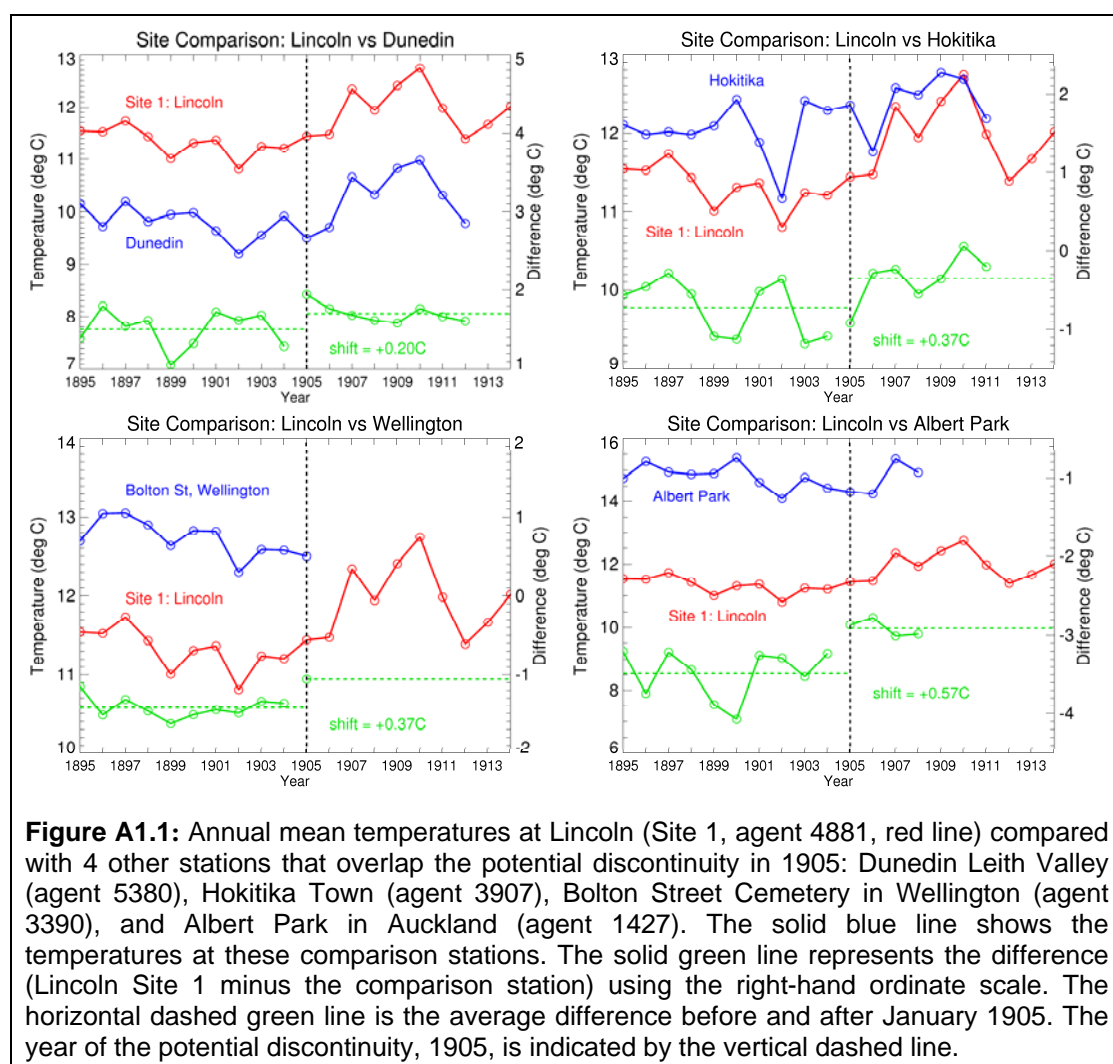
Date: Document originally created 29 October 2010, and revised 13 December 2010 following review from the Australian Bureau of Meteorology.

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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



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 19th century and very early 20th 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. 49 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 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)