Creating a Composite Temperature Series for Auckland

December 2010

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

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

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

This present document revisits and describes in greater detail the process by which a composite station series has been developed for Auckland. The primary purpose is to demonstrate in an intuitive way how to estimate adjustments to temperature records when combining data from different sites, or when there are changes in exposure or instrumentation at a given site. The focus in this document is on annual mean temperature[1]. The data from different sites should 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 minimum temperature. Further research will determine adjustments to monthly maximum and minimum temperatures separately, and apply statistical methods (e.g., RHtests, Wang *et al*., 2007) to identify other change-points in the data.

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

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

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

Calculation of Adjustments

Table 1 summarises the information about the local sites used to develop the composite temperature series for the Auckland location. A comparison is provided between the adjustments in use as at February 2010 (labelled 'Previous Temperature Adjustment'), and the new ones derived in this document (labelled 'Revised Temperature Adjustment'). The previous adjustments were calculated to one decimal place, whereas the revised adjustments are specified to two decimal places.[6] Table 1 lists six different sites as contributing to the composite Auckland temperature series, and one change in the type of screen[7] used. Thus, there are at least seven change-points, and the temperature record must be closely examined before and after the change-dates, in order to identify potential biases.

In the process of documenting the revised adjustments for all the 'seven-station' series, it was recognised that there was lower confidence in New Zealand's early temperature measurements, and there were fewer comparison sites from which to derive adjustments for non-overlapping temperature series. Thus, a decision was made not to include temperatures prior to 1900. Furthermore, if there were site change adjustments around 1910 that were difficult to quantify, then the time series was truncated at that point. In the case of Auckland, the revised series begins with Site 3 in 1909. In the interests of completeness, adjustments are still estimated for the earlier sites, but discussion of them is relegated to the Appendix, along with other more technical comments.

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

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

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

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

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

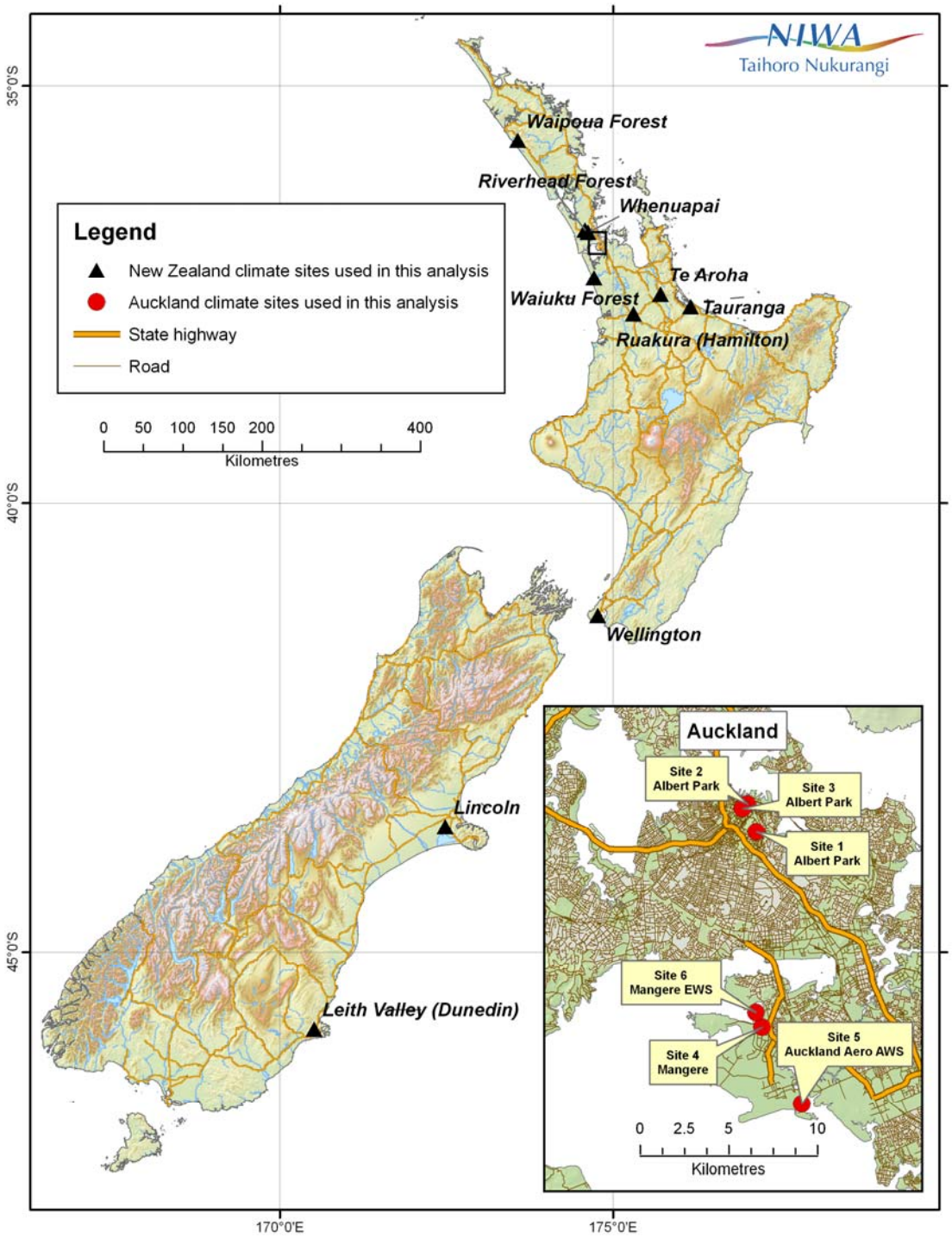

Figure 2: Map showing sites of temperature records referred to within this document. The inset map locates the local Auckland sites.

Adjustment for Site Change in 1998

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

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

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

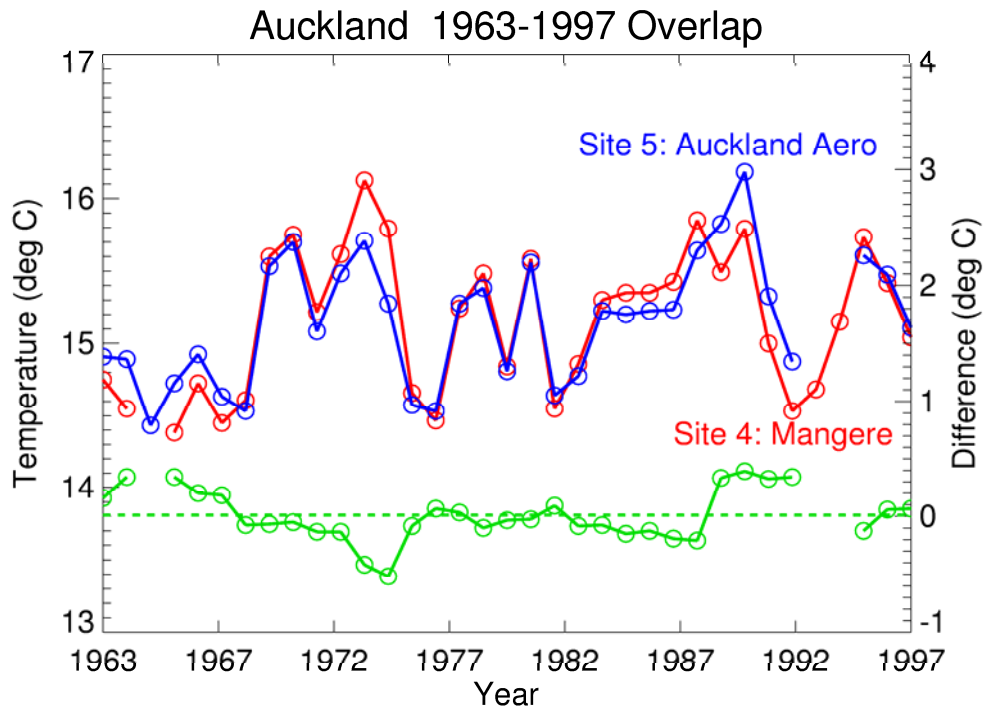

Figure 3: Annual mean temperature series for Mangere (Site 4, agent 1945, red line) and Auckland Aero AWS (Site 5, agent 1962, blue line) from 1963 to 1997. The annual difference, Site 5 minus Site 4, is plotted by the green solid line, using the right-hand ordinate scale, and the mean annual difference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

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

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

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

Adjustment for Site Change in 1975/76

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

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

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

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

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

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

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

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

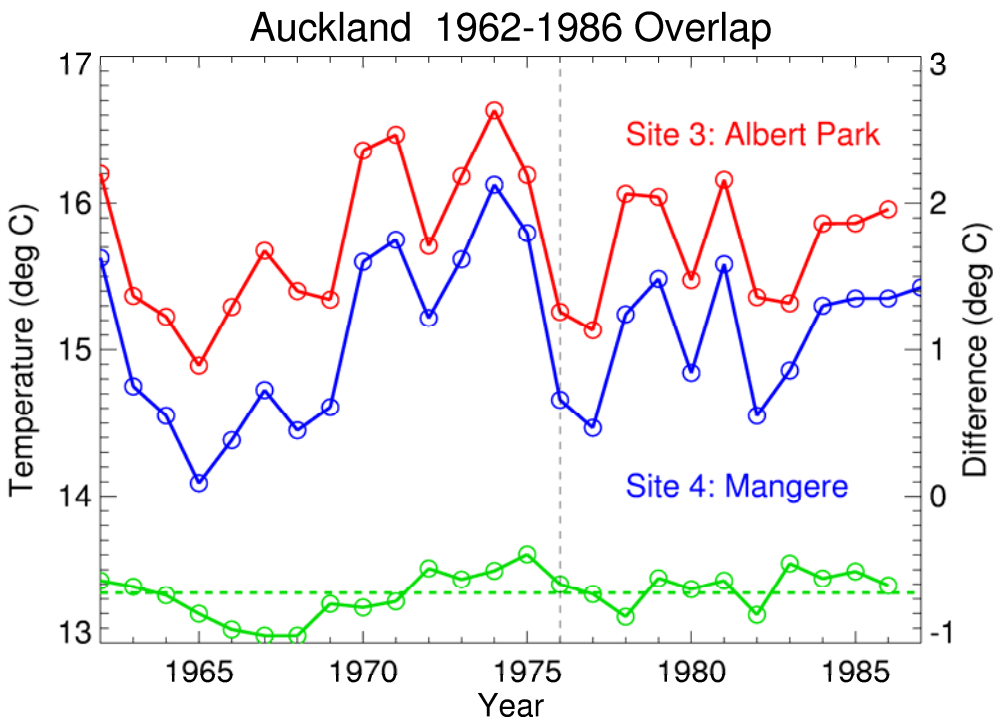

Figure 4: Annual mean temperature series for Albert Park (Site 3, agent 1427, red line) and Mangere (Site 4, agent 1945, blue line) from 1962 to 1986. The annual difference, Site 4 minus Site 3, is plotted by the green solid line, using the right-hand ordinate scale, and the mean annual difference is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

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

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

Adjustment for Screen Change in 1950/51

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

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

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

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

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

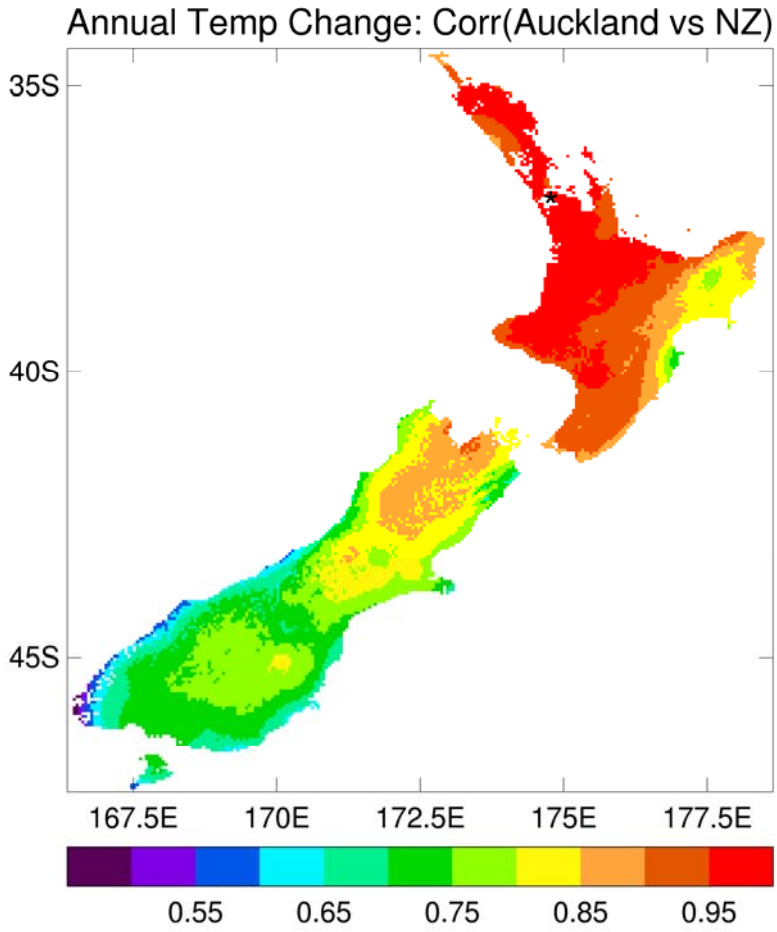

Figure 5: Map of correlation between interannual temperature changes at the grid-point nearest to Auckland Aero (Site 5, location marked by asterisk) near Auckland, 1972-73 to 2007-08, and all other grid-points in the NIWA 0.05° gridded "Virtual Climate Station" data set.

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

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

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

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

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

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

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

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

Site Adjustments Prior to 1910

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

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

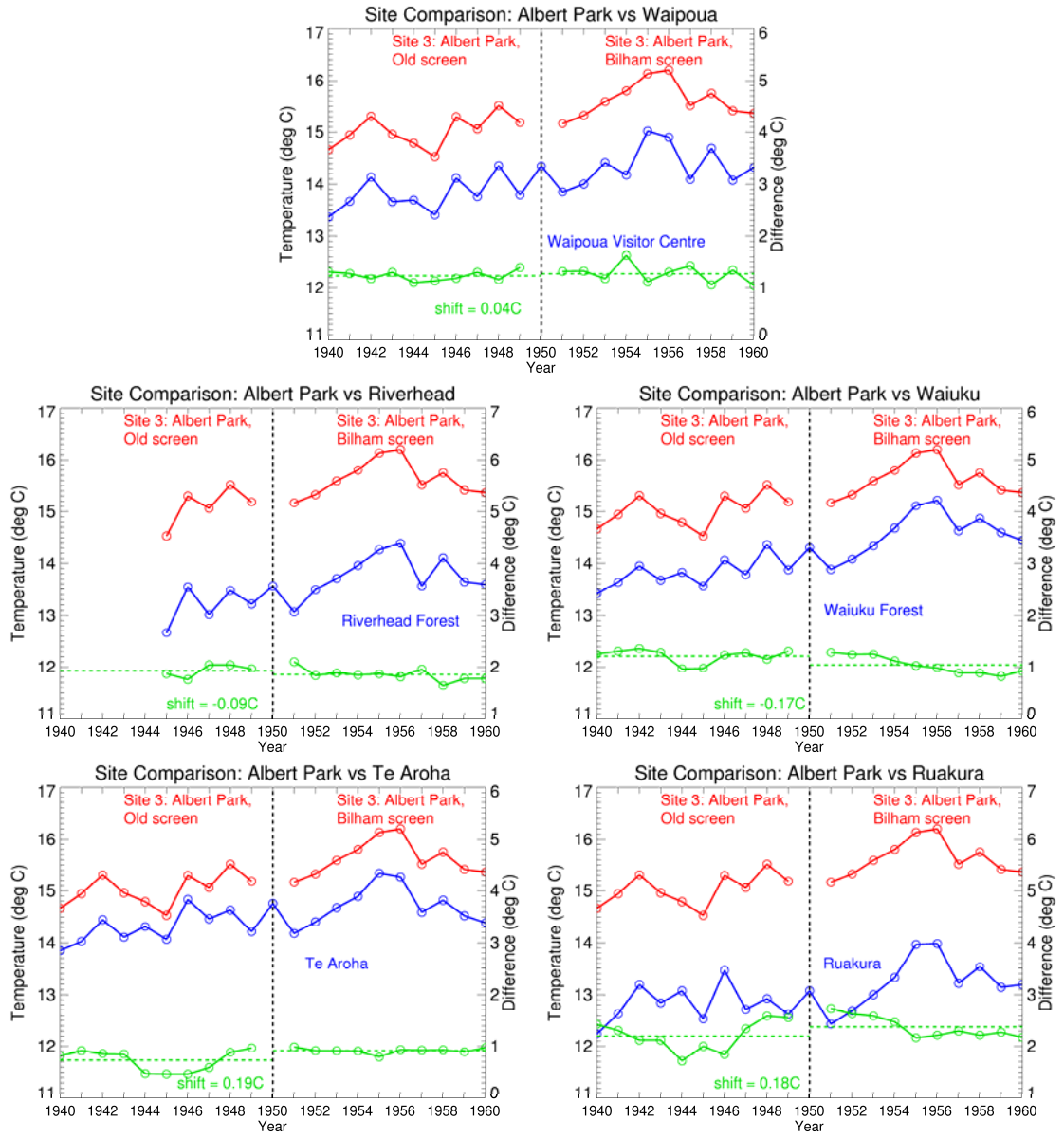

Figure 6: Comparisons of annual mean temperature series at Albert Park (Site 3, agent 1427, red lines on each plot) before and after the screen change in 1950/51 with Waipoua Visitor Centre (agent 1155), Riverhead Forest (agent 1405), Waiuku Forest (agent 2011), Te Aroha (agent 1565), Hamilton, Ruakura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

Putting the Time Series Together

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

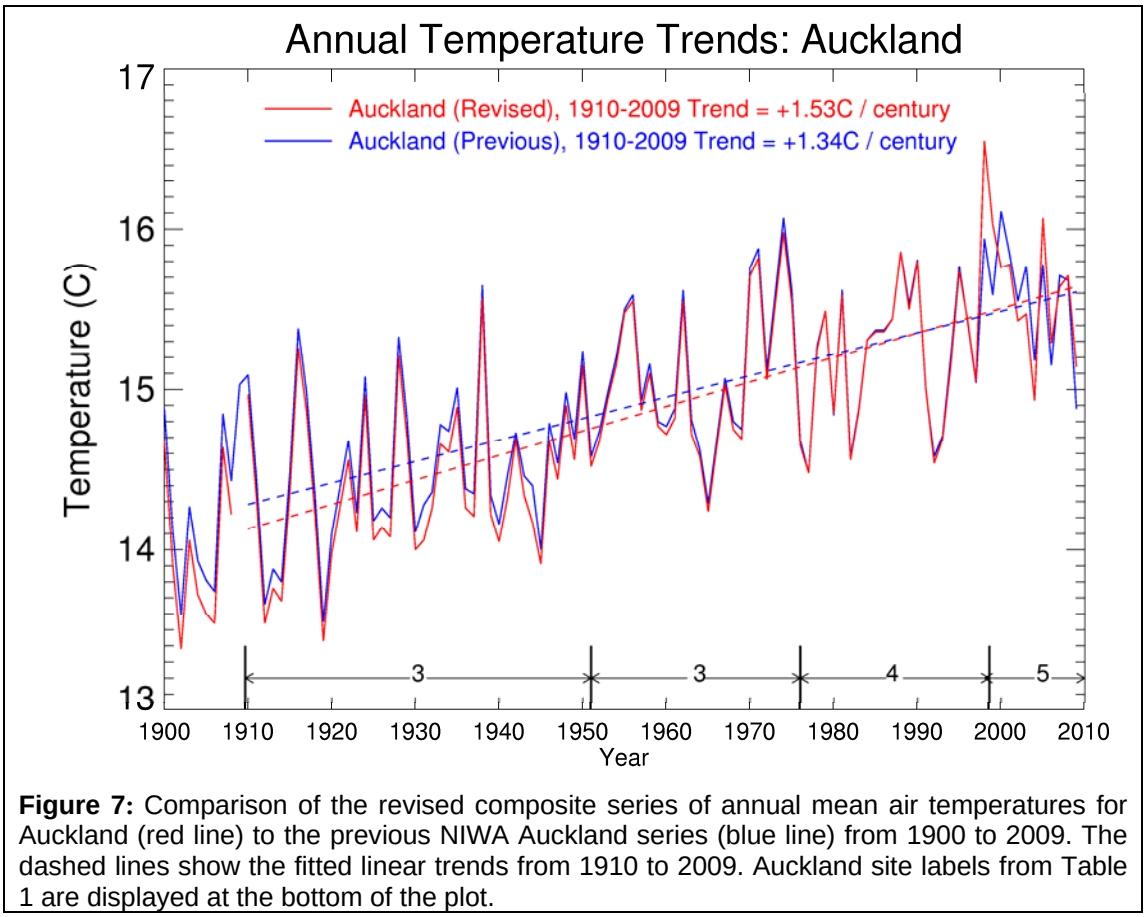

Figure 7: Comparison of the revised composite series of annual mean air temperatures for Auckland (red line) to the previous NIWA Auckland series (blue line) from 1900 to 2009. The dashed lines show the fitted linear trends from 1910 to 2009. Auckland site labels from Table 1 are displayed at the bottom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

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

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

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

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

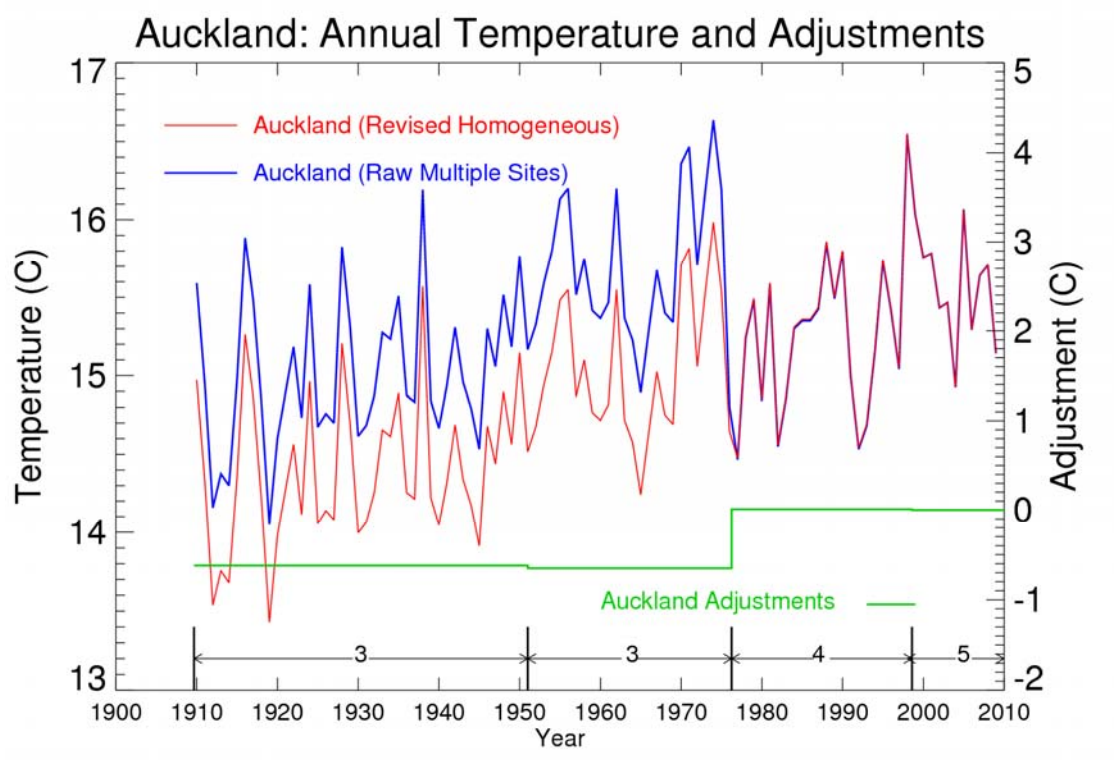

Figure 8: Comparison of the revised composite temperature series for Auckland from 1910 to 2009 (red line), with the raw multi-site series (Sites 3-5, blue line). The green line (using right-hand axis) indicates the cumulative step adjustments to each site as shown at the bottom of the graph, and corresponds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

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

Further Information

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

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Appendix 1

Technical note on the treatment of missing data

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

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

Appendix 2

Adjustment for Mangere EWS in 2002

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

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

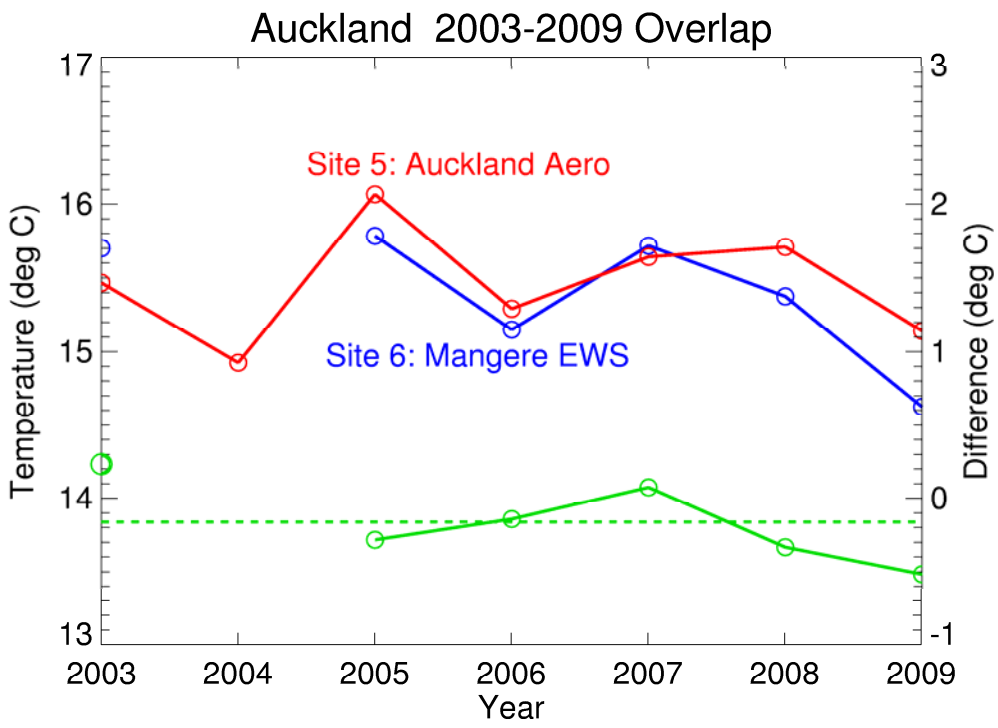

Figure A2.1: Annual mean temperature series for Auckland Aero AWS (Site 5, agent 1962, red line) from 2003 to 2009, and Mangere EWS (Site 6, agent 22719, blue line) from 2005 to 2009 and for the year 2003 (blue circle). The annual difference, Site 6 minus Site 5, is plotted by the green solid line, using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

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

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

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

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

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

Appendix 3

Further discussion of 1950/51 Albert Park screen change

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

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

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

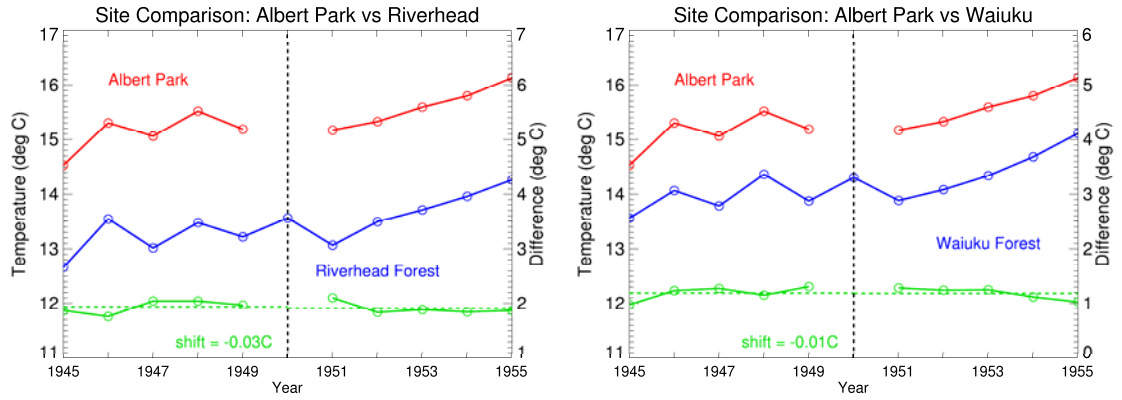

Figure A3.1: Comparisons of annual mean temperature series at Albert Park (Site 3, agent 1427, red lines on the left of each plot) with Riverhead Forest (agent 1405) and Waiuku Forest (agent 2011) from 1945 to 1955, which is the same period as Hessell (1980). The solid blue line shows the temperatures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

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

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

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

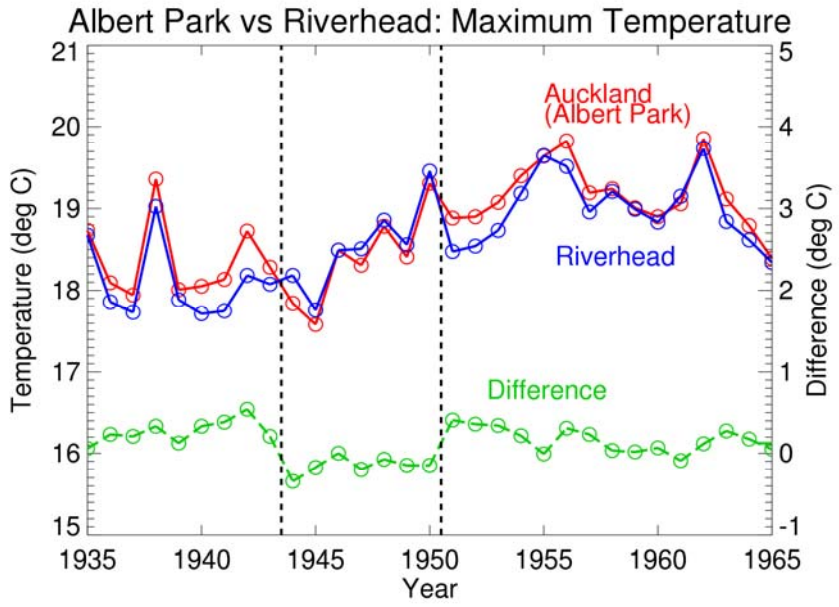

Figure A3.2: Comparison of annually averaged maximum temperature series at Albert Park (Site 3, agent 1427, red line) with Riverhead Forest (agent 1405, blue line) from 1935 to 1965. The difference (Albert Park minus Riverhead) is indicated by the green dashed line, using the right-hand ordinate scale.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

Appendix 4

Adjustment for Site Change in 1909

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

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

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

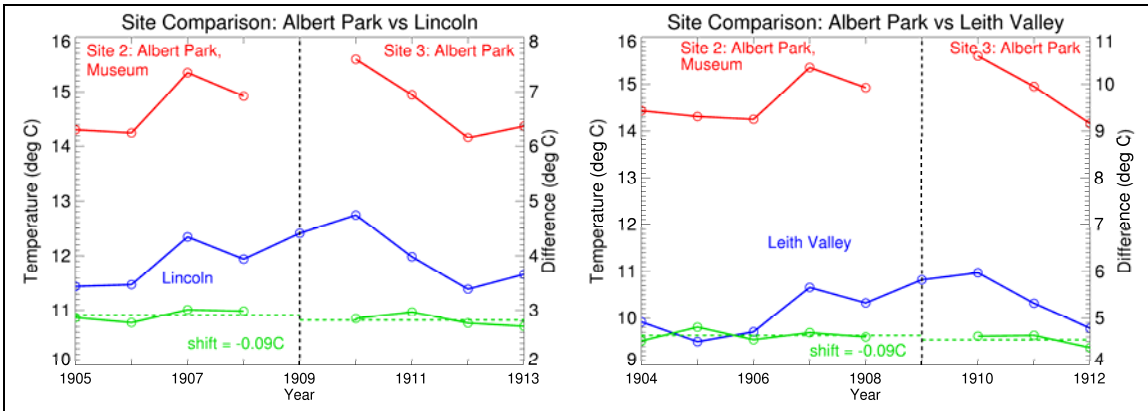

Figure A4.1: Comparisons of annual mean temperature series at the Museum (Site 2, agent 1427, red lines on the left of each plot) and Albert Park (Site 3, agent 1427, red lines on the right of each plot) with Lincoln (agent 4881) from 1905 to 1913, and Dunedin, Leith Valley (agent 5380) from 1904 to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

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

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

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

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

Adjustment for Site Change in 1883

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

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

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

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

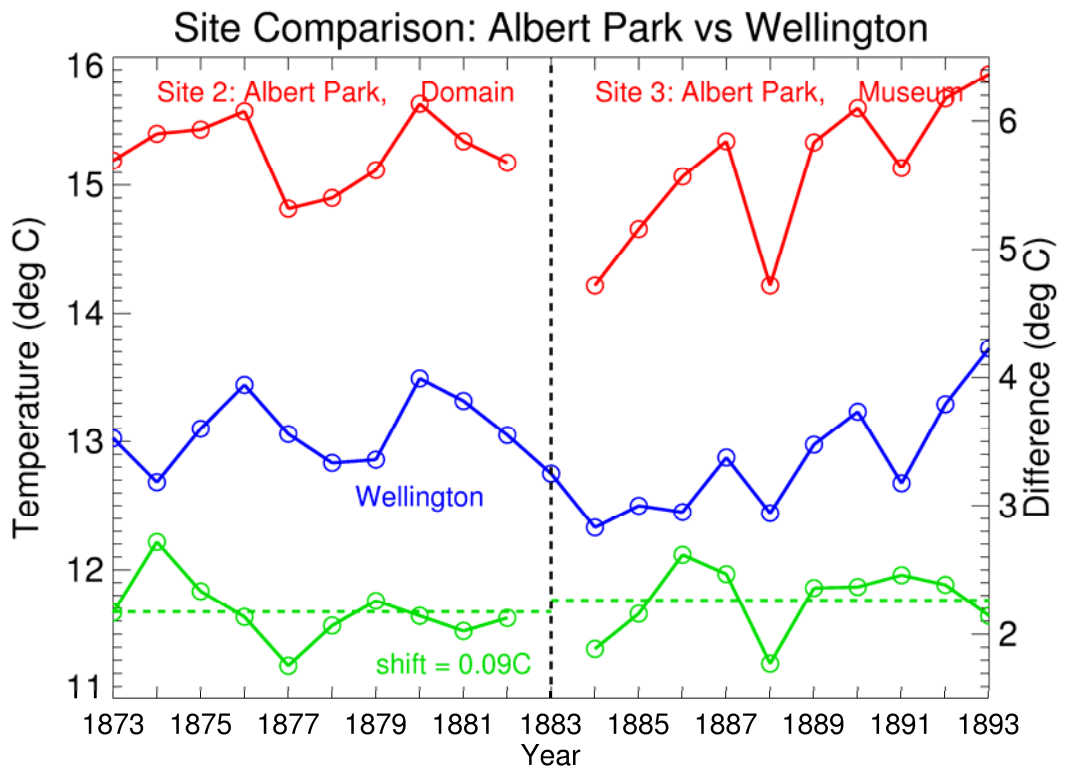

Figure A4.2: Comparisons of annual mean temperature series at the Domain (Site 1, agent 1427, red lines on the left of the plot) and the Museum (Site 2, agent 1427, red lines on the right of the plot) with Wellington, Bolton Street Cemetery (agent 3390, blue line). The differences (Domain/Museum minus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

Appendix 5

Technical note on sheltering/urban heating effects at Albert Park

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

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

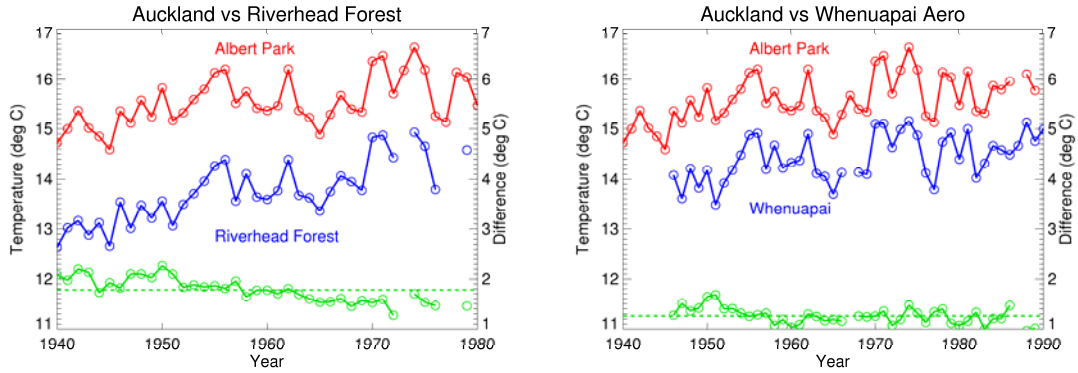

Figure A5.1: Comparison of composite annual temperatures for Auckland Albert Park with Riverhead Forest from 1940 to 1980 (left panel), and Whenuapai Aero from 1940 to 1990 (right panel). The green line indicates the temperature difference, Albert Park minus the other site. Riverhead Forest and Whenuapai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

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

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

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

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

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

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

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

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

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

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

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

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

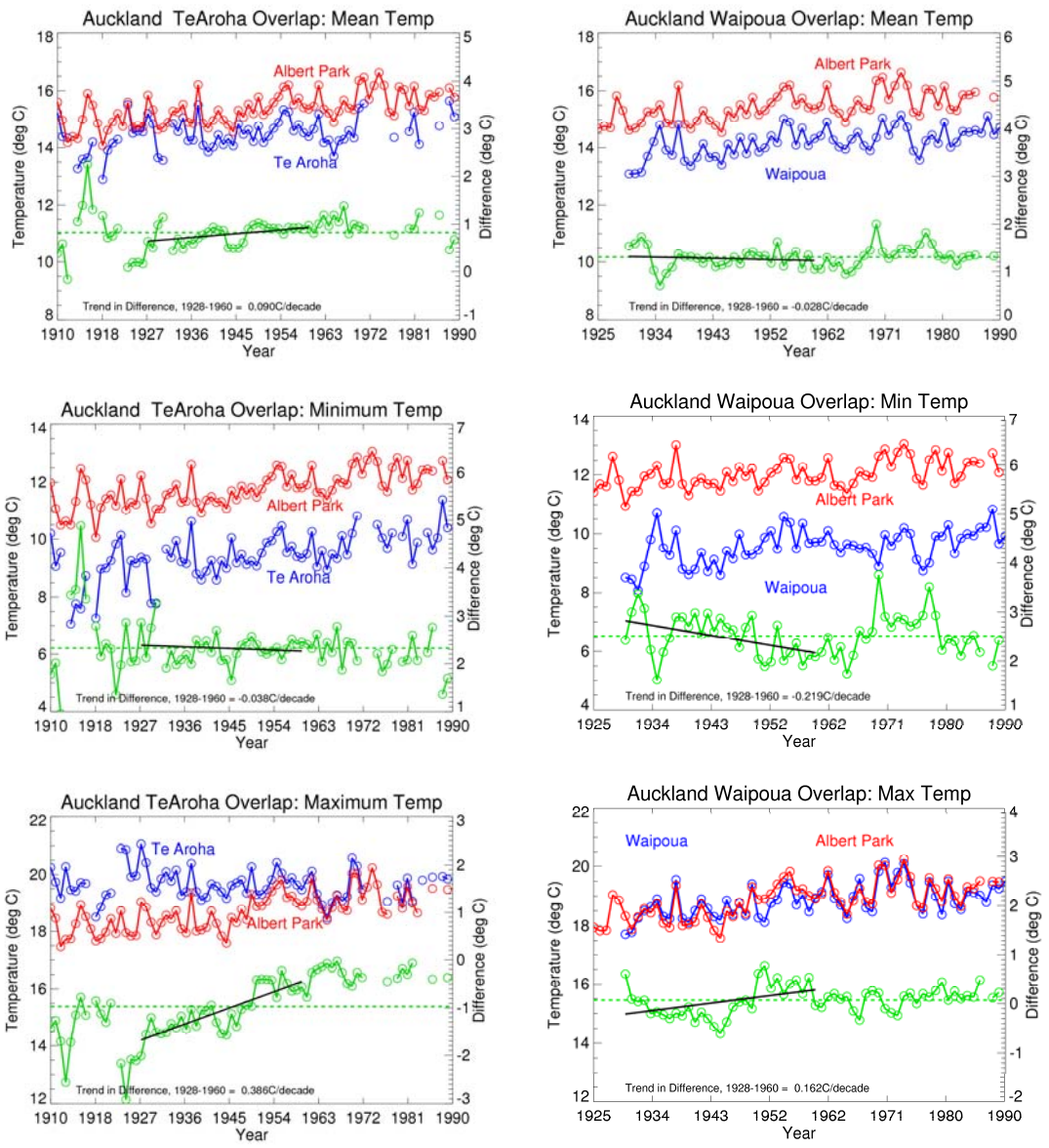

Figure A5.2: Comparison of annual temperatures at Auckland Albert Park with those at Te Aroha (agent 1565, left-hand panels) and at Waipoua Forest (agent 1155, right-hand panels): mean (top), minimum (centre) and maximum (bottom) temperature. In all cases, Albert Park is shown in red and the other site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

Appendix 6

Further discussion of Albert Park temperatures vs other Auckland sites

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

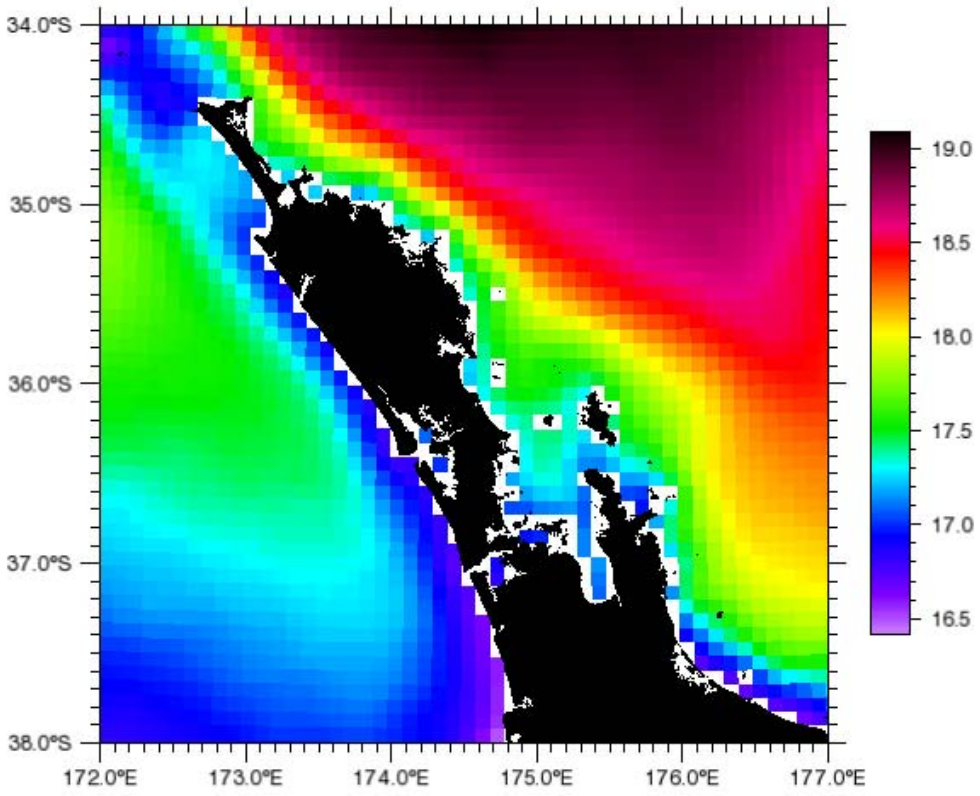

Figure A6.1: Annual mean sea surface temperatures around the northern part of the North Island, based on satellite observations over the period 1993-2002.

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

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

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

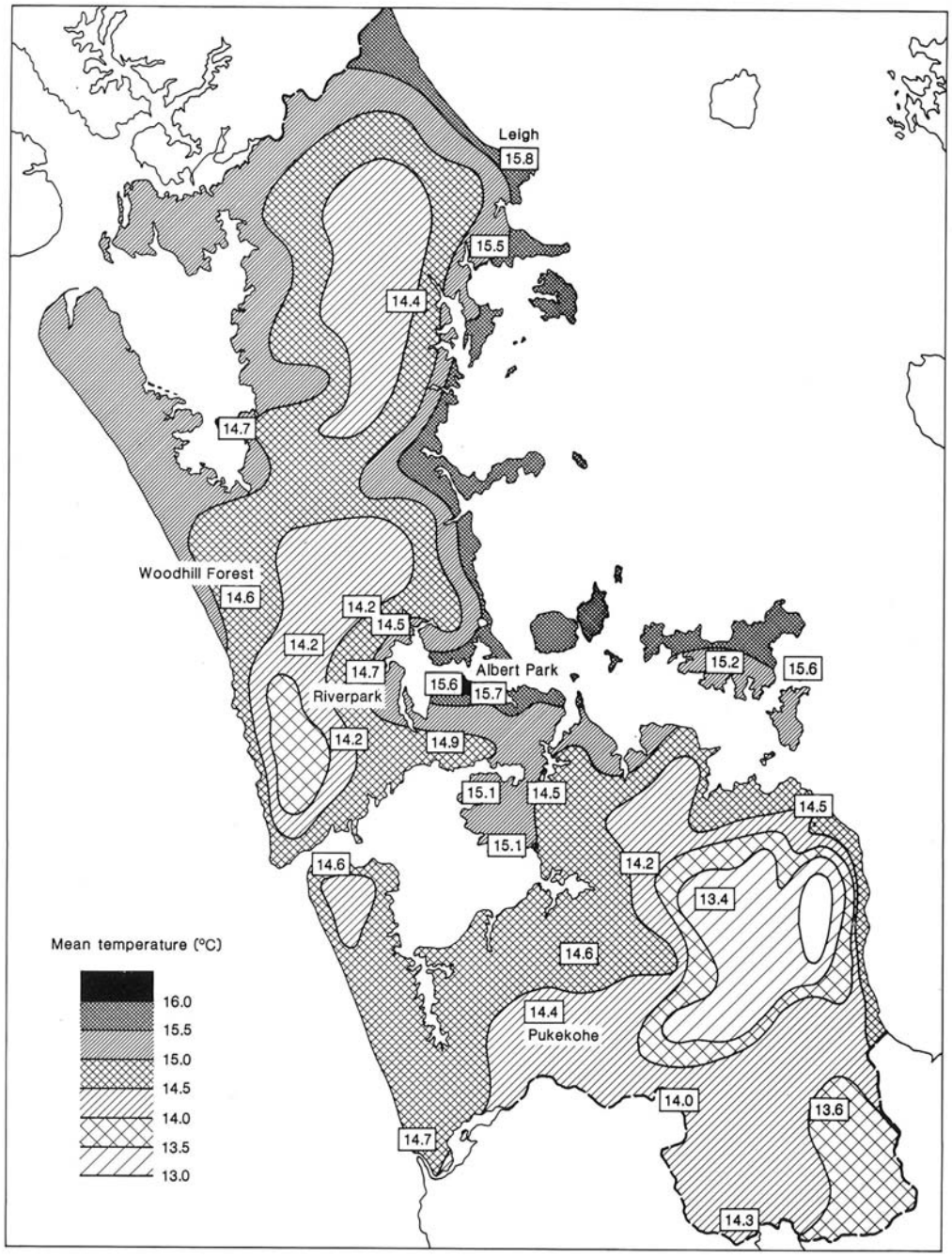

Fig. 21. Mean air temperatures, Auckland region

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