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

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

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

Key Points

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

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

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

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

Further discussion of these points is given below.

Brief History

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

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

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

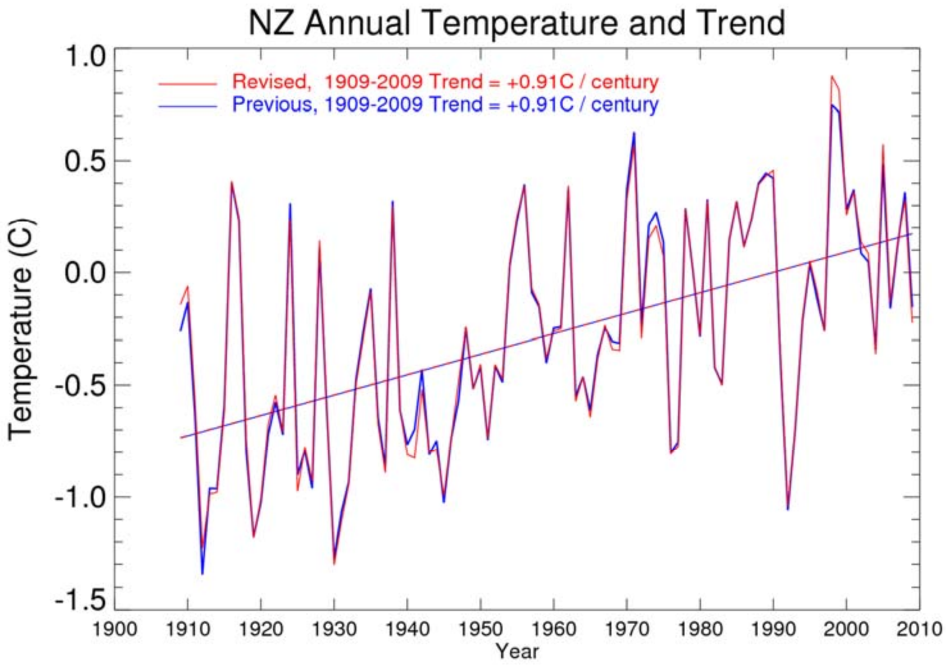

Figure 1: Comparison of the revised seven-station series with the previous one, plotted as anomalies from the 1971-2000 climatology. Averaged over the seven locations, the revised New Zealand trend is +0.91 °C/century compared with the previous estimate of +0.91 °C/century. The 95% confidence interval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

Have our estimates of overall temperature trend changed?

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

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

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

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

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

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

What is the effect of urban heating in Auckland?

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

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

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

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

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

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

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

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

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

What is driving the temperature trend? – Temporal patterns

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

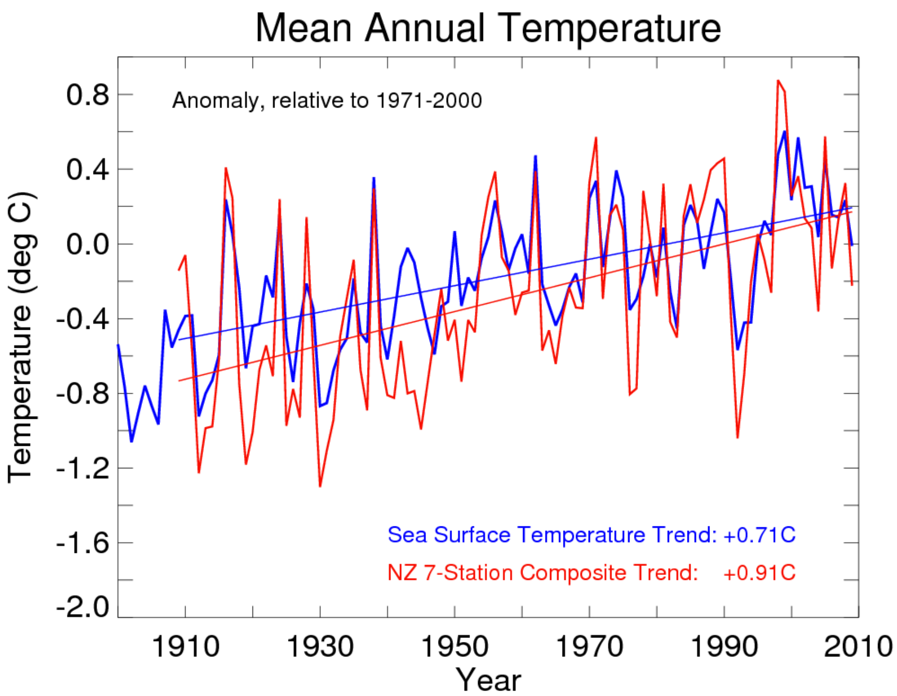

Figure 2: Annual time series NOAA sea surface temperatures (blue line) and NIWA's seven-station composite series (red line), expressed as anomalies relative to the 1971-2000 climatological average. Linear trends over the period 1909-2009, in °C/century, are noted under the graph.

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

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

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

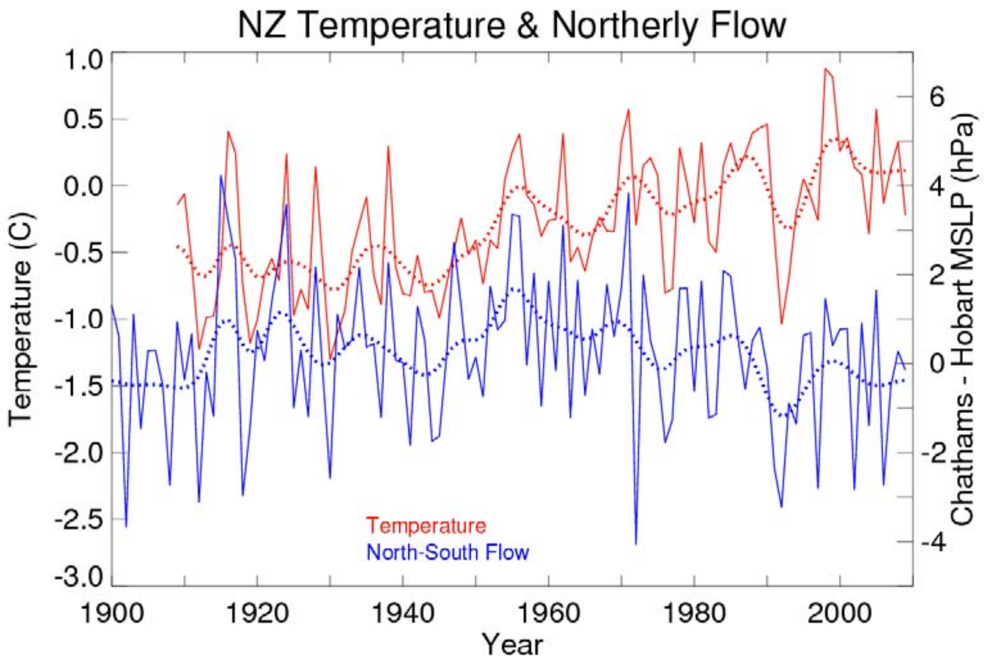

Figure 3: Annual time series of a Tasman Sea Northerly Flow Index (blue line, right-hand axis) and NIWA's seven-station composite temperature series (red line, left-hand axis), expressed as anomalies relative to the 1971-2000 climatological average. The dotted lines are low-pass filtered series which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

What is driving the temperature trend? – Spatial patterns

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

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

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

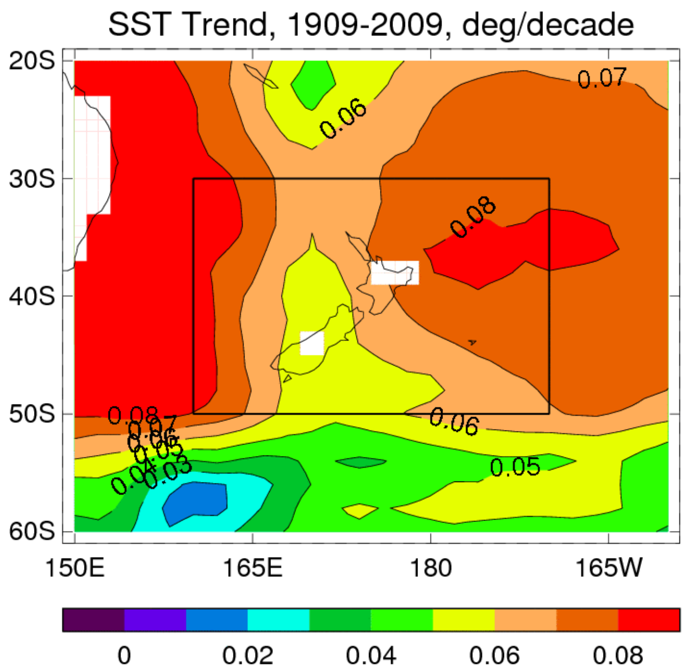

Figure 4: Trends in sea surface temperature, in °C/decade over the period 1909-2009, calculated from the NOAA_ERSST_v3 data-set (provided by NOAA's ESRL Physical Sciences Division, Boulder, Colorado, USA, from their web site at http://www.esrl.noaa.gov/psd/). The data values are on a 2° latitude-longitude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

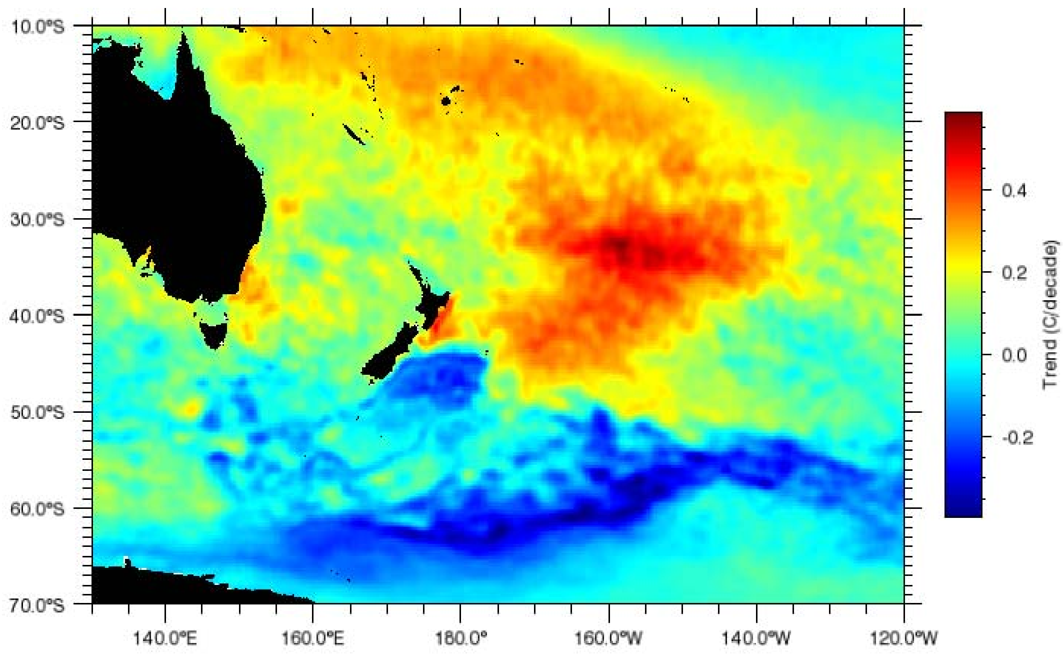

Figure 5: Trends in sea surface temperature, in °C/decade over the period 1982-2009. The data are again taken from NOAA, but are based on daily interpolated satellite measurements over a much finer 0.25° grid.[3]

Further Research

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

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

Why and how we adjust temperature series

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

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

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

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

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

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

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

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

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