Environ Model Assess (2015) 20:399–410
DOI 10.1007/s10666-014-9429-z

A Reanalysis of Long-Term Surface Air Temperature Trends in New Zealand

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Received: 29 December 2013 / Accepted: 7 October 2014 / Published online: 26 October 2014

Abstract Detecting trends in climate is important in assessments of global change based on regional long-term data. Equally important is the reliability of the results that are widely used as a major input for a large number of societal design and planning purposes. New Zealand provides a rare long temperature time series in the Southern Hemisphere, and it is one of the longest continuous climate series available in the Southern Hemisphere Pacific. It is therefore important that this temperature dataset meets the highest quality control standards. New Zealand's national record for the period 1909 to 2009 is analysed and the data homogenized. Current New Zealand century-long climatology based on 1981 methods produces a trend of 0.91 °C per century. Our analysis, which uses updated measurement techniques and corrects for shelter-contaminated data, produces a trend of 0.28 °C per century.

Keywords Data quality control · Climate change · Temperature time series · New Zealand

1 Introduction

Although many studies have assessed the quality of national climate datasets for use in long-term climate change detection [2–5, 6, 7, 12, 19, 21, 24], a homogenized New Zealand national temperature record has only once appeared in the literature [18]. This work did not set out a schedule of adjustments and was based on a measurement technique that was significantly improved by its author [17] over a decade later. Applying that improvement could have a significant effect on trends, but this has never previously been published. The aim here is to apply the method set out by [17] (i.e. Rhoades and Salinger, 1993) exactly as they describe, without adjusting it in any way. In our analysis, we supply the missing schedule of adjustments, recalculated to reflect the improved technique. We also correct for the contamination of raw data identified in the refereed literature [10]. The aim is to derive a modernized New Zealand Temperature Record (NZTR) providing a 100-year time series of mean monthly land surface temperature anomalies.

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2 Background

New Zealand was one of the first countries in the Southern Hemisphere to establish an official nationwide system of weather records. These records provide a rare long time series for temperatures in the Pacific Ocean, informing the data sparse interpolations required for early temperature series. Extant 1868 archives record the national normal mean surface temperature at 13.1 °C (when converted from degrees Fahrenheit) being the average of 10+years read at six representative weather stations. Another major compilation, covering 35 years and based on nine stations, was published by the Dominion Meteorologist in 1920, which showed that the country's average temperature has remained remarkably stable since records began. In 2010, the National Institute for Water and Atmospheric Research (NIWA) assessed the current national normal at 12.74 °C being the average of 30 years read at seven stations. On the face of it, New Zealand's long-term mean temperature has remained relatively stable at 12.6 °C over the past 150 years.

In 1980, M.J. Salinger published a homogenized "Composite New Zealand Temperature Series" [18]. Cluster analysis was used to divide the country into six temperature response areas, which were considered well represented by seven stations (Auckland, Masterton, Wellington, Nelson, Hokitika, Lincoln and Dunedin) selected for their long history, low errors and relatively homogeneous data (see Figs. 1 and 2). The degree of temporal conformity of temperature fluctuations and trends between response areas was tested by correlating temperature data. It was found that warming and cooling anomalies were generally synchronous throughout New Zealand, facilitating the use of a nationwide temperature curve. The paper notes that the raw data were "carefully adjusted for site changes and other disturbances", but no detail is provided. The composite New Zealand Temperature Record (NZTR or "seven-station series" or "7SS") that was then produced is said to be highly correlated with shorter-term area-weighted studies of New Zealand as a whole. The Salinger [18] paper shows a warming trend of approximately 1 °C per century during 1853–1975, noting that "the last 25 years (1950–75) have been particularly warm".

In an annex to an unpublished 1981 doctoral thesis ("New Zealand Climate: The Instrumental Record") undertaken at Victoria University of Wellington, the author M.J. Salinger elaborated on the adjustments he had used in homogenizing the 7SS temperature data. They were based on the principle of neighbour station comparisons, with an elastic definition of the term "neighbour", using comparisons of trend variances within the seven station datasets. This was justified (at p.71) by noting: "As there are only a handful of stations operating for the early record, comparisons are instead made with all available stations in operation. The larger distances between the earlier sites mean that comparisons are no longer 'neighbour station', but these comparisons are better than none for assessing homogeneous data series." It is also relevant that temperature fluctuations at all

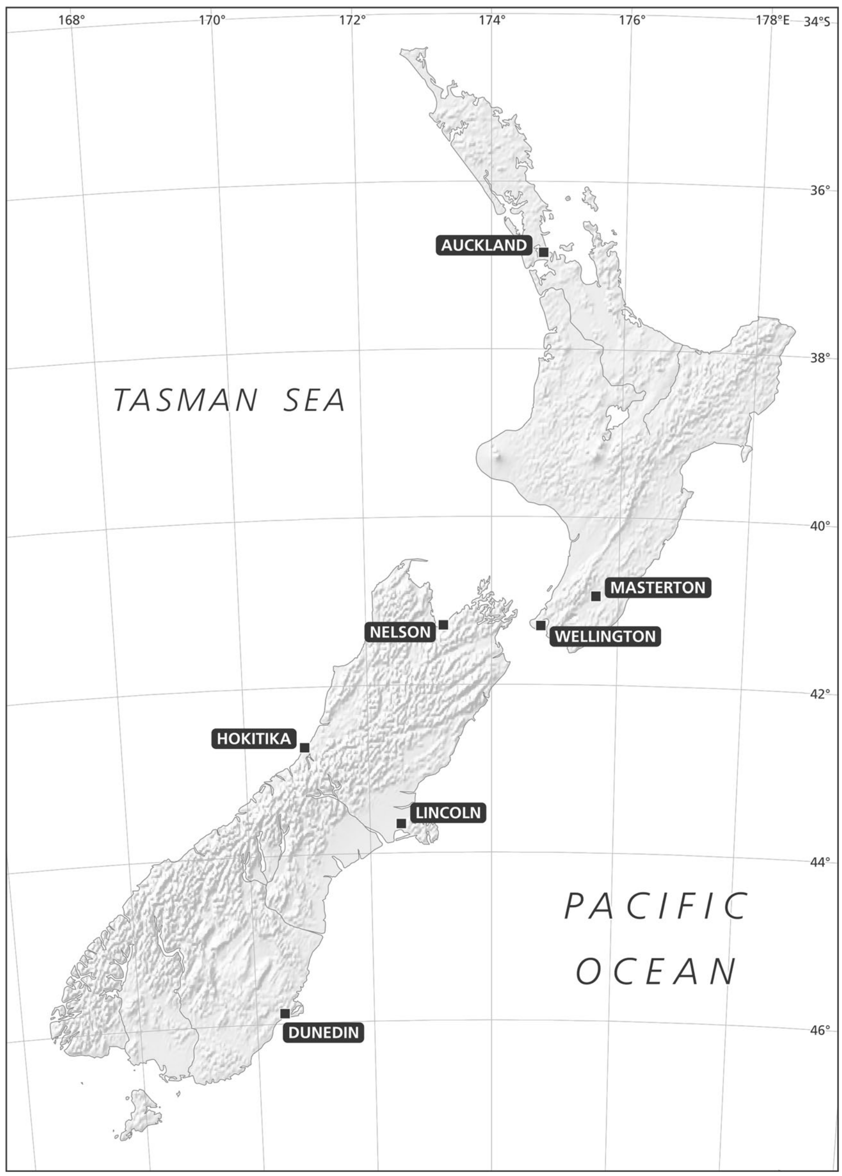

Fig. 1 Location of seven climate stations in New Zealand that have long records, namely, Auckland, Masterton, Wellington, Hokitika, Nelson, Lincoln and Dunedin

Fig. 2 Location of Auckland regional stations Whenuapai, Albert Park, Mangere, Auckland Aero and Ardmore

New Zealand stations are broadly synchronous. The method for statistical measurement of adjustments was described in the thesis annex, but calculations were omitted. We will hereafter use the term "S81" to refer to the published 1980 paper [18] in conjunction with the unpublished thesis elaborations.

James Hessell, senior climatologist at the New Zealand Meteorological Service, produced a contemporaneous peer-reviewed journal paper on the subject of New Zealand temperature records [10]. He identified which weather stations were "reliable" (i.e. unaffected by site changes) and found that those stations showed no warming trend during the half-century from 1930 to 1979. The Hessell paper conducted wind-run tests and urban–rural station contrasts to identify and exclude sites affected by shelter or urban heat island (UHI) effects. In essence, he found that any warming appearing from the 1930 to 1979 raw data was attributable to non-meteorological site effects. Amongst the stations found to be unreliable were Auckland and Wellington, which are components of Salinger's 7SS. Notably, S81 had conducted no tests for "creeping" inhomogeneities such as sheltering or UHI and consequently made no attempt to correct the 7SS for site effects.

In 1993, in collaboration with a statistician D. A. Rhoades, Salinger published "Adjustment of Temperature and Rainfall Records for Site Changes" [17] or "RS93". This paper was accepted locally as a seminal authority for the statistical techniques to be used in measuring differences between the temperatures of compared stations.

3 The New Zealand Temperature Record

In 1999, the 7SS was recognized by NIWA and posted on its website in graphical form. Since that time, its derived 1 °C per century trend has been used constantly in official government publications. This usage drew attention to the fact that its high warming trend was attributable to undisclosed adjustments insofar as there was no record of what adjustments were made or reference to existing material that might shed light on alterations made. The question also arises as to why data concerns raised in the undisputed findings of the two journal papers [10, 17] were not considered. NIWA scientists reanalysed the 7SS in 2010 [25] and derived a 'Schedule of Adjustments', showing the station time and value of some 35 adjustments. This work is the 'revised 7SS', referred to hereafter as "M10". M10 uses the period 1909–2008, which showed the same trend as the original 7SS, namely, 0.91 °C per century. The reason for omitting the years prior to 1908 was that very large gaps in the available data failed to satisfy modern quality standards.

In this paper, we address the mean temperature data for the 7SS stations in respect of the century-long period 1909–2008, agreeing with NIWA that data gaps prior to 1909 reduce reliability below acceptable levels. Our starting point is the Schedule of Adjustments showing the 20 data adjustments made by S81 during the 1909–1975 period. The dates and circumstances of 7SS site changes were initially identified in

S81 through a detailed analysis of station histories and other available metadata. Two well-documented post-1975 Auckland site changes are added. We use the same broad methodology as S81/M10 in differencing the target station data from those of comparison stations before and after the dates of inhomogeneities. The selection of comparison stations is necessarily confined by the dearth of high quality data pre-World War II, and we have used the same comparison stations as M10 for all adjustments. In the result, our methodology and data inputs wholly coincide with M10 except in two respects: (a) the use of RS93 statistical techniques to measure differences, as opposed to S81/M1 measurement techniques (Table 1), and (b) acceptance of the findings of Hessell's [10] paper regarding the contamination of Auckland and Wellington raw data.

4 Rhoades and Salinger—RS93

The Rhoades and Salinger [17] paper (RS93) deals with the detection and elimination of temperature data movements that are of non-meteorological origin. With respect to changes in the environment adjacent to observation sites, the authors advise that "for studies of climate change, it is best to choose stations that are unlikely to be affected by gradual changes in shading or urbanisation" ([17], p. 899). However, sudden changes, such as those caused by shifts in observation sites or replacement of measuring devices, can be identified, measured and corrected by the application of appropriate statistical methodology.

The work Rhoades and Salinger [17] are concerned with is the measurement of site change effects when the nature and times of changes are known a priori from station records or other metadata. It describes a method for target stations where neighbouring stations are available for comparison—defining "neighbouring" as "subject to similar local weather conditions" ([17], p. 900). A different method is provided for isolated stations, noting that it is more difficult to distinguish site change effects from regional meteorological effects. The authors warn that statistical tests for change usually assume that successive observations are independent identically distributed random variables, whereas the complexity of weather systems may mean that those assumptions are violated.

In dealing with a site change known a priori by way of comparison with "neighbouring" stations, RS93 faces the same measurement issues as did S81. Both papers consider statistical differences between before-and-after temperature averages at the target station and those at comparison stations. In RS93, the measurement techniques for those differences contrast with those applied in S81 in the following respects:

1. RS93 uses monthly data whilst S81 used annual data.
2. RS93 takes short before-and-after periods (e.g. 24 months), whilst S81 used long periods (e.g. 10 years or more).
3. RS93 weights the averages of data from comparison stations based on relative correlation coefficients, whist S81 used unweighted averages.
4. RS93 excludes proposed adjustments that are not statistically significant at the 95 % level, whilst S81 did not measure confidence intervals for adjustments.

In summary, the RS93 method is a pairwise station comparison technique to quantify the magnitude of a site move by differencing data from two similar stations before and after a known site change. To minimize the potential impact of unrecognized long-term gradual inhomogeneities (such as shelter growth or UHI) at one or both of the stations, RS93 reduces the length of the comparison period using monthly data. Seasonal effects are eliminated by differencing each series by corresponding months only, either 1 or 2 years removed. A strong (fourth power) weighting is applied to reduce the effects of poorly correlating stations while enhancing the influence of well-correlated stations. The RS93 method has been applied as exactly as possible, without attempting to improve or adjust it, to determine what effect its application has on the S81 seven-station series.

The use of monthly (if not daily) data and significance testing [15] has become standard international practices, reflected in recent papers such as [23] and [22]. The use of monthly data offers more degrees of freedom, while significance testing balances the risks between type I and type II errors. Weighting the average outcome of comparisons is also standard, although the drivers of that weighting may vary with the circumstances. In the case of the 7SS, the reference stations are not "neighbouring" and are sometimes geographically distant. Using the heavy correlation weightings of RS93

Table 1 Statistical techniques employed in the S81 and RS93 analyses

	S81	RS93
Data	Annual means	Monthly means
Length of comparison (±)	Maximum period available	Up to 36 months
Weighting	Unweighted	Correlation (power of 4)
Significance testing	Untested	95 % confidence tests
Station selection	Any	No known site changes

self-selects those reference stations with the highest relevance for the strongest role.

The limited comparison period circumscribes the ever-present risk of distortion by undocumented data inhomogeneities, whether sudden or gradual, at a reference station. This risk is greater when the raw data have not been screened or tested for data irregularities or suspected site effects, as is the case with the S81/M10 datasets. RS93 ([17], at p. 900) notes: "The use of monthly differences means that the t-statistic has relatively high degrees of freedom even when computed from a short time interval of only 1 or 2 years before and after the site change. The period of comparison is kept relatively short in order to avoid contamination by gradual effects, or sudden but unrecognized effects, at one or more of the neighbouring stations… The usual concern to maximise the power of the test is balanced by an opposing concern that the modelling assumptions are likely to be more seriously invalidated as the period of comparison is lengthened." We note that [14] (p. 1206) also used ±24-month comparison periods by default for their algorithm based on pairwise comparisons. RS93 illustrates its overall method in a detailed example of adjustments for a known site change in Christchurch using ±2-year periods ([17], p. 104–108).

We regarded the RS93 method as superior to that of its predecessor S81 for several reasons. Foremost among them is that RS93 itself makes a compelling case for each of the method's four characteristics. Secondly, the author common to both papers, Salinger, clearly regarded his published 1993 version as an improvement upon his earlier unpublished attempts. Thirdly, RS93 was published in the peer-reviewed literature, chosen as one of 21 exemplars in the omnibus paper by Peterson et al. [16] and cited with approval in the WMO 'Adjustments' Manual of 2003. It has been the adjustment method of choice in New Zealand climatology for two decades, and we are unaware of any serious criticism or dispute regarding it. All this is not to say that improvements could not be found, particularly amongst modern automated homogenizing methods. Rather, this seminal local paper provides an obvious foundation for homogenizing any New Zealand temperature series.

5 Method

5.1 Description

Our method follows the RS93 neighbour comparison techniques for estimating the effect of known site changes but extends that approach to comparisons between well-correlated distant stations. We de-trend the inhomogeneous section where necessary by using the slope calculated from a reference time series. Note that we have not modified the RS93 method at all, and we follow the same process as laid out in the worked example (section 2.4) in that paper.

Each of the n stations is denoted using the convention $i=0,1,2,\ldots,n$ where $i=0$ is the 'candidate' station with the site change. The other stations are the reference stations. We denote $x_t^{(i)}$ as the average temperature measured in month number t at station i where $t=1,2,\ldots$ Assume a station site change occurred at time τ and that τ falls on the first day of the month. This is a valid assumption for most planned site changes in New Zealand. First, the difference series $y^{(i)}$ are calculated, for 12-month ($k=1$) and 24-month ($k=2$) cases; that is:

$$y_t^{(i)} = x_{\tau+t}^{(i)} - x_{\tau+t-12k}^{(i)} \quad where = 1, 2, \ldots, 12k$$

In other words, if the station change occurred at the end of December 1975, y_1 for any station (when $k=1$) is the January 1976 temperature minus the January 1975 temperature. The term y_2 is February 1976 minus February 1975, up to December 1976 minus December 1975. For $k=2$, y_1 is January 1976 minus January 1974, y_2 is February 1976 minus February 1974, up to December 1976 minus December 1974. So, when $k=1$, there are just 12 $y_t^{(i)}$ values, and when $k=2$, there are 24. The differencing "is intended to remove any seasonal effect, and, in the absence of a trend or a real effect due to the site change, $y_t^{(i)}$ would be a random variable with zero mean" [9] (RS93, p. 904).

Once all the $y^{(i)}$ series have been assembled, the correlations ρ_i are calculated (using $k=1$ in this case, although other values of k are permissible [13] (RS93, p.906)) between each differenced series $y^{(i)}$ ($i=1,2,\ldots,n$) and $y^{(0)}$ as follows:

$$\rho_i = \frac{\sum \left(y_t^{(0)} - \overline{y_t^{(0)}}\right)\left(y_t^{(i)} - \overline{y_t^{(1)}}\right)}{\sqrt{\sum \left(y_t^{(0)} - \overline{y_t^{(0)}}\right)^2 \sum \left(y_t^{(i)} - \overline{y_t^{(1)}}\right)^2}} \text{where } t = 1 \text{ to } 12k$$

The overbar in the preceding equation indicates an average over all t. The weights (w) are computed using the 4th power of the correlations, where:

$$w_i = \rho_i^4 \Big/ \sum_{j=1}^{n} \rho_j^4$$

The weighted differences (z) between the $y^{(i)}$ series and the base series $y^{(0)}$ are:

$$z_t = \sum_{i=1}^{n} w_i y_t^{(i)} - y_t^{(0)}$$

Finally, the mean of the differences is calculated:

$$\bar{z} = \sum_{t=1}^{12k} \frac{z_t}{12k}$$

The preceding calculations are performed for both cases $k=1$ and $k=2$. The 95 % confidence intervals are computed in the standard manner: $\bar{z}$ ±2.201 s for $k=1$ and $\bar{z}$ ±2.069 s for $k=2$, where s is the standard error of $\bar{z}$, with no adjustment for autocorrelation of the time series. Throughout this document, the 95 % confidence interval will be quoted unless explicitly stated otherwise. If the 95 % confidence interval does not contain zero, the adjustment is valid. The adjustment is made by subtracting $\bar{z}$ from the base $x_t^{(0)}$ series for all values pre-change (i.e. replace $x_t^{(0)}$ by $x_t^{(0)}-\bar{z}$ for $t<\tau$). This has the effect of raising pre-change values if the value of $\bar{z}$ is negative and lowering them if $\bar{z}$ is positive.

The convention has been to use the mean of both the significant results, for $k=1$ and $k=2$, when making an adjustment. If, on the other hand, the 95 % confidence interval contains zero (i.e. the 95 % confidence limit is greater than the shift itself), no adjustment is made. In some cases, where there are conflicting results between $k=1$ and 2, $k=3$ has been used to break the deadlock, but these cases are rare. RS93 advocates taking a conservative approach: adjustments should not be made unless there is clear and unambiguous evidence of a genuine shift in temperatures as the result of a site change.

5.2 Gradual Inhomogeneities

Many archivists exclude stations in metropolitan areas from the calculation of national long-term temperature trends, a clear example being the Australian Bureau of Meteorology, as explained in [6] and [20]. McAneney et al. [13] found that sheltering by nearby trees can increase daily maximum temperatures by 1 °C per 10 m of shelter growth over a 6-year period. After examining a range of New Zealand stations, [10] determined that two of the stations used in the 7SS were climatically unrepresentative and assessed them "to have increased sheltering from trees … and/or significant urbanisation and/or screen changes" [[10], p. 5]. The sites are Albert Park in Auckland and Kelburn in Wellington. These sites, within the central business districts of two of New Zealand's largest cities, form the major portion of the Auckland and Wellington temperature series.

Hessell ([10], p. 1) describes the Albert Park site (1909–1976) as follows:

> Visitors to this central city park today cannot fail to be impressed by the many large exotic trees, most of which were planted about the turn of the century and some of which … are still growing. The instrument enclosure is surrounded on all sides by trees and buildings which shelter the site to a great degree.

The metadata refers to "a considerable effect on windflow" as well as sunshine. The daily mean wind run data 1916–1975 graphed by [10] (p. 4) displays a continuing dramatic reduction (except at the time of an anemometer change) not experienced elsewhere in the region. Hessell [10] also finds a strong temperature trend bias in the data "unlikely to be due to a broadscale climatic effect". A 12-year comparison suggested that Albert Park had warmed 0.6 °C more than a rural counterpart 10 km distant ([10], p. 8, Table 6).

There are no nearby long series to compare with Albert Park. The closest, which is described as "reliable" in [10], is at Te Aroha, some 114 km to the southeast. A Te Aroha comparison suggests that steady relative mean warming at Albert Park averaging 0.09 °C per decade during the period data from this station is available. If that distortion is not subtracted, any overlap comparison performed on this series will compound the error. This is illustrated in Fig. 3 using a diagram from [9].

For the full 1916–1975 period of Albert Park contamination, the only available reference series comprises the homogenized datasets for Masterton, Nelson, Hokitika, Lincoln, and Dunedin. The averaged trend of these five stations is compared to Albert Park in Fig. 4. This averaged trend was used to reduce the Albert Park trend over 1916–1975.

From 1976, Auckland data are drawn from the Mangere treatment plant, sited amongst newly commissioned settling ponds (Fig. 2). In 1998, the site moved a short distance to Auckland Aero, the country's principal international/domestic

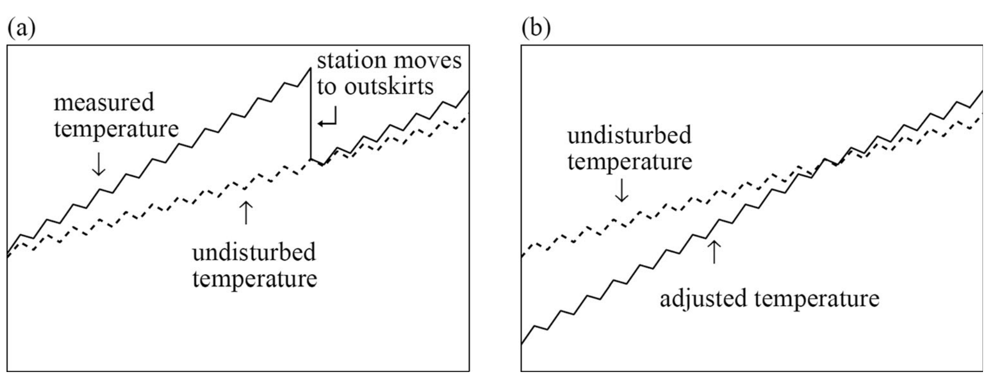

Fig. 3 Schematic illustration of a temperature record at a site experiencing urban warming. The full caption for this figure from [9] reads: **a** Schematic illustration of a temperature record at a site experiencing urban warming and a station moved from the urban center to the urban outskirts. **b** The temperature record adjusted for the discontinuity has a stronger warming trend than that in the undisturbed environment

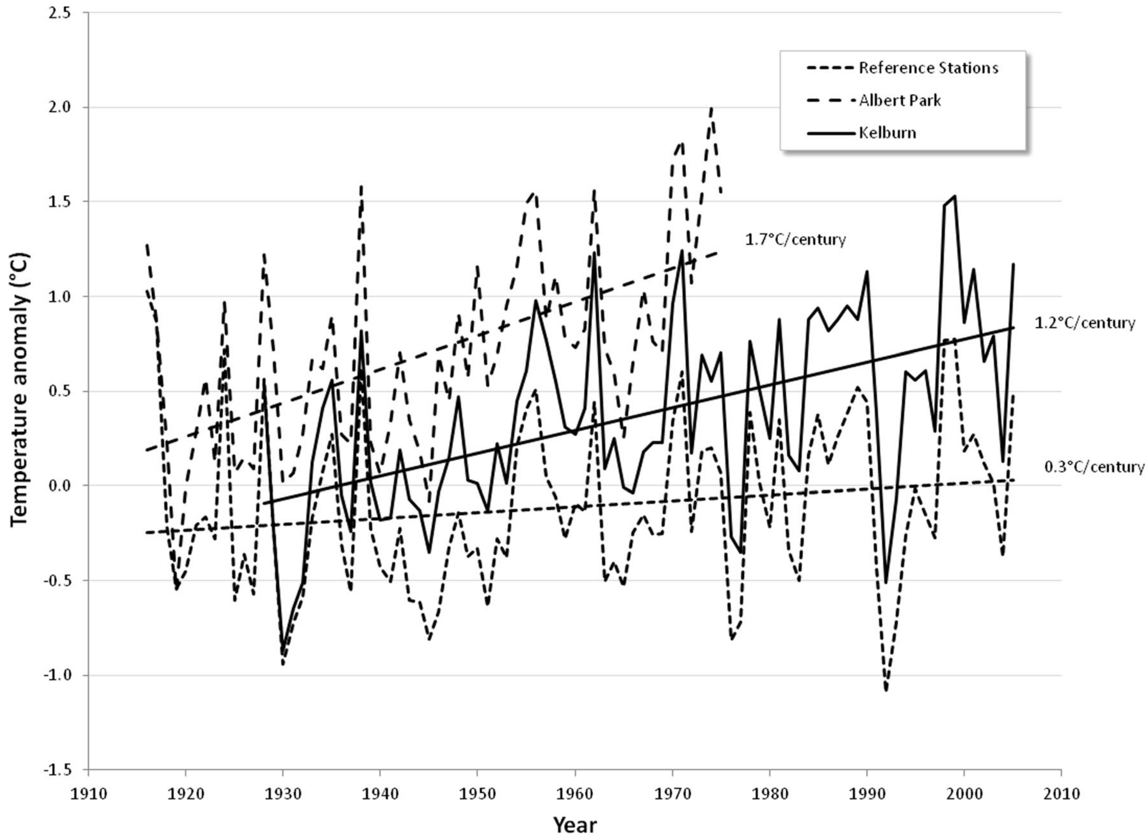

Fig. 4 Albert Park (1916–1976) and Kelburn (1928–2005) mean temperature anomalies relative to five homogenized reference stations

airport. Apparent warming trends in the dataset for Auckland Aero (southwest of Auckland) were de-trended [1] by reference to two other less urban airports on the metropolitan fringes, namely, Whenuapai (27 km to the northwest) and Ardmore (17 km to the southeast). The station histories for these two stations reveal no significant site changes during 1976–2009, and screening disclosed no abrupt shifts. For the period 1962–1993, Auckland Aero warmed 0.96 °C/century faster than Whenuapai, and over 1969–2011 it warmed 0.97 °C/century faster than Ardmore (Table 2). The Mangere station was compared with the same two airports and showed a similar relative warming, implying that the overall Mangere region was greatly affected by UHI, as the population grew by 1,200 % from 15,700 in 1957 to 190,000 in 1981. The data from the Mangere sites during 1976–2009 are detrended by reference to the average slope of Whenuapai and Ardmore. Mangere station was decreased by 0.0093 °C/year and Auckland Aero by 0.00965 °C per year.

Hessell [10] also found downward trends since 1930 in mean daily wind-run at the Kelburn site in Wellington, which has a high mean wind speed of about 12 knots, calculating that the shelter effect during 1945–1970 was about one half that of Albert Park. The metadata discloses that the encroaching vegetation was cut back in 1949, 1959 and 1969. In 1986, it was reported in "The Dominion" daily newspaper that the New Zealand Meteorological Service had relocated the anemometer and was considering relocation of the other instruments as wind speeds were being permanently reduced by about 25 % by the "Pohutukawa factor" (in reference to a common native tree species). Kelburn's contaminated period, 1928–2005, is detrended as proposed by [1] by reference to the average slope of the five homogenized non-contaminated stations, as with Albert Park (see Fig. 4).

6 Results

To illustrate the homogenization process used, the following details the procedure for the Dunedin temperature record for

Table 2 Summary of the difference in trends between two independent Mangere sites (Mangere and Auckland Aero) and more rural Auckland airports Whenuapai and Ardmore. The results show that there is a consistent and significant difference between the Mangere sites and more rural sites. Also shown are 95 % confidence intervals

Station	Period	Trend difference (°C/century)
Mangere minus Whenuapai	1959–1993	0.92±0.28
Mangere minus Ardmore	1969–1998	0.94±0.39
Auckland Aero minus Whenuapai	1962–1993	0.96±0.36
Auckland Aero minus Ardmore	1969–2011	0.97±0.25

the period 1909–2009 using the RS93 [17] method (Table 3). Reported changes for the Dunedin climate station occurred in 1997, 1960, 1947, 1942 and 1913. The first instrument change occurred at the end of August 1997. The reference stations chosen are other South Island stations, namely, Ashburton Council, Timaru 2, Palmerston and Invercargill Aero. Correlations are 0.97, 0.95, 0.97 and 0.96 respectively, while the corresponding weighting factors are 0.26, 0.24, 0.25 and 0.24. The RS93 shifts are calculated to be −0.04±0.20 °C for k=1 and −0.04±0.20 °C for k=2. The calculated shift is not significant at the 95 % confidence level, so no adjustment is made.

At the end of October 1960, the site was moved a few hundred yards. We examine the effect of this move on the temperature record using the following stations: Kelburn,

Table 3 Summary of homogenization adjustments to the Auckland, Masterton, Nelson, Hokitika, Lincoln and Dunedin temperature series using the RS93 method. Included are the various site names, the period of operation, the RS93-calculated adjustment for each site change and the accumulated adjustment sum (relative to the reference site) as applied to each unadjusted series

Station	Site name	From	To	Adjustment (°C)	Sum (°C)
Dunedin	Leith Valley	Jan 1900	Dec 1912	0.00	+0.16
	Botanical Gardens	Jan 1913	Nov 1942	−0.69	+0.16
	Beta Street	Dec 1942	May 1947	+0.85	+0.85
	Musselburgh	Jun 1947	Oct 1960	0.00	0.00
	Musselburgh	Nov 1960	Aug 1997	0.00	0.00
	Musselburgh EWS (reference)	Sep 1997	present	0.00	0.00
Auckland	Albert Park	Sep 1909	Mar 1976	−0.12	−0.10
	Mangere	Apr 1976	Jul 1998	+0.02	+0.02
	Auckland Aero (reference)	Aug 1998	Present	0.00	0.00
Masterton	Waingawa	Feb 1912	Apr 1920	0.00	0.00
	Waingawa	Jun 1920	Sep 1942	0.00	0.00
	Waingawa	Oct 1942	Dec 1990	0.00	0.00
	East Taratahi (reference)	Jan 1991	Oct 2009	0.00	0.00
Wellington	Buckle Street	Jun 1906	Jun 1912	+0.21	−0.48
	Thorndon	Jul 1912	Dec 1927	−1.00	−0.69
	Kelburn (reference)	Jan 1928	Aug 2005	0.00	0.00
	Kelburn AWS	Sep 2005	Present	−0.06	−0.06
Nelson	Nelson	Oct 1907	Nov 1920	−0.40	−0.35
	Nelson	Dec 1920	Dec 1931	0.00	+0.05
	Appleby	Jan 1932	Nov 1996	−0.23	+0.05
	Nelson Aero	Dec 1996	May 1997	+0.28	+0.28
	Nelson Aero (reference)	Jun 1997	present	0.00	0.00
Hokitika	Hokitika Town	Jan 1900	Aug 1912	−0.50	−0.27
	Hokitika Town	Sep 1912	Oct 1928	0.00	+0.23
	Hokitika Town	Nov 1928	Jul 1943	+0.57	+0.23
	Hokitika Town	Aug 1943	Dec 1944	−0.68	−0.34
	Hokitika Southside	Jan 1945	Dec 1963	+0.29	+0.34
	Hokitika Aero	Jan 1964	Oct 1967	+0.05	+0.05
	Hokitika Aero (reference)	Nov 1967	present	0.00	0.00
Lincoln	Lincoln	Jan 1905	Nov 1915	−0.45	−0.42
	Lincoln	Dec 1915	Oct 1923	+0.59	+0.03
	Lincoln	Nov 1923	Dec 1925	−0.51	−0.56
	Lincoln	Jan 1926	Dec 1943	−0.60	−0.05
	Lincoln	Jan 1944	Apr 1964	+0.55	+0.55
	Lincoln	May 1964	Dec 1975	0.00	0.00
	Lincoln	Jan 1976	May 1987	0.00	0.00
	Lincoln Broadfield EDL	Jun 1987	Dec 1999	0.00	0.00
	Lincoln Broadfield EWS (reference)	Jan 2000	present	0.00	0.00

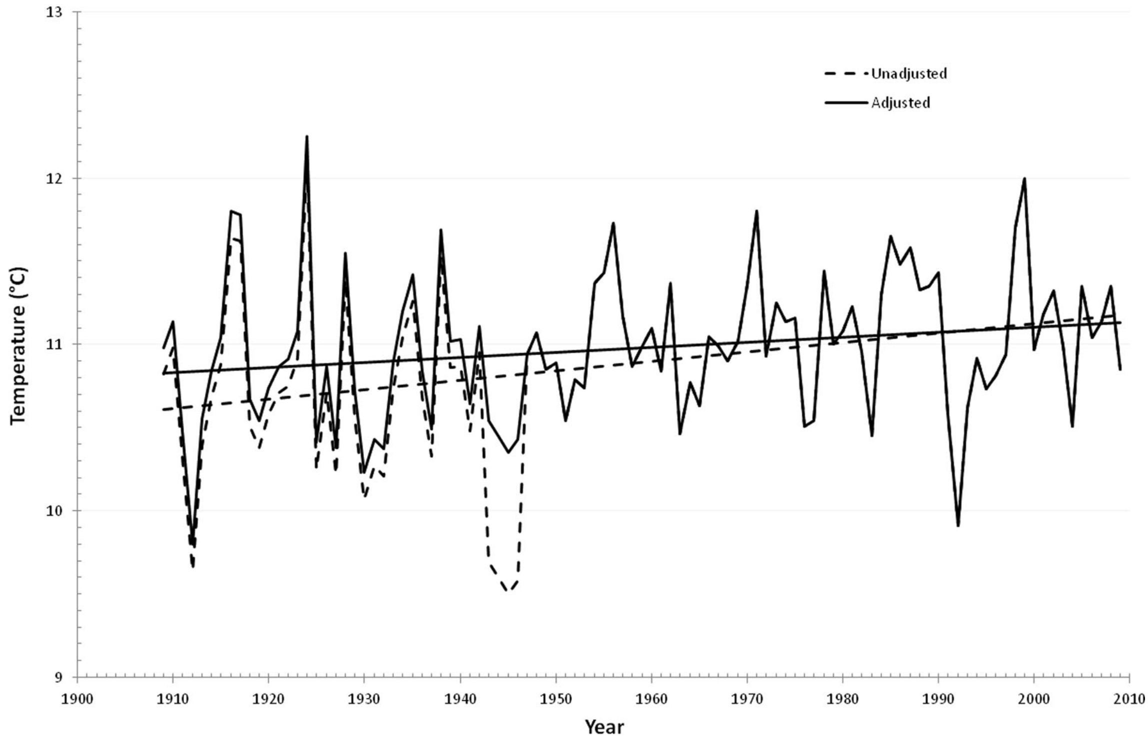

Fig. 5 Annual mean temperatures for Dunedin from 1909 to 2009 showing the unadjusted and RS93-adjusted series. The *dashed lines* indicate the linear trends of each series

Adair, Waimate and Invergargill Aero. The correlations for 1 year on either side of the shift (k=1) were 0.41, 0.82, 0.85 and 0.55, respectively. The weightings were therefore 0.02, 0.42, 0.47 and 0.08. Note that the two lesser correlated sites Kelburn and Invercargill Aero have been weighted very low. The RS93 shifts are calculated to be −0.23±0.27 °C for k=1 and −0.24±0.24 °C for k=2. Because this shift is not significant at the 95 % confidence level, no adjustment is made.

At the end of May 1947, the site was moved. To check the effect of this move, we use the RS93 method with reference stations Kelburn, Alexandra and East Gore. The correlations (k=1) are 0.84, 0.90 and 0.87, respectively, and the weightings are therefore 0.29, 0.38 and 0.33. The shifts for k=1 and k=2 are +0.86±0.36 °C and +0.84±0.26 °C. As these are both clearly significant at the 95 % confidence level, the shift is valid. So, the adjustment is to raise all the pre-June 1947 values by (0.86+0.84)/2=+0.85 °C.

At the end of November 1942, the site was moved. The reference stations used here are once again Kelburn, Alexandra and East Gore, with correlations 0.71, 0.96 and 0.89, respectively, giving weightings of 0.15, 0.50 and 0.35. The shift is calculated using the RS93 method to be −0.72±0.26 °C for k=1 and −0.65±0.35 °C for k=2. Because this result is significant at the 95 % confidence level, the shift is

Table 4 Summary of trends before and after homogenization for the seven sites Auckland, Masterton, Wellington, Nelson, Hokitika, Lincoln and Dunedin. Included are the station names, time period and unadjusted and adjusted trends of each. Also given are 95 % confidence intervals

Station	Period	Trend (°C/century)	
		Unadjusted	Adjusted
Auckland	1909–2009	0.69±0.35	0.24±0.32
Masterton	1912–2009	0.36±0.36	0.36±0.36
Wellington	1909–2009	0.01±0.36	0.43±0.30
Nelson	1909–2009	0.07±0.35	0.27±0.32
Hokitika	1909–2009	0.44±0.38	0.21±0.35
Lincoln	1909–2009	0.04±0.35	0.19±0.30
Dunedin	1909–2009	0.57±0.33	0.30±0.30
7SS average	1909–2009	0.27±0.31	0.28±0.29

Table 5 Outcomes of the different adjustment methods (°C/century)

	Unadjusted data	7SS (S81)	7SS (RS93)	Difference[a]
Auckland	0.69	1.34	0.27	−1.07
Masterton	0.36	0.80	0.36	−0.44
Wellington	0.01	0.79	0.43	−0.36
Nelson	0.0	0.81	0.27	−0.54
Hokitika	0.44	1.07	0.21	−0.86
Lincoln	0.08	0.99	0.19	−0.80
Dunedin	0.53	0.58	0.24	−0.34
7SS average	0.27	0.92	0.28	−0.64

[a] This column is the result of subtracting column 2 (S81) from column 3 (RS93)

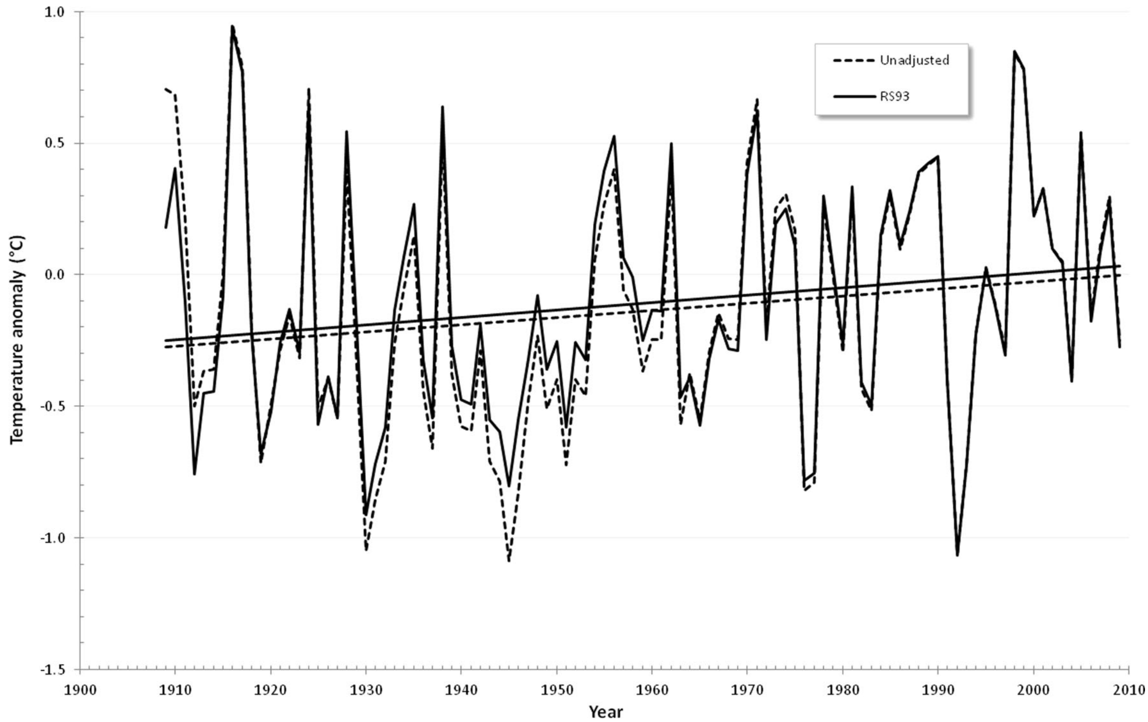

Fig. 6 Unadjusted and RS93-adjusted mean annual temperature anomalies 1909–2009 for New Zealand (baseline 1971–2000) using the seven homogenized series from Auckland, Masterton, Wellington, Nelson, Hokitika, Lincoln, and Dunedin. The linear trends are 0.27±0.31 °C/century for unadjusted and 0.28±0.29 °C/century for RS93-adjusted

valid. In light of this, the adjustment undertaken is to lower the pre-December 1942 values by (−0.72–0.65)/2, giving an adjustment of −0.69 °C.

A site move occurred at the end of January 1913. The reference stations used are Albert Park, Nelson, Christchurch Gardens and Lincoln, with correlations of 0.45, 0.68, 0.81 and 0.86 and weightings of 0.03, 0.18, 0.36 and 0.44, respectively. The calculated shift is +0.28±0.46 °C for k=1 and +0.37± 0.37 °C for k=2. The shift is not significant at the 95 % confidence level and is therefore not valid. Consequently, no adjustment is made for the 1913 site move.

Table 3 summarizes the adjustments for Dunedin, and Fig. 5 shows the adjusted and unadjusted time series for the site from 1909 to 2009. The effect of the adjustments is to reduce the trend from 0.57±0.33 °C/century to 0.30±0.30 °C/century. Note that in the 7SS, NIWA have excluded pre-1913 years due to poor data quality. If these early years are excluded, then the trend drops to 0.24±0.30 °C/century. The results for the six remaining stations are also summarized in Tables 4 and 5.

Combining the seven homogenized station histories into one series, we find that over the past century the warming trend for 1909–2009 is 0.28±0.29 °C per century (Fig. 6). This is similar to the raw data trend for the same period (0.27± 0.31 °C/century). These results are reassuring as New Zealand site changes were wholly random, displaying no apparent pattern, and there were no systematic changes made to all stations at the same time. It is to be expected, therefore, that the random changes would tend to balance over time. If the contaminated stations at Auckland and Wellington are excluded from the series, the warming trend drops slightly to 0.26± 0.30 °C per century. A comparison with the S81/M10 trend is discussed in the "Conclusion" section.

Table 6 Summary of the pre-1960 adjustments using the methods of Salinger (1981) and that of the current work

Station	Year	Salinger	RS93
Albert Park	1950	+0.1	0.0
Waingawa	1920	−0.7	0.0
Waingawa	1942	−0.4	0.0
Buckle St	1912	−0.9	+0.21
Thorndon	1927	−1.2	−1.0
Nile St	1920	−0.7	−0.4
Cawthron	1931	−0.2	0.0
Hokitika Tn	1943–1944	−0.6	−0.11
Lincoln	1915	−1.0	−0.45
Lincoln	1923	+0.6	+0.59
Lincoln	1929	−0.8	−0.51
Lincoln	1943	−0.3	−0.6
Dunedin	1912	+0.3	0.0
Dunedin	1942	−0.1	−0.69
Dunedin	1947	+0.6	+0.85
Average		−0.35	−0.14

7 Discussion

Hessell [10] examined apparent continuous warming over New Zealand since 1930 but concluded ([10], p. 1): "… no important change in annual mean temperature since 1930 has been found in stations where these factors [changes in shelter, screenage, and/or urbanization] are negligible." Our study similarly concludes that no "important" change in mean temperature occurred over the period 1909–2009 once the known contamination is corrected.

Table 5 highlights the disparity of our results with those of S81. The major disagreements occur as a result of the application of significance testing and the correction of Auckland's distorted trend. S81 did not attempt to quantify or correct for UHI or sheltering effects. The two rural stations (Hokitika and Lincoln) show average warming of 0.2 °C/century in contrast to the 0.32 °C/century of the five city stations. A concern highlighted by RS93 [17] is that all seven datasets have not yet been thoroughly screened for possible UHI effects or other undocumented changes. There are few adjustments in the second half of the series and no material differences between analyses in that period. The adjustments for 1909–59 are set out in Table 6. Folland and Salinger [8] estimated 1871–1993 SST variations for an area including New Zealand at about 0.6 °C/century but acknowledged that there is low confidence in the data in the crucial pre-1949 period.

8 Conclusion

Detecting trends in climate variables is important in assessments of global and regional change based on long-term observations as they are widely used as inputs for societal design and planning purposes [11]. The information is also extensively used in hindcast verifications for regional and local models. The ongoing controversy regarding the contribution of human versus natural causes of climate change has increased the importance of scrutinizing the instrumental record of climate data for the longest possible time periods. For all these reasons, it is important that we have the best temperature trend estimates possible.

Using well-accepted homogenization methods, we have derived a mean land surface air temperature trend for New Zealand over the past century of 0.28±0.29 °C per century, which is considerably less than the S81/M10 value of 0.91± 0.30 °C per century. By excluding weighted averages and including adjustments which are not statistically significant, S81 may have allowed too many "false positives" to occur. In addition, using long comparison time periods may have allowed creeping inhomogeneities and undocumented shifts at reference sites to skew the individual adjustments. This is borne out by Table 5, which demonstrates that in every case the S81 station adjustments greatly increased the individual trends, while the RS93 method resulted in equal numbers of increases and decreases. As noted previously, S81 did not account for gradual effects such as sheltering or UHI. The detrending of Albert Park in Auckland and Kelburn in Wellington also contributed significantly to the mean trend result. We have also shown that a very similar outcome would follow if those two stations were not corrected but simply omitted from the series.

References

1. Aguilar, E., Auer, I., Brune, M., Peterson, T. C., & Wieringa, J. (2003). *Guidelines on climate metadata and homogenization*. Geneva: World Meteorological Organization. WCDMP No. 53, WMD/TD No. 1186.
2. Auer, I., Böhm, R., Jurkovic, A., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Brunetti, M., Nanni, T., Maugeri, M., Briffa, K., Jones, P., Efthymiadis, D., Mestre, O., Moisselin, J. M., Begert, M., Brazdil, R., Bochnicek, O., Cegnar, T., Gajic-Capka, M., Zaninovic, K., Majstorovic, Z., Szalai, S., Szentimrey, T., & Mercalli, L. (2005). A new instrumental precipitation dataset for the Greater Alpine Region for the period 1800–2002. *Int J Climatol, 25*, 139–166.
3. Begert, M., Schlegel, T., & Kirchhofer, W. (2005). Homogeneous temperature and precipitation series of Switzerland from 1864–2000. *Int J Climatol, 25*, 65–80.
4. Böhm, R., Auer, I., Brunetti, M., Maugeri, M., Nanni, T., & Schöner, W. (2001). Regional temperature variability in the European Alps 1760–1998 from homogenized instrumental time series. *Int J Climatol, 21*, 1779–1801.
5. Camuffo, D. and Jones P. (eds) (2002). Improved understanding of past climatic variability from early daily European instrumental sources. *Climatic Change*, 53,1–392.
6. Della-Marta, P., Collins, D., & Braganza, K. (2004). Updating Australia's high-quality annual temperature dataset. *Aust Meteorol Mag, 53*(2), 75–93.
7. Della-Marta, P. M., & Wanner, H. (2006). A method of homogenizing the extremes and mean of daily temperature measurements. *J Clim, 19*, 4179–4197. doi:10.1175/JCLI3855.1.
8. Folland, C. K., & Salinger, M. J. (1995). Surface temperature trends and variations in New Zealand and the surrounding ocean 1871–1993. *Int J Climatol, 15*, 1195–1218.
9. Hansen, J., Ruedy, R., Sato, M., Imhoff, M., Lawrence, W., Easterling, D., Peterson, T., & Karl, T. (2001). A closer look at United States and global surface temperature change. *J Geophys Res, 106*, 23. 947–23 963.
10. Hessell, J. W. D. (1980). Apparent trends of mean temperature in New Zealand since 1930. *N Z J Sci, 23*, 1–9.
11. Livezey, R. E., Vinnikov, K. Y., Timofeyeva, M. M., Tinker, R., & anden Dool, H. M. (2007). Estimation and extrapolation of climate normals and climate trends. *J Appl Meteorol Climatol, 46,* 1759–1776
12. Manton, M. J., & Coauthors. (2001). Trend in extreme daily rain-fall and temperature in Southeast Asia and the South Pacific: 1961–1998. *Int J Climatol, 21*, 269–284.
13. McAneney, K. J., Salinger, M. J., Porteus, A. S., & Barber, R. F. (1990). Modification of an orchard climate with increasing shelter-belt height. *Agric For Meteorol, 49*, 177–189.
14. Menne, M. J., & Williams, C. N. (2009). Homogenization of temperature series via pairwise comparisons. *J Clim, 22*, 1700–1717.
15. Neyman, J., & Pearson, E. S. (1933). The testing of statistical hypotheses in relation to probabilities a priori. *Math Proc Camb Philos Soc, 29*, 492–510. doi:10.1017/S030500410001152X.

16. Peterson, T. C., Easterling, D. R., Karl, T. R., Groisman, P., Nicholls, N., Plummer, N., Torok, S., Auer, I., Boehm, R., Gullett, D., Vincent, L., Heino, R., Tuomenvirta, H., Mestre, O., Szentimrey, T., Salinger, J., Forland, E. J., Hanssen-Bauer, I., Alexandersson, H., Jones, P., & Parker, D. (1998). Homogeneity adjustments of *in situ* atmospheric climate data: a review. *Int J Climatol, 18*, 1493–1517.
17. Rhoades, D. A., & Salinger, M. J. (1993). Adjustment of temperature and rainfall records for site changes. *Int J Climatol, 13*, 899–913.
18. Salinger, M. J. (1980). The New Zealand temperature series. *Climate Monitor, 9*(4), 112–118.
19. Serra, Y. L., A'Hearn, P., Freitag, H. P., & McPhaden, M. J. (2001). ATLAS self-siphoning rain gauge error estimates. *Journal of Atmospheric and Oceanic Technolology, 18*, 1989–2002.
20. Torok, S. J., & Nicholls, N. (1996). A historical annual temperature data set for Australia. *Aust Meteorol Mag, 45*, 251–294.
21. Tuomenvirta, H. (2001). Homogeneity adjustments of temperature and precipitation series? Finnish and Nordic data. *Int J Climatol, 21*(4), 495–506.
22. Venema, V. K. C., Mestre, O., Aguilar, E., Auer, I., Guijarro, J. A., Domonkos, P., Vertacnik, G., Szentimrey, T., Stepanek, P., Zahradnicek, P., Viarre, J., Muller-Westermeier, G., Lakatos, M., Williams, C. N., Menne, M. J., Lindau, R., Rasol, D., Rustemeier, E., Kolokythas, K., Marinova, T., Andresen, L., Acquaotta, F., Fratianni, S., Cheval, S., Klancar, M., Brunetti, M., Gruber, C., Prohom, D. M., Likso, T., Esteban, P., & Brandsma, T. (2012). Benchmarking homogenization algorithms for monthly data. *Clim Past, 8*, 89–115.
23. Williams, C. N., Menne, M. J., & Thorne, P. W. (2012). Benchmarking the performance of pairwise homogenization of surface temperatures in the United States. *J Geophys Res, 117*, D05116. doi:10.1029/2011JD016761.
24. Wijngaard, J. B., Klein Tank, A. M. G., & Können, G. P. (2003). Homogeneity of 20th century European daily temperature and precipitation series. *Int J Climatol, 23*, 679–692.
25. Mullan, A.B., Stuart, S.J., Hadfield, M.G., Smith, M.J. (2010). Report on the review of NIWA's 'seven-station' temperature series. NIWA Information Series No. 78. 175 p.