INTERNATIONAL JOURNAL OF CLIMATOLOGY, VOL. 13, 899–913 (1993) 551.501.9:551.524.34:551.577.34:519.74

ADJUSTMENT OF TEMPERATURE AND RAINFALL RECORDS FOR SITE CHANGES

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Received 10 July 1992
Accepted 2 February 1993

ABSTRACT

Methods are presented for estimating the effect of known site changes on temperature and rainfall measurements. Parallel cumulative sums of seasonally adjusted series from neighbouring stations are a useful exploratory tool for recognizing site-change effects at a station that has a number of near neighbours. For temperature data, a site-change effect can be estimated by a difference between the target station and weighted mean of neighbouring stations, comparing equal periods before and after the site change. For rainfall the method is similar, except for a logarithmic transformation. Examples are given. In the case of isolated stations, the estimation is necessarily more subjective, but a variety of graphical and analytical techniques are useful aids for deciding how to adjust for a site change.

KEY WORDS Temperature Rainfall Time series Homogeneity Cusums

1. INTRODUCTION

Most meteorological time series are subject, from time to time, to changes of non-meteorological origin. The causes of such changes include replacement of measuring devices, shifting observation sites, changes of vegetation or construction in the vicinity of a station, gradual changes in the environment or urbanization, and changes in the time-of-day of observation, which can affect monthly averages (Salinger, 1979; Karl *et al.*, 1986).

These introduce inhomogeneities into the time series. The meteorological time series is considered to be homogeneous if the variations are caused only by variations in climate. Early work considered the evaluation of the relative homogeneity of two or more series (Conrad and Pollack, 1950), where one series is relatively homogeneous with a synchronous series at another place. However, the evaluation of relative homogeneity is only a process to assist in the evaluation of the absolute homogeneity of one series in particular (WMO, 1966) in order to determine meteorological trends and variations.

Some changes are gradual and some sudden. We use the term *site change* to mean any sudden change of non-meteorological origin. Gradual changes can seldom be assigned with any certainty to non-meteorological causes. Where long-term homogeneous series are required, for example, for studies of climate change, it is best to choose stations that are unlikely to have been affected by gradual changes in shading or urbanization. This is no easy task. Karl *et al.* (1988) have concluded that urban effects on temperature are detectable even for small towns with a population under 10 000.

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Various methods of evaluating inhomogeneity of monthly or annual temperature and rainfall series have been discussed by the World Meteorological Organization (WMO, 1966). Buishand (1981, 1982) devised methods to adjust monthly or annual rainfall amounts for series considered to be stationary.

There is a growing literature on the estimation of change points in climate series. Sometimes the times of changes are known a priori and sometimes not. Alexandersson (1984) gave a method for identifying a change in a rainfall series when the time of the change was not known a priori. It is based on comparing standardized ratios between the target station and a set of neighbouring stations. Karl and Williams (1987) have developed a detailed procedure for adjusting for site changes when the times are known a priori, again using comparison with neighbouring stations. They use the longest period possible during which none of the neighbouring stations had a site change with a minimum period of comparison of at least 5 years; they use t-tests and Wilcoxon rank-sum tests to assess the significance of changes.

This paper is concerned with the estimation of site-change effects when the times of changes are known a priori, such as when the station was moved or the instrument replaced.

There are many global and regional influences on meteorological observations at a site. Cyclical effects, large-scale pressure differences and natural and man-made atmospheric pollution all have an influence and can produce apparent changes in level of varying size and duration. If neighbouring stations are used to adjust for site changes, global or regional effects are easily distinguished from site-change effects, without modelling the different physical influences. For isolated stations, regional effects are not so easily distinguished from site-change effects. This makes the adjustment more difficult.

A method for detecting site changes without reference to neighbouring stations was proposed by Thompson (1984) and Thompson and Revfeim (1985). Their method recognizes changes in the size and frequency of rainfall events following a site change. The whole period between known site changes is used for the adjustment. It is possible that such a method might accidentally remove the long-term trend from the climate record in the course of adjusting for site changes, since, without using neighbouring stations, there is no way of distinguishing changes of meteorological origin from site-change effects. It is important to preserve the long-term trend for studies of climate change.

One of the difficulties in adjusting meteorological series is that the processes generating the series are complex and not understood in detail. Statistical tests for change are usually based on the assumption that successive observations (after removal of seasonal effects) are independent, identically distributed random variables. In reality, complex effects present in the data may so violate the underlying assumptions that the value of any estimation procedure based on them is questionable. For this reason it is imperative to examine the series involved in the adjustment by suitable graphical methods before applying any standard adjustment procedure. This means looking at each of the neighbouring series, where these are to be used, as well as the target series. It seems preferable to retain simple statistical methods, such as t-tests, backed up by a careful scrutiny of the data, rather than to attempt more complex modelling to accommodate a possibly limitless variety of deviations from the assumptions.

2. ADJUSTMENT OF STATIONS WITH NEIGHBOURS

First, let us consider the adjustment of data from a target station that has a number of neighbouring stations, subject to similar local weather patterns. The data from the target station and its neighbours are then usually highly correlated. The adjustment for a site change can be based on a comparison of the target station data with weighted averages of the neighbouring stations. The method proposed here, unlike that of Karl and Williams (1987), is to use a symmetric interval before and after the site change and select only those neighbouring stations that have no site changes over the period of comparison. The standard error is based on the variation of a set of differences (between the target station and its neighbours) of monthly differences (before and after the site change). 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. If no such effects are present it is optimal to use as long a period of comparison as possible. However, in this case, the usual concern to maximize 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.

An adjustment is carried out only after a careful visual examination of the data from all stations, using the methods described below.

2.1. Graphical examination of data from a set of neighbouring stations

Plots of the cumulative sum (cusum) of observations are generally better for visually detecting changes than plots of the observations themselves. For this reason cusum plots are now used widely in a variety of fields for detection of changes. A shift in the level of the observations appears in the cusum plot as a change of slope.

For a set of neighbouring stations, plotting cusums of the data from all stations on a single graph facilitates comparison of the similarity of the records, both in their general trends and in detail. Such plots we call parallel cusums. Parallel cusum plots can be specialized to visually emphasize the differences between a target station and its neighbours. This is done by accumulating the difference between the target station and each of its neighbours in the case of temperature measurements, and the logarithm of the ratio of the target station to each of its neighbours in the case of rainfall measurements.

Figures 1 and 2 are parallel cusum plots of observations from stations in and around Christchurch, New Zealand. Figure 1 shows mean daily minimum temperature and Figure 2 rainfall. The data were obtained from the data base maintained by the New Zealand Meteorological Service and are monthly values. Seasonal effects have been removed by computing the monthly time-of-year mean at each site. The differences from these monthly means have been accumulated on the graph. Thus the model fitted is

$$x_t = \mu_{j_t} + e_t$$

where j_t denotes the month of the year corresponding to time t. The statistic plotted is cusum(t), given by

$$\text{cusum}(t) = \sum_{s \leq t} \hat{e}_t$$

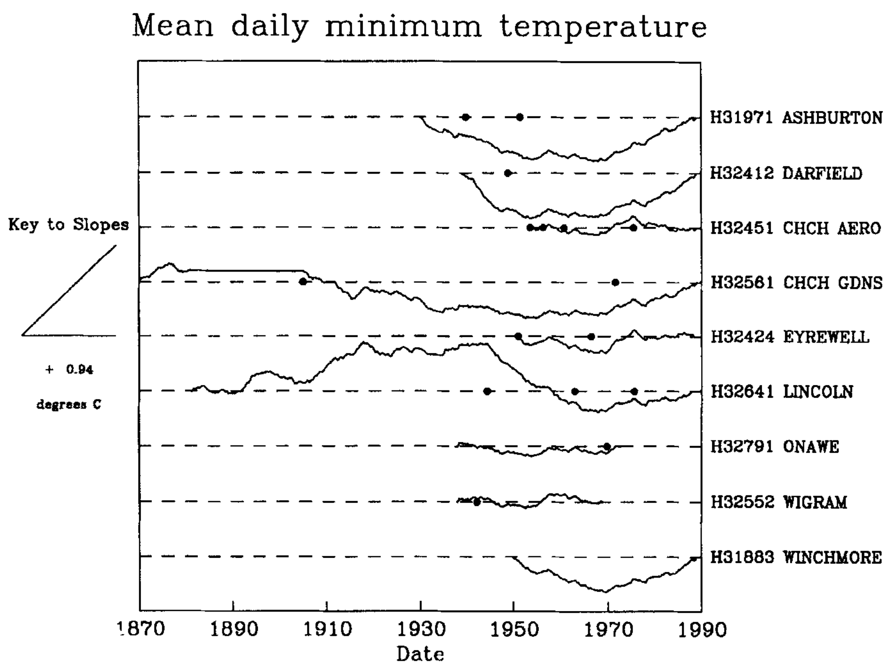

Figure 1. Parallel cusums of mean daily minimum temperature for stations in and around Christchurch, New Zealand. Dots show the times of known site changes, determined from station histories; Chch Aero, Christchurch Airport; Chch Gdns, Christchurch Gardens. The seasonal cycle has been removed as described in the text.

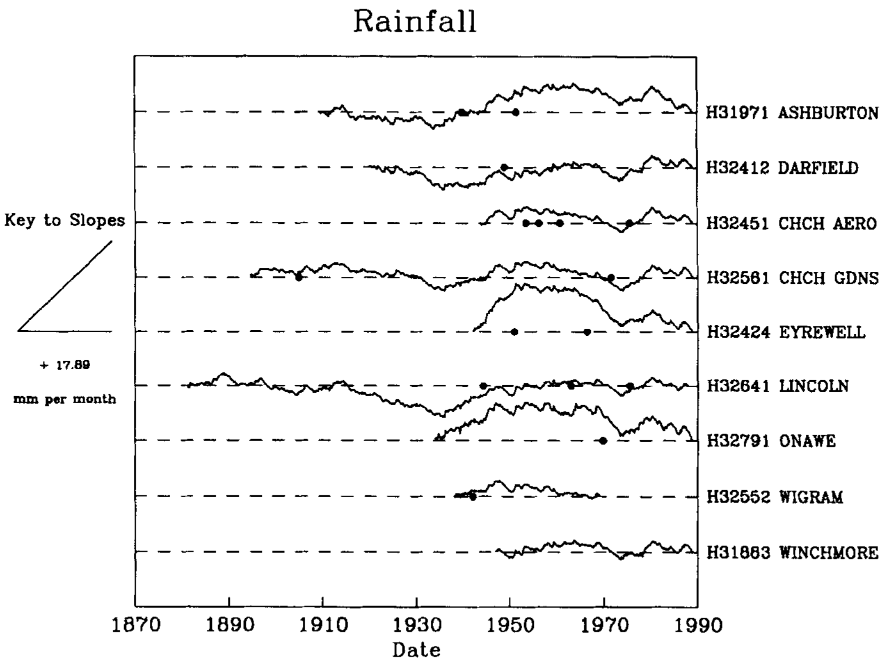

Figure 2. Parallel cusums of rainfall for the stations of Figure 1. Dots show the times of known site changes; Chch Aero, Christchurch Airport; Chch Gdns, Christchurch Gardens. The seasonal cycle has been removed as described in the text

where $\hat{e}_t = x_t - \hat{\mu}_{j_t}$ and $\hat{\mu}_{j_t}$ is the mean of $\{x_s\colon j_s = j_t\}$. In Figure 1, dots indicate the time of known site changes. Thus, for example, there are two known site changes at the Ashburton station. These occurred in 1939 and 1951.

High correlations between neighbouring stations are reflected in Figures 1 and 2 by similarities in the pattern of gradient changes. The definition of the cusum above ensures that the average gradient is horizontal for each station, i.e. the cusum begins and ends at zero. Since the data from different stations cover different time periods, the slopes themselves are not comparable, but the changes in slope are. The cusum is drawn as a horizontal line through periods of missing data.

The 'key to slopes' shows the slope that corresponds to the stated difference from the mean value. Thus, for example, in Figure 1, there is a change in the mean daily minimum at Lincoln—a reduction of about 1°C—which occurred at the time of the first Lincoln site change. It probably represents a site-change effect at Lincoln, because no similar change of slope is present in the cusums for the other stations. In contrast, a sharp decrease in slope at Christchurch Airport at the time of the last site change for that station seems unlikely to have been caused by a site change. In that case a similar change of slope is present in the cusums for the other stations.

Parallel cusum plots also highlight changes in relativities between stations that are not related to known site changes. For example, in Figure 1, there is a marked difference between Christchurch Gardens and Lincoln during the period between 1910 and 1920. A sharp increase in the mean daily minimum at Christchurch Gardens is not seen in the Lincoln record. Given the otherwise similar trends at these two stations it is unlikely that such a divergence is a true meteorological effect. In such a case it is necessary to investigate the histories of both stations for evidence on which of the two records is likely to be most reliable over that period.

Figures 3 and 4 are specialized parallel cusum plots, designed to compare the record of a target station with that of each of its neighbours. In Figure 3 the differences between mean daily minimum temperature at Lincoln and each of the neighbouring stations have been accumulated. The times of known site changes at Lincoln are shown on the bottom graph labelled 'Mean'. This graph shows the difference between Lincoln and the mean of the other stations, but only covers the period for which all stations have data.

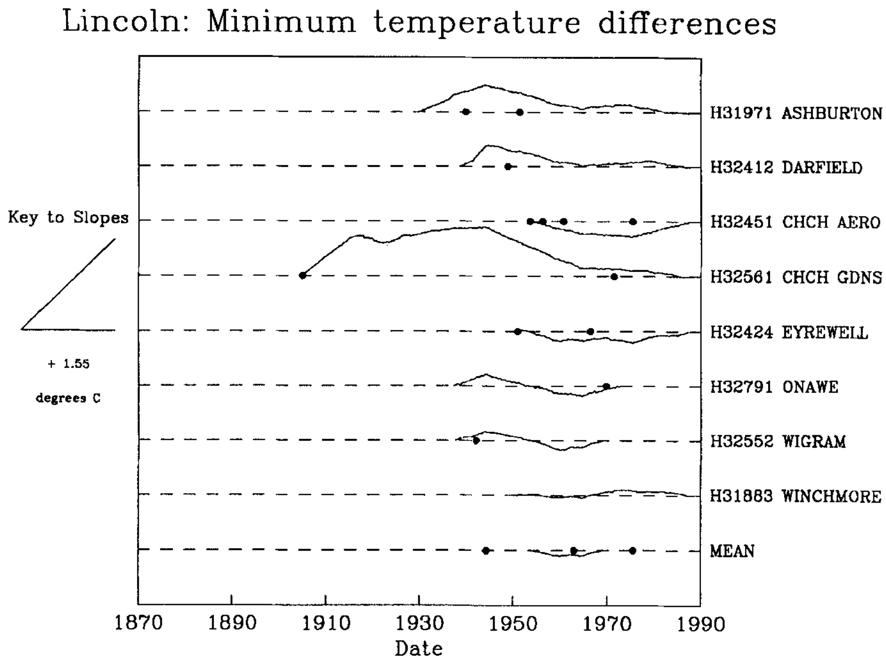

Figure 3. Parallel cusums of differences between the mean daily minimum temperature at Lincoln and the other stations. Dots show the time of known site changes; Chch Aero, Christchurch Airfield; Chch Gdns, Christchurch Gardens

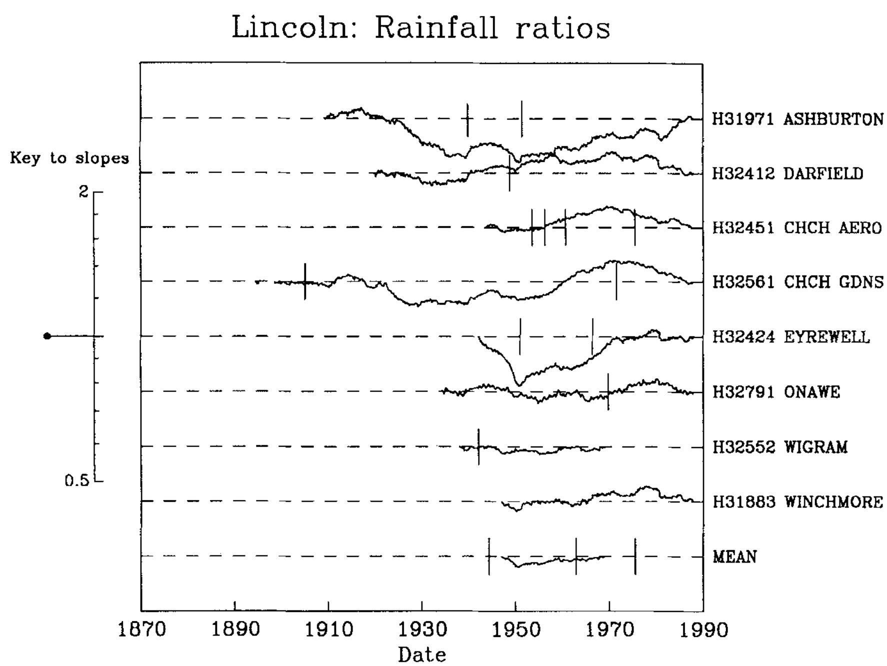

Figure 4. Parallel cusums of logarithm of the ratio of monthly rainfall at Lincoln to that at neighbouring stations. Vertical lines show the time of known site changes; Chch Aero, Christchurch Airfield; Chch Gdns, Christchurch Gardens

A significant site change at Lincoln would appear in Figure 3 as a change of slope in most or all of the curves simultaneously. An example of this is the first site change at Lincoln, referred to above. There is an abrupt decrease of slope in each of the curves at the time of this site change. This indicates that the site change at Lincoln affected the measurement of mean daily minimum. From the size of the slope changes, the effect was a reduction in the measured value by about 1°C.

Figure 4 shows a similar plot for the ratio of Lincoln rainfall to that of the other stations. In this case the logarithm of the monthly ratio of Lincoln rainfall to that of the other stations has been accumulated. A zero gradient corresponds to the mean ratio between a pair of stations. Changes of slope mark changes in this ratio over time. For instance, the ratio of Lincoln rainfall to Eyrewell rainfall was lower than average until 1951, but since then has been higher than average. From the key to slopes, the change in the ratio in about 1951 was an increase by a factor of about 1·5. The graph does not show which of Lincoln or Eyrewell has the higher rainfall; it only shows how the ratio changes with time.

A site change affecting rainfall observations at Lincoln would appear as a simultaneous change of slope of all curves in Figure 4. On this basis there have been no site changes affecting the measurement of rainfall at Lincoln.

2.2. *Estimating a shift at the time of a known site change*

In this section a t-statistic is proposed for estimating the size of site-change effects, for temperature series and for rainfall series.

2.2.1. Adjusting temperature series. Suppose we have a set of monthly temperature series at neighbouring sites. Let the series to be adjusted (the target series) be denoted by $x^{(0)}$ and the series at neighbouring sites by $\{x^{(i)}, i=1, \ldots, n\}$. Suppose we wish to adjust $x^{(0)}$ for a site change at a known time τ based on k years of data before and after τ. Assume that the neighbouring series have been preselected so that none of them has a known site change in the interval used for adjustment. For each $\{x^{(i)}, i=0, \ldots, n\}$ we can form the series $y^{(i)}$ of monthly differences, given by

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

Thus $y_t^{(i)}$ is the difference between the temperature t months after the site change and the temperature in the same month k years previously. This 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.

The next step is to estimate the trend from the neighbouring stations and remove it by differencing with the target station. Let $\{w_i, i=1, \ldots, n\}$ be a set of chosen weights, with each $w_i > 0$ and $\sum_{i=1}^{n} w_i = 1$. The choice of weights is discussed below. Form the sequence $\{z_t, t=1,2, \ldots, 12k\}$, given by

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

The z_t are assumed to be independent, identically distributed normal random variables. This assumption is not satisfied in practice if individual station records are subject to drift for either instrumental or environmental reasons. The shift due to the site change is estimated by the mean

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

which has standard error

$$s = \left[\frac{\sum_{t=1}^{12k} (z_t - \bar{z})^2}{12k(12k-1)} \right]^{1/2}.$$

A $100(1-\alpha)$ per cent confidence interval for the site change is $\bar{z} \pm t_{12k-1;\alpha/2} \times s$. Following what seems to be the standard convention, we adjust for the site change only if the change is significant at the 5 per cent level, i.e. if the 95 per cent confidence interval does not contain zero. The adjustment is to replace $x_t^{(0)}$ by $x_t^{(0)} - \bar{z}$ for $t < \tau$. The significance level α is, of course, a matter of choice. It has a profound effect on the statistical properties of the adjusted series. A rational choice of α would involve minimizing a loss function, which balances the risks of the type I and type II errors (i.e. adjusting when no shift occurred and failing to adjust for a real shift). An introduction to the terms is found, for example, in Mood, Graybill and Boes (1974). However, a complicating factor is that an adjustment is usually only made after examining the results of tests carried out with several different values of k.

The following model for $\{x^{(i)}, i=0, \ldots, n\}$ is the motivation for the method described above:

$$x_t^{(i)} = \mu_{j_t}^{(i)} + d_t + \sum_{\tau \leqslant t} \delta_\tau^{(i)} + e_t^{(i)} \tag{1}$$

In this model j_t denotes the month of the year corresponding to t, $\mu_{j_t}^{(i)}$ is the time-of-year mean for the ith station, d_t is a drift or trend common to all stations and $\delta_\tau^{(i)}$ is the effect of a site change at time τ, and $e_t^{(i)}$ is the deviation of the ith station at time t. The station deviations $\{e^{(i)}, i=0, \ldots, n\}$ are assumed to be uncorrelated series of independent, identically distributed normal random variables with zero mean.

If $\{x^{(i)}, i=0, \ldots, n\}$ are as in model (1), then z_t, calculated as described above, satisfies

$$z_t = \sum_{i=1}^{n} w_i(e_{\tau+t}^{(i)} - e_{\tau+t-12k}^{(i)}) - (e_{\tau+t}^{(0)} - e_{\tau+t-12k}^{(0)}) - \delta_\tau^{(0)}$$

which is of the form

$$z_t = u_t - \delta_\tau^{(0)}$$

where $\{u_t, t=1, \ldots, 12k\}$ is a sequence of independent, identically distributed normal random variables with zero mean. The method described above is thus designed to work for series conforming to model (1), and has been shown to do so by applying it to numerous simulated data series conforming to this model.

2.2.2. Adjusting rainfall series. The adjustment of rainfall series is similar to the adjustment of temperature series, except that logarithms are first taken of all series, i.e. if the monthly rainfall series for the target station and its neighbours are denoted by $\{r^{(i)}, i=0, \ldots, n\}$, the transformed series $\{x^{(i)}, i=0, \ldots, n\}$, where $x_t^{(i)} = \log r_t^{(i)}$, are computed and $\{y^{(i)}, i=1, \ldots, n\}$, being logarithms of ratios of monthly rainfalls k years apart, and $\{z_t, t=1, 2, \ldots, 12k\}$ are calculated as described above. The underlying assumption is that the transformed series satisfy the model of equation (1). The statistic $\bar{z}$ is an estimate of the logarithm of the factor by which the site change affected rainfall observations. Confidence limits for this factor are obtained by exponentiating the confidence limits for $\bar{z}$. To correct for the site change, rainfalls prior to time τ should be divided by $\exp(\bar{z})$.

Other transformations, such as the fourth root, might be applied to rainfall to induce approximate normality in the station deviations. A similar approach could be used for these other transformations, as for the logarithm. However, lack of independence of the site deviations is potentially a more serious problem than lack of normality.

2.3. Correlations between neighbouring stations

The weights $\{w_i, i=1, \ldots, n\}$ are based on correlations between the target station and neighbouring stations. It is better to use correlations between the differenced series $\{y^{(i)}\}$ (with $k = 1$) than between the raw series $\{x^{(i)}\}$. This reduces the effect of change points on the correlations, since a site change in one series then affects only the 12 monthly differences that span the site change. These values can be excluded specifically from the computation of correlations if desired. On the other hand, if correlations between $\{x^{(i)}\}$ are computed, the change points are not so easily isolated. The relationship between $x_t^{(i)}$ and $x_t^{(0)}$ is then a mixture of two possibly different relationships—one before the site change and the other after. A shift due to the site change would thus reduce the apparent correlation between the two stations.

Note that the value of k used in the above computation does not, in principle, affect the correlation (at least when the data are not serially correlated). This permits the choice of a different k when estimating correlations between series.

In the case of rainfall series, the correlations are calculated between differenced series, after first taking logarithms of the monthly rainfall totals.

The question of how best to weight neighbouring stations, given the correlation of the target station with each, is worthy of future study. There are at least two, somewhat conflicting, considerations here: the power of the test for a change, and its robustness against defects in the record of any one neighbouring station. Also, the question of weighting is not entirely separate from that of how to select neighbouring stations in the first place. Alexandersson (1986) reports on several different weighting options. The possibilities include equal weighting of neighbouring stations and minimization of the variance of the sequence of differences (or the coefficient of variation of the sequence of ratios). Alexandersson suggests that the weights are more simply based on the squares of the correlations, i.e.

$$w_i = \rho_i^2 / \sum_{j=1}^{n} \rho_j^2$$

where ρ_i denotes the correlation between the target station and its ith neighbour. Alexandersson approximates the correlation by an exponential formula using the distance d_i between the target station and its ith neighbour.

$$\rho_i = \exp(-\alpha d_i).$$

In the example below the weighting is proportional to the fourth power of the correlation, i.e.

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

The reason the fourth power is preferred to the square is that it gives more weight to those neighbouring stations that are most highly correlated with the target station.

2.4. *An example*

The method is now applied to the series plotted in Figures 1–3. The shifts due to the site changes at each station are estimated using the other stations as neighbours. These examples are presented for illustration of the method only. In practice a particular selection of neighbours would be made for each target station.

The results are given for estimating all the site changes indicated in the figures for mean daily minimum temperature and rainfall.

2.4.1. Mean daily minimum temperature. For mean daily minimum temperature, the correlation matrix, calculated as described above, is given in Table I.

The method of section 2.2.1 was applied, with $k = 2$. Table II shows the time (year and decimal) of each site change, the estimate of the effect of the site change on mean daily minimum temperature based on 2 years of data before and after, the standard error of the estimate, the number of monthly differences used, and the neighbouring stations used for the adjustment. The stations used were those that had complete data and no site changes of their own for 2 years before and after the site change. In some cases no estimate was possible due to insufficient data.

For most of the site changes there is no significant effect on mean daily minimum temperature. Exceptions are the 1960 and 1975 site changes at Christchurch Airport and the 1944 site change at Lincoln. In the latter case the estimated shift is 0·96°C. The Lincoln data prior to April 1944 should thus be adjusted downwards by 1·0°C. A 95 per cent confidence interval for the shift is $0{\cdot}96 \pm t_{23;0.05} \times 0{\cdot}135$ or (0·68, 1·24).

The weights used were proportional to the fourth power of the correlation with the target station, as explained in section 2.3. Thus, for example, for the 1944 Lincoln adjustment, the weights used were 0·22, 0·17, 0·23, 0·16 and 0·22 for Ashburton, Darfield, Christchurch Gardens, Onawe, and Wigram respectively.

Table I. Correlation matrix of mean daily minimum temperature for the stations of Figure 1. Correlations are between differenced series as explained in section 2.3

		1	2	3	4	5	6	7	8	9
Ashburton	1	1·00								
Darfield	2	0·91	1·00							
Christchurch Airfield	3	0·89	0·88	1·00						
Christchurch Gardens	4	0·87	0·83	0·96	1·00					
Eyrewell	5	0·89	0·90	0·89	0·85	1·00				
Lincoln	6	0·89	0·83	0·94	0·89	0·85	1·00			
Onawe	7	0·82	0·81	0·87	0·87	0·82	0·82	1·00		
Wigram	8	0·85	0·80	0·89	0·93	0·80	0·88	0·84	1·00	
Winchmore	9	0·97	0·94	0·89	0·87	0·88	0·90	0·83	0·86	1·00

Table II. Estimated site change effects for mean daily minimum temperature for the stations of Figure 1, based on comparisons with neighbouring stations 2 years before and after each site change

Station number and name	Time of site change	Estimated shift	Standard error	Number of observations	Stations used
1 Ashburton	1939·83	−0·005	0·142	24	4, 6, 7, 8
	1951·50	−0·107	0·103	24	2, 4, 6, 7, 8
2 Darfield	1948·92	0·263	0·133	24	1, 4, 6, 8
3 Christchurch Airfield	1953·58	No estimate			
	1956·33	0·000	0·080	24	1, 2, 4, 5, 6, 7, 8, 9
	1960·75	−0·235	0·080	24	1, 2, 4, 5, 6, 7, 8, 9
	1975·50	0·450	0·099	24	1, 2, 4, 5, 9
4 Christchurch Gardens	1905·00	No estimate			
	1971·58	0·027	0·134	24	1, 2, 3, 5, 6, 9
5 Eyrewell	1951·00	No estimate			
	1966·50	0·098	0·155	24	1, 2, 3, 4, 6, 7, 8, 9
6 Lincoln	1944·33	0·963	0·135	24	1, 2, 4, 7, 8
	1963·00	0·140	0·136	24	1, 2, 3, 4, 5, 7, 8, 9
	1975·58	−0·131	0·119	24	1, 2, 4, 5, 9
7 Onawe	1969·83	−0·072	0·146	24	1, 2, 3, 5, 6, 9
8 Wigram	1942·08	0·190	0·072	24	1, 2, 4, 6, 7

The significant result for the 1975 site change at Christchurch Airport occurred in spite of the fact, noted above, that the cusums for all stations showed a marked decrease in slope at this time (Figure 1). Thus, in this case, a significant site change effect at one site apparently coincided with a much larger shift in temperature due to some other cause.

2.4.2. Rainfall. The correlation matrix, calculated from differences of the logarithm of monthly rainfall totals, is given in Table III.

Table IV shows the estimated factor by which rainfall readings were affected by each site change and its 95 per cent confidence interval, using the method of section 2.2.2 and data from 2 years before and after each site change. It also shows the number of monthly ratios used and the neighbouring stations used in the estimate.

Only two of the site changes had a significant effect at the 0·05 level, namely those at Eyrewell in 1951 and Onawe in 1969, since the confidence intervals for these two site changes do not span unity. The large change of Eyrewell is evident in Figure 2. The adjustment to the Eyrewell record is to divide rainfall prior to 1951 by 1·80. This factor is much larger than normally would be expected for a site change, and its seems likely that some kind of gross observation error affected the data at Eyrewell prior to 1951. The effect of the 1969 site

Table III. Correlation matrix of rainfall data for the stations of Figure 1, calculated from differences of logarithms of monthly rainfall totals, as explained in section 2.3

		1	2	3	4	5	6	7	8	9
Ashburton	1	1·00								
Darfield	2	0·87	1·00							
Christchurch Airfield	3	0·80	0·88	1·00						
Christchurch Gardens	4	0·77	0·82	0·95	1·00					
Eyrewell	5	0·83	0·95	0·88	0·83	1·00				
Lincoln	6	0·84	0·86	0·92	0·90	0·86	1·00			
Onawe	7	0·73	0·77	0·84	0·87	0·75	0·84	1·00		
Wigram	8	0·79	0·85	0·97	0·96	0·83	0·93	0·84	1·00	
Winchmore	9	0·96	0·91	0·84	0·80	0·87	0·87	0·76	0·81	1·00

Table IV. Estimated site change factors for rainfall observations for the stations of Figure 1, based on comparisons with neighbouring stations 2 years before and after each site change

Station number and name	Time of site change	Estimated factor	95 per cent confidence interval	Number of observations	Stations used
1 Ashburton	1939·83	1·224	(0·963, 1·557)	24	2, 4, 6, 7
	1951·50	1·145	(0·973, 1·348)	24	2, 4, 6, 7, 8, 9
2 Darfield	1948·92	1·128	(0·980, 1·297)	24	1, 4, 5, 6, 8
3 Christchurch Airfield	1953·58	1·051	(0·945, 1·169)	23	1, 2, 4, 5, 6, 7, 8, 9
	1956·33	1·050	(0·922, 1·195)	24	1, 2, 4, 5, 6, 7, 8, 9
	1960·75	0·980	(0·864, 1·111)	24	1, 2, 4, 5, 6, 7, 9
	1975·50	1·033	(0·935, 1·142)	24	1, 2, 4, 5, 7, 9
4 Christchurch Gardens	1905·00	1·080	(0·890, 1·311)	23	6
	1971·58	0·952	(0·816, 1·110)	24	1, 2, 3, 5, 6, 9
5 Eyrewell	1951·00	1·798	(1·572, 2·058)	24	2, 4, 6, 7, 8, 9
	1966·50	0·961	(0·839, 1·102)	23	1, 2, 3, 4, 6, 7, 9
6 Lincoln	1944·33	1·027	(0·918, 1·148)	24	1, 2, 4, 5, 7, 8
	1963·00	0·982	(0·881, 1·094)	24	1, 2, 3, 4, 5, 7, 9
	1975·58	0·960	(0·839, 1·099)	24	1, 2, 4, 5, 7, 9
7 Onawe	1969·83	1·222	(1·005, 1·485)	24	1, 2, 3, 5, 6, 9
8 Wigram	1942·08	1·071	(0·922, 1·244)	24	1, 2, 4, 6, 7

change at Onawe is not obvious visually in Figure 2. However, it can be discerned in Figure 5, which shows the cusum of the ratio of Onawe rainfall to that at the other stations.

3. ADJUSTING AN ISOLATED STATION

Sometimes it is desired to adjust a station that has no near neighbours, e.g. stations on isolated islands or early records. Such an adjustment involves much greater uncertainty than the adjustment of a station with many neighbours. A greater degree of subjectivity is inevitable. In the absence of corroborating data there is no way of knowing whether an apparent shift that coincides with a site change is due to the site change or not. However, several statistical procedures can be used alongside information on station histories to assist in the estimation of the effect of a site change. These include graphical examination of the data, simple statistical tests for detecting shifts applied to intervals of different length before and after the site change, and identification of the most prominent change points in the series independently of known site changes. Finally, a subjective judgement must be made whether to adjust the data or not, taking into account the consistency of all the graphical and analytical evidence supporting the need for an adjustment and any other relevant information. The statistical procedures are described in more detail below. Only the tests for temperature

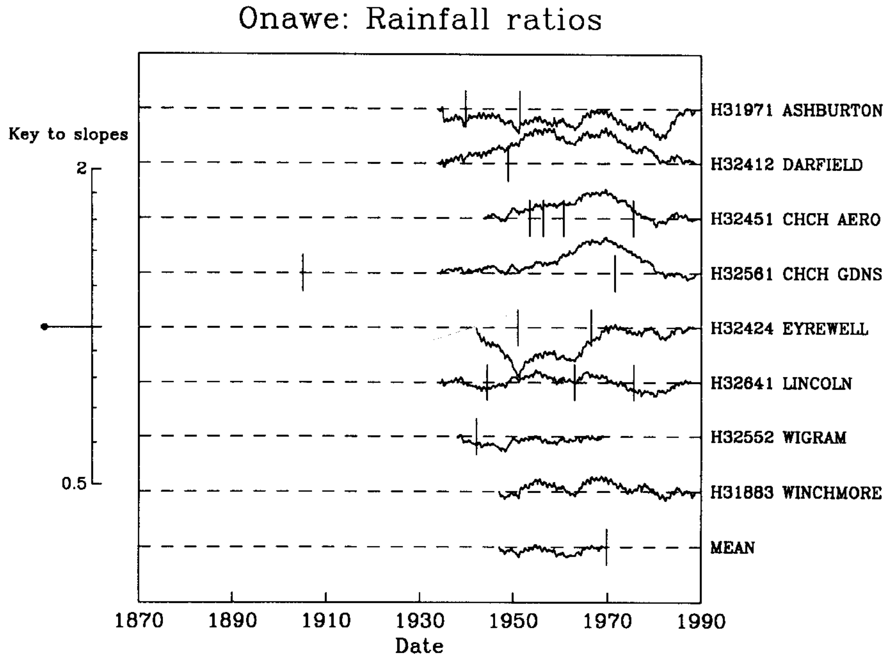

Figure 5. Parallel cusums of the ratio of the rainfall at Onawe to that at the other stations. Vertical lines show the time of known site changes; Chch Aero, Christchurch Airfield; Chch Gdns, Christchurch Gardens

series are described; a logarithmic or other suitable transformation should be applied for rainfall data, as for the neighbouring station methods above.

3.1. Graphical analysis

A visual examination of the data is the first and most important step. In many cases it is the only analysis needed. Again a cusum of differences from the time-of-year mean is useful, as it highlights changes in level without sacrificing detail. If there is no obvious change of slope at about the time of a known site change, then no further analysis is necessary and no adjustment need be made to the data. If there is an apparent change of slope at about the time of a site change, then the size and statistical significance of the change are investigated.

3.2. Test using annual values

The size and standard error of the effect of a site-change can be estimated using a comparison of annual values (means or totals) before and after the site change. The use of annual values gives protection against the influence of short-term autocorrelations in the series. On the other hand, the need for adequate degrees of freedom requires that a moderate number of years before and after the site change be used in the estimation. There is therefore some danger of a long-term trend being confused with a site change effect. In detail the method is as follows.

Let τ_0 denote the beginning time of the data series, τ_i the time of the ith site change ($i = 1, \ldots, k$) and τ_{k+1} the time of the last value in the series. Let $\{x_{-1}, \ldots, x_{-n_b}\}$ denote annual values working backwards from τ_i to τ_{i-1}, and $\{x_1, \ldots, x_{n_f}\}$ annual values working forwards from τ_i to τ_{i+1}. A simple t-test on the differences of the means of $\{x_{-1}, \ldots, x_{-n_b}\}$ and $\{x_1, \ldots, x_{n_f}\}$ then gives an estimate of the size of the site change at time τ_i.

3.3. *Test using subannual differences over symmetric intervals*

Another approach is to choose a symmetric interval about the time of the site change and estimate the change by the mean of subannual (e.g. monthly or quarterly) differences spanning the time of the site change. The use of subannual differences gives an adequate number of degrees of freedom from a relatively short time period. In comparison with the previous method there is less likelihood of the site change effect being confounded with the long-term trend but a greater susceptibility to the effects of short-term autocorrelations.

Let $\{x_t\}$ denote the series of subannual observations and let τ denote the time of a known site change. Suppose there are h subannual time periods in a year and the symmetric interval is k years on either side of τ. From the series $\{y_t, t=1, 2, \ldots, kh\}$, given by

$$y_t = x_{\tau+t} - x_{\tau+t-kh} \qquad t=1, 2, \ldots, kh.$$

In the absence of trends and autocorrelation in the original series, $\{y_t\}$ are independent random variables with expected values equal to the shift at time τ, the seasonal cycle having been removed by differencing. Assuming $\{y_t\}$ to be normal with a common variance, we could estimate the site change by $\bar{y}$, the mean of $\{y_t, t=1, \ldots, kh\}$, which is a t-statistic with $kh-1$ degrees of freedom. A $100(1-\alpha)$ per cent confidence interval for shift is $\bar{y} \pm t_{kh-1;\alpha/2} \times s_{\bar{y}}$.

3.4. *Finding the most prominent change points*

Meteorological series usually contain a number of apparent change-points, where the level seems to change from one value to another. The more prominent a change-point associated with a site change is, the more confidence one has that it is a real site change effect. It is therefore of interest to identify the times of the most prominent change-points in a series and to see if the site changes are amongst them. Let $\{e_t, t=1, \ldots, n\}$ be the series of residuals of $\{x_t\}$ from a time-of-year mean. Then, to fit the most prominent k change-points, we seek a partitioning set of integers $n_1 < n_2 < \ldots < n_k = n$ and values $\mu_1, \mu_2, \ldots, \mu_k$ such that the residual sum of squares (RSS)

$$\text{RSS} = \sum_{t=1}^{n_1} (e_t - \mu_1)^2 + \sum_{t=n_1+1}^{n_2} (e_t - \mu_2)^2 + \ldots + \sum_{t=n_{k-1}+1}^{n_k} (e_t - \mu_k)^2$$

is minimized. For a given partitioning set, RSS is minimized when

$$\mu_j = \frac{1}{n_j - n_{j-1}} \sum_{t=n_{j-1}+1}^{n_j} e_t \qquad j=1,2, \ldots, k.$$

For a given k, the optimal partitioning set is efficiently determined by dynamic programming, as discussed by Seward and Rhoades (1986).

3.5. *An example*

The use of the methods described above is now illustrated with reference to the mean daily minimum temperature data already presented from stations in and around Christchurch. Although these stations are not isolated, except for the early records of Christchurch Gardens and Lincoln, they are treated as isolated for the purpose of this analysis. A comparison with the combined analysis already carried out above may then help us to gauge the usefulness and limitations of the techniques.

The cusums for all stations are found in Figure 1. It can be seen from Figure 1 that abrupt changes of slope, representing apparent shifts, are not at all uncommon. Several or more can be seen on each of the curves plotted there. However, it is only occasionally that a change of slope coincides with a known change point. Marked changes of slope coincide with the last site change at Christchurch Airport and the first site change at Lincoln. Less marked changes coincide with the site change at Darfield, the last site change at Christchurch Gardens, and the last two site changes at Lincoln. Thus in more than half of the cases the need for an adjustment can be ruled out by a visual inspection of the cusum graph.

We now proceed to the statistical testing. Table V shows the results of a range of tests applied to the six changes for which graphical evidence indicates a possible shift. The tests illustrated use annual values over the full period between site changes and monthly values for symmetric intervals 2 and 4 years before and after each site change. In practice a wider range of tests might be examined but this selection suffices for illustrative purposes. Table VI shows the years of the four most prominent change-points for each of the four stations in Table V, calculated according to the method of section 3.4.

In the light of the weaknesses in each individual test, it seems best to take a conservative view in deciding when to adjust, i.e. to adjust for site change only when the combined evidence strongly supports it. Our policy is to adjust only when there is consistency among the different tests, and a high level of statistical significance. Also the site change should be one of the few most prominent change-points in the data set. In Table V, only two site changes satisfy the first two requirements, namely Christchurch Airport 1975 and Lincoln 1971. These are also the only two site changes that appear amongst the four most prominent change-points (Table VI).

Our inclination, based on the graphical and statistical evidence would be to adjust only for these two site changes by an amount indicated by the median of the three estimates in Table V, namely 0.8°C for the

Table V. Estimated shifts in mean daily minimum temperature at the time of site changes based on methods for isolated stations

Station name	Time of site change	Method[c]	Estimated shift	Standard error
Darfield	1948·92	A	0·92[b]	0·22
		B	−0·58[a]	0·28
		C	−0·09	0·25
Christchurch Airport	1975·50	A	−0·34[a]	0·16
		B	−1·58[b]	0·32
		C	−0·84[b]	0·22
Christchurch Gardens	1971·58	A	0·31[a]	0·12
		B	−0·75[a]	0·29
		C	−0·14	0·22
Lincoln	1944·33	A	−0·86[b]	0·13
		B	−1·46[b]	0·31
		C	−1·16[b]	0·18
Lincoln	1963·00	A	0·67[b]	0·18
		B	−0·66[a]	0·30
		C	−0·08	0·22
Lincoln	1975·58	A	0·02	0·20
		B	−0·85[a]	0·37
		C	−0·27	0·23

[a] $p<0.05$;
[b] $p<0.001$.
[c] A, Annual values, full period between site changes; B, monthly values, 2 years before and after site change; C, monthly values, 4 years before and after site change.

Table VI. Four most prominent change points for stations showing graphical evidence of a shift coinciding with a site change

Darfield	Chch Aero	Chch Gdns	Lincoln
1946	1967	1876	1906
1969	1975	1915	1917
1975	1977	1917	1944
1977	1978	1967	1964

Christchurch Airport site change and 1.2°C for the 1971 Lincoln site change. The corresponding adjustments using neighbouring series were 0.5°C and 1.0°C respectively (Table II). One site change (Christchurch Airport 1960·75), which would have been adjusted using neighbouring series, does not qualify for adjustment when treated as isolated.

The 1975 site change at Christchurch Airport is somewhat overestimated, when compared with the neighbouring stations analysis. The contrast between the estimates based on 2 years data before and after this site change is particularly marked. For the neighbouring stations analysis the estimate is 0·45°C (Table II); for the isolated station analysis the estimate is 1·58°C (Table V). This is to be expected when a site change coincides with an actual shift in temperature, as occurred in this case. The isolated station analysis then estimates the sum of the site change effect and the actual shift.

4. CONCLUSION

Adjustments for site changes can probably never be done once and for all. For stations with several neighbours, the decision to adjust for a site change usually can be taken with some confidence. The same cannot be said for isolated stations. However, large shifts can be recognized and corrected, albeit with some uncertainty. Ideally, for isolated stations, tests for site change effects would be incorporated into the estimation of long-term trends and periodicities as suggested by Ansley and Kohn (1989). This is not practicable at present on a routine basis, but may be in the future.

Even for adjustments using neighbouring stations, there are important elements in the adjustment procedure that are presently a matter of choice. These include the selection of neighbouring stations, the weighting formula, and the period of time to be used for adjustment. Future research may lead to better guidelines in some of these matters.

Further investigation is needed of the performance of the methods proposed here in comparison with other methods in the literature. This can best be done by simulation studies, in which the stochastic nature of the series is strictly controlled. In particular we would like to know how well the methods perform in the presence of certain types of autocorrelation and cyclic effects other than annual cycles, which are likely to be present in all meteorological data to some extent.

In the meantime researchers using homogenized series need to be constantly aware of the present limitations of homogenization methods. Homogenized series, although an improvement and sometimes a vast improvement, on the original series, should not be treated as 'clean' data. Whatever adjustment procedures are used, the presence of site changes causes an accumulating uncertainty when comparing observation that are more distant in time. The cumulative uncertainties associated with site change effects, whether adjustments are made or not, are often large compared with effects appearing in studies of long-term climate change. For this reason it is a good idea to publish the standard errors of site change effects along with homogenized records, whether adjustments are made or not. This would help ensure that, in subsequent analyses, not too much reliance is placed on the record of any one station.

ACKNOWLEDGEMENTS

This research was funded by the New Zealand Foundations for Research, Science and Technology through the National Climate Centre Data Programme and grant 92-MET-33-352 and the DSIR Physical Sciences Climate Statistics Programme.

The authors are indebted to C. S. Thompson and two anonymous referees who read the manuscript and made several valuable suggestions.

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