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A daily homogenized temperature data set for Australia

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ABSTRACT: A new homogenized daily maximum and minimum temperature data set, the Australian Climate Observations Reference Network – Surface Air Temperature data set, has been developed for Australia. This data set contains data from 112 locations across Australia, and extends from 1910 to the present, with 60 locations having data for the full post-1910 period.

These data have been comprehensively analysed for inhomogeneities and data errors ensuring a set of station temperature data which are suitable for the analysis of climate variability and trends. For the purposes of merging station series and correcting inhomogeneities, the data set has been developed using a technique, the percentile-matching (PM) algorithm, which applies differing adjustments to daily data depending on their position in the frequency distribution. This method is intended to produce data sets that are homogeneous for higher-order statistical properties, such as variance and the frequency of extremes, as well as for mean values. The PM algorithm is evaluated and found to have clear advantages over adjustments based on monthly means, particularly in the homogenization of temperature extremes. Copyright © 2012 Royal Meteorological Society

KEY WORDS temperature data; Australia; homogenization

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1. Introduction

High-quality temperature data sets are vital for climate monitoring, and especially the monitoring of climate change. Many temperature data sets exist at the global (Hansen *et al*., 1999, 2001; Brohan *et al*., 2006; Smith *et al*., 2008), regional (Klein Tank *et al*., 2002) and national scales.

If a temperature data set is to be used for monitoring climate change it is important that it be homogeneous; that is, changes in the temperature as shown in the data set reflect changes in the climate, and not changes in the external (non-climatic) conditions under which the observations are made. Potential non-climatic influences on temperature observations, which are discussed in more depth in sources such as Peterson *et al*. (1998), Aguilar *et al*. (2003) and Trewin (2010), include changes in local ground conditions around an observation site, changes in instruments and changes in observation procedures. In addition, many station 'series' are taken from more than one location, despite often appearing under a single geographical name.

Very few century-scale temperature station series are totally free of such influences, and thus careful homogenization is required in order to produce a homogeneous data set. Whilst site-specific inhomogeneities have only a marginal impact on observed temperature trends at the global scale (Jones and Wigley, 2010), they can have a much more substantial effect on outcomes at the local and regional scale.

The homogenization process is a two-stage process: firstly the detection of inhomogeneities in the data and secondly the adjustment of data to remove those inhomogeneities. The detection of inhomogeneities at the annual and monthly is a well-explored problem, both in climate science and in the broader statistical literature. Reviews on this topic include those of Peterson *et al*. (1998) and Reeves *et al*. (2007), although there have been more recent developments, such as Li and Lund (2012) and Toreti *et al*. (2012).

Adjustment procedures have received much less attention, with most data sets applying adjustments on the basis of annual (Della-Marta *et al*., 2004) or monthly (Jones *et al*., 1986; Begert *et al*., 2005) means. However, homogenization of mean temperatures does not necessarily imply homogenization of higher-order statistical properties such as variance, or derived statistics which are a function of those higher-order properties, such as the occurrence of extremes. This issue was initially identified by Trewin and Trevitt (1996), who found that in some cases an inhomogeneity, such as a site move, affected different parts of the frequency distribution of daily temperature in different ways. This is illustrated by the example shown in Figure 1.

Detection and adjustment of inhomogeneities have also been the subject of the European *Advances in homogenization methods of climate series: an integrated approach* (HOME) project (www.homogenisation.org);

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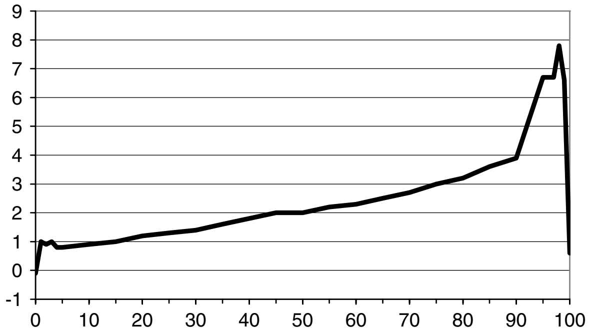


Figure 1. Differences (°C) between percentile points of summer maximum temperature at Albany airport (009741) and Albany town (009500) during the overlap period (2002–2009). The 0th and 100th percentiles indicate the lowest and highest values recorded during the overlap period.

the results of a benchmarking of numerous homogenization methods, carried out as part of that project, were reported in the studies of Venema *et al*. (2012).

Most national and international data sets which have been homogeneity-adjusted use adjustments calculated on the basis of annual or monthly means. In most cases these apply a uniform adjustment for each calendar month or across the year, although there have been some data sets (some of which use the term 'daily homogenization') which apply a different adjustment for each calendar date, normally derived from monthly data (Vincent *et al*., 2002; Brunet *et al*., 2006). Whilst a number of techniques have been developed, as described later in this article, to adjust data at the daily time scale using adjustments which are different for different parts of the frequency distribution, or are otherwise dependent on weather types, the only previous known application of such techniques to a large network in a year-round national-level data set is the 1957–1996 Australian daily data set (Trewin, 2001).

This article describes the methodology used for the construction of a new data set, the Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) data set. This data set makes use of substantial recently digitized data (from paper records) to allow homogeneous maximum and minimum temperature data to be produced at the daily time scale for the period from 1910 to the present, with coverage across the Australian continent. Documentation and traceability of the data and adjustments at all stages, an increasing priority as described by Thorne *et al*. (2011), are also a high priority in the ACORN-SAT data set.

2. Data and metadata availability

2.1. Australian network coverage

Temperature observations have been made in Australia since the days of initial European settlement in the late 18th century (Gergis *et al*., 2009). Various short-term observations (data sets of a few years or shorter) were made up until the middle of the 19th century. From the 1850s onwards, more systematic observations began to be made across Australia. The longest currently available 'continuous' temperature record in Australia commenced in the city of Melbourne in 1855, and by the early 1860s a number of additional stations existed in New South Wales, Victoria and South Australia. The number of stations increased steadily over time, and there was reasonable coverage of the eastern mainland by 1890. Progress was slower in Tasmania and Western Australia, where there were very limited observations outside Hobart and Perth before 1900.

The creation of the Bureau of Meteorology in January 1908 brought all meteorological observations under federal government control. This resulted, within a short time, in the implementation of common standards for observations and instrumentation (discussed in more detail below). It also resulted in a rapid increase in the number of stations taking observations. The number of stations then stabilized through most of the 1910–1940 period, before increasing further from 1940 through the early 1950s, initially as a result of the Second World War, then the growth of civil aviation. There have not been dramatic changes in the number of stations since then, although the spread of stations over Australia has become more comprehensive, with observations beginning in the 1950s and 1960s in a number of strategic locations in remote parts of central and northern Australia. Coverage of high-altitude areas in southeastern Australia has also improved greatly in the last 20 years.

Figure 2 shows the networks in 1930 and 2010, while a summary of the number of stations is shown in Figure 3. The distribution of stations is uneven over Australia (Figure 2), with stations most heavily concentrated in the more densely populated parts of southeastern and southwestern Australia. Elsewhere many stations are more than 100 km from their nearest neighbour, with two ACORN-SAT stations (Giles and Rabbit Flat) more than 200 km from their nearest neighbour, and substantial areas in the western and eastern interior have no observations at all.

2.2. Elements available and data digitization

Nearly all stations which measure temperature, with some very limited historical exceptions (almost all pre-1900), observe daily maximum and minimum temperature. They also observe temperatures at a variety of fixed hours. Manual stations make from one (normally 0900 local time) to eight (0000, 0300, ..., 2100) observations per day, with the majority making observations at 0900 and 1500. Most automatic weather stations (AWSs) have data at 30- or 60 min resolution (as do a few major city stations prior to automation), and an increasing number has data at 1 min temporal resolution. The fixed-hour temperatures do not form part of the ACORN-SAT data set but support the quality-control checks described later in this article, as do other elements such as terrestrial minimum temperature, where available.

Until recent years, there were only very limited digital daily maximum and minimum temperature data available

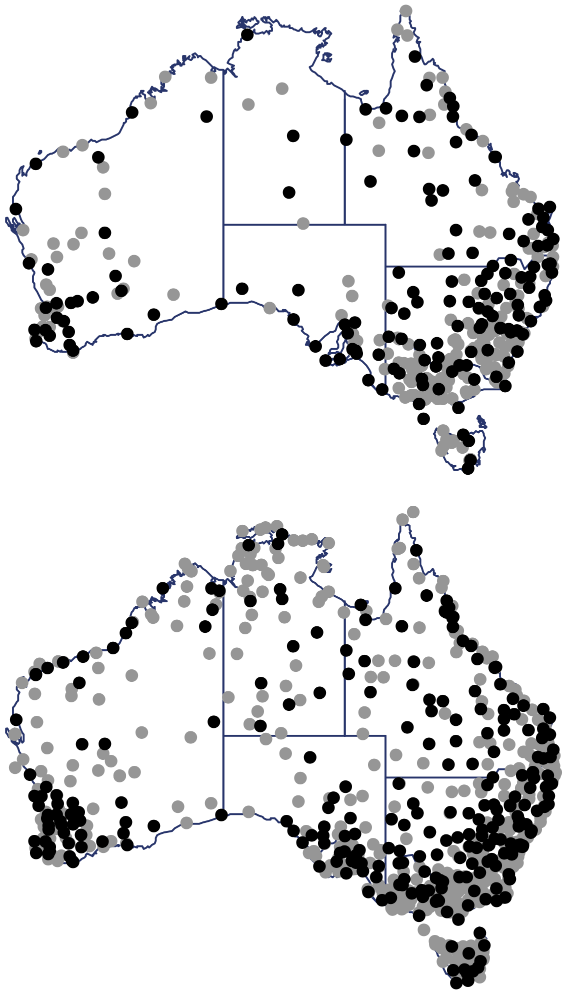


Figure 2. The Australian temperature observing network in 1930 (top) and 2010 (bottom). Stations with 40 or more years of data are shown in black. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

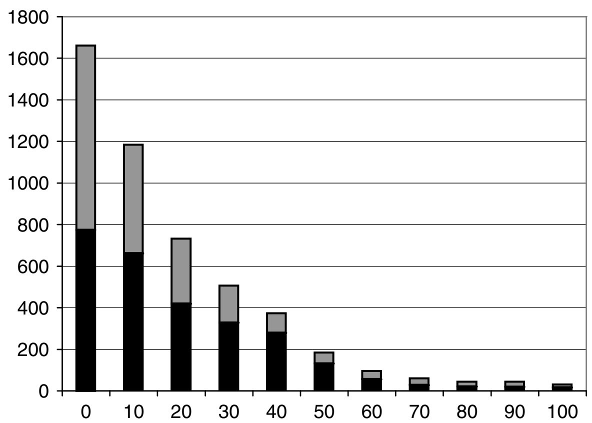


Figure 3. Number of Australian temperature stations with at least *N* years of digitized daily temperature data. The number of stations, which are currently open, is shown in black.

prior to 1957 or fixed-hour data (except at 0900 or 1500) prior to 1987, with most data prior to that date available only on paper manuscripts. In contrast, monthly data, which underlie the data set of Della-Marta *et al*. (2004), have been almost entirely digitized for some time, which is why the earlier high-quality data sets for Australia focused on the annual or monthly time scale.

In the last decade, there has been an ongoing effort to digitize pre-1957 daily temperature data as part of the CLIMARC project (Clarkson *et al*., 2001) and associated projects, although large quantities of daily temperature data remain undigitized. Some newly digitized data have not yet undergone any Bureau of Meteorology quality control and are yet to be incorporated into the main Bureau database; these data were used in ACORN-SAT but with particular care.

2.3. Availability of metadata

Metadata – that is, information about the way in which the data have been observed – are important in documenting non-climatic influences which can affect temperature measurements. These include issues which are specific to individual sites (such as site relocations, instrument changes or changes in local site conditions), or issues which affect large parts of the observing network (such as changes in observation times).

The major sources of site-specific metadata available for the ACORN-SAT stations are a digital metadata database (SitesDB) for post-1997 material (and some limited pre-1997 information) and hard-copy station files and instrument registers for pre-1997 material. Major items of relevance for the ACORN-SAT project include:

- Details of site relocations.
- Station inspection reports, including site photographs (or in some earlier periods, sketches) and diagrams. In recent decades, these have been approximately annual at ACORN-SAT stations (although there are a few notable exceptions, particularly at locations which are difficult to access). In the historical data they are much less frequent, with inspection reports often a decade or more apart prior to 1960.
- Changes in instruments. These are perhaps the best-documented changes historically, in part because they involved the expenditure of public funds.
- Instrument tolerance checks carried out at individual sites.

Obtaining metadata which are not specific to individual stations is often more challenging than obtaining site-specific metadata, as there has not always been a specific store for such information. Observation manuals (Bureau of Meteorology, 1925, 1954, 1984) are a detailed description of observation practices at a specific point in time, although they are less useful in determining the exact date of any relevant changes. More recently, changes in policy have been documented in a series of Observations Instructions (or similar) issued by the Bureau's Observations and Engineering Section. However, some issues (e.g. the use of 0000/1200 UTC observations for a time at some AWSs) are not documented in any formal publications and are known to the ACORN-SAT project only through the corporate knowledge of individuals involved with the project. It is likely that other such changes have occurred historically but without any documentary evidence.

Other information from third parties can also be considered as metadata. This includes maps (particularly topographic maps), and population data, from the Australian Bureau of Statistics, for urban centres near observing sites.

3. Instruments and observation practices

Temperatures in Australia are measured in a Stevenson screen. This screen has been in place as the standard instrument shelter since shortly after the formation of the Bureau of Meteorology as a federal government organization in 1908, with only a small number of stations continuing to use non-standard screens after that date. Prior to the introduction of the Stevenson screen, a wide variety of instrument exposures existed (Parker, 1994; Torok and Nicholls, 1996). For this reason, the ACORN-SAT data set begins in 1910 (except at Eucla, where a Stevenson screen was not installed until 1913).

The major instrument change which has taken place during the post-1910 period has been the transition from manually read liquid-in-glass thermometers (mercury for maximum temperature and alcohol for minimum temperature) to platinum resistance temperature probes in AWSs. The latter began to be introduced into the ACORN-SAT network in 1992 and are now used as the sole or primary instrument at 89 of the 112 ACORN-SAT locations. At those locations where both manual and automatic observations were made, the automatic probe became the primary instrument from 1 November 1996. Unlike many countries, the screen design did not change when automated probes were introduced, with the probes continuing to be housed in a Stevenson screen.

The current standard is for maximum and minimum temperatures to be measured for a 24 h period ending at 0900 local time, with minimum temperature attributed to the current day and maximum temperature to the previous day (consistent with maximum temperatures typically occurring during the afternoon). This standard has been in place, with limited exceptions, since 1964 (although the introduction of daylight savings time in summer in some states has introduced an effective 1 h shift in observation time, since local clock time rather than standard time is used). Prior to 1964, two main standards were used: a notional midnight–midnight standard at stations staffed by Bureau personnel, and 0900–0900 maximum (with some modifications) and 1500–0900 minimum at other stations. A full description of these standards and their implementation is described by Trewin (2012).

Temperatures are measured in general to the nearest 0.1 degree, although in practice many observations were rounded to the nearest degree or half-degree, particularly prior to 1972 when measurements were made in degrees Fahrenheit (Trewin, 2001). Some AWSs only recorded temperatures in whole degrees in their early years due to limitations in software.

Most temperature stations are now visited by Bureau of Meteorology staff at least once per year, with many being visited twice. Tolerance checks of instruments are carried out at these visits, with thermometers considered to be 'in tolerance' if they are within 0.5 °C of a reference instrument. An analysis of the results of these checks (Trewin, 2012) shows little evidence of any systematic tendency of instruments in the field to drift in either direction.

A fuller description of observing procedures over time can be found in Bureau of Meteorology (1925, 1954, 1984).

4. Selection of the ACORN-SAT network

Only some of the stations in a network are suitable for use in long-term climate change analyses. Most have too little data (less than 30 years), and some have excessive missing data, poor site or observation quality, or are otherwise unsuitable.

Ideally, stations used in a data set for climate change analyses would meet the following criteria:

- A long period (preferably 100 years or more) of continuous data with few or no missing observations.
- No site changes, changes in observation practices or instruments, or significant changes in local site environment.
- Located well outside any urban or potential urban growth area.

No such temperature stations exist in practice in Australia, so it is necessary to make some compromises in the selection of a station network. Jones and Trewin (2002) found that a network of 100–200 stations was sufficient to define temperature variability to a reasonable degree of accuracy over Australia, while Vose and Menne (2004) obtained similar results for the similarly sized continental United States. In practice, given the number of long-term stations available (Figure 3), constructing a network of this size requires making use of most of the stations with an acceptably long record, with careful homogenization required to obtain consistent records.

Two major temperature data sets have previously been used for climate change analyses in Australia. The first is an annual data set of 134 stations, originally developed by Torok and Nicholls (1996) and enhanced by Della-Marta *et al*. (2004). The second is a daily data set of 103 stations developed by Trewin (2001) and mostly covering the period from 1957 to 1996. The core of this data set was based on the network of Reference Climate Stations, a network selected by the Bureau of Meteorology (1995), in response to a request made by the World Meteorological Organization in 1990 for its member nations to identify a network of recommended reference climate sites.

The ACORN-SAT temperature data set consists of daily maximum and minimum temperature data for 112 stations (Figure 4). At least 60 stations are available in

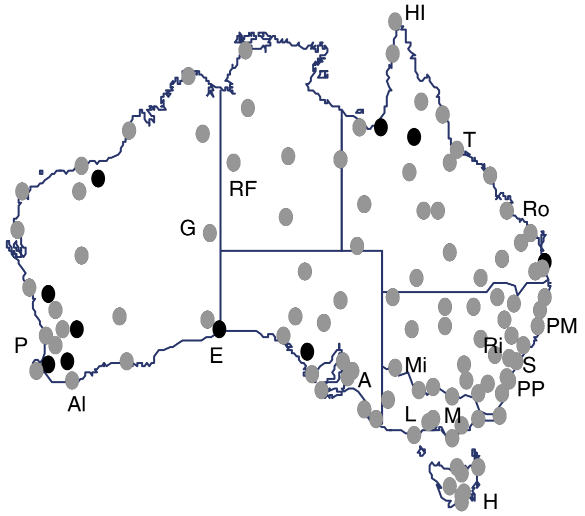


Figure 4. Stations in ACORN-SAT data set. Stations which were not in the previous daily data set (Trewin, 2001) are shown in black. Stations named in the text are labelled as follows: A, Adelaide; Al, Albany; E, Eucla; G, Giles; H, Hobart; HI, Horn Island; L, Laverton; M, Melbourne; Mi, Mildura; P, Perth; PM, Port Macquarie; PP, Point Perpendicular; RF, Rabbit Flat; Ri, Richmond (NSW); Ro, Rockhampton; S, Sydney; T, Townsville. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

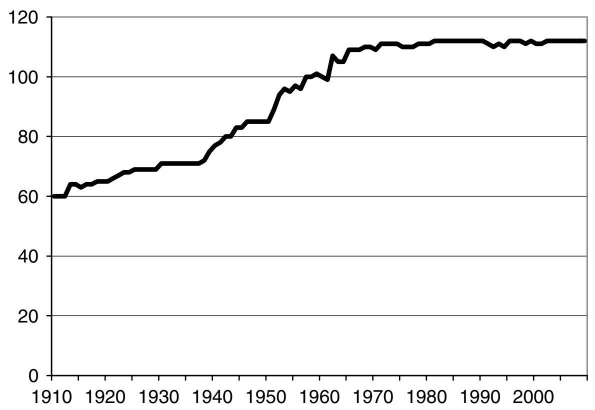


Figure 5. Number of ACORN-SAT stations with available data, by year.

every year from 1910, at least 85 in every year from 1946, and at least 99 in every year from 1957 (Figure 5). From 1971 onwards, there are no more than two stations missing in any individual year.

The Trewin (2001) network forms the basis for the ACORN-SAT data set. Compared with the Trewin (2001) set, ten stations have been added, most with substantial newly digitized data, and one deleted. A full listing of the ACORN-SAT stations, coordinates and elevation and years of data is available in Trewin (2012).

5. Quality control of ACORN-SAT data

Data quality control is a very important part of any climate data set. Errors can occur in meteorological observations for a wide variety of reasons, the most common being instrument faults, observer errors, errors in data transmission and clerical errors in data processing. A distinction, somewhat arbitrary, is drawn here between short-term issues which affect observations over a finite period (most commonly a single observation, but sometimes persisting for a period of a number of days or weeks), and longer-term influences on a climate record (inhomogeneities) which are considered separately.

The underlying philosophy in the ACORN-SAT project has been to subject data throughout the historic record, to the extent possible, to a level of quality control similar to that currently applied operationally to new data by the Bureau of Meteorology. The level of quality control over most of the period prior to the introduction of the current quality-control system in 2008, particularly prior to the introduction of the Bureau of Meteorology's relational computer database in 1994, falls well short of current standards, mainly because, without modern computer analysis tools, the ability to perform data-intensive checks (such as spatial intercomparisons) is severely limited.

Each of the daily temperature time series in the ACORN-SAT data set was subjected to a range of quality-control checks for internal and spatial consistency (described in detail by Trewin, 2012). Any data flagged by any of these checks was subjected to follow-up investigations. A distinction was drawn here between observations which had been flagged because of a violation of hard limits (e.g. recorded maximum temperature less than temperature at 1500), for which at least one observation must be wrong, and those which were flagged because of a violation of soft limits (e.g. excessive variation from neighbours). In the former case, a 'guilty until proven innocent' approach was taken, with the maximum/minimum temperature considered suspect unless evidence pointed to the inconsistency arising from another cause (e.g. an incorrect 1500 temperature). In the latter case, an 'innocent until proven guilty' approach was taken with marginal observations generally included.

In follow-up investigations all readily available data were used, including fixed-hour temperatures, data from other stations including the all-stations Bureau operational analyses (Jones *et al*., 2009), and other variables such as terrestrial minimum temperature, dewpoint, wind, cloud and rainfall. Clearly, the availability (or lack thereof) of such supporting data affects the ability to detect errors, and it is highly likely that some errors will remain undetectable, particularly in the most data-sparse areas.

As a result of the quality-control process, 18 216 individual observations and 508 blocks of three or more consecutive days of observations, out of a total of about 6 million observations, were identified as suspect and excluded from the ACORN-SAT data set, or in limited cases (as described in Trewin, 2012) amended.

In addition, any maximum or minimum temperature observation from a liquid-in-glass thermometer which followed one or more missing observations was assumed to have been the maximum/minimum for the full period of missing data, unless that period was more than 5 days.

Whilst there is provision for accumulated data to be flagged in the Bureau's climate database, the use of these flags has been too inconsistent historically to be useful for ACORN-SAT.

6. Detection of inhomogeneities

Potential inhomogenities in the ACORN-SAT data set were detected using a combination of metadata and statistical methods. The use of metadata is preferable if it is available, since it can demonstrate definitively that a change has occurred, and in many cases will also indicate the exact date of the change, whereas even the strongest inhomogeneities detected by statistical means will have some level of uncertainty attached to their timing. Statistical methods are essential to cover those inhomogeneities which are not identified in metadata, as metadata are often incomplete; in particular, site-based metadata often fail to capture changes which occur outside the immediate instrument enclosure but still have the potential to affect observed temperatures (e.g. vegetation changes or building development in the surrounding area).

A comprehensive search of metadata, both hard-copy and electronic, was undertaken to identify changes at a site which could indicate potential inhomogeneities, with a particular emphasis on site moves and significant developments in the vicinity of the observation site. All such changes were viewed as potential inhomogeneities in the initial assessment. In practice, some of these changes did not have any substantial effect on temperature observations; such non-significant 'inhomogeneities' were filtered out of analyses during the adjustment process, as described in that section.

For statistical detection of inhomogeneities, the principal problem is that of determining where a breakpoint exists in a time series which is larger than can be attributed to chance (to a certain level of confidence). This problem has a well-developed statistical literature. The techniques which have been used in the major global scale, and many national scale, climate data sets mostly fall into two broad categories: the standard normal homogeneity test of Alexandersson (1986), and two-phase regression, originally developed for climate use by Easterling and Peterson (1995), and with a number of refinements since, which have been implemented in the widely used RHtest software suite (Wang *et al*., 2010). In a review, Reeves *et al*. (2007) found that the two methods achieved a broadly similar overall level of performance, with their ranking depending on user priorities (e.g. accurately detecting the date of a breakpoint, or minimizing the number of false alarms).

Since the detectability of a breakpoint in a time series is a function of the ratio of the size of the breakpoint to the standard deviation of the data, a common technique to improve the signal-to-noise ratio is to apply statistical tests to the difference between the time series at the candidate station and that of a reference series which is representative of the background climate at the candidate station – the principle here being that doing so removes the background noise from interannual climate variability, leaving a station-specific signal.

Reference series are commonly constructed as a weighted mean of data from neighbouring stations; this method was used in the previous Australian work of Della-Marta *et al*. (2004) and Trewin (2001). However, the use of such a reference series depends on the assumption that the reference series itself is broadly homogeneous around the time of the potential inhomogeneity being investigated, something which may not hold if, for example, there is a substantial change in the composition of the reference series (e.g. a neighbouring station opening or closing), or a change affects a substantial proportion of the reference series around the same time as it affects the candidate station (e.g. an observation time change). An alternative approach used, for example, by Menne and Williams (2009) is to undertake a series of pairwise comparisons, with the candidate station being compared one-by-one with its neighbours (which will indicate breakpoints both at a candidate station and at each neighbour), then using an iterative procedure to isolate which breakpoints are most likely attributable to the candidate station rather than one or more of its neighbours.

The method used for statistical detection (but not adjustment) of potential inhomogeneities in the ACORN-SAT data set broadly follows the method used by Menne and Williams (2009) for the continental United States, with some simplifications as described in Trewin (2012). The most substantial of these simplifications is that all breakpoints are treated as step changes with no anomalous trend (model M3 of Menne and Williams), based on their finding that the method was only moderately effective in reliably identifying more complex breakpoint models. A check for anomalous trends at stations potentially affected by urbanization was carried out following the main homogenization process.

For each candidate station, testing for inhomogeneities was carried out separately for time series of mean maximum and minimum temperature anomalies for annual means, and for seasonal means for each of the four seasons (December to February, March to May, June to August and September to November). This procedure was followed because, in some cases, an inhomogeneity will vary seasonally – for example, if a site moves from a coastal location to one further inland, the difference in maximum temperatures between the sites is likely to be greatest in summer and least in winter. In such cases, a monthly difference time series will have an annual cycle which may affect the detection of breakpoints; the testing of seasonal series independently is to ensure the detection of any cases where there are opposite inhomogeneities in summer and winter, which could cancel out in annual data.

For each candidate station, 40 neighbour station time series were chosen. These neighbouring stations were initially chosen as the 40 best-correlated stations (using monthly anomalies, and considering maximum and minimum temperatures separately) from among the 150 nearest neighbours, chosen from the full observing network. If this procedure resulted in a candidate stations having fewer than 7 neighbours out of the 40 with available data in any given year, the 41st and subsequent stations were substituted for those stations in the original 40 with the least data, until at least seven reference stations were available in each year. We note that Menne and Williams used 100 stations rather than 150, but this would not have been sufficient to achieve at least 7 available stations in all cases for Australia.

Once those significant breakpoints in candidate-neighbour difference series which were most likely attributable to the candidate had been identified (see above), the number of neighbour stations which generated such breakpoints was checked. The breakpoint was considered to be potentially significant if this number of stations exceeded a specified threshold, bearing in mind that a small number of 'significant' breakpoints could occur by chance (e.g. if 40 neighbour stations are available in a given year then two difference series would be expected by chance to generate a breakpoint for that year significant at the 95% level). The threshold used was two stations if there were fewer than 5 stations with sufficient comparison data, three if there were 5–9, four if there were 10–19 and five if there were 20 or more; these thresholds were chosen as a number of stations for which there was less than a 5% probability that 'significant' breakpoints in difference series could occur by chance. If potentially significant breakpoints were found in two or more consecutive years, the breakpoint was attributed to the year for which the greatest number of neighbour stations generated breakpoints in the difference series.

The potentially significant breakpoints from the annual and seasonal time series were consolidated. An inhomogeneity was considered to be potentially significant if it was identified in the annual time series, or in at least two of the four seasonal time series (to within $\pm$ 1 year). If both criteria were satisfied then the year of the inhomogeneity in the annual time series took precedence.

Finally, the inhomogeneities identified by metadata were consolidated with those found by statistical methods, with the metadata-identified inhomogeneity taking precedence if it occurred within 2 years of a statistically identified inhomogeneity. All inhomogeneities were assumed, for the purpose of further analysis, to have taken place on 1 January unless a date could be identified from metadata.

7. The PM algorithm for adjustment

Once potential inhomogeneities have been identified, the next step is to adjust the data to produce a homogeneous data set for each station. As discussed earlier in earlier sections, adjusting monthly or annual mean values is not necessarily sufficient to produce homogeneous time series of higher-order statistical properties or indicators which are derived from those, such as the frequency of extremes, as some inhomogeneities affect different parts of the frequency distribution of daily temperatures in different ways.

A number of different techniques have been proposed to address this problem, although none are known to have been previously applied to the adjustment of a large national-scale year-round data set. (The closest equivalent applications have been those of Della-Marta *et al*., 2007, who applied their method to a network of 25 stations spread widely across Europe, and Kuglitsch *et al*., 2009, whose network covered the Mediterranean region but only considered the summer months.) These include methods which attempt to homogenize data across the full range of the frequency distribution, by matching percentile points in the frequency distribution (Della-Marta and Wanner, 2006) or by other means (Brandsma and Können, 2006; Toreti *et al*., 2010; Wang *et al*., 2010; Mestre *et al*., 2011), as well as methods which explicitly test the homogeneity of higher-order statistical properties such as mean daily variability (Wijngaard *et al*., 2003) or exceedances of percentile-based thresholds (Allen and DeGaetano, 2000).

For the homogenization of the ACORN-SAT data set the percentile-matching (PM) algorithm, which has two main variations (PM95 and PM99, which were evaluated separately as part of the process), was used. This algorithm is similar conceptually to those used by Trewin (2001) and Della-Marta and Wanner (2006), although there are some differences, principally in the details of generating transfer functions.

The PM algorithm takes two forms. The first, simpler, form is for the case of merging data from two sites where there is an overlap between the site records. The second, more complex case, is where there is no overlap (or an overlap which is not useful because it is too short or there have been further changes at the original site), and the adjustment is a two-step process involving the use of neighbouring stations.

7.1. The overlap case

In cases where two sites have at least 1 year of overlap with at least 50 daily observations in common for each set of three consecutive months of the year, the algorithm involves the following steps.

(a) Define $A_{n,d,m,y}$ as the daily temperature anomaly (for a daily normal, calculated by linear interpolation from the monthly normals) at site n ($n = 1$ for old site and $n = 2$ for new site) on day d of month m of year y.
(b) For each of the 12 calendar months m, define the sample of observations to be used in defining the transfer function as the values of $A_{n,d,m,y}$ for all days within a specified time window in which m is either the candidate month or the month preceding or following (e.g. if the candidate month is January, $m = 12$, 1 or 2) and $A_{n,d,m,y}$ is non-missing for both $n = 1$ and $n = 2$. In general, the specified time

window was the full period of overlap, but a subset was chosen in some cases where an inhomogeneity had been identified at one or both of the sites during the overlap period.

(c) Define $P_{n,m,v}$ as the vth percentile of the sample defined above for site n for month m, and $TP_{n,m,v} = P_{n,m,v} + M_{n,m}$, where $M_{n,m}$ is the monthly normal at site n for month m.

(d) Define $D_{m,v} = (TP_{2,m,v} - TP_{1,m,v})$ for

$$(100 - L) \le v \le L$$

$$(TP_{2,m,L} - TP_{1,m,L}) \text{ for } v > L$$

$$[TP_{2,m(100-L)} - TP_{1,m(100-L)}] \text{ for } v < (100 - L)$$

where $L = 99$ for the PM99 variation, 95 for the PM95 variation and 90 for the PM90 variation. For the practical implementation of the algorithm, for values of v satisfying $(100 - L) \le v \le L$, $D_{m,v}$ is calculated by linear interpolation using, as fixed points, $D_{m,1}, D_{m,2}, D_{m,3}, D_{m,4}, D_{m,5}, D_{m,10}, \ldots, D_{m,90}, D_{m,95}, D_{m,96}, D_{m,97}, D_{m,98}, D_{m,99}$.

The estimated equivalent temperature at site 2 on any given day in month m, T_2, is then defined from the temperature at site 1, T_2, by the function:

$$T_2 = T_1 + D_{m,j}, \text{ where } j \text{ is a value such that } TP_{1,m,j} = T_1.$$

The effect of this is that a transfer function is defined between the two sites, using (for the PM99 variation), as fixed points, the 1st, 2nd, 3rd, 4th, 5th, 10th,..., 90th, 95th, 96th, 97th, 98th and 99th percentiles, and assuming a constant intersite difference below the 1st percentile, and above the 99th percentile. For the PM95 variation a constant difference is assumed below the 5th and above the 95th percentile.

7.2. The non-overlap case

The majority of adjustments could not use the overlapping method (above), either because they involved an inhomogeneity within a single record which was identified either through metadata or by statistical methods, or because a composite record involved no overlap or insufficient overlap (generally less than 1 year) to define a transfer function.

In the non-overlap case, the algorithm operates as follows:

(a) Identify a set of N neighbouring stations with sufficient overlapping data with the candidate station both pre- and post-inhomogeneity (a minimum of 50 observations for each set of three consecutive months of the year).

(b) For each neighbour separately, define transfer functions for each month between the candidate station pre-inhomogeneity and the neighbour, and between the neighbour and the candidate station post-inhomogeneity, using the method for the overlap case as described above. The period of comparison was generally the calendar years prior to, and the 5 years following, but not including, the year of inhomogeneity (e.g. if the inhomogeneity was in 1994, 1989–1993 and 1995–1999 data were used), although in some cases this was shortened if there was a known inhomogeneity during the 5 year period.

(c) Define T_k as the estimated equivalent at neighbour k to temperature T_1 at the candidate station pre-inhomogeneity, using the transfer function between the candidate station pre-inhomogeneity and the neighbour.

(d) Define $T_{2,k}$ as the estimated equivalent at the candidate station post-inhomogeneity to temperature T_k at neighbour k, using the transfer function between the neighbour and the station post-inhomogeneity.

(e) Define T_2, the estimated equivalent at the candidate station post-inhomogeneity to temperature T_1 at the candidate station pre-inhomogeneity, as:

$$T_2 = \text{median } (T_{2,1}, T_{2,2}, \ldots, T_{2,N})$$

The effect of this is that the final estimate of the adjustment for any given temperature value is the median of a set of N estimates derived separately from the N reference stations.

Figure 6 shows this process, based on a 2000 site move at Kerang and using Swan Hill as a neighbour. The figure shows a transfer function based on Swan Hill; based on matching frequency distributions, a July minimum temperature of 0 °C at the pre-2000 Kerang equates to −1.2 °C at Swan Hill, which in turn equates to −0.5 °C at the post-2000 Kerang. Hence, using Swan Hill as the neighbour, a temperature of 0 °C at Kerang pre-2000 would be adjusted to −0.5 °C to be homogeneous with the post-2000 period. This value would then be composited with those estimated from remaining neighbours to develop the final transfer function.

7.3. Monthly adjustment method

An adjustment method was also defined using monthly data, for use in method evaluation (see below), and for cases where insufficient neighbours existed with available daily data for the PM algorithm to be used (noting that the availability of digitized monthly data prior to 1957 considerably exceeds that of daily data).

These monthly adjustments were calculated using an interpolated estimated monthly anomaly (1961–1990 base period) which was calculated for the location of the candidate station for each month in the candidate station's record, using a weighted mean of the monthly anomalies from a set of neighbouring stations with the weighting function $w_s = 1/\exp[(d/100)^2]$, where d is the distance in kilometres between station s and the candidate station. Adjustments were then calculated for each of the

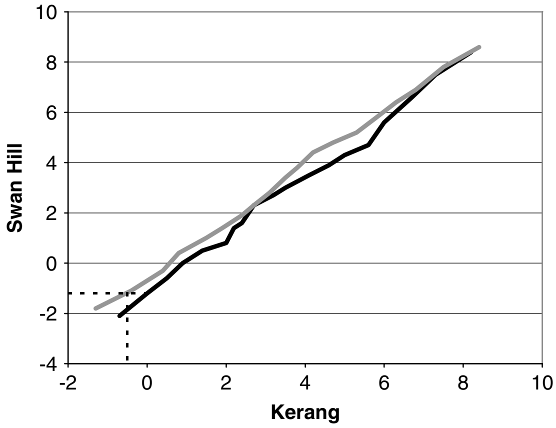


Figure 6. Example of use of transfer functions to adjust data, for July minimum temperature at Kerang, for an inhomogeneity in 2000 using Swan Hill as a neighbour. Using 1995–1999 data (black line), 0 °C at 'old' Kerang equates to −1.2 °C at Swan Hill, which, using 2001–2005 data (grey line), equates to −0.5 °C at 'new' Kerang.

12 calendar months using the change in the candidate-neighbour anomaly difference series for, in general, the 5 years preceding and following the inhomogeneity.

Where the station did not have at least 12 years of observations in the 1961–1990 base period, its all-years mean was corrected to a 1961–1990 equivalent using those neighbours which did have at least 12 years of observations in the 1961–1990 base period.

8. Evaluation of the PM algorithm

The PM algorithm and some other adjustment methods were evaluated to verify that the method being used performed better than a selection of other methods in widespread use. The evaluation was carried out using a set of 16 ACORN-SAT stations (Table I) which had a period where two sites had overlapping data, and where no known inhomogeneity existed during the overlap period at either site. The overlap data covered time spans ranging between 4 and 11 years during the 1992–2009 period.

In each case, a potentially inhomogeneous 'test' series was created by switching from the older site to the newer site at the start of the overlap period. Data from the period after the switch were then adjusted to be homogeneous with the older data (the reverse of, but effectively equivalent to, the process used for the ACORN-SAT homogenization). The accuracy of the adjustment was then evaluated for the overlap period, using the continuation of the old site as the 'truth'. The methods evaluated are shown in Table II.

The metrics which were used for evaluation were:

- The daily root-mean-square (RMS) error.
- The proportion of all observations where the simulated value was within 0.5 °C of the actual value.
- The percentage difference between the actual and simulated number of days with maximum and minimum temperatures above the 90th percentile, and below the 10th percentile, calculated using standard ETCCDI definitions (http://cccma.seos.uvic.ca/ETCCDI/list_27_indices.shtml).
- The difference between the actual and simulated highest and lowest value of maximum and minimum temperature for each of the 12 months during the overlap period.

The results of this evaluation are shown in Tables III and IV and Figures 7 and 8.

Table I. Site pairs used for adjustment technique evaluation (stations in italics not used for the 1930 network comparisons). Mean temperature differences were classified as large if they exceeded 0.6 °C, medium if they exceeded 0.3 °C annually or 0.5 °C in any season, and small otherwise.

Station	Site numbers (old/new)	Period of overlap observations	Length of overlap observations (years)	Mean temperature difference (new−old, °C) and classification	
				Maximum	Minimum
Kalumburu	1021/1019	1998–2005	6.5	−0.03 (small)	−0.89 (large)
Cunderdin	10035/10286	1996–2007	10.5	0.09 (small)	−0.55 (medium)
Wandering	10648/10917	1998–2003	4.2	−0.34 (medium)	−0.65 (large)
Port Lincoln	18070/18192	1992–2002	9.9	−0.76 (large)	−1.18 (large)
Burketown	29004/29077	2001–2009	7.7	0.91 (large)	−0.34 (medium)
Birdsville	38002/38026	2000–2005	4.7	−0.23 (medium)	0.20 (small)
Gayndah	39039/39066	2003–2009	6.4	−0.28 (small)	−0.25 (small)
Brisbane AP	40223/40842	1994–2000	5.8	−0.23 (small)	0.23 (medium)
Miles	42023/42112	1997–2005	7.6	−0.34 (medium)	−0.05 (small)
Thargomindah	45017/45025	1999–2005	5.7	−0.51 (medium)	0.74 (large)
Port Macquarie	60026/60139	1995–2003	7.6	0.62 (large)	−1.43 (large)
Dubbo	65012/65070	1993–1999	6.9	−0.41 (medium)	−0.16 (small)
Deniliquin	74128/74258	1997–2003	6.1	−0.14 (small)	−0.49 (medium)
Nhill	78031/78015	2003–2008	5.5	0.34 (medium)	0.92 (large)
Sale	85298/85072	1996–2008	9.2	−0.16 (small)	−0.71 (large)
Launceston	91104/91311	2004–2009	4.9	0.69 (large)	−0.10 (small)

Table II. Adjustment methods evaluated in this study.

Method	Definition
(a)	No adjustment (the 'control' case)
(b)	PM99 algorithm, using the 10 nearest neighbours with available daily data over the evaluation period
(c)	As for (b), but considering only neighbours which also had available daily data in 1930 (to test the performance of methods using sparser networks typical of earlier years).
(d)	As for (b), but using the PM95 algorithm
(e)	As for (b), but using the PM90 algorithm
(f)	As for (d), but using a maximum of five neighbours
(g)	Monthly adjustments, using the 10 nearest neighbours with available monthly data over the evaluation period
(h)	As for (g), but considering only those neighbours which also had available monthly data in 1930
(i)	The QM algorithm used in the RHtestsV3 software (Wang *et al*., 2010)

A separate evaluation was carried out to assess explicitly the effect of correlation of reference stations on the effectiveness of the PM95 method. This evaluation used only those stations (eight for maximum temperature, four for minimum) where there were at least 15 potential reference stations with a correlation of 0.8 or better. For each station/element, separate adjustments were made, and the metrics above calculated, for a series of separate trials, using five separate sets of ten reference stations drawn randomly from all those stations correlated with the candidate station at better than 0.8, 0.7 and 0.6, respectively (15 trials in total). The results from this evaluation are shown in Table V.

The key points to emerge from the evaluation are as follows:

- No adjustment method consistently outperforms the control case for stations with small inhomogenities (Table III), suggesting that 0.3 °C is near the lower limit for the size of inhomogeneity that can be adjusted for with useful skill (Figure 8).
- The quantile-matching (QM) method performs more poorly than the PM family for almost all metrics, and only outperforms the control case for maximum temperature for stations with large inhomogeneities, although for minimum temperature it also outperforms the control case for stations with medium inhomogeneities. It should be noted that the QM method does not use reference series for adjustment (although this is planned in future versions; X. L. Wang, pers. comm.), and is hence likely to perform poorly when applied in situations where there are rapid changes in the background climate; the results for maximum temperature in this evaluation are driven to a large extent by particularly poor results for four stations in inland New South Wales and Queensland, a region where 5 year mean maximum temperatures warmed by up to 1 °C over the 1992–2009 period.
- There is little difference between the daily (PM) and monthly adjustment methods for the RMS and proportion within 0.5 °C metrics. However, the daily methods outperform the monthly methods substantially in simulating extremes, especially for stations with large inhomogeneities, except for some extent for extreme high maximum temperatures.
- The PM95 method performs similarly to PM99 on the first three metrics, but is generally much better than PM99 in simulating the highest and lowest values. It is likely that this reflects instability in the transfer functions towards the ends of the distribution when the 1st and 99th percentiles are used; in most cases those percentiles are based on only a few observations, and may therefore be vulnerable to data quality issues at neighbour stations, or effects of unusual weather events. The PM90 method performs marginally worse than PM95 on most measures.
- The five-neighbour case performs marginally worse than the ten-neighbour case on most measures.
- Across the set of evaluation stations as a whole, the relative performance of daily and monthly methods using the 1930 network was similar to that using the more recent network. However, at some individual stations where the availability of neighbouring monthly data in 1930 was much better than that of neighbouring daily data, the monthly adjustment method outperformed daily methods.

Whilst the performance of the PM95 method generally declines with decreasing correlation of reference stations, it still outperforms both monthly adjustments and the control case for stations with medium or large inhomogeneities for reference station correlations of 0.6 or above. This contrasts with the results of Della-Marta and Wanner (2006) and Mestre *et al*. (2011) who found that a reference station correlation of greater than 0.8 was required. Whilst a full reconciliation of these different results is beyond the scope of this article, some differences between this evaluation and those presented in the aforementioned article, which may be relevant to the results, include:

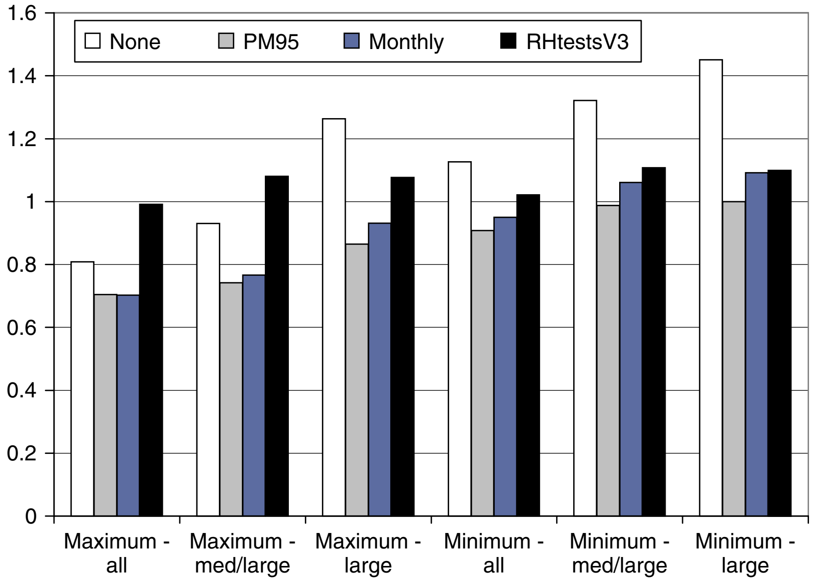
- The earlier methods both use a single reference station rather than a combination of multiple reference stations, and their evaluation is carried out using a single base data set.
- The correlation between stations is defined in a different way in this evaluation.

Table III. Comparison of adjustment methods, current network (S – small; M – medium; L – large).

Test	Variable	Station type	Adjustment method						
			None	Daily PM99	Daily PM95	Daily PM90	Monthly	Five neighbours	RHtests
RMS (°C)	Maximum	All	0.808	0.711	0.704	0.703	0.702	0.705	0.991
		S	0.604	0.637	0.642	0.631	0.595	0.557	0.843
		M/L	0.930	0.754	0.742	0.746	0.766	0.744	1.080
		L	1.263	0.888	0.865	0.879	0.931	0.856	1.077
	Minimum	All	1.126	0.913	0.908	0.910	0.950	0.911	1.021
		S	0.697	0.741	0.731	0.727	0.707	0.720	0.828
		M/L	1.321	0.991	0.988	0.993	1.061	0.998	1.108
		L	1.451	1.003	1.000	1.006	1.092	1.009	1.099
Prop within 0.5 °C	Maximum	All	0.491	0.568	0.568	0.572	0.588	0.567	0.331
		S	0.598	0.590	0.586	0.595	0.627	0.596	0.370
		M/L	0.426	0.554	0.557	0.558	0.565	0.549	0.307
		L	0.280	0.520	0.528	0.525	0.536	0.531	0.385
	Minimum	All	0.399	0.467	0.472	0.469	0.449	0.474	0.396
		S	0.594	0.552	0.559	0.558	0.573	0.567	0.432
		M/L	0.310	0.429	0.433	0.429	0.392	0.431	0.380
		L	0.262	0.417	0.423	0.418	0.368	0.423	0.381
Indices count (mean percent error)	Maximum 10th percentile	All	28.7	15.4	14.6	12.8	17.1	13.4	55.2
		S	14.7	16.7	14.9	13.4	10.9	12.2	39.8
		M/L	37.1	14.6	14.4	12.5	20.8	14.1	64.5
		L	65.1	18.1	15.2	15.7	38.5	15.8	81.1
	Minimum 10th percentile	All	75.4	17.4	16.0	18.4	28.5	16.3	40.6
		S	13.9	8.8	7.5	10.0	8.0	8.8	26.6
		M/L	103.4	21.3	19.8	22.3	37.8	19.7	47.0
		L	143.4	23.5	20.6	23.9	52.9	20.1	53.3
	Maximum 90th percentile	All	28.3	11.3	11.8	11.3	11.0	12.1	31.3
		S	12.9	14.6	15.2	13.9	8.6	15.2	28.1
		M/L	37.5	9.3	9.8	9.8	12.4	10.1	33.2
		L	67.3	10.4	12.4	12.2	11.8	12.1	37.2
	Minimum 90th percentile	All	16.6	11.7	9.9	9.5	19.9	9.8	20.4
		S	8.8	9.1	8.7	7.9	14.6	8.9	22.1
		M/L	20.2	13.0	10.4	10.2	22.3	10.2	19.6
		L	23.2	15.1	11.1	10.2	22.9	10.5	14.9
Extremes error (°C)	Lowest maximum	All	0.46	0.60	0.50	0.49	0.49	0.50	0.71
		S	0.50	0.65	0.59	0.37	0.52	0.41	0.67
		M/L	0.44	0.58	0.45	0.55	0.48	0.54	0.74
		L	0.55	0.68	0.49	0.56	0.66	0.54	0.71
	Lowest minimum	All	1.19	0.78	0.69	0.75	0.85	0.70	0.89
		S	0.56	0.68	0.55	0.57	0.48	0.54	0.61
		M/L	1.48	0.82	0.76	0.84	1.01	0.78	1.02
		L	1.64	0.81	0.71	0.83	1.05	0.71	0.94
	Highest maximum	All	0.76	0.73	0.61	0.63	0.65	0.63	0.90
		S	0.59	0.70	0.67	0.57	0.58	0.53	0.78
		M/L	0.87	0.75	0.58	0.65	0.69	0.68	0.98
		L	1.22	1.01	0.70	0.63	0.94	0.66	0.85
	Highest minimum	All	0.54	0.66	0.58	0.59	0.69	0.60	0.69
		S	0.47	0.60	0.58	0.58	0.56	0.57	0.70
		M/L	0.58	0.69	0.58	0.59	0.74	0.61	0.69
		L	0.63	0.79	0.63	0.65	0.83	0.66	0.69

Table IV. Comparison of adjustment methods, 1930 network.

Test	Variable	Station type	Adjustment method			
			None	Daily PM99	Monthly	RHtests
RMS (°C)	Maximum	All	0.804	0.763	0.742	1.005
		S	0.579	0.585	0.571	0.799
		M/L	0.904	0.824	0.817	1.097
		L	1.298	0.970	1.038	1.127
	Minimum	All	1.162	1.010	1.020	1.041
		S	0.745	0.898	0.827	0.885
		M/L	1.348	1.060	1.106	1.111
		L	1.440	1.045	1.128	1.073
Prop within 0.5 °C	Maximum	All	0.514	0.535	0.550	0.332
		S	0.658	0.596	0.645	0.399
		M/L	0.450	0.508	0.507	0.302
		L	0.304	0.493	0.498	0.398
	Minimum	All	0.380	0.408	0.407	0.379
		S	0.576	0.463	0.489	0.406
		M/L	0.293	0.384	0.371	0.367
		L	0.269	0.394	0.358	0.391
Indices count (mean percent error)	Maximum 10th percentile	All	31.1	17.9	21.1	59.0
		S	18.3	11.5	15.4	36.1
		M/L	36.8	20.8	23.5	69.3
		L	73.5	27.1	37.4	101.0
	Minimum 10th percentile	All	74.2	20.1	30.4	34.3
		S	14.2	27.3	14.1	27.4
		M/L	100.9	16.9	37.6	37.4
		L	136.6	14.1	47.1	41.6
	Maximum 90th percentile	All	22.3	10.1	12.1	25.4
		S	13.0	5.3	6.2	23.2
		M/L	26.5	12.2	14.7	26.4
		L	44.0	13.5	15.5	18.2
	Minimum 90th percentile	All	17.1	12.5	18.9	19.6
		S	6.5	11.0	14.4	20.8
		M/L	21.8	13.2	21.0	19.1
		L	25.4	11.2	24.5	11.3
Extremes error (°C)	Lowest maximum	All	0.46	0.67	0.52	0.74
		S	0.49	0.64	0.51	0.67
		M/L	0.44	0.69	0.52	0.76
		L	0.60	0.73	0.66	0.78
	Lowest minimum	All	1.21	0.90	0.89	0.86
		S	0.59	0.93	0.60	0.66
		M/L	1.48	0.89	1.03	0.95
		L	1.58	0.85	1.00	0.84
	Highest maximum	All	0.78	0.90	0.70	0.94
		S	0.64	0.70	0.60	0.85
		M/L	0.84	0.99	0.75	0.98
		L	1.26	1.37	1.11	0.81
	Highest minimum	All	0.58	0.72	0.74	0.73
		S	0.53	0.77	0.64	0.73
		M/L	0.60	0.70	0.79	0.73
		L	0.64	0.75	0.92	0.73



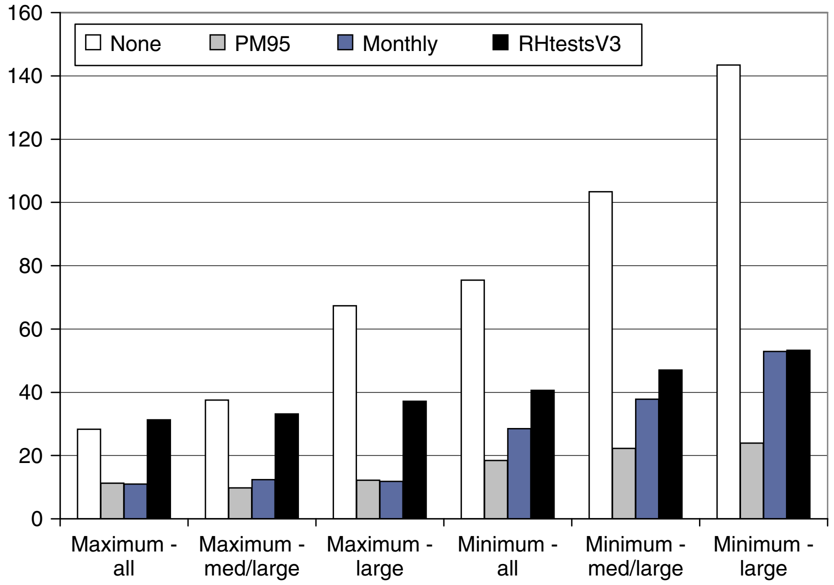


Figure 7. Performance measures of adjustment techniques across different classifications of station pairs: (top) RMS error (°C), (bottom) percent error in count of days with maximum above 90th percentile and minimum below 10th percentile. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

- Both earlier methods carry out their evaluation using a synthetic data set where the correlation is degraded using a random noise process, and an idealized set of inhomogeneities. In practice, it is likely that some of the degradation of correlation between neighbouring stations below 1.0 is due to factors such as time shifting (through the movement of synoptic-scale weather systems) or non-linearity of the relationship between temperatures at the two stations, and is not truly random. Furthermore, the behaviour of the inhomogeneities at the range of stations used for evaluations in this article may not match the idealized examples used in earlier studies.
- The evaluation in this article uses a wider range of metrics than Della-Marta and Wanner (2006) (although a similar range to that of Mestre *et al.*, 2011). In general, the improvement which the PM methods offer

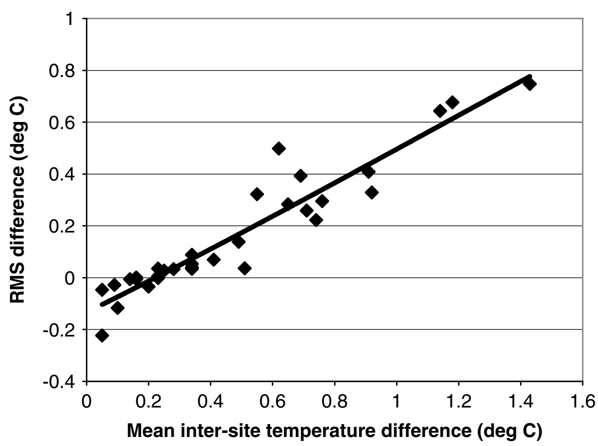


Figure 8. Difference in RMS errors (no adjustment − PM95 algorithm) for station pairs, by size of mean temperature differences between paired stations.

Table V. Evaluation of adjustment methods for different reference series correlation thresholds.

Inhomogeneity size	Correlation threshold	RMS (°C)			Indices count (mean percent error)			Extremes error (°C)		
		Daily	Month	None	Daily	Month	None	Daily	Month	None
Large (3 stations)	0.8	1.114	1.184	1.419	12.2	27.5	71.4	0.60	0.90	1.01
	0.7	1.138	1.190	1.419	19.4	26.2	71.4	0.66	0.91	1.01
	0.6	1.144	1.196	1.419	20.7	28.9	71.4	0.65	0.90	1.01
Medium (5 stations)	0.8	0.797	0.815	0.914	12.1	14.8	23.4	0.61	0.65	0.74
	0.7	0.816	0.844	0.914	12.7	18.0	23.4	0.62	0.67	0.74
	0.6	0.826	0.836	0.914	12.9	17.2	23.4	0.63	0.66	0.74
Small (4 stations)	0.8	0.593	0.552	0.556	9.4	8.4	12.4	0.57	0.47	0.45
	0.7	0.627	0.576	0.556	10.3	9.6	12.4	0.59	0.48	0.45
	0.6	0.647	0.606	0.556	11.3	13.3	12.4	0.61	0.51	0.45
Medium/large	0.8	0.916	0.953	1.103	12.1	19.6	41.4	0.61	0.74	0.84
	0.7	0.937	0.974	1.103	15.2	21.1	41.4	0.64	0.76	0.84
	0.6	0.945	0.971	1.103	15.8	21.6	41.4	0.64	0.75	0.84
All	0.8	0.808	0.819	0.921	11.2	15.9	31.7	0.59	0.65	0.71
	0.7	0.834	0.841	0.921	13.6	17.3	31.7	0.62	0.67	0.71
	0.6	0.846	0.849	0.921	14.3	18.8	31.7	0.63	0.67	0.71

over monthly adjustments is more evident in extremes-based metrics than it is in the RMS error.

9. Implementation of adjustment methods for the ACORN-SAT network

Following the evaluation of the PM algorithm and other methods, adjustment methods were implemented for the ACORN-SAT network using the following rules:

- Other than in the specific cases outlined below, the PM95 method was used. Neighbours (up to ten) were selected in descending order of correlation with the candidate station, with a lower correlation limit of 0.6. (For the purpose of this section, the 'correlation' value was derived by taking correlations between daily temperature anomalies for each of the 12 months, with the final value taken as the 6th highest – i.e. near the median – of these 12 values.)
- If fewer than three sufficiently correlated stations existed with daily data around the time of the inhomogeneity, or the tenth best-correlated station with monthly data was better correlated than the third best-correlated station with daily data, the monthly adjustment method was used. In a few cases neighbours with correlations between 0.5 and 0.6 were used to provide at least three reference stations. (Had there been any location with no available reference series, the RHtestsV3 method, which does not use reference series, would have been an option.)
- In the event of a 'spike' (defined as an inhomogeneity, followed by another inhomogeneity of opposite sign within 3 years, or alternatively two metadata-defined inhomogeneities within 3 years), monthly adjustments were used to adjust the data during the 'spike' period to the period before the 'spike', as daily adjustments were considered to be too unstable for such short-period corrections. These were only implemented if the annual mean adjustment during the 'spike' period was at least 0.5 °C. The 'spike' period was also excluded from the overlaps used for the calculation of transfer functions for other inhomogeneities.
- The size of adjustments generated by the techniques above was checked by comparing the means of pre- and post-adjustment data for, in general, the five calendar years prior to the inhomogeneity. The adjustment was only implemented if the means differed by at least 0.3 °C on an annual basis, 0.3 °C (not necessarily of the same sign) in at least two of the four seasons, or 0.5 °C in at least one season. If the difference failed to satisfy one or more of these criteria the inhomogeneity was considered to be too small to justify adjustment, as the results of the evaluation above suggest that such small adjustments add no skill.
- A special case was the 1965 move at Albany in southern Western Australia from the town to the airport, with no overlap. A station was re-established in Albany town in 2002 and monthly data indicated it was approximately homogeneous with the pre-1965 town station (and much better correlated with the airport than any other neighbour was). The post-2002 town site was therefore used as a proxy for the pre-1965 site, with the adjustments for the 1965 move calculated using a transfer function derived from the 2004 to 2009 overlap.

Once adjusted data sets for all ACORN-SAT stations were produced, a spatial comparison of trends over a number of time periods in mean maximum and minimum temperatures, and in the frequency of temperatures above the 90th and below the 10th percentile, was undertaken; where this process revealed inconsistencies between neighbouring ACORN-SAT stations, a pairwise comparison of ACORN-SAT time series was undertaken, and the robustness of adjustments checked by recalculating them using subsamples of neighbour stations. As a result of this process, a number of adjustments were recomputed using different sets of neighbour stations (most often because one or more neighbours were inhomogeneous), or with time periods other than those immediately preceding/following the inhomogeneity used to derive transfer functions (most often because a station deteriorated sharply in the 1–2 years prior to a move or other change).

In a small number of cases, the PM95 algorithm was not able to homogenize extreme values, as the relationship between sites for 95th (or 5th) percentile values is not representative of that for the most extreme values. This mostly occurs with extreme high maxima at near-coastal locations (Figure 1), where large differences between sites on 95th percentile days collapse to near zero on the very hottest days when offshore winds override the sea breeze. Stations which showed evidence of one or more inhomogeneities of 2 °C or more in the time series (highest value of year – 95th percentile value for year), or equivalently for low extremes, were considered unhomogenizable for extremes and excluded from some downstream products. Four stations, all coastal, failed this test: Albany and Port Macquarie for high maximum temperatures, Eucla for high minimum temperatures and Horn Island for low minimum temperatures.

The total number of adjustments, the frequency distribution of adjustments, and the distribution of positive and negative adjustments through time, are given in Table VI and Figure 9. Positive and negative adjustments are fairly evenly balanced for maximum temperatures, but negative adjustments (i.e. where there has been an artificial drop in temperatures as a result of an inhomogeneity) are somewhat more numerous for minimum temperature, which is likely to result in the ACORN-SAT minimum temperature showing a stronger warming trend than the raw data do.

The imbalance between positive and negative adjustments for minimum temperature is concentrated in the 1940s and 1990s, which coincides with the two main periods in which stations moved from town centres to out-of-town locations (mostly airports) a move which typically results in a drop in minimum temperatures. Most of the positive adjustments in minimum temperature in the 1960s are small adjustments associated with changes in observation times in 1964 (see later section).

10. Changes affecting large parts of the temperature network simultaneously

Changes which affect large parts of the network simultaneously provide a particular challenge for homogenization, since they can affect reference series as well as a candidate station, causing assumptions of a locally homogeneous reference series around the time under examination to break down. Furthermore, whilst an inhomogeneity considered too small for adjustment (less than 0.3 °C) under the criteria discussed in the previous section is unlikely to have a substantial impact on large-scale analyses, such an inhomogeneity occurring across a large part of the network simultaneously could have an impact on indicators such as trends at the national or regional scale.

Three such changes have been identified in the period covered by the ACORN-SAT data set:

- Changes in observation time, principally the shift to an 0900–0900 observation day for maximum and minimum temperature in 1964, as well as the use of 0000/1200 UTC observation day at some AWSs in the 1990s and early 2000s, and the effective shift of observation time by 1 h with the introduction of daylight saving time in some states from the early 1970s onwards.
- The change from imperial to metric measurements which took place on 1 September 1972, and associated changes in the frequency of rounding.
- The introduction of AWSs across large parts of the network from the early 1990s onwards.

10.1. Effect of observation time changes

To estimate the effect of observation time changes which have occurred over time, available 1 min data (mostly from the period 2003–2009) from 32 ACORN-SAT stations were used to calculate daily maximum and minimum temperatures for a range of time periods which have been used historically, as shown in Table VII. These were compared with temperatures measured using the current standard of 0900–0900 local time. This study, and its results, is described in more detail in Trewin (2012).

Table VI. Summary of adjustments carried out in ACORN-SAT data set.

	Maximum	Minimum
Total number of adjustments	315	345
Number of adjustments supported by metadata (number related to site moves in brackets)	160 (138)	171 (141)
Number of positive adjustments	153 (49%)	154 (46%)
Number of negative adjustments	160 (51%)	184 (54%)
Number of ‘spike’ adjustments (excluded from percentages above)	2	7
Number of adjustments > +1 °C (number metadata supported in brackets)	9 (6)	9 (3)
Number of adjustments < −1 °C (number metadata supported in brackets)	8 (7)	24 (17)

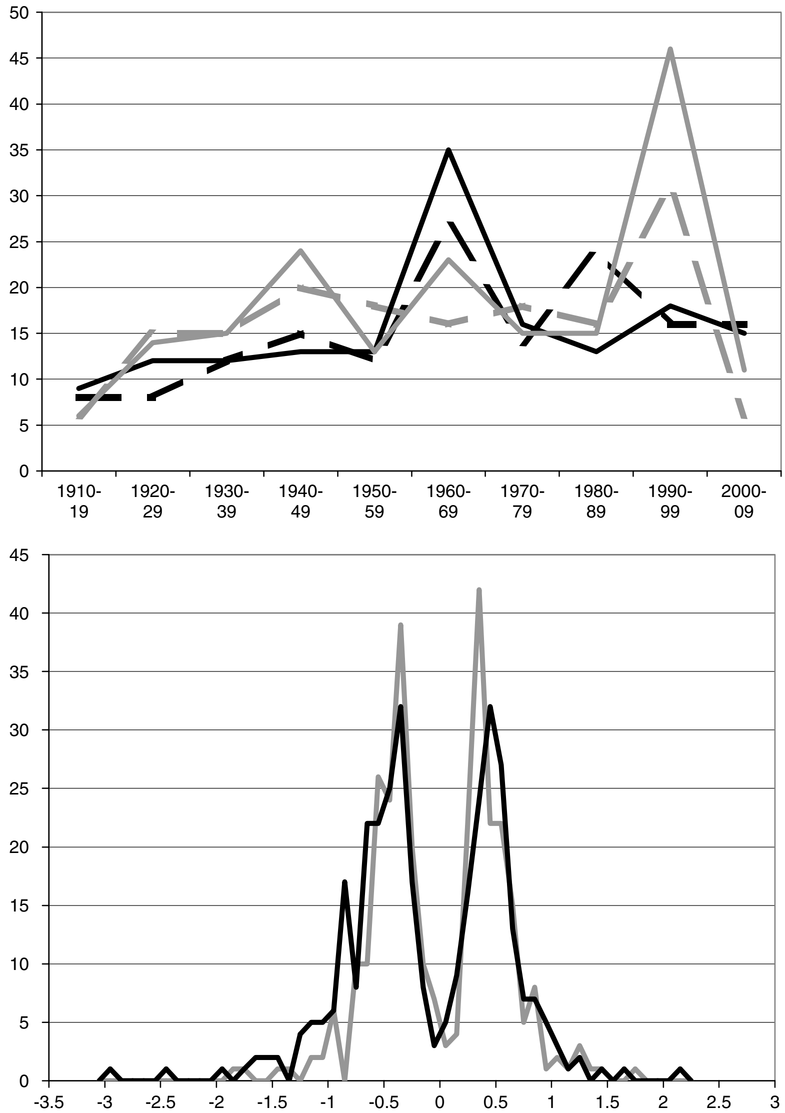


Figure 9. (top) Number of positive (black) and negative (grey) adjustments by decade, for maximum (dashed line) and minimum (solid line) temperature (bottom). Frequency distribution of mean annual adjustment size (°C) for maximum (grey) and minimum (black) temperature.

The 1 min data indicate that the only historical observation practice which shows substantial systematic differences from the current standard is the measurement of minimum temperatures using 0000–0000 day (i.e. midnight to midnight). Averaged across the 32 stations, this gives mean minimum temperatures 0.25 °C cooler than the current standard, whilst the impact on extremes is stronger, with the mean value of the highest minimum temperature of each month being 0.58 °C cooler on average. All 32 stations show cooler minimum temperatures for 0000–0000 day than 0900–0900 day, but the differences were smallest (typically near 0.1 °C) in the tropics. They were largest (0.4–0.6 °C) at some southern coastal stations. As about 30% of the network was using 0000–0000 day in some form prior to 1964, these results would suggest a potential inhomogeneity in Australian mean minimum temperatures of approximately +0.08 °C in 1964.

As a result of these findings, it was decided to define 1 January 1964 as a metadata indicated potential inhomogeneity at all locations which were believed to use 0000–0000 day prior to 1964, were outside the tropics and had not already had an adjustment made in the 1962–1966 period, and to adjust for that inhomogeneity, excluding stations subject to 0000–0000 day as reference series, whether or not it reached the 0.3 °C threshold defined as a minimum for adjustment in earlier sections (this takes into account the likelihood of extremes being affected more significantly than means).

This procedure was carried out at a total of 19 locations. However, at many of these locations, the inhomogeneity was much smaller than expected from the 2003–2009 1 min data (or even non-existent), suggesting that in practice 0000–0000 observation day may not have been fully implemented at these locations. At the capital city sites, which had 24 h staffing and where the fullest compliance with standards might be expected, differences were generally close to those expected. The results also suggest that, at the majority of the locations where 0000–0000 day had been fully implemented, the

Table VII. Comparison of major observation times in previous use with current standard.

Method	In use	Temperature differences with current (0900–0900 local clock time) standard (°C)			
		Mean maximum	Mean minimum	Highest monthly minimum	Lowest monthly maximum
Maximum and minimum 0000–0000 (standard time)	1932–1963 at Bureau-staffed sites (and a few others)	−0.01	−0.25	−0.58	0.00
Maximum and minimum 0900–0900 standard time (i.e. no daylight saving)	1964–1972, later in states without daylight saving	0.00	−0.01	−0.05	−0.01
Maximum 1200–1200 UTC, minimum 0000–0000 UTC	Some AWSs from early 1990s to mid-2000s	0.02	−0.01 (−0.06 WA, 0.06 NSW/Vic/Tas)	−0.04 (−0.23 WA, 0.24 NSW/Vic/Tas)	0.08
Maximum 0900–0900 standard time (reverting to 0900–1500 if 0900 reset temperature within 0.5 °C of maximum), minimum 1500–0900 standard time	Non-Bureau-staffed sites pre-1964	−0.03	0.03	0.13	−0.12

resultant inhomogeneity had already been detected and adjusted for as part of the main ACORN-SAT procedures.

10.2. Effect of metrication

Metric measurements for temperature were introduced across the Australian network on 1 September 1972, with new instruments being issued to all stations. Previous research (Nicholls, 2004) had found no discernable impact of this change on temperatures. These conclusions, however, were partly based on the results of instrument testing for which no documentation could be located at the time of the current project. It was therefore decided to carry out a number of further tests, these being:

- Comparison of Australian mean temperatures with sea surface temperatures in the Australian region.
- Comparison of mean temperatures at ACORN-SAT locations where upper-air observations were taken with the mean 850 hPa temperatures at those locations.
- Comparison of mean maximum and minimum temperatures at ACORN-SAT locations with the temperatures at 1500 and 0600, respectively (excluding locations/months where daylight saving time was in use).

Whilst the comparison data sets are not independent in the sense that they also changed to metric measurements at or near the same time, they used different instruments and hence an inhomogeneity affecting a particular instrument type could be detected by these methods.

All three comparisons showed mean Australian temperatures in the 1973–1977 period were from 0.07 to 0.13 °C warmer, relative to the reference series used, than those in 1967–1971. However, interpretation of these results is complicated by the fact that the temperature relationships involved (especially those between land and sea surface temperatures) are influenced by the El Niño-Southern Oscillation (ENSO), and the 1973–1977 period was one of highly anomalous ENSO behaviour, with major La Niña events in 1973–1974 and 1975–1976. It was also the wettest 5 year period on record for Australia, and 1973–1975 were the three cloudiest years on record for Australia between 1957 and 2008 (Jovanovic *et al*., 2011).

The broad conclusion is that a breakpoint in the order of 0.1 °C in Australian mean temperatures appears to exist in 1972, but that it cannot be determined with any certainty the extent to which this is attributable to metrication, as opposed to broader anomalies in the climate system in the years following the change. As a result, no adjustment was carried out for this change.

10.3. Introduction of AWSs

AWSs were introduced widely across the network from the early 1990s onwards. In many cases, their introduction coincided with a station move (often with a period of parallel observations). In other cases, they were introduced without any site move.

A check was undertaken at those ACORN-SAT locations which had changed from manual to automatic observations without a documented site move (those where moves had taken place had already been dealt with in earlier parts of the process), using the adjustment procedure described earlier with only manual stations considered as reference stations. This showed a mean inhomogeneity with AWS introduction of −0.04 °C for maximum temperature (positive at 8 locations, negative at 14) and −0.03 °C for minimum temperature (positive at 13 locations, negative at 13). These results do not suggest any substantial inhomogeneity arising from the replacement of manual observations by automated observations *in situ*.

This conclusion is reinforced by results from two locations where parallel AWS and manual observations are available, Cape Byron (28.64 °S, 153.64 °E) (where the instruments were in the same screen) and Point Perpendicular (where the manual and automatic instruments were in different screens about 3 m apart). In both cases the difference between manual and automatic temperatures during the overlap period matches, to within a few hundredths of a degree, the outcome of tolerance checks on the AWS temperature probe during the overlap period.

11. Potential influence of urbanization and other land-use changes

As has been well-documented in many previous data sets, both within Australia (Della-Marta *et al*., 2004) and internationally (Hansen *et al*., 2001), the potential exists for warming in urban centres driven by changes in the local site environment. Whilst a number of studies (Peterson, 2003; Parker, 2010) have found such warming to have a minimal influence on large-scale data sets as a whole, it could affect data at the station level.

To assess this in ACORN-SAT, locations were initially divided into three categories:

- Urban: sites within the built-up area of population centres with a population in excess of 10 000.
- Urban fringe: sites associated with a population centre with a population centre in excess of 10 000, which are located either outside the urban boundary but within 2 km of it, or in a large non-built up area (e.g. a park) inside the urban boundary.
- Non-urban: sites not associated with a population centre with a population centre in excess of 10 000, or associated with such a centre but more than 2 km from the urban boundary.

The final definition of sites potentially affected by urbanization was then determined by comparing trends in minimum temperature at urban fringe locations, and locations which are non-urban now but have been urban at some time in the past (e.g. where a site has moved from a town centre to an airport), with those from non-urban ACORN-SAT locations in the region. This comparison was carried out from the point at which the town's population reached 10 000 (as precisely as this could be determined from available Census data) to either the end of the data set, or, where applicable, the year in which the site moved out of the urban centre.

As a result of this process, eight of the 112 ACORN-SAT locations were classified as influenced by urbanization: four (Sydney, Melbourne, Adelaide, and Hobart) which were urban in the initial classification, and four [Townsville, Rockhampton, Richmond (NSW) and Laverton] which were initially classified as urban fringe locations. The four latter locations are all airports within, or adjacent to, cities, and in all cases except Rockhampton there has been rapid urban development in recent decades in the area surrounding the airport.

Although it did not affect the assessment, the four locations initially classified as urban were also tested for anomalous trends in minimum temperature. Of these four locations, only Adelaide showed anomalous minimum temperature warming. This indicates that either any urban influence on temperatures at the remaining three locations was fully developed by 1910 (similar to the results found by Jones and Lister, 2009, for London) or the urban influence on temperatures at those locations is manifested as step changes which were detected and adjusted for by the homogenization procedure described earlier.

Some other land-use changes have also been found to affect local temperature observations (Trewin, 2010). One possible example of this in the ACORN-SAT data set is at Mildura, where there is no trend in maximum temperatures over the 1910–2009 period, compared with trends near 0.1 °C/decade at other ACORN-SAT locations in the region. The Mildura area saw rapid development in intensive irrigated agriculture in the period between the two World Wars (1918–1939). A closer analysis of trends at Mildura found that anomalous maximum temperature trends at Mildura were largely confined to the 1920–1949 period, over which maximum temperatures showed a trend of −0.23 °C/decade, compared with a regional average of about −0.1 °C/decade. Similar results were found at the non-ACORN-SAT station of Griffith (34.32 °S, 146.07 °E), which has a similar history of irrigation development to Mildura. This indicates a strong possibility that land-use change is a major contribution to pre-1950 maximum temperature trends at Mildura, with the magnitude of the difference (0.3–0.4 °C over 30 years) comparable with that found in irrigated regions of India (Roy *et al*., 2007) and the north-central United States (Mahmood *et al*., 2006). There is no evidence of anomalous trends at Mildura after 1950, by which time irrigated agriculture had reached approximately its current extent in the region.

Stations determined as being influenced by urbanization or other local land-use change remain in the ACORN-SAT data set, but their designation allows them to be excluded from downstream products such as the calculation of national and regional temperature anomalies for the analysis of large-scale climate change.

12. Concluding remarks

The ACORN-SAT data set provides national coverage of daily homogenized data for Australia for the period from 1910 to the present, although with a lower station density in the first half of the 20th century. This, in turn, will support century-scale analyses of changes in mean temperatures (which have been carried out in the past using existing data sets), as well as of extremes (which has not previously been possible).

The use of the PM algorithm for adjustment does not greatly alter the effectiveness of homogenization for mean temperatures compared with methods based on uniform monthly or annual adjustment, but does considerably improve the representation of extremes.

The techniques used in the development of the ACORN-SAT data set are portable, in principle, to any region with a sufficient density of reference series. In cases where no reference series is available (e.g. remote islands), techniques such as RHtestsV3, which do not use reference series, are available. The use of alternate elements, such as local sea surface temperatures for island locations (Jovanovic *et al*., 2010), as reference series is also a possibility at some locations.

The methods implemented for the ACORN-SAT data set were very labour intensive, particularly for quality control. This presents an obstacle to such methods being scaled up to be applied continental or global-scale data sets, along with the limited international availability of supporting data (for reference series) and metadata. In principle, however, it should be feasible to automate the homogenization process, at least up to the point of producing an initial set of homogenized data.

A further paper will be produced in due course describing long-term temperature trends, and the uncertainties in them, derived from the ACORN-SAT data set.

13. Data availability

The ACORN-SAT data set, a full listing of site locations and periods of record, and supporting metadata, is freely available through the Bureau of Meteorology website (http://www.bom.gov.au/climate/change/acorn-sat).

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