The development of a high quality historical temperature data base for Australia


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Submitted in total fulfilment of the requirements of the degree of Doctor of Philosophy.

1996.

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ABSTRACT

A high quality, historical surface air temperature data set is essential for the reliable investigation of climate change and variability. In this study, such a data set has been prepared for Australia by adjusting raw mean annual temperature data for inhomogeneities associated with station relocations, changes in exposure, and other problems. Temperature records from long-term stations were collated from the set of all raw data held by the Australian Bureau of Meteorology. These long-term records were extended by combining stations, and manually entering previously unused archived temperature measurements. An objective procedure was developed to determine the necessary adjustments, in conjunction with complementary statistical methods and station history documentation. The objective procedure involved creating a reference time series for each long-term station, from the median values at surrounding, well-correlated stations. Time series of annual mean maximum and mean minimum temperatures have been produced for 224 stations, and the adjusted data set has been made available to the research community. The adjusted data are likely to be more representative of real climatic variations than raw data due to the removal of discontinuities. The adjusted data set has been compared with previously used temperature data sets, and data sets of other parameters. The adjusted data set provides adequate spatial coverage of Australia back to 1910. Additional adjusted data are available prior to this date at many stations. Trends in annual mean maximum, minimum, the mean of the maximum and minimum, and the range between the maximum and minimum, have been calculated at each site. Spatially averaged time series for Australia have been calculated and trends examined. Maximum and minimum temperatures have increased since about 1950, with minimum temperatures increasing faster than the maximum temperatures.
ACKNOWLEDGMENTS

Friends are the DNA of society. They are the basic building blocks of life.

— Jerry Seinfeld.

First of all, thanks are extended to my official supervisors, Neville Nicholls (who originally suggested this project) and Ian Simmonds, both of whom gave me valuable suggestions.

Thanks are also owed to an unofficial supervisor, Neil Plummer. The project would not have been completed without his ideas, suggestions and jokes.

I have received plenty of advice from people around Bureau of Meteorology Research Centre, National Climate Centre and the School of Earth Sciences, as well as directors and staff in Regional Offices. I should especially thank Brendan Coutts, Alex Kariko, Beth Lavery and Zhenjie Lin.

Tom Peterson and David Easterling, of the U.S. National Climatic Data Center, provided their computer program for the identification of a change in mean, and offered many useful and enjoyable discussions.

Thanks to my family and friends, especially Rachel for helping emotionally, editorially and scientifically, and never letting me forget that I was having a good time.

The project was supported by a National Greenhouse Advisory Committee dedicated research grant.
DECLARATION

This thesis is less than 100 000 words in length.

Simon Torok, November 1996.

PREFACE

Several of the sections of this thesis are similar to works or parts of works (previously published, under review or in preparation) by the author in collaboration with others. Specifically:

- Sections 7.2.2.3 and 7.3.2.2: Torok and Nicholls, 1996.
- Section 3.1: Torok et al., 1996.
- Section 4.2.2: Lin et al., 1993.
- Barnes analysis in section 7.2.2.2: Power et al. 1997.
- Section 7.3.2.5: Work in progress with Henry Pollack and Shaopeng Huang, University of Michigan, U.S.A.
ABBREVIATIONS

A.M.O  Airport Meteorological Office
AVHRR  Advanced Very High Resolution Radiometer
AWS    Automated Weather Station
BoM    Bureau of Meteorology
CA     Cluster Analysis
CBD    Central Business District
COADS  Comprehensive Ocean Atmosphere Data Set
DTR    Diurnal Temperature Range
ENSO   El Niño-Southern Oscillation
EST    Eastern Standard Time
GST    Ground Surface Temperature
HAC    Hawkesbury Agricultural College
ISB    Initial Search Boundary
LST    Local Summer Time
MO     Meteorological Office
NCC    National Climate Centre
NDVI   Normalised Difference Vegetation Index
NIR    Near-infrared wavelength (0.72–1.1 mm)
NOAA   U.S. National Oceanographic and Atmospheric Administration
NSW    New South Wales
NT     Northern Territory
RCS    Reference Climate Station
RO     Regional Office
RMO    Richmond Meteorological Office
SA     South Australia
SAT    Surface Air Temperature
SST    Sea Surface Temperature
T4     Thermal infrared wavelength 4 (10.3–11.3 mm)
T5     Thermal infrared wavelength 5 (11.5–12.5 mm)
TABS   Tabulated elements
<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<td>$T_{sfc}$</td>
<td>Surface temperature</td>
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<tr>
<td>TO</td>
<td>Tebbutt's Observatory</td>
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<tr>
<td>UHI</td>
<td>Urban Heat Island</td>
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<tr>
<td>UTC</td>
<td>Universel Temps Coordonne (Coordinated Universal Time)</td>
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<tr>
<td>VIS</td>
<td>Visible wavelength (0.58–0.68 mm)</td>
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<td>WA</td>
<td>Western Australia</td>
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<td>WCDP</td>
<td>World Climate Data Program</td>
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<td>WMO</td>
<td>World Meteorological Organisation</td>
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CHAPTER ONE: INTRODUCTION

In any collection of data, the figure most obviously correct, beyond all need of checking, is the mistake.

– Anonymous

This chapter introduces the need for a high quality temperature data set and reviews past research into Australian temperatures and international methods for identifying inhomogeneities in the climate record.

• The presence of discontinuities in the historical temperature record casts doubt on the representativeness of trends calculated from raw, unadjusted temperature data. Although research had been conducted on a global scale, as well as in other regions, a high quality, long-term air temperature data set had not previously been prepared for Australia.

• Increases in Australian temperature had been identified in the past using unadjusted data and in shorter data sets that took into account urbanisation and discontinuities. Investigations had also identified positive trends in temperatures checked for discontinuities, in various Australian regions.

• Adjustment techniques had been developed for global temperatures and records in other countries, but not for long-term Australian records.

• This project aims to manually investigate individual station history files to identify potential inhomogeneities and subjectively rank the quality of stations; adjust long-term temperature data for discontinuities discovered using station history files and statistical techniques; produce a temporally and spatially consistent historical climate data base of annual mean maximum and minimum temperatures readily accessible to the international scientific community; and analyse the resultant data set to determine changes in Australian regional climate over the historical observation record.
1.1. The need for a high quality temperature data set for Australia

The beginning of the nineteen-nineties has seen an unprecedented level of public interest, government reaction and scientific research into climate change due to anthropogenic factors, such as the enhanced greenhouse effect (e.g. Houghton et al., 1990, 1992, 1996). The community now understands that, in order to continue the current rate of development, we must address various matters to ensure the changes accompanying progress do not adversely affect the environment. Information from studies into the changing climate are vital to many aspects of Australian life, from agriculture and farming to the country’s infrastructure. The confidence in the validity of these and other larger scale climate change studies hinges on the quality of the historical climate data incorporated in trend analyses and numerical models. Therefore there is a need to accurately identify, evaluate and correct any problems, or inhomogeneities, in the record due to problems such as poor observing practices, missing data, and changes in instrumentation or station location. The record must also be extended both spatially and temporally by filling in missing data.

There is still much scientific debate over whether climate is changing significantly and, if so, what the impacts will be and what preventative measures need to be taken. However, a more accurate data base is required on which to base investigations into such arguments (e.g. Bridgman and Nicholls, 1990). Even if humans can mitigate or adapt to relatively large changes in the climate, a clear and correct picture of the past is required before options for the future can be decided.

There are both positive and negative aspects regarding the historical climate record of the region due to Australia’s relatively late settlement by Europeans. Fortunately, by the time official observations of the climate had commenced in the middle of the last century, the need for scientific precision had been recognised in meteorology. Many international standards of observation practices had been introduced. For example, minimum and maximum temperatures were recorded rather than just 9 am and 3 pm temperatures. In addition, most monthly temperature records have been processed so the lengthy and costly action of digitisation is not necessary for this project. Unfortunately, long records
are scarce and those that do exist are potentially contaminated by the effects of urbanisation.

The aims of this project are to:

(a) Manually investigate individual station history files held by the National Climate Centre (NCC) at the Bureau of Meteorology (BoM) and other archives to expose potential inhomogeneities. To use this information to subjectively rank the quality of stations which have temperature records for a long period of time, and are still operating;

(b) For any discontinuities discovered using documentation and statistical techniques, adjust the temperature data using statistical techniques developed at the U.S. National Climatic Data Center, which have been modified for Australian conditions where necessary;

(c) Produce a temporally and spatially consistent historical climate data base of annual mean maximum and minimum temperatures;

(d) Analyse the resultant data set in an attempt to determine changes in Australian regional climate over the historical observation record; and

(e) Make the data base readily accessible at low cost for use by the international scientific community.

The need for a high quality data set

The development of a high quality Australian temperature data set adjusted for inhomogeneities is long overdue. The limitations of climate observations in the U.S. were expressed in Climate (1957). Comments were made such as:

- “The longest climatological series in the United States are not homogeneous and no exact statistical methods exist for making them so. These long series, widely published in the past without qualifying notes, must therefore be used with discrimination.”
• "The longest series... have exclusively come from stations within slowly expanding cities... Also, the occasional need to move stations to new locations with their slightly different climates has blemished their combined record with discontinuities."

• "Virtually all 'first-order' Weather Bureau stations have been located (and relocated) in cities until recent times when many more transferred to nearby airports. Resulting discontinuities in their records can rarely be corrected for."

Similar comments can be applied to observation networks in almost any country, and were still relevant to Australia's network in the late 1980s. A picture of the theoretical effects of discontinuities on the climate record is shown in Fig. 1.1.1. The figure represents a hypothetical town, where temperature has a constant value of 17°C and no trend exists throughout its long-term record. The effect of the introduction of a Stevenson Screen to replace the previously used Glaisher stand is apparent at the turn of the century. As the town expands and grows around the weather observation station, a rising trend in the temperature is observed irrespective of any real climatic change. A negative discontinuity is introduced following a move to an airport, followed by a further rising trend resulting from increased development of the airport. If discontinuities resulting from other changes are included, spurious trends and jumps can arise which can obscure any information about the true nature of the climate. Natural variability in a real climate record would of course disguise changes such as these.

The intrinsic need for high quality data sets and the construction of baseline data sets was discussed by Ruttenberg (1990). He emphasised the importance of station history documentation—data about data, or metadata. Surface air temperature was seen to be the top priority for global climate monitoring. The processes involved in creating such data bases were:

• identifying existing data sources;
• processing and augmenting these sets with data from the original source;
• collecting metadata;
• analysing data to identify and adjust for non-climatic influences; and
• gridding of the data.
These processes were essential to separate natural variability and change from any variability or change ascribable to human activities. The need to build on an existing database using a building block approach was recognised by Wood (1988). It was recommended that priority be given to identifying those key variables for which data were already being collected. Quality controlled sets would then be integrated into one consolidated record. Wood also highlighted the importance of temperature data sets from rural areas. In Australia we needed to lay the foundations of such a database, specifically to obtain reliable temperature and rainfall records, and especially from rural areas. A high quality rainfall data set for Australia had previously been established (Lavery et al., 1992) and used to analyse trends (Nicholls and Lavery, 1992). Therefore the need for a complementary high quality temperature data set was apparent.

The need for a high quality climate data base for Australia was discussed in a workshop summarised by Bridgman and Nicholls (1990). Although the need had previously been recognised, this workshop was the first international cooperative effort towards ameliorating the problem of poor temperature data in Australia, and led to the establishment of this project. It was recognised that in the southern hemisphere, data voids and data sparseness require adjustment methods specific to the region. Although data sets have been refined on a global scale and in other countries, such a data set focussing on Australia had not yet been achieved. Hence long-term studies of local temperature were not reliable. The most significant work had concentrated on the latter part of the temperature record. Inhomogeneity testing needs to be completed locally, as global data bases could not practically focus on Australia’s unique data problems. By completing this project locally the availability of archived documentation and local expertise could be exploited, and a relatively small number of stations could be considered individually rather than as part of a global data set.

Although there is no official obligation, there is an understanding that countries are required to provide quality controlled meteorological data (WMO, 1993). Global climate research relies on the supply of high quality data across international boundaries, therefore Australia has to ensure the climate data being used is as accurate as possible. It was made apparent in Bridgman and Nicholls (1990) that Australia was falling behind the work done in some other countries. A full discussion of the techniques developed
elsewhere is given in Sections 1.2.2 and 1.2.3. It would be beneficial to an understanding of the quality of the global climate data base to use these techniques in all countries with a meteorological service. Also, for an understanding of Australia’s climate per se, it is necessary for similar techniques to be applied to our own regional network.

The selection of stations for the continued monitoring of climate through a Reference Climatological Station (RCS) network was recommended by the World Climate Data Program (WCDP, 1986) and completed for Australia by the NCC. Priorities for this data set are that stations must be permanent, preferably located in an area unaffected by urbanisation, have reliable observations, long records and few significant changes. Around one-hundred stations have been selected, of which most have been operating since 1951. There is a concentration of stations on the eastern side of the continent, with gaps in the network through the remote interior. The data set is intended to provide a reliable base for monitoring climate change and variability in the future. This set should be complemented with a set of stations, not necessarily separate from the RCS network, with much longer records (over 80 years) that have been subjected to careful homogeneity testing.

A greater degree of precision in a temperature data set is now required, as the focus of research in climatology evolves. In previous years, the emphasis has been on a description of climate, where data presented to the closest degree was usually adequate. Current research interest focuses more on a description of climate change, where analysed trends require data accurate to tenths of a degree. The same data are used, but for a different purpose from that for which they were originally collected.

Often the recording of meteorological data commences with the work of an observer without full scientific training, with no knowledge of the downstream uses of these data. By the time an observer’s data are in the possession of a researcher it is one part of a large data set, where small errors can pass unnoticed. In the past, the operational level of quality control has been sufficient for climate and weather applications. However it is now necessary to adjust for these errors to ensure that the undesirable noise does not overshadow the signal of climate change.
Large scale climate change, such as the enhanced greenhouse effect, can be of a similar magnitude to microclimatic changes. Therefore an apparent change in large scale climate in a time series could be due to an undocumented, unidentified small scale change in microclimatic conditions. Therefore, the aim here is to identify how much of the change apparent in a time series is real and likely to be due to large scale effects. This can be thought of mathematically as:

\[ dT_o = dT_t + dT_c \]

where \( dT_o \) is the change in measured temperature, \( dT_t \) is the change in true temperature with no artificial bias and \( dT_c \) is the rate of change of temperature with any change in the local environment.

*Examples of the need for a high quality data set*

The need for a high quality temperature data set can be illustrated practically by the results of Hansen and Lebedeff (1988). In an analysis of global surface air temperatures, it was found that a dramatic warming had occurred in the 1980s around St Helena Island in the east Atlantic Ocean. However, much of this apparent warming had been caused by an inhomogeneity in the temperature time series resulting from a station move to a lower elevation (Peterson and Easterling, 1994).

The results of Balling *et al*. (1992) provide a local example of the requirement for high quality temperature data sets. They describe the results of an analysis of temperature changes over Australia using data from a rural station network extending back to 1911. Some of the trends in the data used may reflect problems in instrument exposure and changes in location. The density of stations used by Balling *et al*. is too sparse to adequately measure continental scale temperature changes. Inspection of BoM records show that there are 145 Australian stations currently operating which have maximum and minimum temperature data prior to 1915. A further 79 stations have been identified which have data over the 1915–1990 period but which have been relocated during their history (Section 2.5). Of these 224 stations, 139 were not selected by Balling *et al*. for their analysis but are non-urban and have data over the required period.
Balling et al. state that the stations incorporated in the study have "continuous records of maximum, minimum and mean air temperatures over the period 1911–1990". However, many of the stations are located at aerodrome sites, which were not operating at such an early date. The data must therefore be a composite of records from different sites. An example of a dubious data record used in Balling et al. is that of Mildura Airport. Measurements were made at the town site of Mildura Post Office from 1889 until 1949, when the erection of buildings caused the instrument site to become inappropriate. Measurements were commenced at the aerodrome in 1946, providing three years of overlapping data for site comparisons. From this overlap, and checks with other stations with no discontinuities during the change over period, it can be shown that the move from the town to the aerodrome site introduced an artificial cooling of 1.0°C in the maximum temperature and of 0.9°C in the minimum temperature record. Many stations were relocated to airport sites during the period from the late 1930s through to the 1960s (Section 2.3.2), partly because their original sites within or near town centres were becoming affected by urbanisation. This negative discontinuity, common in many long-term records where a move away from a town occurred, may appear as a non-climatic cooling trend when a regional average is calculated. Since at least 10 of their 43 stations were associated with such a move it appears likely that non-climatic factors may have contributed to the 1911–1978 cooling observed in Fig. 2 of Balling et al.

The black-and-white photograph on the cover of this thesis is the shed used until 1961 at Bushy Park, Tasmania, a station included in the data set used by Balling et al. From comparisons with nearby stations and dual measurements at the sites it can be shown that the change in screen introduces an artificial cooling of 1.0°C in the maximum temperature and 0.6°C in the minimum temperature record. Balling et al. do not make reference to any adjustments for this problem.

Raw data
In addition to the possibility of incorrect conclusions being drawn from an analysis of inhomogeneous data, a preliminary analyses of the data base of all temperature data available for Australia highlighted the need for discontinuities to be identified and adjusted. Fig. 1.1.2 is a simple average of all available temperature data and as such should not be considered a citable result. It illustrates the need for reducing temperature
data to anomalies, which are the annual values subtracted from the average over a
standard period, and are used to make temperatures over large areas more comparable.
When actual temperatures are averaged, the mean is strongly influenced by the spatial
distribution of the stations, which has obviously varied through the period of record. The
time series is highly biased by the fact that the number of stations used to calculate the
average increases with time, as the spatial distribution of the latter network of stations is
different to that of the early stations. It can be seen from Fig. 1.1.3 that more inland
stations were established later this century, so the trends calculated using all data are
describing a less coastal, warmer climate. Therefore an analysis was completed using
temperature anomalies, relative to the standard 1951–1980 average period (the standard
1961–1990 period could not be used due to the lack of processed 1990 data at the time).
An analysis of a set of subjectively selected high quality stations (based on a detailed
analysis of documentation over the period from last century to the present—Section 2.4
and Appendix A1) differed from an analysis of trends using all available long-term (i.e.
open since 1910) temperature data, illustrating the effect of using poor quality data on
trend analyses. An analysis of annual maximum temperatures is used as an illustration of
the effect on trends using poor quality data. It can be seen from Fig. 1.1.4 that a
difference in time series is evident, even when comparing series compiled from an
average of many stations. The difference is accentuated early in the record, when poor
exposures and fewer stations possibly had a large effect on maximum temperatures. It is
also apparent that even the subjectively selected high quality stations have potential
discontinuities, as seen by the anomalously high averages early in the record. In spite of
the large number of stations used in the average time series, differences are still
noticeable throughout the latter part of the record.

1.2. Previous research into temperature trends

1.2.1. Australian temperature trends and adjustment techniques

Scientists have been interested in the trends in Australian temperature since the days of
colonial meteorology (e.g. Neumayer, 1867). These initial studies were carried out with
limited amounts of observation data, and it was not until the middle of this century that
long-term trends in temperature were investigated. Deacon (1953) noted a decreasing
trend in mean daily maximum temperatures in the second half of the period 1880–1950, with a levelling off or reversal in the trend at the end of the period. However, the introduction of the Stevenson Screen across Australia during this period, to replace the Glaisher stand (sometimes called the Greenwich stand in Australia) and various large thermometer sheds, is likely to have biased this result.

An increasing trend in Australian temperature was first identified in the 1970s. Tucker (1975) found that annual mean temperatures from 1957–1973 had risen at thirty stations around Australia, contrary to negative trends observed in the northern hemisphere over the same period. Coughlan (1979) observed a warming trend in annual mean maximum temperatures from 1946–1975, excluding data from the small number of major urban centres. However, these studies did not take into account the reliability of the records, and in fact Coughlan (1979) states that “for a country the size of Australia such a task would be formidable”. He completed a spatial consistency investigation but considered maximum temperatures only, recognising that maximum and minimum temperatures were related to different atmospheric processes. This difference is discussed in more detail in Section 5.1, but minimum temperatures are also considered in this project.

By the late 1980s studies were still being completed using raw data that had not been checked for inhomogeneities. Drake (1987) used a small, spatially sparse data set of 16 stations from 1943–1984, 30 stations from 1951–1984 and 61 stations from 1958–1984. In the longest data set (1943–1984) maximum temperatures were observed to be generally rising across the country. Minimum temperatures were also observed to be rising, and at a greater rate than maximum temperatures. Over the period 1951–1984 similar trends were observed to those in the 1943–1984 period. For all 61 stations over the period 1958–1984, both maximum and minimum temperatures had risen by an average of 0.015°C per year. In small towns the maximum had risen at a slightly greater rate than minimum temperatures (0.014°C per year and 0.013°C per year, respectively), but in cities the maximum temperatures had risen more slowly than minimum temperatures (0.02°C per year and 0.031°C per year, respectively). Note that Drake (1987) did not consider discontinuities nor make any adjustments to the data.
Coughlan et al. (1990) investigated trends in Australian temperature from 1930–1987. It was noted that the southern hemisphere had fewer data but exhibited a steadier rise in temperature than the northern hemisphere. Urbanisation was investigated, since it was a possible contributing factor in the increasing trend. The influence of urbanisation on temperature records is particularly relevant to a highly urbanised country like Australia, where 85 percent of the population live in urban areas. Temperature records at urban centres were seen to have been influenced by urbanisation, but not all of the warming could be explained by increases in population. A further investigation of urbanisation relevant to the current project is described in Chapter 3. Coughlan et al. (1990) generally observed rising trends in maximum and minimum temperature at 19 non-urban sites. The rise was said to be similar to trends in the southern hemisphere, and broadly consistent with trends in global temperature.

Jones (1991) investigated temperature trends as part of a study of historical cloud cover in Australia. No adjustments were made to the temperature data set, which consisted of 316 stations with a period of record greater than 30 years in length. The period of time over which the temperature trends were calculated is assumed to be from 1910–1990, the same period used for the cloud data. The Australia-wide average trend in minimum temperatures was 0.12°C per decade, with 256 stations exhibiting increasing trends and 60 stations exhibiting decreasing trends. Maximum temperature had shown an increase at 195 stations and a decrease at 121 stations, with an average trend over Australia of 0.06°C per decade. Average temperatures showed a mean trend of 0.08°C per decade (244 stations increasing and 72 stations decreasing) and diurnal temperature range (DTR) showed an average trend of –0.04°C per decade (132 increasing and 184 decreasing).

The first studies into Australian temperature trends that took discontinuities into account appeared in the 1990s. Ruddell et al. (1990) completed a study on the alpine region of southeast Australia, examining (amongst other parameters) temperatures from as early as 1910. Documentation was examined and discontinuities were identified through comparison with nearby stations and calculations using lapse rates. Several types of changes were identified and adjusted for. Trends in annual mean maximum and minimum temperatures were calculated at four stations with records from the 1940s and 1950s to the 1980s. Trends of 0.08, 0.30, –0.06 and 0.15°C per decade were found for
maximum temperatures, and 0.02, -0.33, 0.43 and 0.29°C per decade for minimum temperatures.

Plummer (1991) investigated temperature trends over the period 1949–1990 from 49 non-urban stations around eastern Australia. Anomalies were calculated relative to the 1951–1980 period. Data were estimated from nearby stations in the cases where single months were missing. However, where multiple months of data were missing the station was omitted from the analysis for that year. The data were spatially averaged using a Thiessen polygon method (WMO, 1983b), as used in the analysis of the data for this project. This method gives a greater weighting to sites located in remote areas, and less weighing to densely located observation stations. An overall rise in mean temperature was observed, with a 1.0°C increase occurring since 1949. Cool periods were noted during the 1940s, and during the 1970s. Seven of the ten warmest years were recorded in the last 12 years of the analysed record. The ten warmest years, in descending order, were 1988, 1980, 1973, 1990, 1942, 1983, 1938, 1986, 1981 and 1979. In an updated report (Plummer and Wright, 1993) 1991 was listed 5th but 1992 was much cooler due to atmospheric circulation anomalies and a possible influence from a major volcanic eruption. It was observed that minimum temperatures had risen more than maximum temperatures. Although no attempt was made to adjust for inhomogeneities in the first study, the updated report included seven of the stations adjusted in this project. Further work of this nature was completed in collaboration with the current project (e.g. Plummer et al., 1995).

Regional investigations have identified warming trends in temperatures adjusted, or checked for discontinuities, in Tasmania, South Australia, Victoria, and Queensland. Shepherd (1991) investigated the effect of a small move and major building construction in 1965 on the temperature record at Hobart, Tasmania. The record commenced in 1882 and had no other discontinuities. The monthly record, from May 1958 to June 1965 and from July 1966 to December 1973, was compared with six nearby stations with records of appropriate length and quality. The difference in the comparisons before and after the discontinuity at the two most similar stations indicated a change in minimum temperatures of about 0.3°C and an insignificant (-0.01°C) change in the maximum temperatures. Station history documentation was poor for the two nearby stations used in
the comparison, so it was possible that changes occurred at these sites. It was concluded that the adjustment of temperature records was a difficult but essential task. The study was followed by the homogeneity testing of all Tasmanian stations over the most recent 30 years of record to determine their suitability for climate monitoring (Sloyan, 1992). It was found that inland stations were more sensitive to site changes and hence lighthouse stations, which tended to remain in a fixed location, had more reliable records. It was also found that changes from a large to a small Stevenson Screen had a non-significant effect on maximum temperatures. This is contrary to experimental investigations by Andersson and Mattisson (1991). No adjustments were made to the temperature data.

South Australian maximum temperature data were subjected to concentrated homogeneity testing and augmented with archived data that had previously not been digitised for use (Burrows and Staples, 1991). Although records were available in South Australia as far back as the 1860s, stations were only selected if they had at least 30 years of continuous data, were currently open, had generally recorded temperature seven days a week, and exposed the thermometers in a Stevenson Screen. The data were subjected to a number of statistical tests for quality control and analysis. Temperatures exhibited a rising trend in annual mean maximum temperatures from 1960 of between 0.3°C and 1.4°C. This increase followed a cool period in the 1940s which was preceded by a peak in temperatures in the 1920s. A slight fall in maximum temperatures was apparent in the 1980s. Some contamination was identified in the records resulting from changes in site, however no adjustments for these and other problems were discussed. A study of minimum temperatures is currently being undertaken (K. Burrows, 1993 personal communication).

A comprehensive analysis of the temperature records from five stations in western Victoria was undertaken by Jones (1995). Monthly maximum and minimum temperature records were visually inspected to identify gross errors, documentation was inspected, comparisons were made with neighbouring stations, and missing or poor data were substituted. Adjustments were applied to the temperature data, based on two statistical tests (Potter, 1981; Bücher and Dessens, 1991), and on a sunshine ratio which identified changes in screen type. Average temperatures in western Victoria were observed to have
increased by almost 0.2°C per decade since 1945, following a cool period from 1925, but had only just reached the high values of early this century.

Temperature trends in Queensland this century were investigated by Lough (1995). A set of 49 stations with data from at least 1951 were investigated for outliers. One station was discarded and another was adjusted using monthly correction factors. Thirteen of these stations, with data commencing by 1910 and with populations less than 3 000, were investigated further. Trends over the period 1910–1987 in summer and winter, respectively, were calculated to be 0.68°C and 0.87°C (minimum); −0.74°C and −0.83°C (DTR); 0.34°C and 0.47°C (mean); −0.07°C and 0.02°C (maximum). The trends in minimum temperatures and DTR were seen to be highly significant, and not explained by urbanisation.

Specific problems in the results of Balling et al. (1992) have already been noted, but it is worth reviewing their findings in the context of other work on the Australian temperature record. Data from 43 stations over the whole of the continent were analysed over the period 1911–1990. It was found over the period 1911–1978 that maximum temperatures had significantly decreased by 0.37°C, minimum temperatures had increased by 0.17°C, mean temperatures had decreased by 0.10°C and DTR had decreased by 0.54°C. They noted that the period 1979–1990 experienced a dramatic change to positive trends in maximum, minimum and mean temperatures. In other words, although a warming trend is observed over the entire period of record, a cooling trend was apparent for the first 70 years, followed by a dramatic warming.

1.2.2. International temperature trends and adjustment techniques

Global
Trends in global temperatures have been examined extensively (e.g. Hansen and Lebedeff, 1988) although some studies have not taken into account the homogeneity of the record. Jones et al. (1985, 1986a, b) describe the development of a temperature data set with an improved spatial coverage and homogenised data on a global scale, as opposed to a regional scale as undertaken in the present study. Archived data were sought and digitised, then subjected to a difference technique to identify potential
discontinuities. This involved subtracting average monthly temperatures at one station from corresponding values at a close neighbour to obtain a time series over the period of simultaneous measurement. Any jumps or trends in the difference series indicated a potential change in conditions at one of the stations. By comparing with other neighbours and consulting station records regarding changes, the source of the spurious jump or trend was identified. Correction factors were then applied to the dubious values to make them compatible with the most recent part of the record. This was achieved by differencing the mean temperature before and after the change at the problem station, and comparing this with a similar difference at the ‘correct’ station or stations.

Bottomley et al. (1990) and Folland (1991) describe methods to overcome similar problems in sea surface temperature (SST) data availability and changes in instrumentation. The combined marine and land surface average temperature in the southern hemisphere time series (Jones et al., 1986c) showed little overall trend during the nineteenth century. After 1900 the series showed a warming trend to the mid-1940s, with no trend apparent between 1945 and 1970. The period since 1970 exhibited a strong warming. The overall warming since 1900 was 0.5°C. The resultant data set, as well as a similar data set for the northern hemisphere and consequently the entire globe, constituted a major step forward in the analysis of secular changes in temperature. However, problems in the data set discussed by Hughes (1991), such as the inclusion of urban sites and the exclusion of some long-term data, indicates the difficulties in using such a data set for regional studies. Wood (1988) discusses the possibility of an urbanisation signal being introduced into the data set compiled by Jones et al. (1986c) if particular stations are compared with nearby stations with an unexpected or undetected urban warming trend. A study by Jones et al. (1985) included 80 stations on continental Australia, although only 34 had enough data and were able to be homogenised for use in the final trend analysis, and only 12 of these had records extending from before 1910. Although this and other studies include the Australian region as part of the overall global results, they were not intended to provide detail at the regional scale because the corrections applied were sometimes based on comparisons between well separated stations. The immense size of the global data set necessitates the performance of this task on a regional scale to reduce the possibility of overlooking problems. In addition, comprehensive metadata are more easily accessible locally.
Britain

An early attempt to create a homogeneous regional temperature series was completed by Manley (1953). A time series of monthly mean temperature for the English Midlands was constructed for the period 1698–1952. Records from several stations were averaged over several periods. Non-instrumental observations of wind and weather provided estimates when temperature observations were not available. The data set was subsequently extended to include the period 1659–1973 (Manley, 1974) and updated to 1991 by Parker et al. (1992). The latter study included a daily temperature series, a variance adjustment for changes in the number of stations in the regional average, and a small (<0.1°C) correction for urbanisation.

New Zealand

The New Zealand temperature and precipitation data base has been refined. Salinger (1982) carried out a detailed inspection of New Zealand station history files, eliminating those which appeared suspect. The remaining ‘better’ stations were then compared with neighbours to examine whether any jumps or trends existed in the difference series. Those stations which passed both tests were used in an evaluation of temperature trends in New Zealand. A rise in average temperatures of 0.5°C was seen since 1950. Similar homogeneity tests were conducted on 12 long-term stations, showing warming trends since 1853, with intermittent cool periods (Salinger, 1981). Further homogeneity testing (Rhoades and Salinger, 1993) concluded that “adjustments for known site changes can probably never be done once and for all”, particularly in the case of isolated stations. However, the warming trend found in New Zealand was consistent with trends in surrounding countries and the South Pacific (Salinger et al., 1994).

United States

Homogenising temperature records had been completed earlier in the U.S. by Karl and Williams (1987). They used as many neighbouring stations as possible, with positive correlations (with respect to temperature anomalies) and no discontinuities on either side of the discontinuity at the station under investigation (hereafter referred to as the candidate), to determine annual and seasonal correlations and thus assess the impact of the change. A difference series between the candidate and each of its neighbours was formed around each discontinuity at the candidate, and the confidence interval of each
pair of series was calculated using Student’s t-test. These intervals were ranked and the two narrowest were combined using a weighted average. More intervals were included after repeating the procedure. The confidence intervals measured the magnitude of the effect that the undetected changes had after the adjustments. A station with a narrow confidence interval was more desirable for studies into regional climate change. It was noted that station histories are essential, that these rarely describe environmental changes in the vicinity of the site, and that rural stations should be primarily considered in climate change studies due to the problems involving urbanisation effects in larger towns and cities. Using the results from a subset of the 1 200 stations adjusted for inhomogeneities, it was found that in the second half of this century maximum temperatures had decreased and minimum temperatures had increased, leading to a decrease in the DTR. Similar trends in DTR have subsequently been identified in many regions around the globe (Karl et al., 1993).

Karl et al. (1986) investigated the adjustment of data for the specific problem of changes in the time of observation. A bias can be introduced into the record if an observer changes the time of observation from, for example, the 24 hour period ending at midnight to that ending at 9 pm. This is due to the radiative cooling or warming of the atmosphere at the time of the observation. Changes in the time of observation sometimes can occur several times in one decade in North America. As a result of the radiative properties of the atmosphere, the bias is positive if the time of observation changes from midnight to evening, and negative if the change is from midnight to early morning. The bias can be as large as 2°C but varies between seasons and geographical locations. A numerical model to estimate the bias in monthly mean maximum and minimum temperatures was successfully applied to the U.S. data set. Such a model is similar in aim to the model developed to adjust for the change in SST measurement techniques (Folland, 1991), in that it aimed to solve a specific problem. From station history documentation in Australia, a change in the time of observation did not appear to have been a major problem. However, confusion regarding local summer time (LST) could introduce a bias in the record (Section 2.3.2).

The work on the U.S. Historical Climate Network was expanded to a global data set at the U.S. National Climatic Data Center. Peterson and Easterling (1994) note two types of
inhomogeneities; abrupt discontinuities resulting from instrument or exposure changes, station moves, etc., and effects that cause a gradual increase over time such as changes in the environment due to urbanisation or a change in instrument calibration or condition. They used a reference series made up of the data from five neighbouring stations, rather than a single, potentially inhomogeneous station, to detect and adjust for problems at a candidate station. The nearest, positively correlated, best quality stations were selected from a data set with a changing composition of stations over time. Due to the possibility of simultaneous network changes within a political boundary, at least two of the five stations selected to compile the reference series were required to be from outside the candidate station’s political boundaries. Correlations were based on series of interannual changes in temperature rather than raw temperature data, as the latter were seen to be largely affected by discontinuities. A further test ensured that high correlations were unlikely to have arisen due to chance. It was found that adjusting the standard deviation of the reference series was not required for identifying inhomogeneities in the candidate series. The components of the reference series were combined using a weighted mean. The series of interannual changes in temperatures was then converted back into a temperature time series simply by adding the series together. The resultant series was seen to be efficient in identifying discontinuities however, it was noted that “perfectly homogeneous, century-scale, climatological reference time series are likely to be impossible to create”.

The use of reference climate series in adjusting temperature time series was further investigated by Easterling and Peterson (1995). They used an automated, objective (and hence repeatable) method to identify discontinuities in the difference series between a candidate and reference series. The method is based on a regression of the difference series against time. A two phase regression is fitted, for each year of the series, to all years before and after the year being tested, and the residual sum of squares is calculated for each of the two regressions. The year with the minimum residual sum of squares is noted as a potential discontinuity, and the significance of the two-phase fit is tested. The difference in means of the difference series is also tested using Student’s t-test, and the potential discontinuity is noted. The series is then divided at the point of the identified potential discontinuity and the test repeated automatically until no further discontinuities are identified, or until the series becomes too short. All potential discontinuities are
tested for statistical significance using a non-parametric test. Required adjustments are
calculated from the longest possible discontinuity-free periods either side of the change.
These are applied and the test is repeated automatically until no further discontinuities
are identified.

Easterling and Peterson (1992) evaluated an early version of their technique against other
methods of identifying and adjusting for a change in the mean value of a time series.
Techniques were evaluated by comparing their ability to identify discontinuities in
simulated time series with introduced discontinuities, and in temperature time series with
documented potential discontinuities. The test by Alexandersson (1986) was shown to be
the most efficient detection and adjustment method available at the time. The evaluations
were repeated once Easterling and Peterson’s technique had been further developed.
They concluded that the best available technique was that described in Easterling and
Peterson (1995). Therefore their technique was selected for use in the current project.
However, some changes were made for its effective use on the Australian temperature
data base and a new reference series construction method was used.

1.2.3. Other adjustment techniques

The state-of-the-art methods described above built on the work completed by a number
of scientists around the world over many years. This included early identification of the
problems of unadjusted data (e.g. Ellis, 1891), standard climatological publications (e.g.
WMO, 1966a), the effects of inhomogeneous data on trends (e.g. Murray-Mitchell,
1953), and ways to overcome these problems in the data (e.g. Potter, 1981).

A report on the study of climate change (WMO, 1966a) suggests that subjective
comparisons between temperature observations and observations of other parameters
(frost, dates of rivers freezing, etc.) be complemented with objective statistical tests. In
the identification of inhomogeneities generally, the time series at one station is subtracted
from another and the series of differences is examined for a change in mean. Various
tests are recommended, depending on whether or not the discontinuities are known, but
all were susceptible to a number of shortcomings, such as a failure to detect small
discontinuities, or the production of ambiguous results. The tests are described in the
context of standard statistical practices in WMO (1966b). A more detailed description of quality control tests are given in WMO (1986). These include:

- Correlation tests. Where the temperature at a particular station is known to be correlated with another parameter, then a relationship between the two can be established and used to estimate the temperature. However, correlations with other parameters are seldom high enough for the detailed adjustment of long-term temperature series.

- Comparison with near neighbours. This test is used with some success in the current project, but a more robust objective test is required, due to problems such as discontinuities at the neighbours.

- Running means. A time series can be averaged over a time interval, and the smoothed plot examined for departures from the mean. However, the time and magnitude of any change in mean cannot be resolved in enough detail for the reliable adjustment of the temperature series.

- Examination of accumulated totals. By cumulatively summing the time series of temperature, the scale can be arranged so that the slope is at 45°. Any discontinuities are apparent as a change in slope. This has been found to be an efficient quality control method (e.g. Rhoades and Salinger, 1993), however Easterling and Peterson (1992) found that other tests were more efficient.

- Maronna and Yohai’s (1978) bi-variate method. This method was used successfully on rainfall data by Potter (1981) and on temperature data by Bücher and Dessens (1991). It identifies both the time and magnitude of a change. It assumes serial independence of the two series, which is not a valid assumption for temperature as stations can be close and therefore have similar temperature regimes. An assumption that the series are stationary is also made, which is usually valid for temperature series—although a climate trend may be present in both series, the difference series should be stationary. The method was found to be efficient at identifying a single
discontinuity in a simulated series by Easterling and Peterson (1992). However, where more than one discontinuity existed, and in real time series where correlations with the reference series were not as high, the test did not perform as well. Nonetheless, the Maronna and Yohai (1978) method will be tested with Australian data later in the thesis.

A test developed for precipitation data (Alexandersson, 1986) used a simple test statistic to identify a change in mean in a series of differences between candidate and reference values. The reference values were a form of a mean of surrounding stations’ values. When used to adjust temperature data, the method was found to be sensitive to small discontinuities and trends (Easterling and Peterson, 1992), but was not as efficient in tests on Australian data (Chapter 6). A more developed version of the test, sensitive to trends, was used for the development of a climatological data series for the North Atlantic (Frich and Cappelen, 1992).

Other tests were examined by Easterling and Peterson (1992) but were concluded to be less powerful for discontinuity detection. These included regression techniques, where two regression equations were found for the periods before and after a year in question. A potential discontinuity was flagged if the difference between the two regression estimates fell outside a calculated confidence interval. Similarly, a two-phase regression technique (Solow, 1987) identified a change in the trend of a time series by identifying a change point in the two-phase regression of the series of differences between neighbouring stations versus time. Cluster analyses were also examined as a technique to identify potential discontinuities. Other tests investigated were Student’s t-test and double-mass analysis (Kohler, 1949). However, for the purposes of this project the test developed by Easterling and Peterson (1995) was the most efficient at identifying discontinuities.

The technique of Solow was improved by Vincent (1990) for the identification and adjustment of Canadian temperature time series. As with earlier techniques, this method was based on the relationship between a base station and a reference series produced from some surrounding stations. Several multiple-phase regression models were fitted to the difference series and step changes and trends were identified by change points. The
advantages of this method were that it required no prior knowledge of the change point and it was automated and objective. It also could be used on either monthly or annual temperature data. However, a minimum of four to six good surrounding stations were required, which is usually not possible in the Australian network. It also had the potential to incorrectly identify a discontinuity when there was not one present, resulting from the lack of fit of models explaining the relationship between the two series.

These methods all focus on changes in the mean. Changes in the variance of a station have also been identified and adjusted for (Downton and Katz, 1991). The method was similar to the adjustment for a change in mean, but used ratios of standard deviations in place of differences in means. Although there appears, from a visual inspection of the raw data, to be a possible change in variance in the Australian temperature record last century, this method was not used in this project. This is because the focus is on trends in the annual mean temperatures during the period since 1910.

An investigation into the homogeneity of daily data is under way in Australia (B. Trewin, 1996 personal communication). This will assist in determining whether or not there is any evidence of trends in the occurrence of extreme temperature events in the historic record, and whether or not any changes in their occurrence are likely to be associated with future global climatic change. The frequency of extreme events in an inhomogeneous record does not always match the changes in the mean. For example, paired sites at Inverell in southeast Australia (Soil Conservation Research and Post Office) have a temperature difference that is greater on colder nights (Trewin and Trevitt, 1996).

1.2.4. Other relevant research

Meteorological parameters other than temperature have also been investigated for inhomogeneities. Lavery et al. (1992) describe the composition of an historical rainfall data set for Australia. Available documentation was examined for stations with a continuous record from at least 1910. Details of rain gauge exposure, changes in location, changes in rain gauge type, and an objective test of observer skill were considered. A selection process based on the above criteria eliminated many stations of
poor quality. The remaining records were checked for inhomogeneities by a suite of programs. Those stations with any discontinuities or suspicious trends were rejected. The final product consists of 191 long-term rainfall stations which satisfied all of the above tests. The data have been used to examine trends in rainfall across the Australian region (Nicholls and Lavery, 1992). An extension of the data set has now been completed (Lavery et al., 1997), and a detailed study of stations in the state of Victoria has been completed (Torok et al., 1992). The homogeneity of precipitation records has also been investigated in other countries (e.g. Groisman et al., 1991).

An SST data set was prepared for the globe (Bottomley et al., 1990) using corrections described by Folland and Parker (1990). The method combined experimental results of a physical model of twelve different types of bucket methods used to collect SST data (Folland, 1991), and a statistical test requiring similar variance ratios. The methods involved meticulous, step-by-step corrections to data, where sufficient metadata about the methods of data collection and changes in instrumentation were available. The adjusted data were found to be reliable on comparison with air temperature measurements from ship decks and islands, and provide a global data set for historical analyses (e.g. Parker et al., 1994).

An extension of the pressure record at Tahiti and Darwin and a test of its homogeneity has been completed (Ropelewski and Jones, 1987). This is of particular interest for the studies of El Niño-Southern Oscillation (ENSO), as the Southern Oscillation Index is calculated from the pressure at the two locations. Adjustments to these data were calculated from comparisons with nearby stations, required possibly due to a change in observation time or a change in barometer elevation. Monthly correlations were computed between the data corrected for biases and data from surrounding stations to conclude that no inconsistencies were present in the new data. Further work on the pressure record has been conducted by Allan (1993).

Cloud amount data are recorded in okta (eighths of sky covered by cloud) following a change from measurement in tenths in 1949. Sunshine data are recorded in hours per day. A conversion error in the cloud measurements was rectified to obtain a long-term record from 1910–1989 (Jones and Henderson-Sellers, 1992). Sunshine hours had been
converted to fractions and added to the cloud cover fractions. However, the addition of the two parameters resulted in a sum of 1.2, and not 1.0 as would be expected. It was concluded that in spite of the calculation to adjust for the known problem in the record, unrecognised systematic errors possibly remain in the data set.
Figure 1.1.1. Theoretical effect of various changes on a temperature time series. The solid line represents an artificial trend in the record and the dashed line represents the actual climate.

Figure 1.1.2. Simple average of annual Australian maximum, mean and minimum temperatures. See text for full explanation of the false conclusions that could be drawn
Figure 1.1.3. The location of stations used in the calculation of the time series in Fig. 1.1.2, and an indication of the period in which temperature observations were commenced.

Figure 1.1.4. Average annual maximum temperature anomalies for the set of long-term temperature stations, compared with the same time series using only the subset of subjectively selected high quality stations. The number of stations used in the
CHAPTER TWO: DATA

Documentation is like sex: when it is good it is very, very good, and when it is bad, it is better than nothing.

— Dick Brandon

This chapter reports on the collation of all available temperature data and related station history documentation, and discusses the potential problems in the data.

• Temperature data and related station history documentation were collected from the BoM for all long-term temperature observation sites. Raw monthly temperature data were available for 1,418 stations around Australia.

• A relatively smaller number of stations were available that were currently operating and had a long-term record (at least 80 years in length). To increase the number of long-term stations available, previously unused data were digitised and a number of stations were combined to create composite records.

• The raw data set consisted of 224 candidate stations for further investigation.

• Maximum and minimum thermometers should be exposed in a Stevenson screen and read according to international standards of measurement.

• The station history documentation files held by the BoM and in archives were studied in order to investigate moves and other changes likely to affect temperatures over the period of record covered by the long-term data set.

• Common changes included replacement of instrumentation; location shifts; local environmental changes; and changes in observation practices.
2.1. Availability of Australian temperature data

Stations around Australia and its territories are grouped into 107 regions known as rainfall districts (Fig. 2.1.1). These districts vary in size and have had a varying number of climatological stations operating within them. The districts are numbered from one to 99 (including some sub-regions, e.g. 15A, 15B) and these district numbers make up the first two digits (excluding leading zeros) of the station’s official BoM number (Table 2.1).

The maximum and minimum temperature data available through the NCC exist in two categories:

- Daily data are held in a format known as Card 8. They are widely available from 1957, when digitising of meteorological returns commenced. Meteorological Offices and some selected stations’ data with a high priority for digitising are available from the 1930s and 1940s. Brisbane, Darwin, Melbourne and Sydney are the only sites with daily data available before the 1930s.

- Monthly averages of maximum and minimum temperatures are stored as tabulated elements (TABS). They are available for a much longer period than daily data, with the longest record (Melbourne) commencing in 1855. One value is given for each element, for each month where more than 24 days of measurements have been taken. If fewer observations were made for the month then the monthly value was not calculated and was left as missing.

The monthly category was the source of temperature data for this project. It was decided to concentrate on identifying problems in the longer term record of monthly mean maximum and minimum temperature data, because the shorter record of daily data fails to extend beyond the previously studied period of the Australian record (Section 1.2.1). The processing of some earlier daily temperature data was undertaken (Stone et al., 1996) but these data were subsequently used only to extend the monthly record. Seasonal and annual averages were calculated from the long-term monthly data set for comparisons between stations.
The TABS data set consists of 1418 stations around the country with almost 100,000 station-years of combined maximum and minimum temperature data. Over half of the stations have less than 40 years of data (the mean number of years of data is 35.5). A large number of stations have exactly 87 years of data (having commenced operation following the allocation of meteorology as a Federal responsibility in 1908), and the maximum number of years of data is 139 (Fig. 2.1.2). The data set consists of over 1.2 million monthly values, including null entries. Missing values of maximum and minimum temperatures can occur at different times. Null entries for maximum and minimum data differed due to problems such as a broken thermometer not being replaced. Due to the huge size of the data set a robust statistical technique was required to select and compare periods of the temperature record. One reason such a study may not have been completed to date is that the large magnitude of the problem prevented any attempt prior to the availability of computer technology.

The distribution of stations by latitude versus the years of operation (represented by a bar between the commencement and cessation of precipitation measurement) is shown in Fig. 2.1.3 for bands of longitude 10° in width or 5° in width for eastern Australia. Large gaps are apparent both in a spatial and temporal sense. Crowding of stations can also be seen around certain latitudes that represent locations of city areas that would be affected by urbanisation.

Fig. 2.1.4a shows the spatial distribution of stations with any maximum and minimum data, including telegraphic and non-telegraphic climatological stations, whether currently open or closed. Other stations, which at one time recorded temperature measurements but have since ceased or have been downgraded, are included in the figure. These latter stations will be useful for future correlations and corrections, when shorter lengths of record will be an additional source of data for the construction of a median reference series. Fig. 2.1.4b shows the operation of stations chronologically, without counting stations with only a single year of data. Increases in the number of stations occurred after 1908, as well as after post-war development and atomic bomb tests in the 1950s, and a decrease in the amount of archived data in the 1980s followed the introduction of a priority system (A. Brewster, 1991 personal communication). The number of temperature stations around Australia is more than halved if only those currently open
(and therefore more useful for present climate change studies) are considered (Fig. 2.1.4c).

A long-term station is defined in this study as one which was open prior to 1910. This is the definition of a long-term station given by Lavery et al. (1992), and coincides with the dramatic increase after 1908 in the number of stations operating. The distribution of long-term temperature stations currently open can be seen in Fig. 2.1.4d. These stations are more meaningful to statistical climate studies due to their length. Fig. 2.1.5 combines the spatial and temporal information of the location and establishment of climatological stations. It can be seen that few stations were open last century and that even by 1910 only the east coast and the southwest corner of Australia had a sufficient station coverage. The long-term data set was in practice extended to include data from stations that had been operating since 1915 and had been open at least until 1985.

It was observed after reading documentation and completing an initial investigation of the data visually that only about 50 stations had a long, high quality record with respect to site and observer quality. Of these, not one had consistent sites or equipment throughout their entire history. It was therefore decided that, rather than only selecting high quality stations or ensuring spatial coherence, any station with a long-term record, regardless of quality, would be examined in detail and tested strictly for inhomogeneities. This was essential due to the small number of open long-term temperature stations, relative to the 2 131 long-term rainfall stations.

All mean monthly maximum and minimum temperature data from currently operating long-term stations were retrieved from the NCC. The records were examined to determine the date on which temperature measurements began. An examination was necessary because the period over which temperature has been recorded is in all cases less than or equal to the period since a site was originally provided with a rain gauge, which is noted by the NCC as the period over which the station has been operating. The difference in record length between temperature and rainfall measurement appeared from documentation to be due to the expense and difficulty of supplying a screen and accompanying set of thermometers, relative to the cost of a rain gauge. Even once the need for temperature measurement was established and the instruments had been
supplied, the measurements were not taken as meticulously as for rainfall. This conclusion was drawn from the documentation, and appeared to be due not only to the more complex concepts and procedures, but also to the observers, who were often local residents or farmers, apparently not being aware of the value of any information other than how much rain their land had received. It was seen from documentation that this was a problem particularly at remote country stations, where in addition it was difficult for observers to adhere to regulations such as a grass site. It was also difficult for inspectors to ensure that standards were followed, due to the infrequency of inspection visits.

Only stations which had been recording temperature since at least 1915 were considered. A lengthy investigation was carried out to determine what temperature data are available and how much of it is relevant to this project. Many avenues and leads were followed to ensure no existing digitised temperature data or archived monthly summaries were overlooked.

To increase this data set, the dictionary of surface stations was examined to find any stations which had been open since 1915, had since closed, but had been replaced by a nearby station with a different identification number. Any compatible data sets were extracted and combined to form composite time series.

An attempt to increase the amount of available long-term station data was additionally made through extensive searches for tabulated data in State archives and Regional Offices (ROs) that had not been digitised. Such data were rare, and seldom available in the station history documentation beyond that which had been previously digitised. Other avenues such as global data sets, agricultural, electrical and alpine company records were investigated however, no data of sufficient length or quality were uncovered.

Serendipity led to the discovery of many years of temperature records from 1863–1897 in the area west of Sydney, New South Wales (NSW). This was manually entered, along with previously unused data from the years 1881–1907 and 1975–1993 at the official BoM site in the area. Similarly, monthly mean maximum and minimum temperatures were discovered in the Alice Springs station history files and digitised to become part of
the data set. The record was extended by forty-seven years by adding data from the years 1879–1925 (inclusive). These data had not been available through NCC or the Northern Territory RO, although they had been available in World Weather Records and used previously in global studies (Jones, 1986b). In addition, data from South Australia were obtained during a visit to their RO (K. Burrows, 1993 personal communication) and data from stations in NSW were obtained from the daily data entered for Stone et al. (1996).

Data were requested for the period where a large amount of data is missing (1956–1965), however a consequent project at NCC to digitise this period of data had not commenced in time to be included in this study. The delay was a result of a change to a new system of archiving in mid-1994, so there was no time to enter information other than current data. All data available at the end of July 1994 were obtained for use in this study. An initial calculation and correction was applied to all stations to ensure that archived annual average temperatures equalled the average of the twelve monthly values.

The consolidation of all available long-term temperature data into one data set for this project, including summarised documentation about the methods of their collection, was a time consuming, but essential, first step towards a high quality temperature data base.

2.2. International standards of temperature measurement

Temperature is one of the most commonly used climatic parameters. It is vital that the measurements are made under international standard conditions and times, using common instruments, exposures and observing practices (e.g. WMO, 1983a) for them to be useful for operational and research purposes.

The maximum and minimum thermometers are delicately crafted instruments that were commonly used in other countries before being introduced to Australia (Wragge, 1889). The maximum thermometer should be mounted in a Stevenson Screen on a slight angle (about 2° from the horizontal), about 1.7 m above the ground. Its design is similar to a medical thermometer, in that as the temperature rises mercury is forced through a small twist, constriction or valve in the glass column, about 3 cm above the bulb. As the temperature decreases there is not enough pressure to drag the mercury back through the
constriction in the tube. Hence the mercury remains at the maximum point of extension, recording the maximum temperature. To re-set the thermometer, it should be held bulb-downwards and swung back and forth until the mercury has been returned to the other side of the valve. It must be ensured that a break in the mercury is removed or at least the length of the break accounted for in readings.

The minimum thermometer should be mounted about 20 cm below the maximum thermometer, also on a slight angle with the lower values of temperature on the lower side. An index rides inside a column of alcohol which contracts on cooling, pulling the index with it due to surface tension. When the temperature increases, the surface tension is not high enough to drag the index against gravity back up the tube. Hence the index remains at the maximum point of contraction, recording the minimum temperature. To re-set, the minimum thermometer should be tipped up to allow the index to rejoin the alcohol. It must be ensured that bubbles do not form in the alcohol (this is difficult to detect, as both the alcohol and bubbles are clear), breaks do not occur in the column of alcohol, the index does not fall out of the alcohol partially or fully, and that the correct end of the index is read.

At 9 am the observer should open the screen and read, in the following order and without touching any of them, the dry and wet bulb thermometers, the maximum (in case the maximum temperature has occurred after 3 pm the previous day) and minimum self-registering thermometers. The entries should be recorded in a field book. The maximum thermometer should be re-set and the re-set value recorded in the field book as a check. At 3 pm the minimum should be first re-set, then all of the thermometers read in the above order and recorded. All thermometers should be read to the nearest 0.1°C (observers were originally instructed to read thermometers to the nearest 0.1°F).

The thermometers should be exposed in a Stevenson Screen to shield them from direct sunlight, precipitation and other potential sources of radiation or damage. The screen is ventilated naturally with angled louvres on the interior and exterior of the screen (Fig. 2.2.1). A double layered roof and floor (or a floor of staggered boards), with ventilation between the layers, is required to eliminate the possibility of reflected or direct radiation entering the screen. Internal heating must be kept to a minimum by ensuring the screen is
not overcrowded with instruments, with ample space between instruments and walls. A free circulation of air through the screen is essential for the temperature to reflect that of the surrounding area. The screen should be firmly installed at a height of 1.25 to 2.00 m above the ground. It should be kept clean both inside and out, and be painted white to ensure a consistent and high albedo (shininess or reflectivity). The woodwork must be kept in good condition to ensure no disruption to the flow of air or allowance of the weather to enter the screen. Screens made of plastic are now becoming widely used. The single door to the screen should face south (in the southern hemisphere) so that sunlight does not shine on the instruments when the door is opened for observations.

The screen should be exposed on a plot of short grass, at least 9 m by 6 m in area. The surface below the screen should be horizontal and level, away from steep slopes, ridges, cliffs or hollows. A slope experiences a nocturnal down-flow of air due to cooling, or an upwards flow on warm days, and hollows can form cold pools or other exceptional conditions. These flows can be undetectable by the observer but may have an effect on the temperatures. The site should be relatively open and unaffected by windbreaks and natural or man-made shelters. It should represent the surrounding area, with minimal effects from the local topography, vegetation or man-made structures.

With these international standards in mind, an ideal station for this project would therefore have the following characteristics:

- Permanence, with few moves in the past and a low likelihood of moves or closure in the near future.

- Remoteness, with a lack of industry and urbanisation and an unchanging environment.

- Reliability, in both the observers and the instrumentation, with regular inspections and quality control.

- Lengthy record, dating back to at least 1910.
• No large non-climatic or anthropogenic changes, or small, undocumented effects.

• A detailed station history and a high correlation with nearby stations.

There are no Australian stations that adhere to all regulations and standards for the entire period of record. Hence there are no raw data available for this project from ideal stations.

2.3. General changes and related effects

There are several different types of change that can have an effect on the long-term historical temperature record. Large scale, global changes such as the enhanced greenhouse effect manifest themselves in the record as long-term trends on a decadal to secular scale. Regional oscillations and variability such as the El Niño phenomenon are also apparent in the record from annual to decadal scales. There may also be changes in the microclimate related to the immediate environment, such as vegetation growth or urbanisation. These change the climate in the area of temperature measurement, but are not representative of changes over the larger region. Finally there are artificial changes, such as site moves, which do not relate to real changes in climate. These are not occurring in the broader environment but may be perceived to be occurring due to the change in the temperature record.

Artificial changes can be divided into three groups. Random error, due to accidents, are likely to be clustered either side of the mean value and hence are not the major concern for this project. Mistakes, such as misreading or misrecording, have little bearing as they are likely to have been rejected by NCC quality control due to the obviously incorrect value. However, systematic errors and changes in practices may have a significant, long-term effect on the record and thus must be identified and adjusted for so that the data exhibit only real changes of the largest two types, i.e. global and regional scale changes.

The systematic problems in the record can arise due to a number of changes, as listed by Jones et al. (1986a). These are:
• Changes in instrumentation, exposure and measurement techniques;

• Changes in station location (both altitude and position);

• Changes in observation times and methods used to calculate monthly means; and

• Changes in the environment around the station, including urbanisation effects.

Ruddell et al. (1990) also comment that instrument height, and changes in observers and observer habits can affect the record. Other problems include changes in the time of observation (Kari et al., 1986) and the frequency of observations. All of these problems can appear in the record as a discontinuity, as a change in the variability or as a trend in the data (Fig. 2.3.1).

2.3.1. Specific changes: Introduction of the Stevenson Screen

The Stevenson Screen was introduced to the international scientific community by Thomas Stevenson in 1866 at Greenwich, England. Many experiments both in Australia and overseas (e.g. Ellery, 1881; Gill, 1882; Gaster, 1882) were conducted to determine if this was in fact the ideal form of thermometer exposure. More recently, Parker (1990) gave a summary of the effects on temperature by the many different types of shelter used during the recording of global temperature.

Several of the Australian colonial meteorologists met at three colonial meteorological conferences in 1879, 1881 and 1888 (Section 4.1.2) to discuss, inter alia, the introduction of the Stevenson Screen to the Australian observation network. It was apparent from the minutes of these meetings (Russell, 1879; Ellery, 1881; 1888) that although there was agreement that observing practices needed to be standardised, there was much argument about whether the Stevenson Screen should be the standard exposure. The replacement of thermometer exposures was not seen as a high priority at this early time in the establishment of climate observation networks.
Hughes (1995), interpreting the proceedings of the Colonial conferences, believed that Stevenson Screens were in use at country stations in the state of Victoria by the early 1880s, and in the rest of Australia from 1890. He concluded that there was no need for significant pre-1900 negative corrections. However, this is possibly a misinterpretation and is, in any case, contrary to more substantial evidence from the station histories and other first-hand documentation (Appendix A1).

Nicholls et al. (1996a) completed an extensive search of original and contemporary documentation of late nineteenth century meteorological instrumentation. It was noted that although some stations had been furnished with a Stevenson Screen as early as 1888, it was over the ensuing 20 years that most stations around Australia changed from an earlier form of exposure (such as a Glaisher stand or Thermometer shed in the best cases, and under a verandah or even inside the house in the worst—Appendix A1).

From an investigation of archived documents it was found that some states, such as Queensland under the initiative of Clement Wragge, were quicker to change to the Stevenson Screen, whereas others were slow to introduce the standard, such as Victoria. Stations in Western Australia were most commonly fitted with Stevenson Screens in 1896–1897, following a period where a smaller, single-louvred screen was used (Nicholls et al., 1996a). In South Australia the Glaisher stand was first replaced by the Stevenson Screen in 1887 and the last Stevenson Screen to be installed was at Cape Borda in 1908, but generally the Stevenson Screen was introduced in 1892. Most stations in Queensland had Stevenson Screens installed in 1888–1889. Some New South Wales country stations received Stevenson Screens in 1898, with another group of stations having them installed in 1901, and a further group in 1906–1908 (Nicholls et al., 1996a). Most Victorian stations had thermometer sheds replaced by Stevenson Screens around 1906–1908. It was noted that at older stations, including some of those established this century, thermometers were 4–5 feet above ground in an open-gabled shed with a double roof enclosing an area of 5 by 6 feet (Barrachi, 1907). Fig. 2.3.1.1 represents the introduction of the Stevenson Screen at long-term stations in various states using information available from the archives. Note that there was a dearth of archived information in the early part of the record for New South Wales. The archives for various states had different amounts of documentation regarding the introduction of the screen,
from very little documentation at some stations to detailed documentation for most long-term stations. It is apparent that the screen was generally introduced around the turn of the century, and that some stations had not been furnished with a Stevenson Screen until many years later. In these cases it was likely that a similar, non-standard or home-made screen had been used prior to the supply of a standard screen. Prior to the introduction of this standard, up to six different official stands and screens were in use around the country. This number excludes unique variations to the official designs, developed by individual observers.

The report of an experiment comparing the measurement of temperature in various forms of exposure was originally tabled in Parliament by Charles Todd last century, with a similar experiment reported by Russel (Ellery, 1881; 1888). From Todd’s original 1905 data, Torok and Nicholls (1993a) reported that a warm bias is apparent in the measurements made in a Glaisher stand compared with those in a Stevenson Screen. From the experimental results (Fig. 2.3.1.2) a positive bias of 1.0°F (0.56°C) in maximum temperatures and 1.5°F (0.83°C) in minimum temperatures is apparent in summer. A more comprehensive study of the same experiment by Nicholls et al. (1996a) compared 61 complete years of temperature measurements from 1887–1947 in a Stevenson Screen with those on a Glaisher stand. It was found that annual mean minimum temperatures in the Stevenson Screen were about 0.2°C warmer than those in the Glaisher stand, and maximum temperatures were between 0.2°C cooler in winter and nearly 1.0°C cooler in summer.

Parker (1990) notes that an open cage in a thatched shed was customary in the tropics, including Australia. Field (1920) compared temperatures in a thatched shed with those in a Stevenson Screen and noted higher temperatures of 0.39°C for maxima and 0.46°C for minima, averaged over a year. Overheating of the shed occurred during the day, caused by the reflection of radiation from unshaded ground outside the area of the eaves. At night, downwards longwave radiation from the roof of the shed prevented cooling. Stagnant warm air trapped under the roof also influenced the differences between the two forms of exposure. These experimental results of comparisons would vary considerably depending on the soil and vegetation type at the station.
More recently, concerns have been raised about the effect of changing from the self-registering thermometer inside a Stevenson Screen to an Automated Weather Station (AWS) with thermistor-based thermometers (Quayle et al., 1991). Differences of +0.3°C in daily minimum temperatures and −0.4°C in daily maximum temperatures were found for stations in the U.S.

2.3.2. Other specific changes at observation sites

There have been many other variations from the standards:

- A change from a large to a small screen would theoretically be expected to have a warming effect, resulting from less efficient circulation around the thermometers. This was found to be the case experimentally from a comparison of the two sizes of screen over a period of nearly one year (Andersson and Mattisson, 1991). A cooling effect on the maxima arose from the larger thermal inertia of the large screen. Some large Australian screens have been replaced with small screens in recent years.

- It was found that by employing a dirty and deteriorating screen, the effect on temperature is larger than using a totally different model of screen (Andersson and Mattisson, 1991).

- The orientation of the screen, north to south, is important so as to prevent direct sunlight entering the screen when the door is opened. However, screens are sometimes aligned with the observer’s house for aesthetic value.

- Raising the height of the legs supporting the screen will cause the minimum to be overestimated and the maximum to be underestimated and to occur later in the day, because of the diurnal behaviour of long and short wave radiation. A 0.5 m rise in height can change the temperature by 0.5°C (Geiger, 1950). This is accentuated if the land is particularly dry. Permitting surrounding vegetation to grow too high effectively lowers the screen height. As long as the screen height remained consistent, a change from wooden to iron legs, common in Australia, was unlikely to have had a noticeable effect, in spite of the higher heat capacity of iron, due to the white colour and small mass of material for the wood.

- A move from the ground to a roof top site has been seen to have a large effect on temperatures over a 10 year period between sites on the ground and on the roof of a
building 30 m in height (Laskowski, 1936). Annual minimum temperatures at the
ground were 0.5°F (0.29°C) cooler than those on the roof, and annual maximum
temperatures at the ground were 1.9°F (1.1°C) warmer.

- Variations in soil type, e.g. from clay to sand, can change the temperature by several
degrees at the soil surface, depending on the soil properties, water and air content,
and albedo (Geiger, 1950). A well kept lawn should surround the screen and not, as
has been found in Australia, bare dirt and rocks, light coloured concrete or black
bitumen, which change the albedo of the surface and consequently the microclimate.

- The effect of a wind break or shelter is proportional to its height and the wind speed
(Geiger, 1950). Therefore moves away from windbreaks, or increases in windbreak
size due to vegetation growth or building, will have an effect on temperatures.

- Moves to the airport were common in Australia as urban centres were built up,
necessitating a move to more open exposures. This coincided with the increase in the
use of meteorological information by aviation. Although these moves were common
throughout the second half of this century, most occurred in the 1940s and 1950s
(Fig. 2.3.2.1).

- Moves from coastal sites to airports further inland (e.g. at Cooktown in 1987) have
the effect of reducing the sea breeze. Hence the maximum would occur later and
probably be higher. However the minimum would be lower, particularly in the winter
months when the high land temperatures would not be maintained by the warmer
ocean temperatures. Details about moves were sometimes not provided, or only a
vague idea of distance was given—in one case the distance moved was described as
“five minutes walk”.

- The minimum thermometer was often the instrument with the most problems (other
than the wet bulb thermometer) as inferred from letters and inspections in the
documentation. Problems with bubbles and breaks were more common with the
minimum thermometer’s spirit column than with the maximum thermometer’s
mercury. It also had the problem of an index that slipped back through the spirit
column when the thermometer was vibrated. These difficulties confound the problem
of the minimum temperature being more susceptible to changes in the microclimate.
The maximum thermometer was easily supplied from the manufacturer and thus the
record is relatively good in a temporal sense, whereas if a minimum recording
thermometer was broken replacement could take up to a year.
Author/s:
Torok, Simon James

Title:
The development of a high quality historical temperature data base for Australia

Date:
1996

Citation:

Publication Status:
Unpublished

Persistent Link:
http://hdl.handle.net/11343/39449

File Description:
v.1 Title page - p.47

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